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Lifestyle, Energy Efficiency, and Climate Action

PROCEEDINGS OF ENERGISE 2023

Lifestyle, Energy Efficiency and Climate Action

A Compilation of Select Papers Presented at Energise 2023 November 1–4, 2023, New Delhi, India
Hosted by the Alliance for an Energy Efficient Economy (AEEE) in Collaboration with:

CRDF CEPT RESEARCH AND DEVELOPMENT FOUNDATION
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Preface

India is making a robust and sustained effort towards sustainable growth and a climate-conscious lifestyle, aiming to reduce emissions intensity by 45% by 2030 from a baseline of 2005 and achieve net zero emissions by 2070. These objectives are enshrined in the revised Nationally Determined Contributions (NDCs), the Lifestyle for the Environment (LiFE) movement, and India's presidency of the G20. Energise 2023 aligns with India's national efforts and is structured around lifestyle, energy efficiency, and climate action. By soliciting papers under three main categories—Buildings, Cities, and Governance and Markets—we aspire to make Energise 2023 one of the most significant and pertinent research-focused conferences addressing energy efficiency, net-zero goals, and resilience in the built environment. The third edition of the Energise conference, hosted by the Alliance for an Energy-Efficient Economy (AEEE) in collaboration with the CEPT Research and Development Foundation (CRDF), the Indian Institute of Technology Delhi (IITD), and the Indian Institute for Human Settlements (IIHS), took place from October 1st to November 4th 2023, in Goa, India. This conference brought together civil engineers, urban architects, policymakers, technology experts, and related professionals to showcase the latest developments and advancements in energy efficiency within buildings, cities, governance, and markets, contributing to sustainable development and offering a platform for discussions on future energy efficiency directions.

Approximately 160 abstracts were submitted and rigorously peer-reviewed by the conference steering committee along with a panel of esteemed reviewers. From these, about 60 full technical papers were chosen for presentation at the conference. This published volume features 37 of these peer-reviewed papers.The conference was organized around three central themes: (1) Buildings, (2) Cities, and (3) Governance and Markets. The Buildings theme concentrated on improving energy efficiency and achieving decarbonization in architectural designs. The Cities theme advocated for a holistic strategy to enhance energy efficiency within urban areas, focusing on elements such as urban planning, data management, and the integration of essential infrastructure with renewable energy sources. Lastly, the Governance and Markets theme highlighted the urgent need for robust policy frameworks and dynamic markets to underpin energy efficiency governance, which is crucial for facilitating sustainable energy transitions and development.

Efforts towards utilizing innovative and sustainable solutions, as well as efficiently managing existing resources, are crucial for enhancing the quality of life in urban environments worldwide. We trust that this publication will serve as a valuable resource towards this endeavour. The publication of these peer reviewed Proceedings has been a collaborative effort, and we extend our sincere appreciation to all who contributed to making it possible. Special thanks to Prof. Rajan Rawal (CEPT University), Prof. Amir Bazaz (Indian Institute of Human Settlement (IIHS)) and Prof. Dibakar Rakshit (Indian Institute of Technology Delhi (IITD)), Mr. Prasad Vaidya (Director, Solar Decathlon India) and Dr. Satish Kumar (President and Executive Director, AEEE) for their active assistance in the publication of the Proceedings

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A Wholistic Housing Solution for Onsite Construction Workers

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Highlights

- Modular System for onsite construction housing, designed as DIY kit.
- Wall paneling system designed for thermal insulation.
- Use of eco cooler
- Design and prototyping focusing on affordability, scalability, and adaptability.

Abstract

Construction workers are among our cities' most important service providers, but their contribution to the urban economy is frequently overlooked. Most construction workers are migrants, and the primary reason for their migration is to find good job opportunities along with an improved standard of living. The big question is whether this migration and growth of the infrastructure industry benefits the migrant workers' standard of living. The primary goal of the research has been to design and test a prototype housing system for onsite construction workers for indoor environmental quality. It presents a part of the ongoing research examining the parameters that influence the onsite housing system for construction workers in terms of building materials, services provided, and indoor environmental comfort. Simulation studies were carried out using Design Builder software to assess the annual performance, operational energy use, and indoor thermal comfort condition of the Business-as-usual case and the proposed design case. The EPI for the Business-as-Usual Case is 31 kWh/m^2, while the EPI for the Design Case is 19 kWh/m^2. To put the idea to the test, an actual prototype of a construction worker housing system was created and tested for thermal performance and user experience, along with onsite installation and long-term viability. The primary findings of the study are that onsite workers living in modular prefabricated housing can achieve indoor environmental comfort by using a wall paneling system made of paper honeycomb board sandwiched between powder-coated G.I. sheet can provide thermal comfort with additional aluminum bubble wrap insulation for the roof. Lower U values for the wall assembly and the use of Eco coolers, a passive cooling system, have increased thermal comfort and ventilation, respectively. The research also evaluated the affordability, scalability, and adaptability of the suggested prototype for a holistic housing system. The current study's objective is to assess how well the created unit performs in Pune or another city with a comparable climate.

Keywords: Onsite Construction Workers Housing, Thermal Comfort, Modular Construction, Eco Coolers, Data Loggers

Introduction

The construction sector is one of the biggest employment generators in India. The infrastructure projects that lead to the growth and development of cities generate employment for migrant workers who come from all parts of the country to earn money and grow. But the major question is, are these migrant workers getting any share of this growth? A Construction worker who is the most integral part of the construction sector, is most vulnerable and often gets neglected. We have seen great development in the architectural world, from small shacks to high-rise buildings, but the living conditions of these workers have not changed much [1].

In addition to minimum wages, overtime pay, and weekly off, migrant construction workers should be provided with comfortable housing and other social security benefits under labour laws [2]. As a result, it is the developers' responsibility to ensure that the working conditions for their construction workers meet some basic standards. To understand the developer's perspective and the challenges they face with migrant construction workers, we must first understand that these construction workers are typically migrants who stay onsite for anywhere between 3 months to 3 years. Because construction site locations change repeatedly, developers end up providing these workers with temporary shelters, as building a permanent residence for construction workers does not provide builders with any direct financial benefits, as a result jeopardizing their comfort [3].

Indoor thermal comfort affects humans psychologically and physiologically. It positively impacts health and productivity and improves the sense of well-being [4]. Thermal comfort is defined as "that mental state expressing satisfaction with the thermal environment." The ASHRAE-55 standards recommend an indoor temperature of 26°C for long-term thermal comfort. For all types of buildings, Indian codes require uniform comfort temperatures ranging from 23 to 26°C [5].

For these reasons, thermal comfort for all should become an important goal for all developing countries. Under the 2030 Agendas for Sustainable Development that proposed 17 Sustainable Development Goals, Goal 11 says to make cities and human settlements inclusive, safe, resilient, and sustainable, while target 11.1 of the Sustainable Development Goals aims to "ensure access for all to adequate, safe, and affordable housing by 2030."Developers should consider SDG goals and plan for inclusive development. They should provide these migrant onsite workers with adequate housing that is modular, adaptable, and thermally comfortable so that workers are happy and productive as a result of the comfort they have in their homes [1].

Method

The research was conducted in three stages, starting with a literature review, which was conducted by reading various papers and articles related to the research topic to gain an overview of current research, establish understanding and relevance of research, and identify gaps in current research. The literature review also helped to select a method to be followed for the study.

The next step was to establish a methodology, which is a combination of interviews, case studies, observations, and content analysis. As a result, quantitative data about the selected parameters was gathered via onsite measurements and physical building assessments, and qualitative data was obtained via an occupant satisfaction survey to gather first-hand information about users' experiences of living in labour housing. Leading developers in Pune were identified for research purposes. The primary goal of data collection is to gain a comprehensive understanding of onsite workers' housing and user comfort, for which an interview-based survey of construction workers and developers was conducted. The sample selection was purposive due to permissions to access construction sites.

A survey of 5 officials from the developers' side and 33 construction workers from various backgrounds was randomly conducted. Onsite workers (Male/Female) were the primary respondents. With the help of a pre-tested structured questionnaire, data was collected focusing on user comfort, details of construction techniques, materials, their thermo-physical properties, and various schedules based on the occupant's behaviour and occupancy. The data collection included specific information about comfort in the summer and winter. Other parameters include providing water for drinking and other uses by constructing or organizing necessary water-related infrastructure, sanitation infrastructure, sewage disposal, drainage, solid waste management, provision of electricity, and facilities like creche, health services, and recreation areas.

Further mapping exercise was carried out where photographic documentation and physical measurements were taken to capture the current situation. For checking indoor environmental comfort, Spot measurements of specified parameters of comfort, mainly temperature, humidity, air movement, and air quality, were taken using Five in one meter and a CO_2 data logger.

Figure 1: Interior and exterior spaces at labour camp (Business-as-usual case)

Findings from Developers Survey and Construction Workers Survey

Construction workers occupy housing on construction sites anywhere between 3 months to 6 years. Feedback says indoor temperature in summer is typically unacceptable, there is no ventilation, and lighting conditions are very poor. All the workers use mechanical ventilation, mostly ceiling fans, as an adaptive strategy to reduce temperatures. Following is the set of questions asked to the onsite construction workers as part of the survey:

What is the typical size of one usnit?

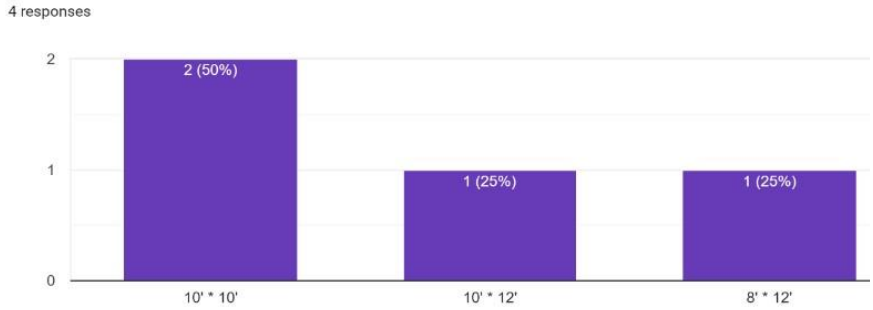

Figure 2: Graph Showing the typical size of labour unit

What materials are used for the construction of housing units for onsite workers?

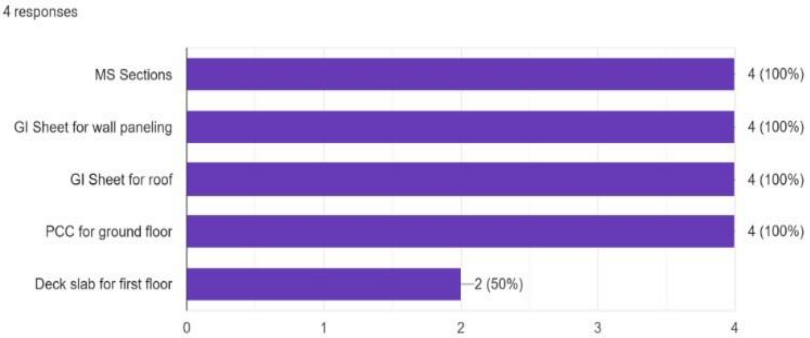

Figure 3: Graph showing materials used for construction

Can these materials be reused again?

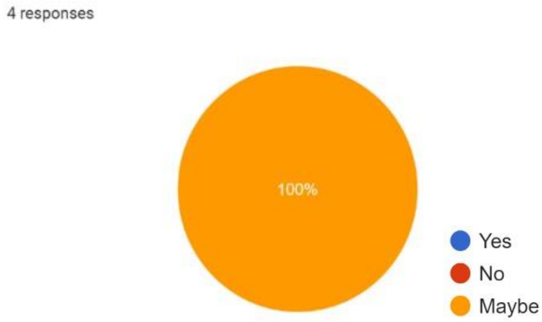

Figure 4: Graph showing the reusability of materials

What is the duration of the construction period for a particular project?

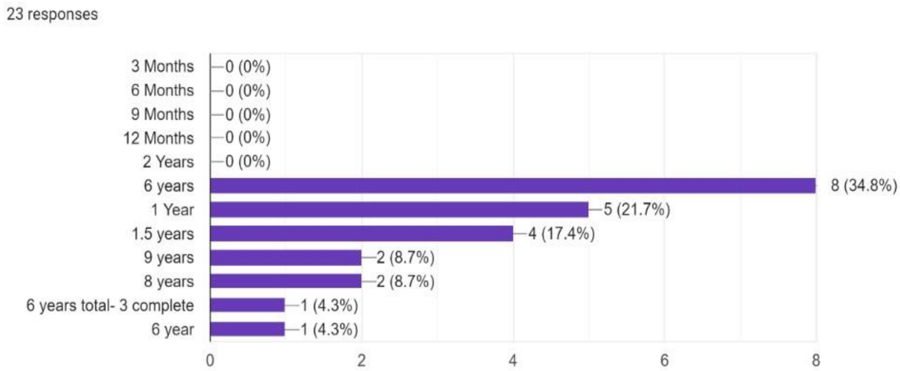

Figure 5: Graph showing the duration of construction

What is the typical duration of occupancy of a construction worker on site?

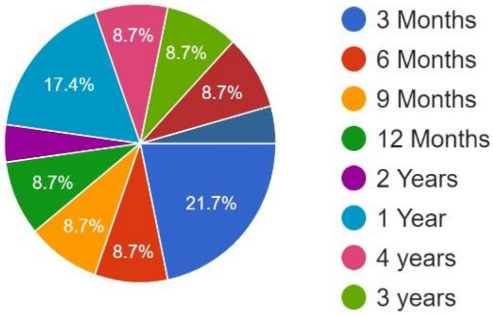

Figure 6: Graph showing occupancy of construction workers on site

Daylight in the house

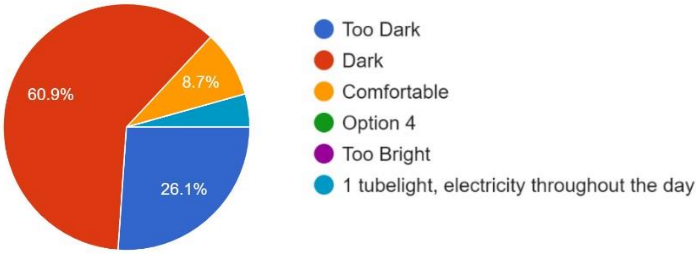

Figure 7: Graph showing daylight hours in the workers' housing unit

Indoor temperature in summer

Figure 8: Graph showing indoor temperature

Air Movement /Ventilation

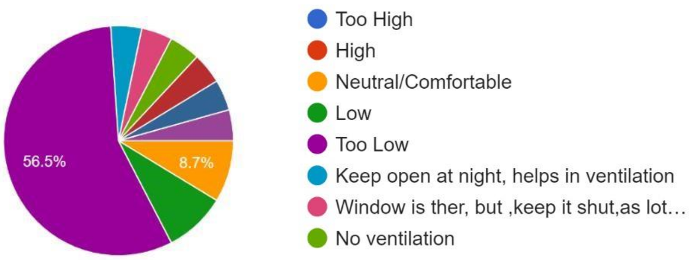

Figure 9: Graph showing the ventilation rate

What is the adaptive strategy in summer?

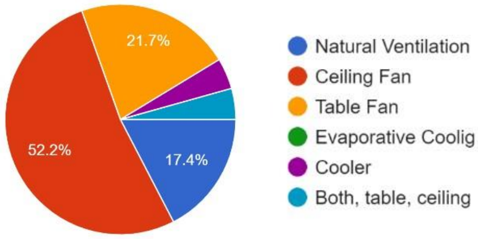

Figure 10: Graph showing adaptive strategy for summer

Based on the literature review and data gathered from the site, the users were not comfortable inside the existing housing due to harsh temperatures and no ventilation. It was decided to build a prototype unit for onsite construction workers' housing to improve environmental comfort parameters. The proposed design's ideation was completed. Design Builder, an energy simulation tool, was used to simulate comfort in the proposed prototype, which was later built to evaluate the thermal comfort solution provided. A comparative analysis of current housing and the proposed prototype was carried out to evaluate thermal comfort. Data loggers were installed in one of the units from the current worker housing unit and proposed built prototype. The data was recorded for 15 days, from the 29th of April to the 15th of May 2022.

A design approach was developed in the last stage based on the literature review and data gathered from the site. The users were not comfortable inside the existing housing due to harsh temperatures and no ventilation. It was decided to build a prototype unit for onsite construction workers' housing to improve environmental comfort parameters.

The proposed design's ideation was completed. Design Builder, an energy simulation tool, was used to simulate comfort in the proposed prototype, which was later built to evaluate the thermal comfort solution provided. A comparative analysis of current housing and the proposed prototype was carried out to evaluate thermal comfort. Data loggers were installed in one of the units from the current worker housing unit and proposed built prototype. Feedback from users was taken at this stage.

Design development of proposed prototype:

Two cases were considered for design development: business-as-usual case and the design case. The business-as-usual case is the existing housing units. These units have metal pipes as structural elements, corrugated metal sheets for the wall and roof paneling, often in poor condition due to multiple reuses, and no or poorly done flooring. The units were hot to live in during the summer. There are no windows and only one door, resulting in insufficient natural light and ventilation. Environmental comfort is rarely considered in this case. The findings from the survey of construction workers say that indoor temperature in summer is typically unacceptable; there is no ventilation, and lighting conditions are very poor. All the workers use mechanical ventilation, mostly ceiling or table fans, as an adaptive strategy to reduce temperatures. The literature review also states that construction workers are the most neglected people in the construction industry, and there is a strong need to redefine labour accommodation. A new design approach to address these issues concerning onsite construction workers' housing requirements was developed through a design case that focuses on providing a comfortable abode to this working class. To achieve this aim, the design intent was defined, focusing on achieving comfort for the user by selecting an appropriate building system and materials constructability of the module. Manufacturing and assembly were also considered in the design case.

To incorporate thermal comfort concepts into affordable housing, POE performance indicators like Design quality, building layout, Interior and exterior appearance, Access to campus facilities, quality of the indoor environment (IEQ), Improved indoor air quality- The quality of air within a facility or the built environment, Acoustic comfort, Visual comfort, Security and fire protection, quality of building support services were identified [6].

Wall and roof assemblies were selected for research as they provide a unique opportunity for energy conservation as these surfaces receive most of the solar radiation. Criteria for selection materials in the proposed case were durability, low cost, local, and healthy comfort creating. At the same time, the parameters defined for the system were sturdy, reusable, transportable, modular, lightweight, additive, fireproof, and waterproof. A series of experiments were carried out to finalize the material and system for the proposed prototype. For wall paneling, various assemblies of material were explored. These assemblies were analyzed for durability, cost, maintenance, strength, moisture resistance, fire resistance, and, most importantly, the thermal comfort they provide. Based on the comparative analysis of assemblies, in the proposed prototype, a paper honeycomb board for the wall paneling is used because it is a good thermal insulator due to the presence of air cavities. It is an indefinitely recyclable material made from wastepaper, which is why it is not naturally waterproof. That's why it is sandwiched between a powder-coated G.I. Panel, which also helps to prevent fire. It is light, strong, and stiff, which helps in building modular systems.

The proposed prototype's walling assembly is 35 mm thick and is fixed within a 50 mm M.S. section. It does not need to be plastered. The components in this assembly can be recycled and have a good market presence. The value of this assembly was checked using the Testo 635 U-value promo set, which essentially measures a material's thermal insulation properties. For the roof, along with G. I. Sheet, an Aluminum bubble wrap sheet is used to control the heat gain from the roof.

(1) (2) (3) (4)

Figure 11:(1) M.S. pipe for the frame, (2) Honeycomb board wall panelling, (3) cement sheet for the floor, and (4) G.I. Sheet with aluminium bubble wrap for insulation

In the business-as-usual case, it is clear from the survey and onsite observations that there is no provision for a window. Ventilation is another crucial aspect of creating a comfortable indoor environment. A highly cost-effective method of improving indoor ventilation is the eco cooler. Mr. Ashis Paul of Bangladesh devised this straightforward assembly. Discarded PET bottles are split in half, fixed on a plywood panel, and then mounted on a window frame. By enabling improved ventilation, this ventilation technique improves not only indoor air quality but also lowers the interior air temperature, which is used in the proposed design case [7].

Figure 12: Eco Cooler

Modular construction is a relatively new concept in India. This concept requires awareness and education among builders and developers in order for its application to be maximized [8]. To make the proposed solution practical, scalable, affordable, and adaptable, it must be simple and quick to build, and that is why modular construction is one of the key approaches used in the proposed prototype.

The prototype has been designed as a DIY kit that can be easily assembled or dismantled on site. The construction of the proposed unit was done in 3 stages: manufacturing, packaging, and transportation. The process of onsite installation is explained in Figures 12, 14, and 15.

Figure 13: Bucket Foundation

Figure 14: Installation Process

Figure 15: Prototype

Conclusion

Despite being the key stakeholders in the construction industry, migrant workers are sometimes disregarded when it comes to ensuring a decent quality of life. According to the research and survey, these onsite construction workers work largely indoors in the evenings and outdoors throughout the day. As a result, it is critical that the workers should feel comfortable inside the dwelling unit at night. The energy simulation technique, as well as survey data, demonstrate that in the current scenario (business-as-usual case) of a temporary dwelling unit, indoor environmental quality is poor due to heat build-up via the envelope and a lack of ventilation. U value of the structure was reduced by increasing the thickness of the envelope using prefabricated paper honeycomb board sandwiched panels and adding aluminium bubble wrap insulation to the roof, resulting in less heat gain and lower temperatures, resulting in better indoor comfort. The addition of an entrance and the usage of eco-coolers aid in ventilating and lowering the temperature of the planned unit. Moving this research forward will necessitate a focus on wall panelling thickness to increase thermal mass and limit heat gain even further.

This research has helped the development of a modular onsite housing system for onsite construction workers that is comfortable to live in. The onsite live-scale prototype building and testing for indoor environmental parameters, as well as user feedback, helped to create a statement of assurance of the workability of the structure and indoor thermal comfort for the users. The research conclusions will be significant to emerging countries where construction workers are important development stakeholders.

Acknowledgements

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An Investigation Into Adoption of Green Measures Within Green Building Rating Programs For Affordable Housing In India

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Highlights

- Green Affordable Housing (GAH) project's sustainability is expressed using four Key Parameters: Climate Response, Climate Resilience, Gender Sensitivity, and Affordability.
- Relationships between prevailing Green Building Rating Programs' (GBRP) criteria and Key Parameters explored.
- Insights into the on-ground execution of GBRP criteria gathered from Green Building Rating Agencies and Consultants.
- Gaps in the prevailing GBRPs were identified.
- Suggestions are made to prevailing GBRPs to enhance their future relevance.

Abstract

Resource-efficient buildings conducive to occupants' health and well-being are termed Green Buildings (GB). Dedicated organizations, called Green Building Rating Agencies (GBRA), are involved in formulating Green Building Rating Programs (GBRP). The GBRPs feature predetermined, intent-based Rating Criteria (RC). Their rating mechanism is based on a relative comparison between the building's base-case and Green-iteration, apathetic to its absolute operational performance.

This study identified four Key Parameters: Affordability, Gender Sensitivity, Climate Response, and Climate Resilience, representing a Green Affordable Housing (GAH) project's holistic – Financial, Social, and Environmental – sustainability. GBRPs were studied to gauge whether and to what extent the RC embodies the Key Parameters. Concurrently, inputs regarding the on-ground execution of GBRPs were gathered from GBRA and Consultants. This study illuminates the gaps in the prevailing GBRPs and makes suggestions to maintain their future relevance. It concludes with the requirement of a rating framework anchored to absolute design baselines and operational performance benchmarks.

Keywords: Green Building Rating Programs; Green Affordable Housing; Climate Resilience; Adaptation; Holistic Sustainability

Introduction

Humans' ever-increasing desire for fast-paced progress has led us to rely heavily on fossil fuel-based mechanical and economic systems, resulting in incessantly increasing carbon emissions, global warming, and climate change. The continual rising of the earth's surface temperatures, disruption of natural weather patterns, and extreme weather events such as heatwaves, flash floods, cyclones, wildfires, droughts, etc., are manifestations of climate change [1]–[5]. These events are predicted to worsen consistently in the coming years, having already resulted in the loss of more than 2 million lives and USD 4.3 trillion in the last five decades [6]. Countervailing efforts to mitigate and adapt to the aggravating climate change scenario are bound to impact individuals, communities, and industries alike.

Construction is the world's biggest industry, constituting thirteen percent of the global Gross Domestic Product (GDP) [7]. On the one hand, the construction industry is responsible for more than one-third of global carbon emissions [8]. On the other hand, it is severely vulnerable to extreme weather events. Such events would not only physically distress the building's construction workers and occupants but also endanger its asset value. Confronted by these consequences, the construction industry, including all products and processes, is currently exploring decarbonization pathways to develop in a sustainable and secure manner. One such market initiative to propel sustainability was Green Buildings (GB). By definition, these are buildings planned, designed, constructed, and operated in a manner that consumes fewer resources, is energy efficient, and is conducive to occupants' health, comfort, and well-being [9]. Dedicated organizations, called Green Building Rating Agencies (GBRA), are currently in place at national- and international levels. Their primary functions include a) formulating Green Building Rating Programs (GBRP) applicable nationally or internationally, tailored to various building typologies, and b) awarding a building 'Green' certification by examining whether it has been designed and constructed as per the GBRPs. Essentially, GBRPs encompass Rating Criteria (RC) that deal with optimizing design, resource use, and construction practices. Another set of organizations involved in the on-ground implementation of GBRPs are Green Building Rating Consultants (GBRC); they play a pivotal role in ensuring the building is executed per the GBRP's requirements.

GBs are treated as a pinnacle in the built environment. They are often sold or rented at a premium, although their incremental development cost in comparison to conventional buildings may be reasonably small [10]. GBs also have significantly lower operational costs. However, their higher upfront cost makes them unaffordable, thus making them inaccessible to the Economically Weaker Section (EWS) and the Lower Income Group (LIG). These groups of people are the most vulnerable to the ill effects of climate change, making it all the more important for them to have access to sustainable residences that are resilient to extreme weather events. Notably, a vast demand-supply gap already exists globally in the affordable housing market. With more than half of the world's population dwelling in cities in 2022 [11], governments worldwide have been struggling to bridge the affordable housing gap. Developing sustainable/Green residences amidst the looming climate change threat is yet another challenge. Green and Affordable Housing (GAH) is the means to overcome these two challenges and unify their intents.

Countries have developed GAH projects under their social and/or affordable housing programmes [12]. India, too, is developing affordable housing through a pipeline of several central and state-level schemes. Notably, the Pradhan Mantri Awas Yojana (PMAY) scheme has contributed to both affordability and sustainability. Alongside developing affordable housing, the scheme has prioritized occupant comfort by incorporating new and alternative construction materials, technologies, and passive design features [13]–[15]. Furthermore, the development of 'adequate, safe, and affordable housing' is one of the United Nation's seventeen Sustainable Development Goals (SDGs); it can further give impetus to other goals, such as 'clean and affordable energy,' 'gender equality,' and 'responsible consumption and production,' unlocking development and social equality [16]. In the context of a GB, 'sustainability' has conventionally referred to Environmental Sustainability; however, in a GAH project, it has a broader meaning. Housing is at the confluence of multiple domains; it is required to provide its occupants with the physical infrastructure/shelter while simultaneously satisfying their social and economic aspirations. Therefore, the GAH framework adopts a holistic outlook of sustainability, which may be seen as a three-tiered pyramid, wherein no one tier is compromised for the other. The types of sustainabilities and their corresponding implications for a GAH project are described in Figure 1.

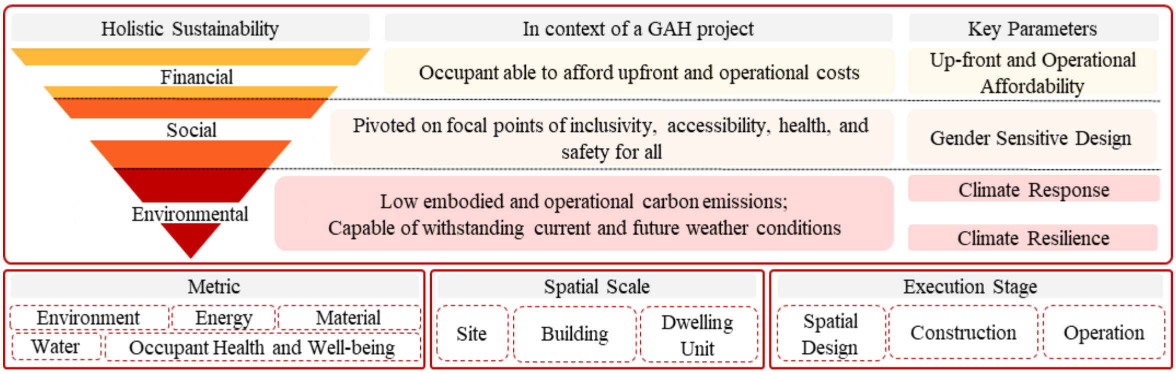

Figure 1: Pyramid of Sustainability and the Four Key Parameters

The first tier – Financial Sustainability – unlocks the means for a person of a weaker economic background to **afford** a Green residence. How affordable a product/service is is one of the primary factors determining its feasibility from the user's perspective, thus their likeliness of choosing it. Therefore, demonstrating Financial Sustainability is the first and foremost step to unlocking market demand for GAH. The second tier – Social Sustainability – acknowledges the integral social needs of the individuals and communities residing in the housing project. **Sensitivity** to the nuanced ways people of varying backgrounds perceive and use the space is at the core of rendering a socially sustainable GAH project. A gender-sensitive lens could do an excellent job of capturing the occupants' distinct contexts and satisfying their needs of inclusivity, safety, health, and well-being through design, construction, and operation. The third tier ensures that the project is environmentally sustainable, requiring the project to be: a) Planned, constructed, and operated resource-efficiently, principled to **respond** to the climatic context – reducing the project's carbon emissions, and b) **Resilient** to the present and future environment/climate and extreme weather events while maintaining a comfortable indoor environment for the users. For this study, the broader core intent of each of the sustainability tiers have been moulded into suitable Key Parameters, namely, Affordability, Gender Sensitivity, Climate Response, and Climate Resilience, shown in Figure 1. Their definitions have been elaborated in Table 1.

These parameters can explicitly communicate the underlying measure to achieve each sustainability tier; they are specific and may be quantified with the help of checklists and/or metrics. The following points shall help the reader gain insight into the author's thought process behind selecting each Key Parameter and their significance from the perspective of affordable housing:

Table 1: Key Parameters and Definitions

Key Parameter	Definition
Climate Response	Defined in terms of how a person, household, community, organization, or state acts in response to climate change. Their response would involve responding to the climate change already in the pipeline, ***reducing emissions***, and stabilizing the levels of heat-trapping greenhouse gases in the atmosphere [1].
Climate Resilience	Defined as the ability of social, economic, and environmental systems ***to cope with a hazardous event***, trend, or disturbance. This would involve responding or reorganizing in ways that maintain their essential function, identity, and structure while also maintaining the capacity for learning and transformation [1]. The "hazardous events" for the scope of this study have been limited to heatwaves and floods – since India is a tropical country and more susceptible to the said events.
Affordability	Generally defined with regards to unit size and cost, occupant's income, and the unit cost-to-income ratio. This study adopts the PMAY guidelines' definition of affordable housing, mentioned below [17]: Unit size: The carpet area of Dwelling Units is required to be up to 30 m^2 for the EWS category and up to 60 m^2 for the LIG category. Occupant's Income: The qualifying annual household income for the EWS is set as INR 0.3 million, and for the LIG, the corresponding value is between INR 0.3 million and INR 0.6 million. This study simply appeals that the upfront and maintenance costs be affordable for the occupant; however, the study does not want to prescribe a specific – absolute or percentage – value to affordability. The GBRPs are free to adopt a befitting value in terms of GB's incremental development cost, unit-to-income ratio, and so on.
Gender Sensitivity	Refers to the ability to acknowledge and highlight the existing gender differences and inequalities between women and men. It guarantees that such ***differences are factored into the design*** and implementation of policies and actions [18]. It is an approach of holistic planning of the built environment, manifesting as but not limited to: • Conscious selection of the GAH site: ensuring proximity to social and public infrastructure. • Appropriate spatial planning: incorporating parks, recreational, entrepreneurial activities, and social gathering spaces. • Dwelling Unit being designed to adapt to occupants' evolving spatial and social needs. • Dwelling Unit being solely or jointly owned by the household's women.

- Affordability: A project would be financially sustainable if it is affordable on an upfront- and operational basis, in line with the definition of affordability.
- Gender Sensitivity: Gender Sensitive design principles pay careful attention to aspects of safety, health and comfort, and inclusivity at all spatial scales. These aspects are equally relevant to and affect all residents. However, females, children, and the elderly spend more time indoors than their male counterparts; hence, the appropriate fulfillment of these aspects would hold relatively higher importance for the former group. Integrating a gender-sensitive design lens would illuminate the challenges women face in the parlance of affordable housing and overcome them by including women as critical stakeholders in the decision-making process.
- Climate Response: A project's local climatic and geographic context provide crucial clues for its design. When used wisely, these clues may enlighten passive design strategies and locally available materials, which could facilitate maintaining a comfortable indoor environment, naturally, without using energy frivolous Air Conditioning (AC) systems. Hence, responding to the climate would lead to a reduction in the operational and embodied carbon emissions of the project.
- Climate Resilience: Over time, a project would be faced with extreme weather events such as heatwaves and floods. Designing with resilience in mind would ensure that the project infrastructure is physically capable of withstanding such events, simultaneously maintaining a comfortable indoor environment for its users. Notably, achieving a comfortable indoor environment without increasing the economic burden on occupants makes the four Key parameter *tenets* of a successful GAH project.

The study has contextualized the Key Parameters' conceptual definitions in terms of physically implementable measures, such that the intent behind the Key Parameters is met. As mentioned in Figure 1, the measures may be applicable at various 'Spatial Scales,' i.e., the entire project (*Site*), one building block (*Building*), and one residence (*Dwelling Unit*), and incorporated during the *Design*, *Construction*, and/or *Operation* 'Execution Stages' of the project. These measures may be in terms of design optimization and integration of components; their efficacy may easily be assessed in terms of 'Metrics,' i.e., resources – by examining a change in their consumption. For instance, Climate Response measures would be (a) using finishes with a high Solar Reflective Index (SRI) – at *Site*-scale, (b) using appropriate walling material having low thermal transmittance value – at *the building* scale, and (c) designing for optimized ventilation – at *Dwelling Unit*-scale.

This study assesses prevailing GBRPs from the perspective of the four key parameters and provides suggestions to maintain their future relevance in the parlance of GAH. The study's objectives included conducting a detailed study of the prevailing GBRPs, understanding whether and the extent to which the RC embodied the Key Parameters, and studying the current market trends concerning GBRP execution by conducting surveys with GBRA and GBRC.

Methods

This study's first stage involved a detailed review of the following GBRPs: The Green Affordable Housing Rating Program from the Indian Green Building Council (IGBC), the Green Rating for Integrated Habitat Assessment (GRIHA), and the Sustainability Certification from the Green and Eco-friendly Movement (GEM) and Excellence in Design for Greater Efficiencies (EDGE) [19]–[22]. The authors selected these GBRPs solely based on their availability in India; this study treats all these GBRPs as independent entities, not comparing them against each other. All GBRPs mentioned above are voluntary compliance-based, encompassing RC related to optimizing the following Aspects: Site, Energy, Environment, Water, Waste, Material, and on-site Practices. While the IGBC and GRIHA have a dedicated GBRP for affordable housing, the GEM and EDGE GBRP apply to all residential, commercial, and factory buildings alike. The Green Affordable Housing Program from the IGBC is a 75-credit-based program, requiring a minimum of 38 credits for certification, with four certification levels, namely – Certified, Silver, Gold, and Platinum; the GBRP from GRIHA is a 100-credit-based system, requiring a minimum of 25 credits for certification, with one-to-five-star certification levels. Similarly, the Sustainability Certification from GEM is a 135-credit-based system, requiring at least 40 credits for certification, with Gem 1 to Gem 5 certification levels. However, the EDGE GBRP is not a point-based system; it calculates the certification level with respect to the project's savings in water, material, and energy. Here, the project would receive a Level 1 certification by achieving 20% savings in water and material. Moreover, the project could receive a Level 2 or Level 3 certification based on the additional savings achieved in energy, i.e., 40% for Level 2 and 100% for Level 3.

Detailed study of the GBRPs led to categorizing the RC into 'Aspects,' 'Variables,' and 'Attributes.' Here, Aspects refer to the overarching domain addressed by the RC, Variables refer to the sub-domain-level strategies, and Attributes refer to the detailed micro-level measures required to achieve compliance. The elaborate list of Aspects, Variables, and Attributes can be found in Figure 3. After that, the relationships between the RC and the Key Parameters were assessed to understand whether and to what extent did the GBRPs embody the latter. Firstly, the one-on-one relationships between the Attributes and the Key Parameters were assessed; the resultant relationship between an Aspect and Key Parameter was derived by averaging the relationship scores of all Attributes of that particular Aspect. The relationship score was marked on a scale of 0 to 2, where 0 indicated 'No Relationship,' 1 indicated an 'Indirect Relationship,' and 2 indicated a 'Direct Relationship;' it was assigned based on the degree of explicitness of the Attribute's connection with the Key Parameter. The relationship scores were marked by building science researchers and GB professionals with a background in architecture, civil, and mechanical engineering, a post-graduate degree, and four years' worth of work experience in the construction industry. The following set of questions was framed to help the building science researchers and GB professionals assign relationship scores:

a) Affordability: Does the Attribute impact the project's upfront and operational costs?
b) Gender Sensitivity: Does the Attribute contribute to acknowledging and satisfying the needs of various occupant categories?
c) Climate Response: Does the Attribute impact the project's carbon emissions?
d) Climate Resilience: Does the Attribute impact the project's ability to withstand heatwaves and floods? How would the Attribute help maintain a comfortable indoor environment?
e) An additional question was posed to help understand the explicitness/directness of the relationship: Can the link between the Attribute and Key Parameter be described as a one-step cause-effect dynamic?

Essentially, the relationship only represents the magnitude of correlation and not its direction – positive or negative. For instance, the relationship score between the 'On-site Renewable Energy' Attribute and Climate Resilience is 1.67, implying that they are directly connected. However, the relationship score does not indicate whether the Attribute improves or impairs the project's Climate Resilience.

The study's second stage involved gathering insights from the organizations engaged in the implementation of GBRPs, namely, GBRA and GBRC. Communication with the high-level officials of the leading GBRAs was established via emails, requesting information regarding the total number of GBs and GAH projects developed in the past five years, their locations, and the most commonly and rarely attempted RC by project proponents. The project location-related data was then superimposed against the following:

a) ***The State Energy Efficiency (EE) Index*** is a measure of an Indian state's readiness concerning energy efficiency [23]. This study desired to 1) test the relationship between a state's EE Index and its available resources to make improvements in affordable housing and 2) perceive whether the projects were only found to be present in those cities having a higher EE Index.
b) ***Net State Domestic Product (NSDP) per capita*** is a measure of the net value of finished goods and services of the state per capita. The NSDP per capita of 2021, for this analysis, was obtained from [24].
c) ***Climate zone*** – The National Building Code (NBC) 2016 [25] divides India into five climatic zones; classifying project locations per their respective climate zones would help determine whether projects are consolidated in a particular climate zone. Subsequently, this classification could also highlight whether there is a climate zone-based trend to achieving ratings within a tight budget.
d) ***Heatwave and Flood Vulnerability zones*** - A project's disaster vulnerability depends on location. Thus, Climate Resilience measures would also be determined with respect to the project's location. Here, the project locations have been superimposed on heatwave [26] and flood vulnerability [27] maps.

Furthermore, dedicated online survey forms were shared with thirteen – large-scale as well as independent – GBRCs requesting information concerning the GB project proponents' most commonly and rarely executed RC. The GBRCs were also asked to rank the Aspects – 'Site Selection,' 'Energy Conservation,' 'Water Conservation,' 'Material,' and 'Environmental Quality' on five-point scales representing their technical and financial feasibility.

Notably, the group of building science researchers and GB professionals involved in assigning Attribute and Key Parameter relationships was separate from the GBRAs and GBRCs.

Results and Observations

The RC in the IGBC, GRIHA, and GEM GBRPs provide detailed instructions about the method/means to be followed to achieve the credits, while the RC in the EDGE GBRP delineates the performance goal to be achieved. All studied GBRPs are pivoted on demonstrating a relative improvement between a project's base-case – one which has no regard for sustainability whatsoever, and its Green-iteration – one which has incorporated green measures. Owing to a difference in the RC nature, this study has presented the assessment of the three GBRPs: IGBC, GRIHA, and GEM. Figure 2 illustrates the credits allocated to different Aspects by various GBRPs.

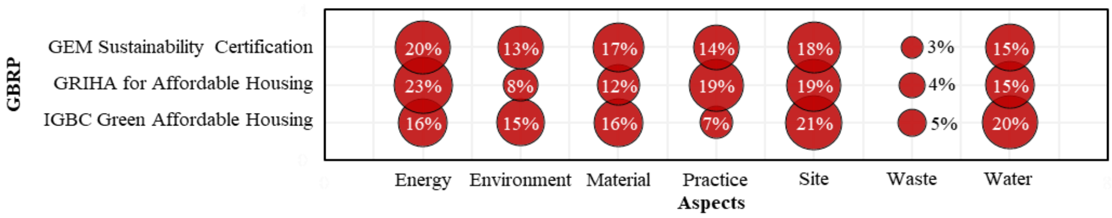

Figure 2: GBRPs and credit distribution as per Aspects

Interrelationship between the RC and Key Parameters

Figure 3 illustrates the relationship between the RC and Key Parameters. The Aspects, their corresponding Variables, and Attributes have been mentioned on the left; the individual one-on-one relationships between the Attributes and the Key Parameters have been averaged and presented as a 'Resultant' relationship between the Aspects and the Key Parameters.

The following observations can be made based on Figure 3:

- ***Affordability*** is strongly related to the 'Energy' Aspect. This is because of Attributes influencing GB's operational affordability, namely – "Incorporation of BEE 5-star rated equipment" and "Provision of on-site renewables." Figure 3 highlights that the 'Environmental' related Attributes – "Ventilation," "Daylight," and "Air quality concerns" – that have the most substantial influence on affordability are a function of window design and operation. Moreover, almost all the 'Material' related Attributes show direct relationships with affordability. Notably, the decisions concerning a) the design and functioning of windows and b) the selection of walling and roofing material are Design-stage inputs. These inputs continue to influence the GB's Affordability during the Construction-stage and Operation-stage.
- ***Gender Sensitivity*** is not directly related to any of the Aspects at the macro level. However, only a few Attributes directly related to Gender Sensitivity, namely – "Adaptive Comfort, Daylight," and "Ventilation," concern spatial

design. The rest of the Attributes directly related to Gender Sensitivity concern the provision of facilities. Moreover, the Attribute of "Access to clean sources of cooking fuel," which has a strong relationship with Gender Sensitivity, was only found in one of the GBRPs [20], surprisingly, not as a mandatory requirement.

- ***Climate Resilience*** is, essentially, the project's capacity to withstand events like heatwaves and floods. Now, the RC can only help equip the building to resist extreme heat and/or drain overflowing flood water but not directly cause the building to be immune to heatwaves and/or floods. Evidently, none of the Attributes would have a direct relationship with Climate Resilience.
- ***Climate Response*** is influenced directly by the 'Energy' and 'Site' Aspects and indirectly by the 'Environment,' 'Material,' and 'Practice' Aspects. The 'Site' and 'Environment' related Attributes deal with Climate Response by employing design strategies according to the local climate, thus reducing the indoor heat gain and mechanical cooling demand. In contrast, the 'Energy' related Attributes employ energy-efficient devices to achieve a reduction in energy consumption. Ultimately, both the design strategies and energy-efficient devices lead to a reduction in operational carbon emissions. Furthermore, the 'Material' and 'Practice' related Attributes contribute to Climate Response by targeting the reduction of embodied carbon emissions. This can be achieved by deploying innovative construction technologies and using materials with recycled content. Additionally, handling – reducing, and recycling – construction waste could significantly reduce the burden on virgin resources while neutralizing their contribution to embodied carbon emissions.

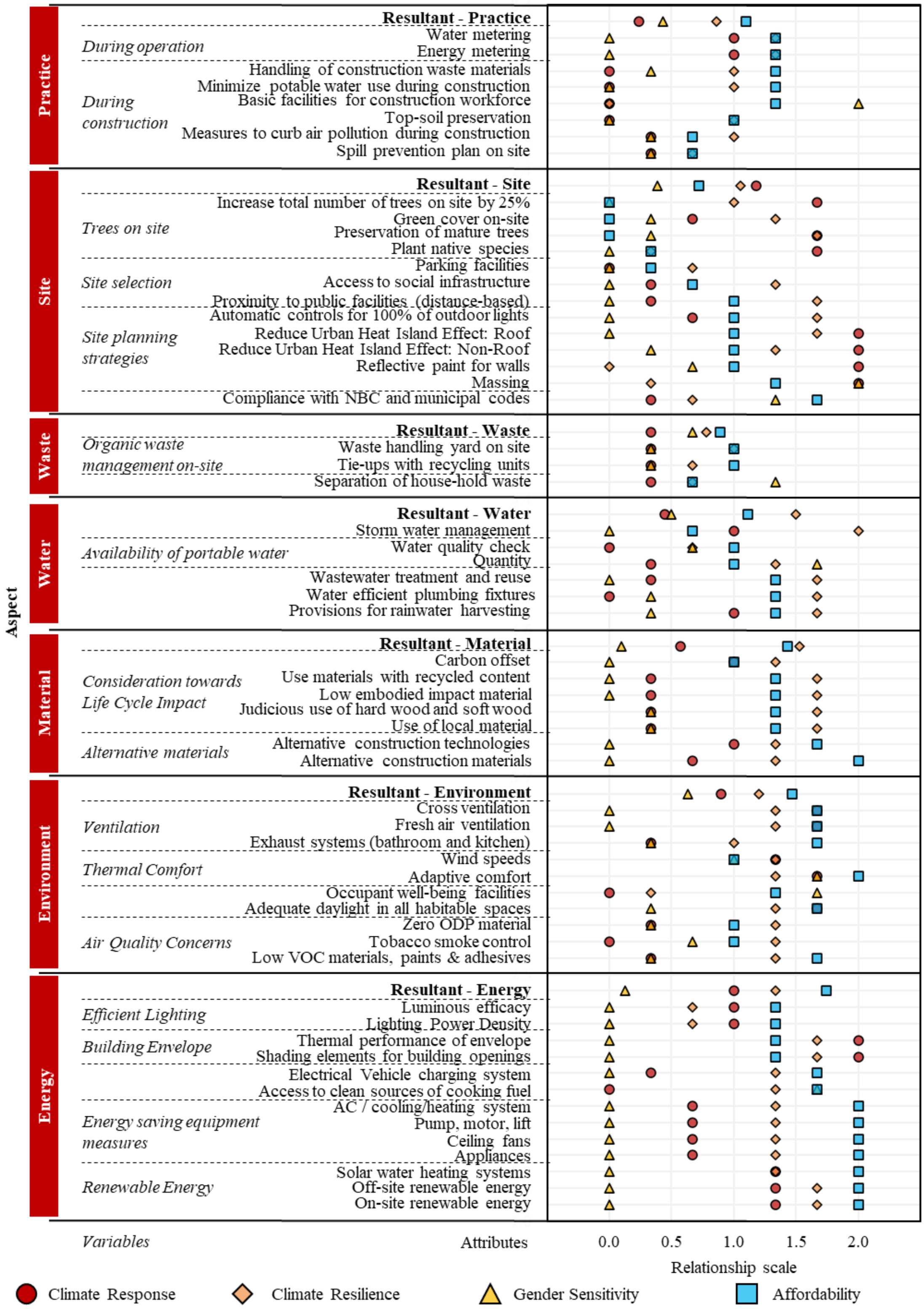

Figure 3: Interrelationship between the RC and Key Parameters

Stakeholders Insights

- ***GBRAs Insights***

The GBRAs' insight showed that the number of generic residential GB projects far exceeded that of their GAH counterparts in the last five years. Their ratio was 1:8. Figure 4 [a] to [d] visualize the project locations against the state EE Index, the NSDP per capita, the climate zone, and the heatwave and flood vulnerability, respectively.

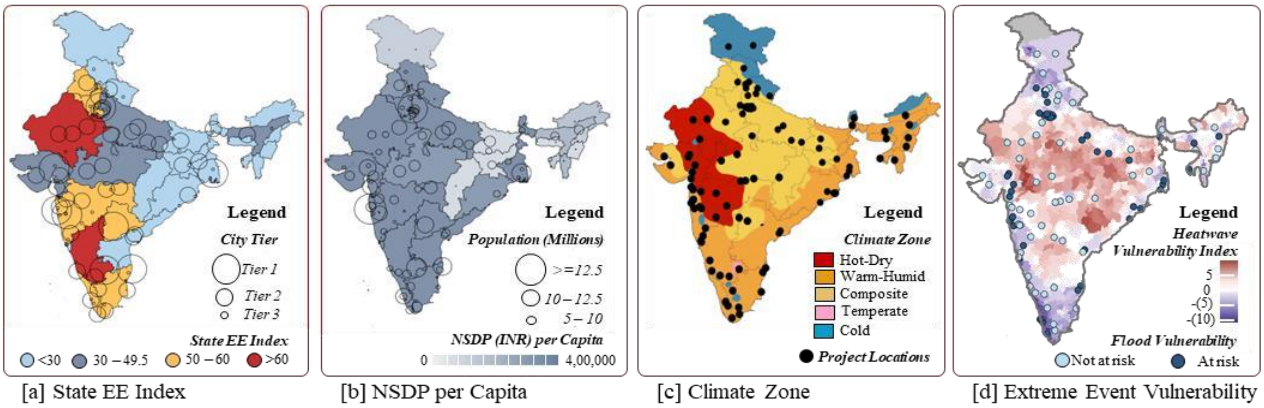

Figure 4: Correlations between Project Locations and [a] State EE Index, [b] NSDP per capita, [c] Climate Zone, and [d] Heatwave and Flood Vulnerability

Figure 4 [a] illustrates the superimposition of the project locations and the state EE index. The current study has been able to establish only an empirical relationship between the two, owing to the limited publicly available data concerning the projects. Also, the spread of GAH projects was found to be more aligned with the metric of NSDP per capita than the state EE Index, as visualized in Figure 4 [b]. In simplistic terms, this could mean that the wealthier states with higher NSDP per capita were better positioned to prioritize spending on GAH projects. Figure 4 [c] shows GAH projects to be scattered across all climate zones. Hence, no trend was found between project locations and climate zones. Figure 4 [d] illustrates the hazard vulnerability of the project locations. Here, the heatwave vulnerability was taken from [26]. It is represented as Heat Vulnerability Index (HVI) and highlighted in the form of the state's background colour, where red indicates a higher degree, and blue indicates the lowest degree of heatwave vulnerability respectively. Additionally, the flood vulnerability derived from [27] has been indicated as solid-blue-coloured circles. Figure 4 [d] indicates that the flood vulnerability has clear patterns across the coast and along the Ganga, Brahmaputra, and Sabarmati. Moreover, the central Indian states were seen to be the most vulnerable to heatwave hazards since the Tropic of Cancer passes over them. The states of Madhya Pradesh, Chhattisgarh, and Jharkhand were identified to be at the highest heatwave risk, yet they had the least penetration of GAH projects. Moreover, the states of Rajasthan, Uttar Pradesh, Maharashtra, and Odisha only had GAH projects in districts with lower heatwave vulnerability. Furthermore, the states of Uttar Pradesh and Bihar were seen to be vulnerable to both floods and heatwaves.

Figure 5 [a] illustrates the most commonly and rarely targeted Attributes per the GBRAs. The most commonly targeted Attributes were the ones related to the 'Site,' 'Energy,' 'Water,' and 'Material' Aspects. Contrarily, the most rarely targeted Attributes were the ones related to the 'Energy' and 'Practice' Aspects. Examining the Attributes' and Key Parameters' one-on-one relationship scores, it can be said that the most as well as least commonly targeted RC by GB projects can significantly strengthen Climate Response and Climate Resilience and directly contribute to affordability. Moreover, the groups of most and rarely targeted Attributes are not strongly linked with Gender Sensitivity.

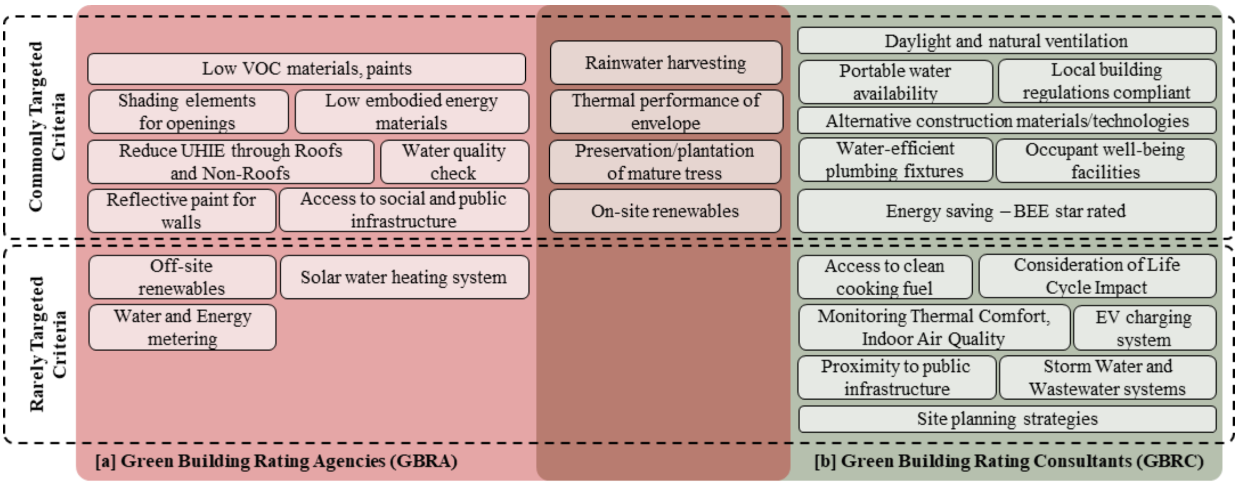

Figure 5: Most Commonly and Rarely targeted RC according to [a] GBRA and [b] GBRC

- ***GBRCs Insights***

Figure 5 [b] illustrates the most commonly and rarely targeted criteria per the GBRCs. The most commonly implemented Attributes are predominantly provision-based criteria; they have no spatial design-related implications on the project. The

GBRCs also highlighted that the Attributes of "Measures for Air Quality" and "Access to Clean Sources of Cooking Fuel" were rarely implemented in affordable housing projects. The 'Environment' related Attributes include "Provision of Proper Ventilation," "Provision of Daylight," and meeting requirements of "Adaptive Thermal Comfort." The GBRCs' responses indicate that an added money constraint would increase the difficulty and complexity of complying with those Attributes.

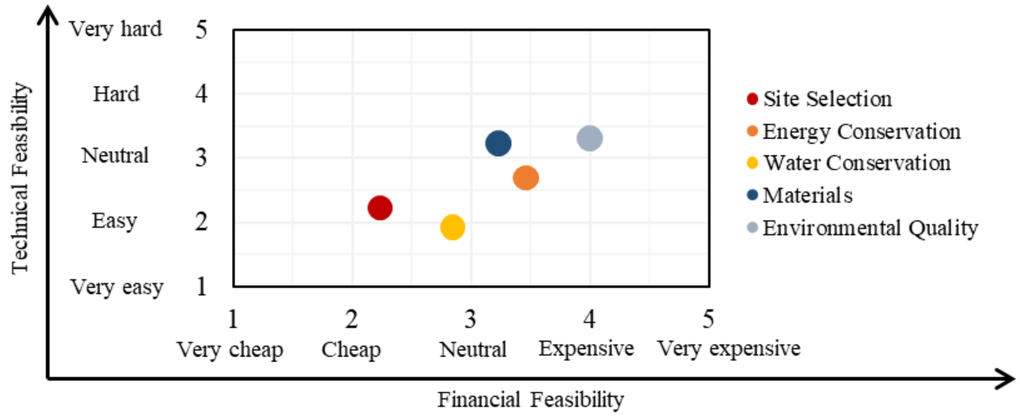

Figure 6: Technical and Financial Feasibility of Aspects

Figure 6 illustrates the average technical and financial feasibility score of various Aspects. The GBRCs' responses delineate that the 'Environment' Aspect is the most complex and expensive to implement in GAH projects. It can be seen that none of the Aspects made it to the ideal scenario, a combination of "Very Easy" in terms of technical feasibility and "Very Cheap" in terms of financial feasibility. The most viable Aspects were found to be "Water Conservation" and "Site Selection," as they fell within the "Neutral" boundary of both feasibilities.

Discussion

A list of Attributes directly (relationship score ≥1.5) influencing two or more Key Parameters was compiled and has been illustrated in Figure 7. These Attributes could impact all Key Parameters, improve occupant comfort and well-being, and render the envelope energy efficient. Moreover, compliance with Eco Niwas Samhita (ENS) [28] can achieve two Attributes. Thus, the prevailing GBRPs can benefit from including "ENS Compliance" as RC.

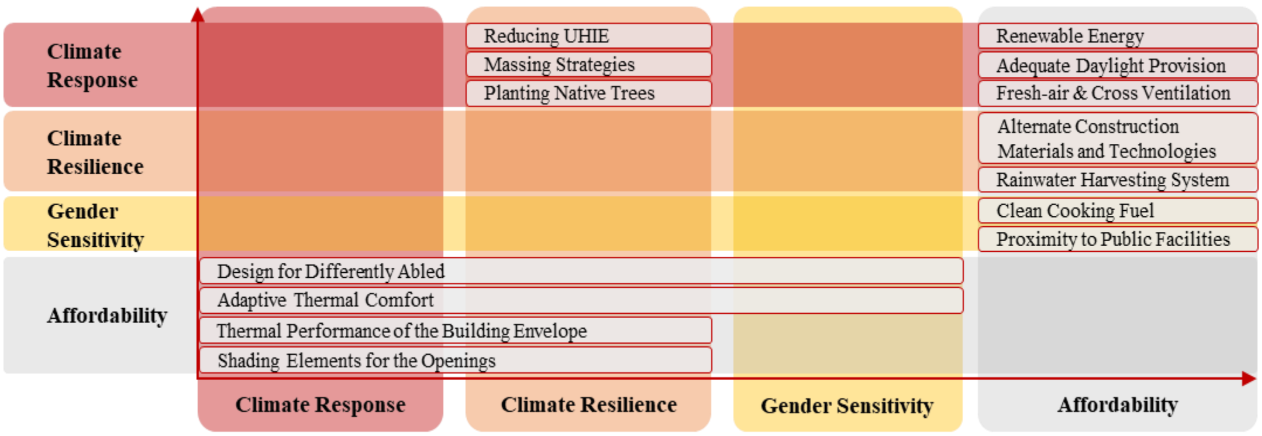

Figure 7: Attributes affecting more than one Key Parameter

The following elaborate on the gaps identified by this study:

a) ***GB's Intent Vs. Performance***: GBRPs certify buildings as '*Green*' based on their compliance with the RC – realizing the intent of the GB. However, there are little to no RC aimed at monitoring and ensuring that the certified GB also performs as a GB.

b) ***Clean Cooking Fuel Access***: It is the only Attribute that has the potential to impact operational carbon emissions and is related to Affordability as well as Gender Sensitivity. Nevertheless, this Attribute is not mandatory in any GBRP.

c) ***Incremental Cost and Split Incentive***: Incorporating green interventions in GB may be accompanied by additional upfront costs – often borne by the developer, which do not get passed onto the occupants; moreover, the occupants of GBs would pay lower operational costs. This creates a split incentive. Thus, the GBRPs can benefit from elaborating on a) the maximum incremental cost and b) the mechanism to address and eliminate the split incentive between the occupants and developers.

d) ***Climate Resilience***: GBRPs have limited RC pertaining to heatwave and/or flood resilience. It must also be noted that both these disasters have seasonal occurrences. The GBRPs do not include any RC or credits involving seasonal strategies or preventive measures for extreme-event management. Moreover, since GBs are subject to disasters of varying intensity, it would make sense for the credits to be weighted accordingly with respect to the Site's disaster prevalence and intensity.

e) ***Adaptive Thermal Comfort***: Despite recent publications [29] suggesting that most heatwave casualties occur in the EWS and LIG, the "Adaptive Thermal Comfort" Attribute was not found to be mandatory in any of the GBRPs. Moreover, occupants' overall comfort is only addressed via post-occupancy surveys, including lighting levels, temperature, relative humidity, etc., while there are no established comfort requirements to adhere to. To ensure the GB's performance as '*Green*', the thermal comfort needs to be evaluated at the design stage through simulations. Moreover, the Residential Envelope Transmittance Value (RETV), as mentioned in the ENS 2017 [28], may serve as a preliminary indicator of thermal comfort. The RETV is a measure of heat escaping into the building, thus lowering the RETV and the occupants' discomfort. This criterion is potent enough to have a significant impact on the building's Climate Response, Climate Resilience, Gender Sensitivity, and Affordability.

f) ***Embodied Energy***: GBRPs include RC concerning the embodied energy of construction materials, but they are rather prescriptive. The percentage reduction in embodied energy with respect to a conventional 'Not Green' is not mentioned, let alone necessitated.

g) ***Supplementing urban-level systems***: Urban-level systems refer to the pre-existing municipal services, systems, and/or programs already in place for the zone/region where the GAH project would be developed. Hence, the GBRPs may benefit from incorporating RC that can supplement and downscale the Urban-level systems in place for waste, water, electricity, environment, and disaster management.

These gaps are essential from the point of view of GB's holistic sustainability. The GBRPs must integrate these gaps by adding new RC or enhancing the existing ones. However, this may not be limited to simply adding or enhancing RC. The prevailing GBRPs are intent-based; they will be required to shift their core ideology in order to create holistically sustainable GB.

Conclusion

This study assessed prevailing GBRPs in India from the perspective of Climate Response, Climate Resilience, Gender Sensitivity, and Affordability. It was found that the prevailing GBRPs approximately assimilate the RC pertaining to the four Key Parameters. However, they forgo the opportunity to establish and enhance the criteria for Climate Resilience. The inputs from GBRAs indicate that GAH projects are spread across the country. The most targeted RC were provision-based, while the least commonly targeted ones were related to spatial planning or building operation.

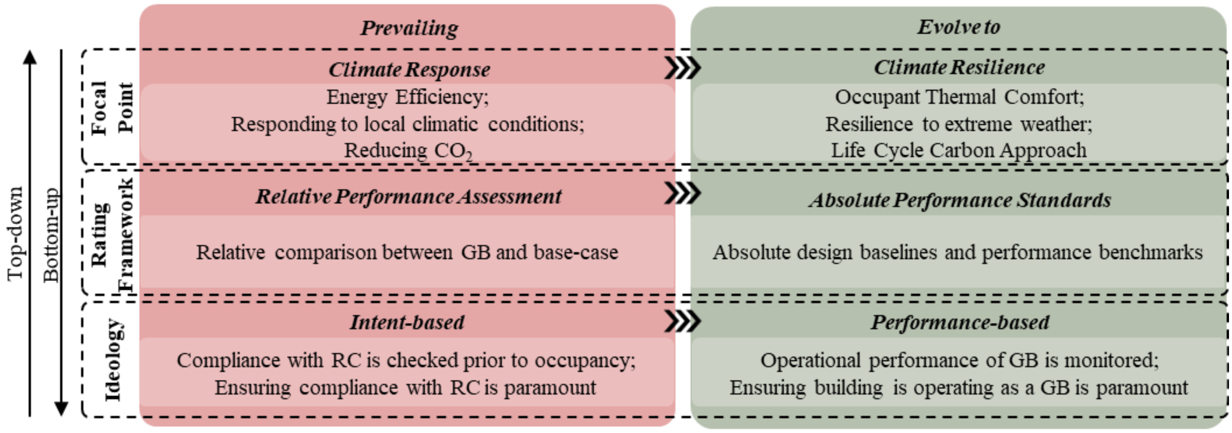

Figure 8: Guidance for enhancing prevailing GBRP

Prevailing GBRPs are primarily focused on mitigating climate change, i.e., Climate Response; their rating framework is relative-comparison based; and their core ideology is based on satisfaction of the intent of a GB. Figure 8 describes the domains in which the prevailing GBRPs may be required to evolve. The two methods – 'Bottom-up' and 'Top-down' are suggestive of the level of making change. The 'Bottom-up' approach would involve starting with surface-level changes, i.e., shifting the focus from Climate Response to Resilience. The 'Top-down' approach would involve making a change in the GBRP's core ideology, i.e., embracing a Performance-based appreciation.

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A Case Study on Thermal Performance in Residences with Laterite Stone and Rammed Earth Walling Materials in A Warm and Humid Climate

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Highlights

- Study of thermal performance of Rammed earth and Laterite stone.
- Monitoring using hand-held instruments in a built environment.
- Rammed earth wall, due to thermal properties, has an overall 2°C lower surface temperature compared to laterite stone.

Abstract

Traditionally in coastal Karnataka, mud was used in residential construction, but due to its labour-intensive nature, the construction shifted to laterite stone in the mid-20th century. Presently, with the growing need for thermal comfort and interest in sustainable approaches, there is increased interest in traditional mud architecture. A study was conducted to understand how these two materials- Rammed earth and Laterite stone perform in their built environment in a warm and humid climate. The analysis of inner surface temperatures of the east wall showed that 45% of the temperature for rammed earth and 97% of the temperature for laterite stone were more than 28°C. 1°C difference in mean WBGT showed that the indoor spaces in rammed earth residences have lower heat stress compared to laterite stone. Additionally, cooling loads can be reduced by 10%, and surface temperature can be reduced by 2°C for rammed earth compared to laterite stone walls.

Keywords: Thermal performance, Laterite stone, Rammed earth, Surface temperature, WGBT.

Introduction

Energy efficiency is the need of the hour with ever increasing population and demand for built spaces and comfort conditions. Energy consumption by the building sector constitutes a significant portion of energy use, which cannot be compromised. Energy use in buildings depends on the indoor environmental requirements and the ability of the building envelope to create an environment that is comfortable for the occupants. In warm and humid climates, passive thermal comfort is mainly attained with the building geometry, placement of openings, natural ventilation, and use of materials in the construction. Walls and roofs form a major portion of the building envelope; hence, an envelope with good thermal performance can act as an energy conservation measure to reduce energy use in a building. Thus, the study of envelope performance will help us optimize the use of energy and provide indoor thermal comfort.

In coastal regions of Karnataka, Mud was the traditional building material used in the construction of residences. The walls built of mud were generally 0.9 m to 1.2 m thick. It helped in controlling the indoor thermal conditions of the built environment. But, due to the high labour and time intensive method of construction for mud walls, the building paradigm shifted to the use of laterite stone for faster and stronger construction. As per the Indian census of 2011, Dakshina Kannada district has almost 67% of the residences built in Laterite stone, and only 22% of residences were built in mud and unburnt bricks. Today, with the introduction of stabilizing agents and better construction technologies, mud is gaining importance again as an eco-friendly, sustainable construction material in the form of rammed earth walling and compressed earth blocks for residential buildings.

The study on the thermal performance of rammed earth walls and laterite stone in a built environment has not been studied in the Indian subcontinent. Hence, the thermal performance study on the two materials will provide an insight into their potential for providing a comfortable indoor environment in naturally ventilated residences in warm and humid climates. The study aims to benefit architects and energy efficiency studies as it will provide insight into the existing building materials used and their performance.

Methodology

Study building selection

The objective of the study was to evaluate the thermal performance of the materials in their built environment; hence, a residence, each built with rammed earth and laterite stone, was considered as the building materials most used in the coastal regions of Karnataka.

The two-case study buildings are selected based on the following criteria.

- Natural ventilated residences
- Construction material used.
- Number of floors (G+1)
- Total built up area.

The rammed earth residence has 3 bedrooms and vaulted ceilings with a clay tile sloped Mangalore roof. The first storey holds a single bedroom and a toilet. The laterite house is a G+1 structure with 3 bedrooms on each floor. The built-up area, WWR, wall thickness, etc., are noted in Table 1. The floor plans are shown in Figures 1 and 2. The study was limited to only the ground floor as the number of rooms on the first floor is not the same, and conducting measurements on the exterior with hand-held devices will be difficult. Additionally, the rammed earth residence has a ventilated roof, and hence, the ground floor of the laterite house was only considered for the study as the first floor can be considered as a ventilated attic.

Table 1: Characteristics of the residences

	Rammed earth residence	Laterite stone residence
Total built up area	205.6sqm.	242.9sqm
Wall thickness	230mm	230mm
WWR	17%	19%
Roof	Vaulted ceiling with compressed earth block and concrete and clay tiles	Concrete slab with Ventilated floor.

Data gathering methods

The data collection technique implemented in the study was Monitoring and Measurements using hand-held instruments (onsite measurements) and simulation through thermal modelling to evaluate the dynamic thermal performance of the material over the year.

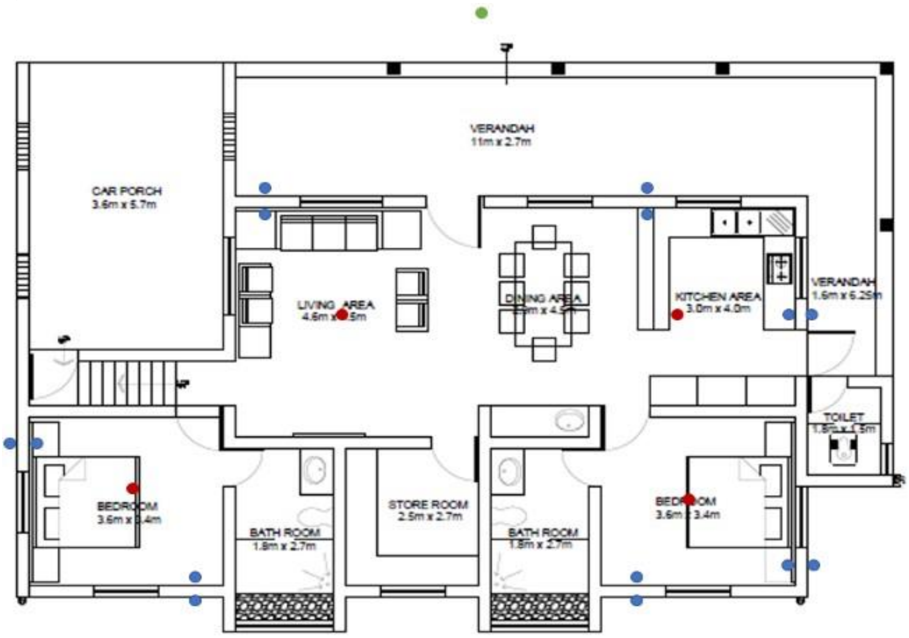

Figure 1: Floor plan and measurement points in the Rammed Earth residence

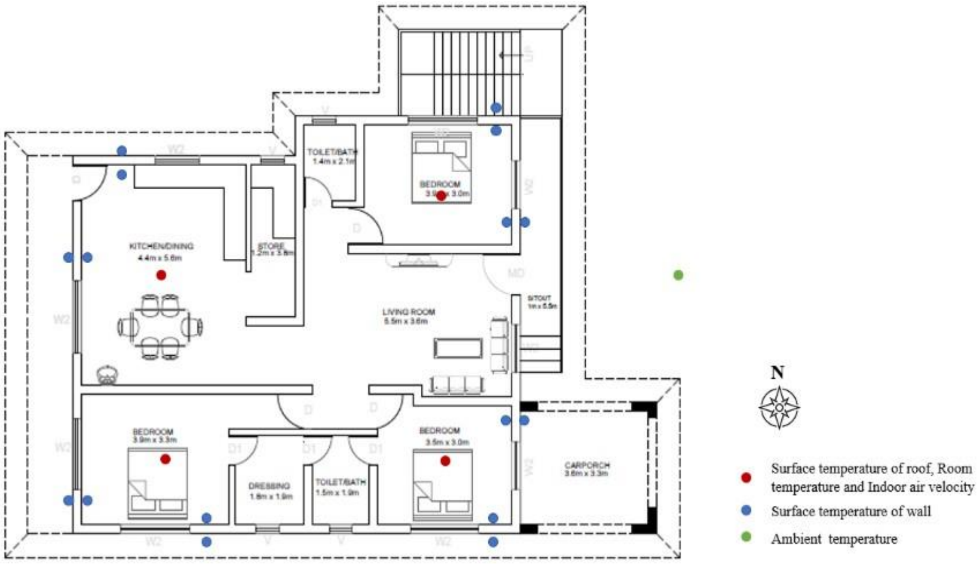

Figure 2: Floor plan and measurement points in the Laterite stone residence

Onsite measurement

Data was collected through on-spot measurements using an infrared thermal thermometer for surface temperature measurement. The surface temperature measurements are taken on different external wall surfaces and ceilings to assess the heat transfer through the day with the movement of the sun. The surface temperature was measured inside and outside of the walls at the same spot to note the decrement caused by the envelope characteristics. The measurements are taken away from any columns, fenestration, or any other composite surface that might influence the heat transfer. The points of data measurements are marked in Figures 1 and 2.

Indoor temperature, Relative humidity, and mean radiant temperature were measured with a Wet-bulb globe thermometer placed at the centre of the room. An anemometer was used to measure the wind velocity at the centre of the room. Outdoor temperature, relative humidity, and wind velocity measurements were taken away from any shaded obstruction within the premises of the residence. The instruments, their resolutions, and their accuracy are listed in Table 2.

Table 2: Parameters measured and Instruments used

Parameter measured	Model	Image of instrument	Measuring Range	Resolution	Accuracy
Surface temperature	HT668 Non-contact Infrared thermometer		0°C to 100°C	0.1°C	±0.3°C (0-35°C) ±0.2°C (35.1-42.4°C) ±1.0°C (42.5-100°C)
Temperature	GM816 Anemometer		-10°C to 45°C	0.2°C	±2°C
Wind velocity			0-30 m/s	0.1m/s	±5.0%
Wet bulb Globe temperature	METRAVI-Heat stress WBGT meter WBGT-188		0°C to 59°C	0.1°C	±1°C
Globe temperature			0°C to 80°C	0.1°C	±0.6°C
Air temperature			0°C to 50°C	0.1°C	±0.8°C
Relative humidity			1% to 99%	0.1%	±3.0% (20-80%)

Measurement protocol

Indoor air temperature, Globe temperature, Relative humidity, and wind velocity were taken at the centre of the room at the height of 1.1m from the floor surface [1]. Wind velocity was taken at the centre of the room at the height of 1.1 m from the floor surface [1], and the anemometer was oriented in the X, Y, and Z directions. Inner and Outer surface temperature measurements were taken at 10cm from the wall as per the optimum distance mentioned on the infrared thermometer. Ambient temperature and Relative humidity were measured at the location outside the residence with at least a 3 m distance from any surrounding obstructions. During the measurements, the windows of the rooms were opened, providing an effective opening area of 50 %, and fans were switched off, allowing the building to be naturally ventilated. The measurements were conducted at an interval of 1 hour from 10:00 to 18:00 hrs.

Observations

Laterite stone residence - Surface temperature

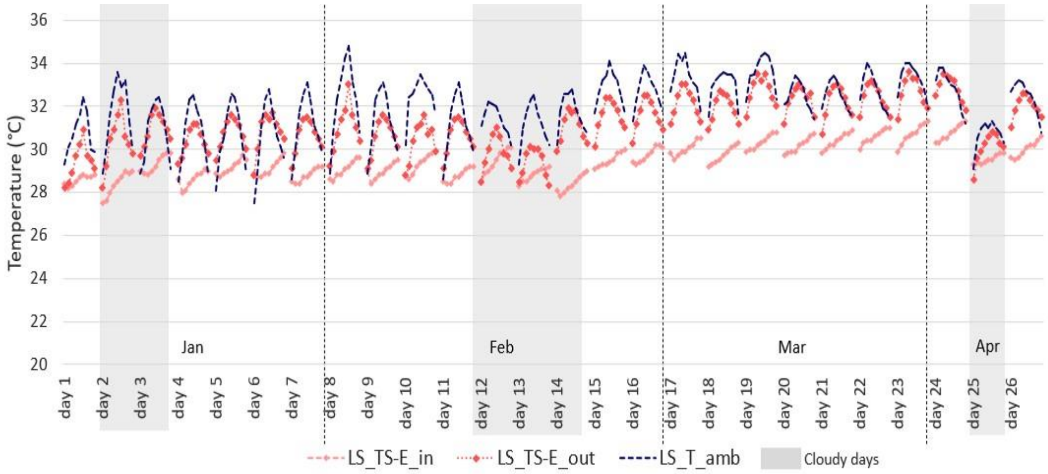

Figure 3: Measured readings of the surface temperature of laterite stone- East wall

The outdoor temperature (T_amb) measured on the premises of the residences ranged within the limits of 27.5°C to 35°C. The grey regions are days when cloudy weather conditions were observed, and hence, lower ambient and surface temperatures are measured. On the 25th day in April, thundershowers were observed on the night before hence, a lower temperature profile was observed. The surface temperature at each wall was analyzed to understand the influence each material had on heat transfer.

The east wall was shaded throughout the day due to the presence of a tiled shaded porch area adjacent to the wall, and measured data is shown in Figure 3. For the east wall, the inner surface temperature (TS_in) ranged between 27.5°C to 31.3°C with a mean of 29.5°C and the outer surface temperature (TS_out) ranged between 28.2°C and 33.6°C with a mean of 31.2°C. The standard deviation of TS_in was 0.8; hence, we can observe that it fluctuates within a narrow band of values. Meanwhile, TS_out has a deviation of 1.25, which shows that its values are 1.2 times away from the mean value. This is due to external ambient temperature and the radiant heating effect of the sun. Hence, TS_out observed a peak temperature at 15:00 hours along with the ambient temperature. From Figure 3, we can observe that the difference between TS_out and TS_in is around 2 to 3°C. This shows that the wall has a higher transmittance as the heat is transferred from the external to the internal at a higher rate.

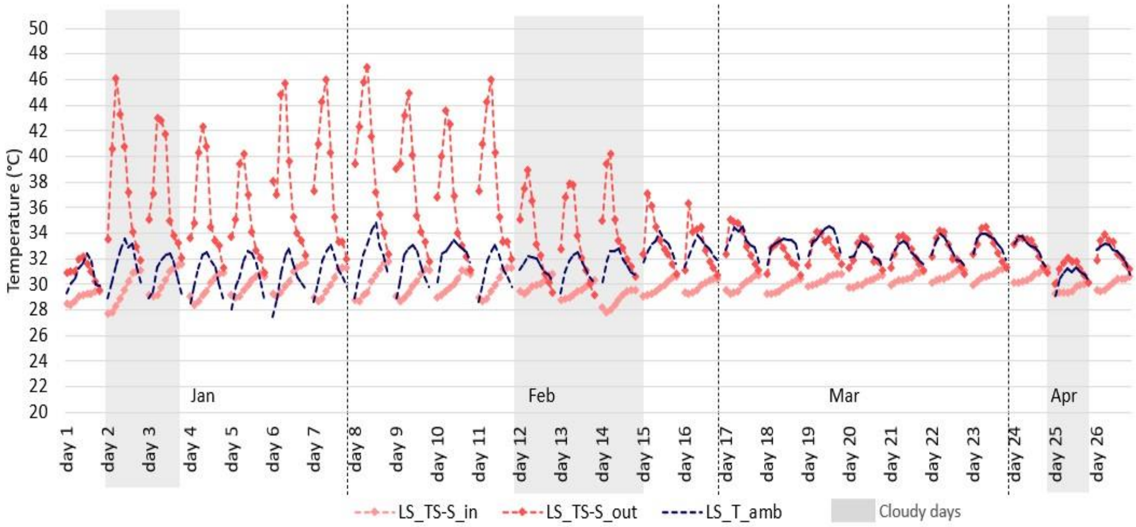

Figure 4: Measured readings of the surface temperature of laterite stone- South wall

The south wall was exposed throughout the day during the months of January and February till 13:00 hours and gets shaded in the latter half of the day, as can be observed in Figure 4. On the south wall, the TS_in ranged from 27.7°C to 31.8°C with a mean of 30.0°C whereas TS_out ranged from 29.2°C to 47.0°C with a mean of 34.5°C. The standard deviation of TS_in was 0.83, and for TS_out, it was 3.9. Due to the high temperature attained due to the solar exposure on the wall surface, TS_out has a high 4 times the deviation from the mean value. In the last few days of February and the month of March, due to the earth's revolution, the south wall was shaded and not exposed to the sun, and hence

TS_out ranged between 31°C to 35°C during which the TS_in varied between 29°C to 31°C. Thus, solar exposure influences the rate of transfer of heat within the wall assembly.

The north wall was shaded throughout the year, and hence the TS_in ranged between 27.8°C to 31.2°C with a mean of 29.3°C and TS_out ranged between 27.5°C and 32.7°C with a mean of 30.6°C. As the wall surface was unexposed, we observed that the surface temperature fluctuated within a range of 2°C and 4°C, respectively. The west wall was exposed to the sun after 15:00 hours, so the outer surface temperature peaked. TS_out ranged from 28.1°C to 46.3°C with a mean of 35.4°C and TS_in ranged from 27.9°C to 32.1°C with a mean of 29.9°C. The standard deviation of TS_in was 0.82, and for TS_out, it was 5.06. Even though the wall has high exposure, during the measurement period, the TS_in fluctuations are within a 1°C range in a day and only start to increase in the latter half of the day (after 15:00 hours). It could be observed that since the wall gets time to lose the heat attained on the previous day and as the measurements are not conducted during the night-time, the steep increase in TS_in temperature is not observed, unlike the south wall.

Laterite stone residence- Indoor conditions of south east room

From Figure 5, we can observe that the Indoor temperature (T_in) ranged from 28.6°C to 32.5°C with a mean value of 30.8°C. The Globe temperature (T_GT_in) ranged from 29°C to 32.6 °C with a mean of 31.0°C. We can observe that the T_in and T_GT_in were almost the same with a very small difference of 0.2°C. This is because the building was maintained in naturally ventilated conditions; the globe temperature, which is a measure of the radiant effect of the surfaces on the air temperature, is in good correlation with an R^2 value of 0.95 with the air temperature as it fluctuates very closely with the outdoor temperature. The Wet bulb globe temperature (T_WBGT_in) is measured as a product of wet bulb temperature and globe temperature; hence, it has a lower range compared to other indoor parameters. T_WBGT_in ranged between 26.2°C to 29.4°C with a mean of 27.9°C and a standard deviation of 0.42. This shows that the T_WBGT_in fluctuates within a narrow band of values. The Indoor relative humidity (RH_in) was higher than the Ambient relative humidity (RH_amb), as its mean values are 67.7% and 64.8%, respectively. The variance for RH_in was 3.09, and RH_amb was 4.73.

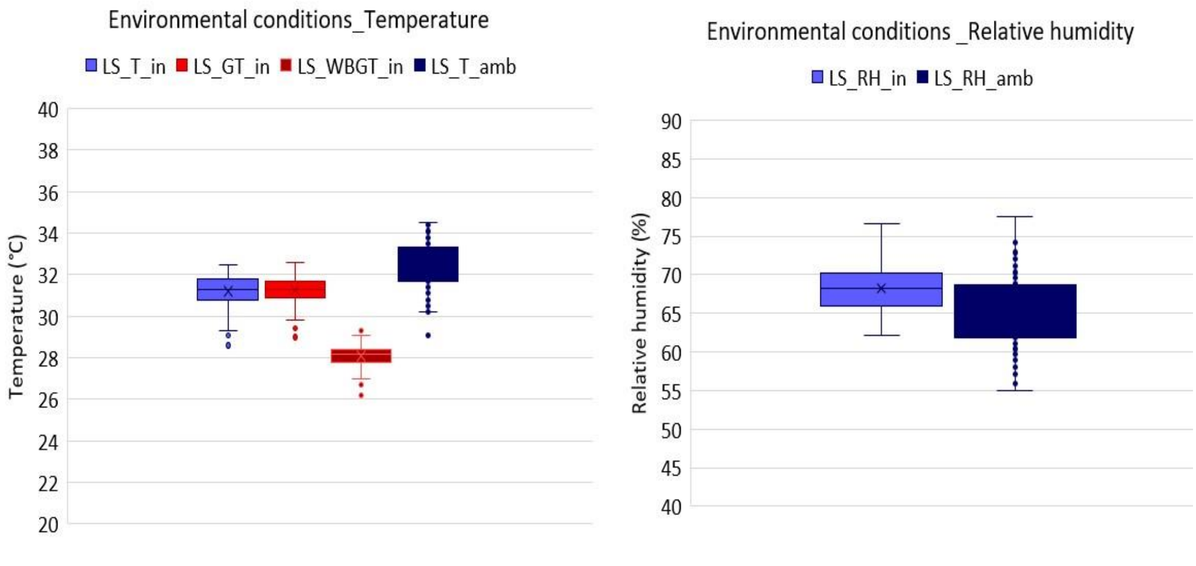

Figure 5: Indoor temperature and relative humidity with the ambient conditions in laterite stone residence

Rammed earth residence- Surface temperature

The outdoor temperature (T_amb) measured on the premises of the residences ranges within the limits of 27.4°C to 35°C. The grey regions are days when cloudy weather conditions were observed, and hence, lower ambient and surface temperatures are measured.

The east wall was shaded throughout the day due to the presence of a tiled shaded area adjacent to the wall. For the east wall, the TS_in ranged between 25.3°C to 30.7°C with a mean of 28.0°C and the TS_out ranged between 24.3°C and 34.7°C with a mean of 30.8°C. The standard deviation of TS_in was 1.33; hence, we can observe that it fluctuates within a band of 2°C. Meanwhile, TS_out had a deviation of 1.87, which shows that its values are 2 times from the mean value. As TS_out varies directly with the ambient temperature, it observes a peak at 15:00 hours along with the ambient temperature, as seen in Figure 6.

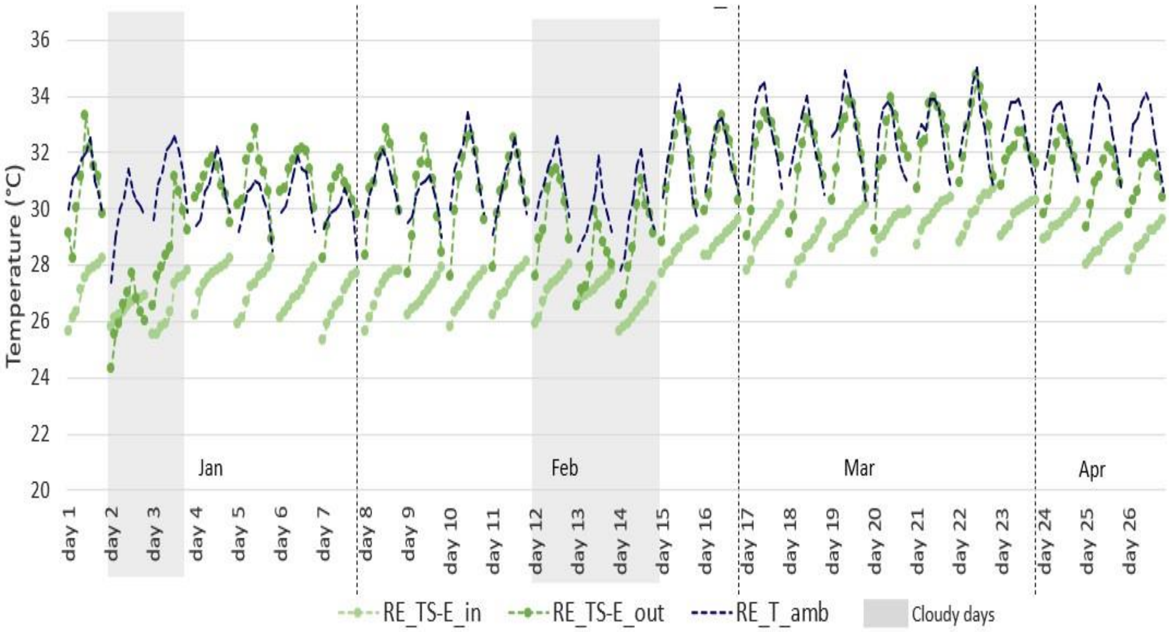

Figure 6: Measured readings of the surface temperature of rammed earth- East wall

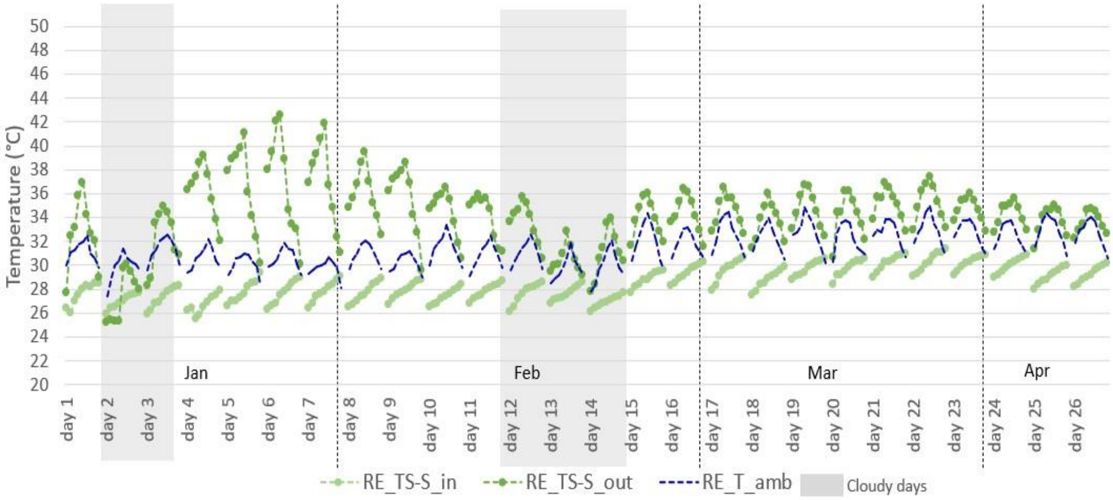

Figure 7: Measured readings of the surface temperature of rammed earth- South wall

The south wall was exposed throughout the day during the months of January and February till 13:00 hours and gets shaded on the latter half of the day, as observed in Figure 7. On the south wall, the TS_in ranged from 25.5°C to 31.3°C with a mean of 28.4°C whereas TS_out ranged from 25.2°C to 42.5°C with a mean of 34.1°C. The standard deviation of TS_in was 1.32, and for TS_out, it was 2.91. Due to the high temperature attained due to the solar exposure on the wall surface, TS_out had 3 times the deviation from the mean value. In the last few days of February and the month of March, due to the sun's path, the south wall got shaded and was not exposed to the sun; hence, TS_out ranged between 32°C to 38°C during which the TS_in varied between 28.5°C to 31°C. This shows that solar exposure and ambient temperature conditions influences the rate of transfer of heat within the wall assembly.

The north wall was shaded throughout the day as it was not exposed to the sun due to the presence of a covered veranda. TS_in ranged between 24.7°C to 30.3°C with a mean of 27.3°C and outer TS_out ranged between 24.1°C and 33.9°C with a mean of 29.4°C. As the wall surface is unexposed, we observe that the surface temperature fluctuates within a range of 2°C and 4°C, respectively. On the west wall, TS_in ranged from 24.8°C to 30.6°C with a mean of 27.8°C whereas TS_out ranged from 24.1°C to 38.1°C with a mean of 31.0°C. The surface temperature measurements of rammed earth show a large difference between TS_out and TS_in. This difference can be attributed to the low transmittance and specific heat characteristics of the wall.

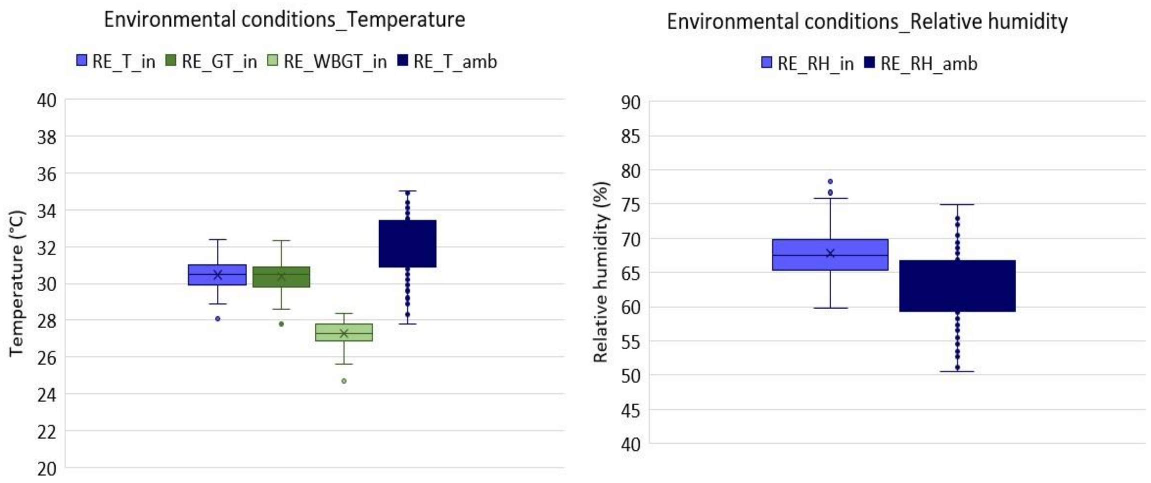

Figure 8: Indoor temperature and relative humidity with the ambient conditions in rammed earth residence

Rammed earth residence- Indoor condition of southeast room

From Figure 8, we can observe that the Indoor temperature (T_in) ranged from 28.0°C to 32.8°C with a mean value of 30.7°C. The Globe temperature (T_GT_in) ranged from 27.8°C to 32.3 °C with a mean of 0.2°C. We can observe that the T_in and T_GT_in have a very small difference where T_GT_in is less by 0.5°C, which shows the cooling effect of the wall surfaces. As the building is maintained in naturally ventilated conditions, the globe temperature, which is a measure of the radiant effect of the surfaces on the air temperature, is in good correlation with an R^2 value of 0.98 with the air temperature as it fluctuates very closely with the outdoor temperature. T_WBGT_in ranged between 24.7°C to 28.4°C with a mean of 27.1°C and a standard deviation of 0.64. The Indoor relative humidity (RH_in) was higher than the Ambient relative humidity (RH_amb), as its mean values were 67.3% and 62.1%, respectively. The variance for RH_in was 3.65, and RH_amb was 5.11. Figure 8 shows the variation of the indoor temperatures over the days the measurements were conducted.

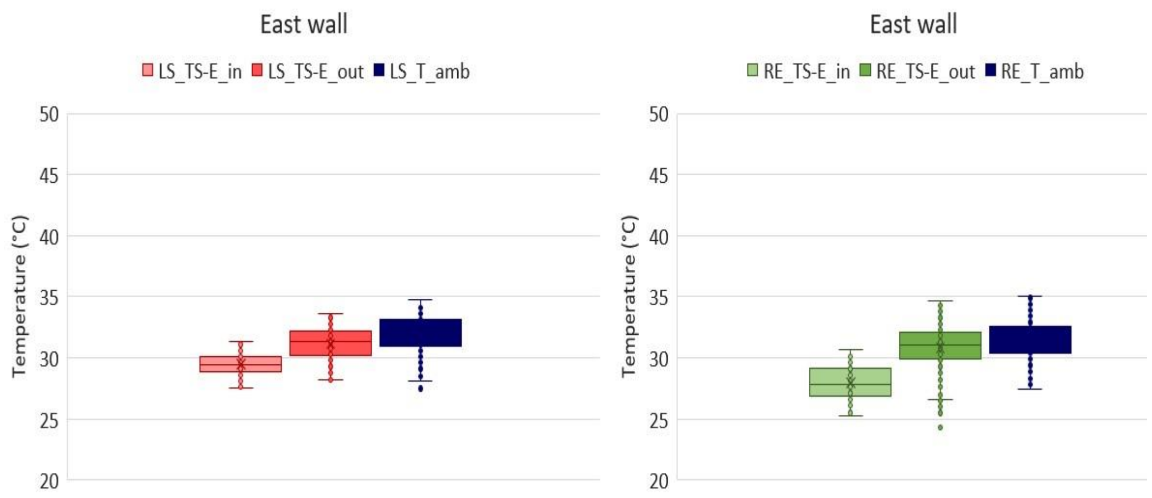

Figure 9: Surface temperature range for the east wall

Study of the buildings and the criteria for selection of similar analysis spaces

As the residences considered for the study are not identical, a direct comparison of the results will be inaccurate as internal conditions and heat transfer are influenced by their surrounding conditions. Each space was analyzed for its building surroundings, and to evaluate the suitability of the analysis space, a shading mask and external wall exposure time were used to evaluate the obstructed area in each of the cases.

Figure 9 shows the measured data range for the east wall, and Figure 10 shows the data for the south wall of the southeast room for both residences. It can be observed from the figures that 75 % of TS_in points for rammed earth residence is lower than the 25% of TS_in for laterite stone. Thus, the heat transferred in the case of the rammed earth house is lower than laterite in both the east and south wall surfaces. The standard deviation of TS_out of rammed earth was 33% higher than that of laterite stone for the east wall, and for the south wall, it was 25% lower.

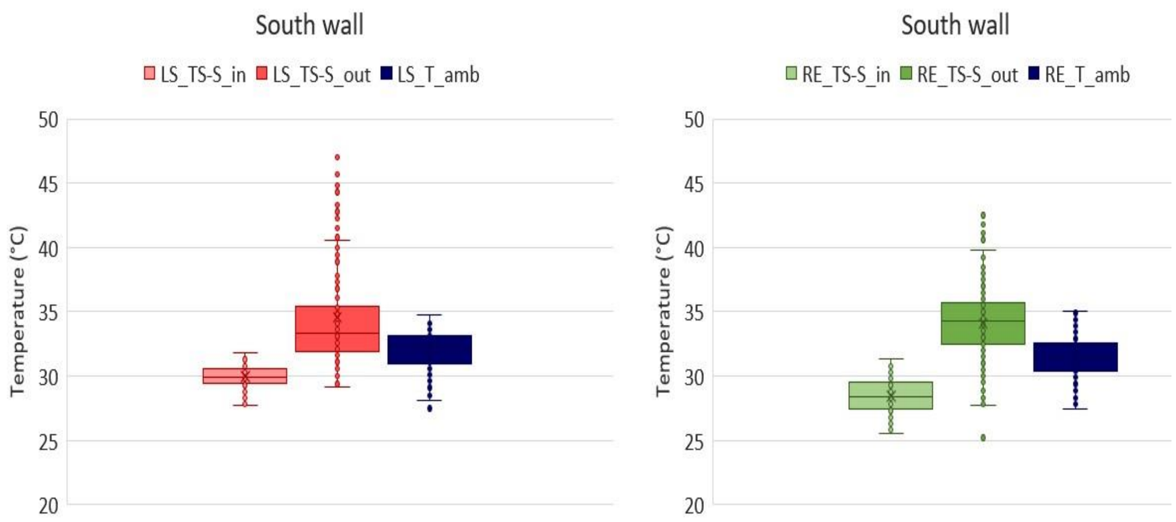

Figure 10: Surface temperature range for south wall

From the surface temperature data, it can be observed that the rammed earth wall showed 2°C lower TS_in compared to laterite stone in the months of January and February. In the months of March and April, the difference between TS_in is reduced to 1°C and could be attributed to the higher ambient conditions. TS_out of the rammed earth wall was higher compared to laterite stone throughout the measurement period of 4 months, as observed in Figure 10. This property of high TS_out and low TS_in of rammed earth compared to laterite stone is due to the thermal conductivity and thermal mass of the material.

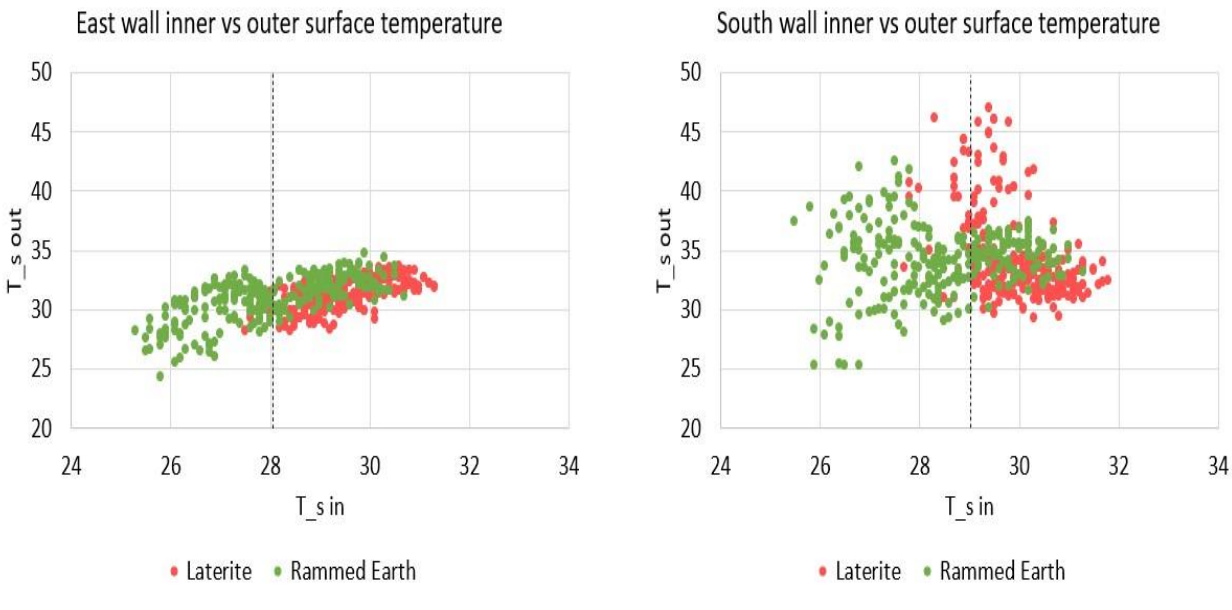

Figure 11: Distribution of the TS_in and TS_out for a) east and b) south walls

Figure 11 shows the distribution of the surface temperature of the east and south walls for the southeast room. In Figure 11 (a), we can observe that even for the same outer surface temperature of the east wall, 45% of TS_in for rammed earth and 97% of TS_in for laterite stone points are more than 28°C. In Figure 11 (b), we can observe that the TS_in shows 35% of rammed earth data points and 88% of laterite stone data points are more than 29°C. The two figures show that the rammed earth wall, due to its thermal properties, has an overall 5% lower surface temperature for both walls compared to the laterite stone wall. Hence, the rammed earth wall has a significant reduction in the heat transferred from the outside to the inside.

Evaluating the indoor air temperature and the relative humidity, it can be observed from Figure 12 that they are inversely proportional as they have equal slopes. As the study subjects are in a warm and humid climate, the relative humidity levels are more dispersed and range between 60 to 80%, whereas the air temperature ranges between 29°C to 32.5°C. Even though the ambient temperature and relative humidity ranges are similar, we can observe that 76% of the data for rammed earth observed a temperature less than 31°C while the relative humidity was less than 68% compared to laterite stone.

The indoor comfort conditions vary with the outdoor conditions in a naturally ventilated building. Hence, the WBGT is measured to assess the indoor comfort conditions as it takes into consideration the climatic conditions. From Figure 13, we can observe that the mean WBGT for rammed earth was lower by 1°C (3%) compared to the laterite stone house, while the outdoor conditions are relatively equal. 61% of the rammed earth data is less than 28°C compared to laterite stone. Hence the occupants in rammed earth houses will experience lower heat stress due to the material and thus a higher sense of indoor comfort conditions.

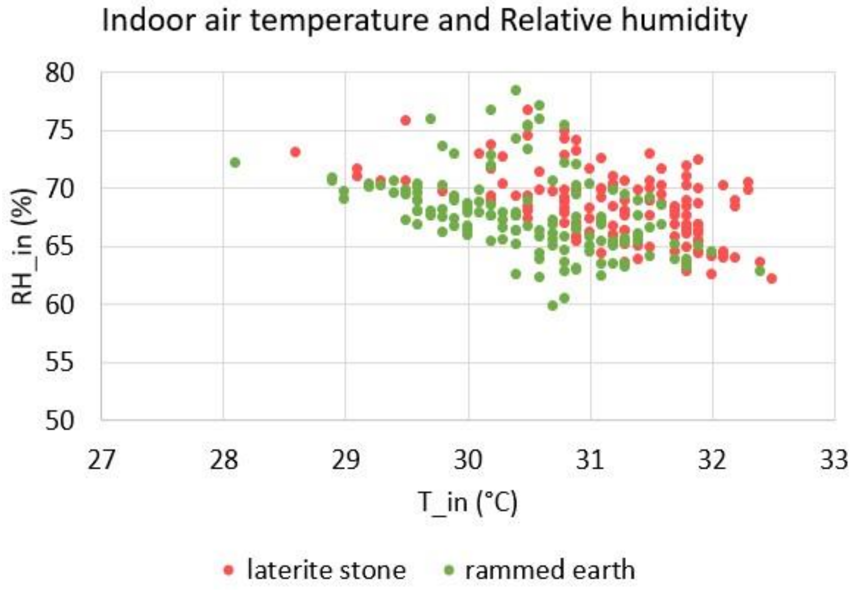

Figure 12: Distribution of Indoor air temperature and relative humidity

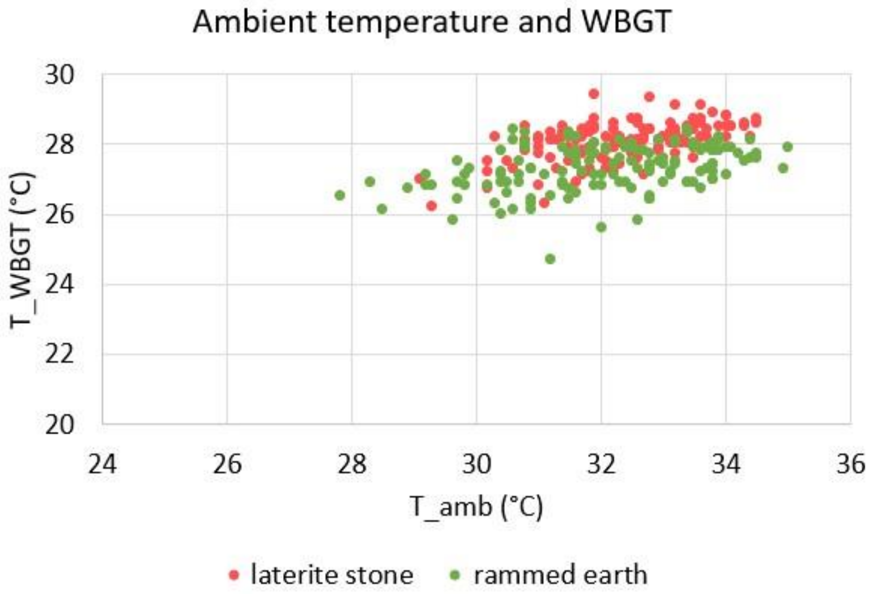

Figure 13: Distribution of WBGT with ambient temperature

Thermal simulation model and its Results

Thermal simulation of the building was conducted to analyze the year-round performance of the walling material. A thermal simulation model was developed on Design Builder software to mimic the as built conditions. The thermal properties of the building envelope are based on various research papers since the exact thermal properties of the material were unknown. The window openings are modelled with a 50% effective opening area and a wind discharge coefficient of 0.65. No HVAC system was provided, and the model was run in a naturally ventilated condition. The simulation output was compared with measured data, and the properties with the highest correlation and least variance were considered for further analysis (The final values are listed in Table 3. The TMY weather file for Mangalore (Warm and humid) was used to simulate the building, and parameters such as indoor air temperature, relative humidity, mean radiant temperature and operative temperature were analyzed.

Table 3: The final selected thermal properties with its correlation and variance w.r.t the measured data

Walling material	Density, ρ (kg/m^3)	Thermal Conductivity, k (W/mK)	Specific heat, C_p (J/kgK)	Thermal effusivity, e ($J/m^2K\ s^{1/2}$)	Thermal diffusivity, a (mm^2/s)	Correlation	Covariance difference
Laterite stone	1930 [2]	0.55 [2]	995.9 [2]	1030 [2]	029 [2]	0.96	0.04
Rammed earth	1730 [3]	0.60 [3]	648.0 [3]	820 [3]	0.54 [3]	0.97	0.02

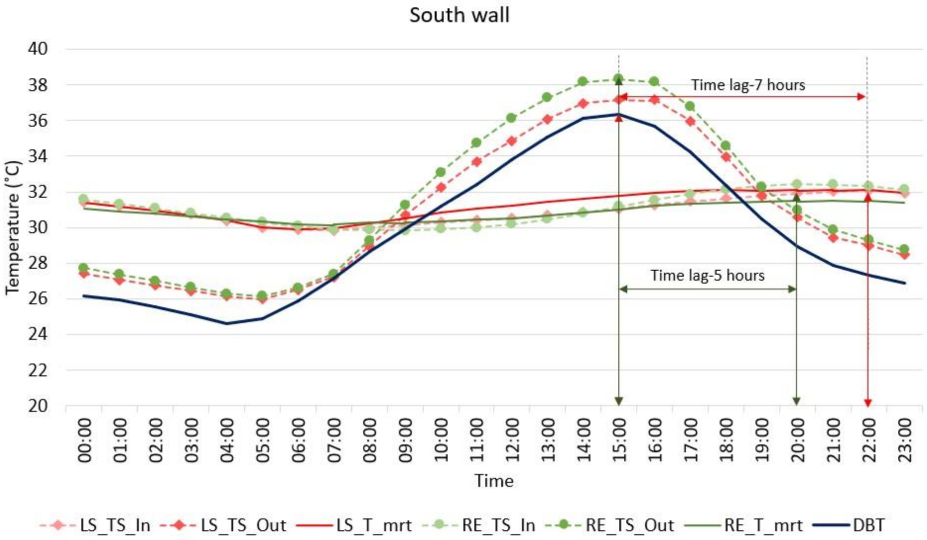

Figure 14: Simulated data for peak summer day (May)

In Figure 14, we can observe that the peak TS_out was attained at 15:00 hours in both cases. The peak TS_in for rammed earth was attained at 20:00 hours, whereas for laterite stone, it was attained at 22:00 hours. The time lag for rammed earth is 5 hours, and for laterite stone, it is 7 hours. The decrement factor for both walls remains the same at 0.85, as both walls have the same thickness. As the walls held the heat longer due to their high specific heat capacity, the laterite wall remained warmer, and the stored heat was dissipated into the room volume. Hence, the Tmrt for laterite stone was higher compared to rammed earth. Comparatively, rammed earth, due to its lower specific heat capacity and density, reaches peak surface temperature 2 hours earlier, giving the wall time to cool faster. Thus, we observe a lower Tmrt for rammed earth during the day-time hours. The high fluctuation in TS_in compared to laterite was due to the thermal conductivity and specific heat capacity of rammed earth.

Conclusion

As the properties of the wall influence the amount of heat conducted into the room, it is essential to understand the thermal properties and how they directly influence the indoor conditions. In this study, an experimental take on the thermal performance of two materials rammed earth and laterite stone, was conducted in its built environment. The study was done with hand-held devices measuring the surface temperature, indoor temperature, and humidity conditions at intervals for 1 hour for 9 hours in the day.

The study observed that laterite stone walls showed a mean inner surface temperature range of 29.3°C to 30°C on all the walls oriented along different directions. The lowest inner surface temperature was observed on the north wall and the maximum on the south wall due to its exposure to the sun. The outer surface temperature depends on its exposure to the sun and ranges from a mean of 30.6°C on the north wall to 35.4°C on the west. The indoor air temperature was observed to have a mean of 30.8°C, whereas the indoor globe temperature, a measure of the radiant impact of the surfaces, had a mean of 31°C. The small increase in the globe temperature compared to the air temperature showed that the walls are radiating heat to indoors.

In the rammed earth residence, the mean inner surface temperature was the lowest for the north wall at 27.3°C and highest for the south wall at 28.4°C. The mean outer surface temperature ranged from 29.4°C on the north wall to 34.1°C on the south wall. A consistent increase in outer surface temperature on the west wall was not observed due to the presence of trees facing the wall. The presence of trees and other shading elements can help reduce the high surface temperatures. The large difference between the outer surface temperature and inner surface temperature of the rammed earth wall can be attributed to the higher thermal conductivity of the wall. The indoor air temperature was observed to have a mean of

30.7°C, whereas the indoor globe temperature had a mean of 30.2°C. Lower globe temperature compared to the air temperature showed that the walls provide a cooling effect for the indoor spaces.

As the building designs are not identical, an attempt was made to analyze spaces with similar exposure and adjacency to have a preliminary understanding of the difference between the two materials. The distribution pattern of the surface temperatures of the east wall showed that 45% of the inner surface temperature for rammed earth and 97% of the inner surface temperature for laterite stone points are more than 28°C. Hence, the rammed earth wall, due to its thermal properties, has an overall 2°C lower surface temperature for both walls compared to the laterite stone wall. Comparing the indoor air temperature and relative humidity levels, it was observed that 76% of the data for rammed earth observed a temperature less than 31°C while the relative humidity was less than 68% compared to laterite stone. The 1°C lower mean WBGT shows that the indoor spaces in rammed earth residences have lower heat stress compared to laterite stone and hence provide a higher degree of comfort. To understand the impact on the built environment, a thermal simulation study was conducted considering the thermal properties obtained from other studies and compared with the measured data. This study showed that rammed earth had a thermal conductivity of 0.6 W/mK, and for laterite stone, it was 0.55 W/mK. Evaluating the thermal properties of a single residence, it was found that with the use of rammed earth, the cooling load for a space can be reduced by 10%. Additionally, the rammed earth wall had a lower time lag of 5 hours compared to laterite stone of 7 hours, which showed that the walls cool faster due to its higher thermal conductivity, which helps naturally ventilated buildings to lose heat faster and cool, leading to higher comfort levels.

Limitations and Future scope of work

As the study was conducted for a period of 3.5 months, the data from peak summer months couldn't be measured. The actual thermal properties of the walls are not measured or calculated, and properties from other studies are relied on to understand the material performance. Since thermal properties are taken from other studies and variations of weather data (TMY) with actual climatic conditions, the simulation results will not match the exact on-site conditions. Additionally, the measurements are conducted using hand-held instruments due to the unavailability of digital data loggers and are conducted hourly from 10 am to 6 pm; hence, the measured data will show the thermal response for the daytime hours and not the night-time hours.

Although preliminary comparisons are made by identifying similar living spaces, identical rooms, or spaces, there is uncertainty due to the design, presence of other buildings and trees, elevation, etc. These uncertainties can cause discrepancies in understanding the thermal performance of the materials. The study can be further tuned by using identical building cells with data loggers, which can be built in the same location and have the same surroundings, thereby reducing the design and locational discrepancies for the study. Additionally, testing of the material used for its thermal properties will help better evaluate and understand the nature and heat transfer abilities of the material.

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A Baseline Study for Residential Energy Consumption Using Socioeconomic and Physical Building Attributes: A Case of Jaipur

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Highlights

- Identification of critical parameters influencing energy consumption in Indian homes, finding the correlation of selected parameters with energy consumption and EPI
- This study provides insight into energy consumption behaviour at the end-user level.

Abstract

Indian residential energy consumption increased nearly 50 times its levels in 1971. Studies have reported a wide variation between the statistically projected and actual energy consumption values in residential buildings. Access to reliable energy consumption data is limited in Indian cities. This study aims to use primary datasets to develop a baseline for residential energy consumption in India. Its first objective is to understand the prevailing practices adopted in residential energy studies. The second is to understand the contributions of socioeconomic factors to it. This research analyses 2327 primary survey samples from Jaipur. The dataset was analyzed using the multivariate statistical technique. The results highlighted the uptake in appliance ownership and its implications on energy consumption across income groups. The study has also compared the relevance of EPI (annual consumption/total area) and annual energy consumption as indicators in the building benchmarking process for Indian homes.

Keywords: baseline study, residential energy consumption, Socioeconomic factors

Introduction

Under various user conditions, the behaviour of building systems can create a wide range of variations in the energy consumption pattern. Researchers must learn about the distinctive components and their dynamics within the structural assembly of a building. Hence, it is necessary to study them and various building types at different scales [1]. With the development of better computing capacity and building energy modelling tools, accessing future consumption in various user conditions (including new technologies and materials) is becoming more accessible. With higher income levels, average household-level equipment ownership has also increased. It has significantly enhanced the volume of consumption data and created a scope for data-driven decision-making [2] for Indian homes to achieve better energy efficiency.

India is the third largest energy consumer in absolute terms; it stands at 47th in per capita energy consumption globally, which is 62% lower than the world average [3]. It indicates the vast, repressed demand potential for energy, which will eventually surface with growth in per capita income levels. Since 2000, the Indian energy sector has undergone development and reform. With increasing political focus on making electricity more accessible to all, governments (at all levels) have been interested in developing policies to facilitate this. As a result, many publicly funded surveys have been done to learn about equipment ownership, energy mix, access quality, and several similar socioeconomic factors related to energy consumption behaviour at the household level. CENSUS and NSSO are two notable national-level sampling survey agencies with reliable databases. In addition, NCAER has done two sets (2004-05 and 2011-12) of nationwide household-level sample surveys. The survey is IHDS (open database), which is currently available on the ICPSR website. This development led to independent academic studies across the country and abroad. Several of these studies have used secondary or aggregator-level datasets. Few of them have referred to the above-mentioned national-level databases. A few studies have used primary datasets obtained by surveys or intrusive monitoring. Additionally, the expansion of the real estate market in India has influenced dwelling typologies in urban areas. Hence, researchers need to look at this sector with fresh eyes and reposition its relevance in the context of future energy demand.

Methodology

Different kinds of literature use many parameters in other contexts. From a methodological point of view, it was essential for us to investigate each of them. Moreover, in an Indian context, collecting every data point may not always be feasible due to the wide variation of building types. Hence, the study intended to find out the correlation of various parameters with energy consumption reported in the literature for the Indian context. The relevant parameters are shortlisted in three stages (Figure 1).

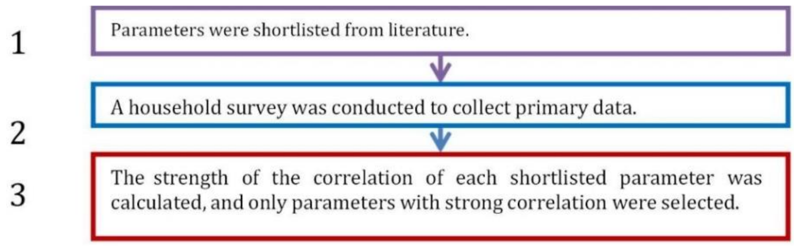

Figure 1: Methodological flow chart

Identification of relevant parameters

The parameters were shortlisted in two phases. In the first stage, a list of parameters was prepared based on the literature review. It comprised journal papers, reviewed reports (by government and non-government agencies), and national-level survey documents. The focus was more on Indian studies or studies relevant to the Indian context. Several studies from other countries were also reviewed to identify the number of possible parameters. Then, a logical assessment was done to eliminate parameters from the list. For example, studies in several countries classify building stock based on the utility companies that provide electricity connections [4]. In the Indian context, we have a single utility for each city.

Similarly, being a single-location study, the climatic context remained constant. However, this study does not discount the eliminated permanents' contribution to household energy consumption. It was a decision purely taken considering the context of this study. Hence, we strongly recommend that future researchers make their assessments before shortlisting their parameters. A reference to the processes followed in this study may be helpful for them to supplement their methodology. The final list of parameters was broadly divided into three categories: Socioeconomic, equipment, and geometric. Similar parameter classification is adopted in the TABULA project [5] and DoE [6]. However, this study also included socioeconomic data sets besides geometry, construction, system, and operation data. It is essential to note that the building specifications could be more standardized in India, unlike the U.S. and Europe. Hence, depending on standard specification data can be misleading. Moreover, socioeconomic factors like household income can significantly influence consumption behaviours. Similarly, there is no standard norm for maximum occupancy for a dwelling unit in India. Hence, these parameters need to be scrutinized. Table 1 contains the shortlisted parameters for the building stock classification.

Table 1: The table contains the shortlisted parameters

	Classification of Parameter Used for Building Archetypes				**[The shortlisted parameters]**
SR. No.	**Refereed Journals (2001 onwards)**	**Other Published Literature**	**Census of India**	**National Building Code (NBC)**	**Remarks**
1	High-rise/ Low rise	Building Height High-rise / Low rise	--	Building Height High-rise /Low rise	As per part 4, buildings above 15 meters are considered high-rise. As per the norms of NBC, fire provisions are mandatory for such buildings.
2	Age of the buildings	--	--	--	Several building classifications (energy consumption based) have used building age as a significant criterion for classification.
3	Household Income	Household Income	--	--	Journal papers focusing on residential energy consumption in the Indian context have suggested household income as a critical factor.

4	Occupancy	--	Household sizes	--	The number of people living in a dwelling may influence the energy consumption in the buildings.
5	HVAC Type	HVAC Type			Using air conditioners significantly contributes to the building's total energy consumption. This parameter will be addressed as a part of the "Equipment Ownership" criteria.
6	Area/size	Area/size	Number of rooms		The area/size of the building also demands more cooling/heating and illumination.
7		Equipment Ownership	Equipment /Asset		Indian studies focusing on residential energy have used equipment ownership to understand the consumption pattern.

While conducting the survey, data for the above-shortlisted parameters are collected for principal component analysis (PCA) to shortlist the parameters further. Different data types are collected from each household, including the data related to the parameters shortlisted above.

Data collection

The survey conducted in Jaipur was designed to investigate the finer aspects of energy consumption in Indian households. The study identified a list of parameters from the existing literature and tested its correlation with energy consumption. This paper elaborates on factors that nudge end-user's consumption behaviour and other related decisions that contribute to the same. The survey was limited to the municipal boundary of Jaipur. Hence, the climatic and cultural aspect of consumption was a constant for this study. The survey only considered census households with a legal electricity connection. The squatter settlements and semi-formal housing stock were not included in this sample. Random sampling was done to select the households for each income class and dwelling type. The survey study depends on user feedback to derive its conclusions. Independent sensor-based monitoring was not a part of this study. That is why equipment-based consumptions are represented in ranges instead of absolute values. The feedback was collected through structured and semi-structured questionnaires. The survey form is divided into three sections: the socioeconomic section, the equipment data section, and the geometric and construction data section. In each section, the different types of data points are included, which are listed in the table below.

Table 2: Classification of data collected through the survey

Categories	Description
Socioeconomic	Household size, Household income
Equipment	Ownership of equipment, Hours of operation [within a range], annual energy units consumed [actuals]
Geometric & Construction	Building type (single family unit, multifamily units, single/multi-storied unit), area, number of rooms, building envelop specification, Fenestrations (window types and material)

The samples were spatially distributed across the city in various residential neighbourhoods. The distributed sample collection locations and their percentage share are presented in Figure 2.

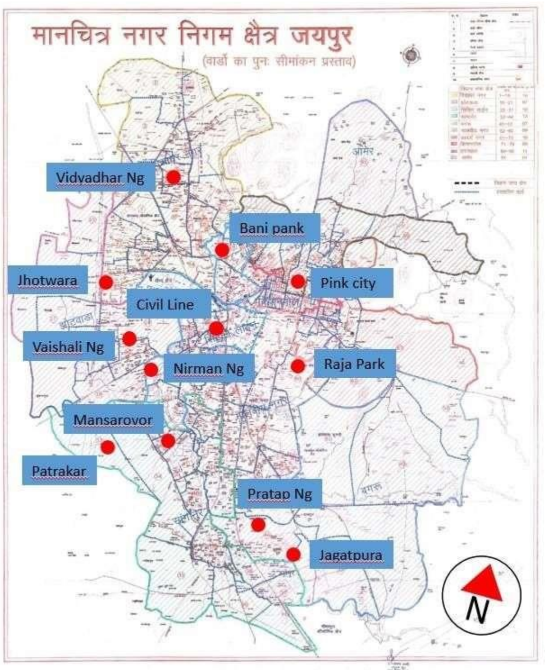

Figure 2: Sample distribution across Jaipur. Source of the map used: Jaipur Municipal Corporation (CC BY-NC)

Distribution of samples across various building types and BHK configurations

There are broadly three significant configurations of these building units:

1. Single-family units (both single-floor and multi-stories)
2. Multifamily Mid-rise Buildings (usually ground + 3 floors)
3. Multifamily High-rise Buildings (usually six floors and above)

The survey team aimed to gather data samples that accurately represent the full spectrum of residential buildings in Jaipur, encompassing both spatial and typological diversity. A comprehensive collection effort yielded 2345 samples from various locations throughout the city. Of these, only 2,327 samples were finally selected for further analysis. Table 3 shows the distribution of samples across various BHK configurations.

Table 3: Distribution of sample collected during the case study across different BHK Types

Sample required	**1536**	**For a 95% confidence level in each BHK type**
Samples collected	2345	Assuming 15-20% of samples may be lost due to unforeseen circumstances.
1 BHK	526	23 % of the total sample size
2 BHK	601	26 % of the total sample size
3 BHK	622	27 % of the total sample size
4 BHK	578	25 % of the total sample size
Total number of samples after eliminating the inconsistent samples	2327	

The survey samples include dwelling units from all floor levels. Many low- and middle-income families usually live in multi-storied apartments in Jaipur. There are also a good number of duplex units within the sample. These units are independent, two-storied buildings occupied by one household. Hence, they are treated as one single unit in the data set. During the survey, it was observed that most old habitable buildings had been renovated periodically. Thus, the building envelope has changed due to the application of new materials. Hence, the old building behaves like a new building despite being considered old by its occupant.

The household is classified into five broad income groups. This study has adopted the income classification from the PMAY program of the Government of India. The program classifies households into four groups, based on their income level, to provide them with appropriate housing assistance. The first group's income goes maximum up to 0.3 million INR per year; the second group lies between 0.3 to 0.6 million INR per year, the third group earns between 0.6-1.2 million INR per year, and the fourth group's income remains within the range of 1.2-1.8 million INR per year. A fifth income group was added to this study to bring more diversity to the sample. The fifth group includes a household income higher than 1.8 million INR per year. The figure below shows the distribution of samples across five income groups. Central government's housing schemes classify housing based on income. Housing allocations are done based on income levels. In addition, we found that in the real estate market, both for rental and purchase, dwelling units are usually classified in BHK terms. BHK stands for Bedroom (B), Hall (H), and Kitchen (K) dwelling configuration. Most units are often referred to as 1BHK, 2BHK, or 3BHK units, meaning a team with 1, 2, or 3 bedrooms. It is necessary to mention that these units do not necessarily have a standard size or shape.

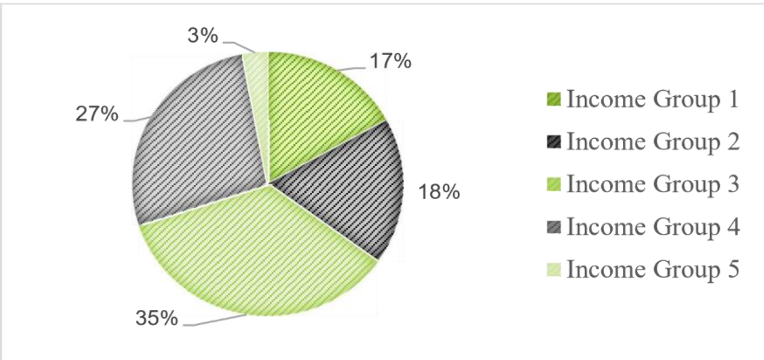

Figure 3: Percentage distribution of samples across income groups

Moreover, in CENSUS of India 2011, the dwelling units are also classified based on number of rooms. It makes this classification more practical. This study has four BHK types (1BHK, 2BHK, 3BHK, and 4BHK) that were considered for sampling. One of the prime objectives of this study was to understand the consumption pattern in Indian homes. As per the studies done by Prayas in 2008, 90% of the annual residential energy consumption was contributed by lighting, cooling, heating appliances (fans, evaporative coolers, room heaters, geysers, refrigerators, and air conditioners) and Television [7]. Though this study had made few assumptions, the broader range defined by this study was helpful. Similar studies by the World Bank [8] and NITI Aayog [9] have also found similar trends. However, a large-scale intrusive monitoring study must define these equipment-level consumption averages. Hence, for this case, only the devices mentioned above are considered for the survey. A wide range of variation is found in appliance ownership across various households from different socioeconomic backgrounds. Previous studies show that the equipment ownership pattern at the household level reveals the suppressed potential of growth in consumption levels soon [10] [11] [8] [9]. Hence, the paper presents an overview of the current state of equipment ownership reported during the survey.

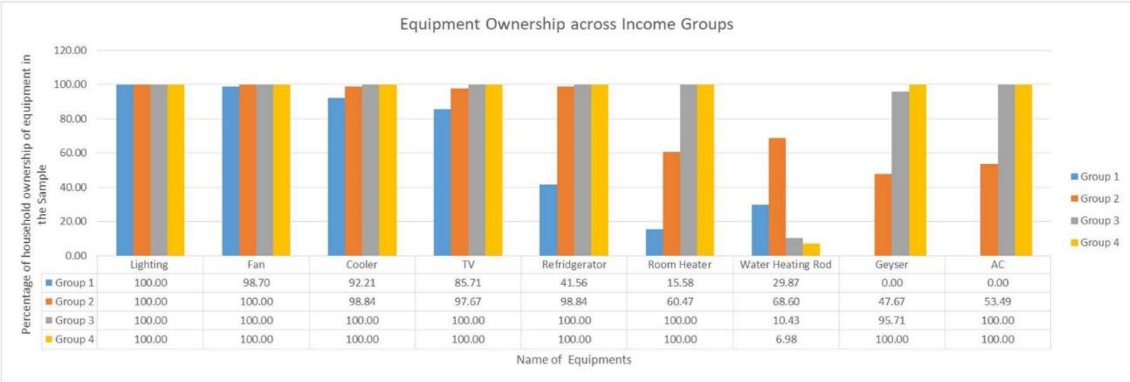

Figure 4: Equipment Ownership of different Income groups.

The survey only considers houses with formal electricity connecting with monthly bills only. The fan was available in almost all households except a few homes in the low-income class (only two houses were reported on fans). The evaporative cooler is one of the most used electrical appliances in homes in Jaipur, with a minimum ownership of 92%. To our surprise, even high-income homes (Group 4) also have evaporative coolers in Jaipur and use them to cool down large common spaces during the summers. In most cases, they prefer A.C. over evaporative coolers during the summers. It is important to note that many high incomes homes also have air-conditioners in the common areas. It shows critical aspects of user behaviours. Many low-income homes have old evaporative coolers bought from the second-hand market. Refrigerators have a moderate presence (only 41 %) in low-income houses (Group 1). Despite low-cost new models and good deals from the second-hand markets, low-income groups hesitate to buy this equipment due to the recurring monthly cost of consumption.

In some cases, households reported seasonal use of the equipment in low-income homes. Television has a very high penetration in almost all kinds of households. Some households reported (17 out of 451) mobile phones or laptops as preferred entertainment devices. Room heaters are rare among low-income families in Jaipur. Many said burning dry wood during winter for heat. However, in high-income homes, heaters are prevalent for warmth during winter. A very peculiar trend was found in geysers and immersion heating rods. The ownership of geysers increases with income level, and the ownership of immersion rods drops. Few high-income houses reported safety concerns over using immersion rods at home. Whereas in low-income homes, this was reported as quick and handy for heating water. All surveyed homes from Groups 3 and 4 (higher income band) own air-conditioners. In Group 2, only 53% ownership is found, whereas no household from Group 1 has air-conditioners. Extensive examples exist of multiple air-conditioners in one home from Groups 3 and 4 (high income). In some cases, people from Group 2 reported having used air- conditioners purchased from the second-hand market.

Table 4: Pearson correlation coefficients for each selected parameter

	Floor Level	**BHK Type**	**Age of Building**	**Occupancy**	**Occupancy /Area**	**Income Class**	**Built-up area**	**Equipment Load**	**Load /Area**	**Target/output Variable**	
										EPI	**Annual Consumption**
Floor Level	1.00	0.16	-0.29	0.12	-0.04	0.14	0.13	0.18	0.12	0.10	0.18
BHK type	0.16	1.00	-0.24	0.20	-0.52	0.79	0.55	0.88	0.78	0.66	0.89
Age of Building	-0.29	-0.24	1.00	-0.10	0.11	-0.28	-0.11	-0.29	-0.32	-0.28	-0.28
Occupancy	0.12	0.20	-0.10	1.00	0.60	0.09	0.02	0.15	0.13	0.12	0.15
Occupancy /Area	-0.04	-0.52	0.11	0.60	1.00	-0.55	-0.50	-0.52	-0.44	-0.30	-0.53
Income class	0.14	0.79	-0.28	0.09	-0.55	1.00	0.59	0.89	0.84	0.75	0.89

Built-up area	0.13	0.55	-0.11	0.02	-0.50	0.59	1.00	0.57	0.38	0.24	0.56
Equipment load	0.18	0.88	-0.29	0.15	-0.52	0.89	0.57	1.00	0.94	0.76	0.94
Load/Area	0.12	0.78	-0.32	0.13	-0.44	0.84	0.38	0.94	1.00	0.86	0.88
EPI	0.10	0.66	-0.28	0.12	-0.30	0.75	0.24	0.76	0.86	1.00	0.85
Annual consumption	0.18	0.89	-0.28	0.15	-0.53	0.89	0.56	0.94	0.88	0.85	1.00

Result and Discussion

A correlation matrix was generated for all the parameters selected in the preceding section. In addition to the previously identified parameters, several new variables were evaluated to enhance understanding of their correlation with annual energy consumption. Table 4 (correlation matrix) contains each parameter's Pearson correlation coefficient.

The income groups are transformed into corresponding numerical values arranged in ascending order. The numerical value of 1 indicated the lower socioeconomic stratum, denoted as group 1. Analogously, the values 2, 3, 4, and 5 corresponded to groups 2, 3, 4, and 5, respectively. Likewise, representative numerical values are assigned to the age of buildings. Parameters that exhibit an r-value greater than 0.5 are deemed significant and are subsequently chosen for further analysis. Notably, the correlation between energy consumption and two variables changed significantly upon factoring them in. The variable of household size exhibits a weak correlation (0.15) with energy consumption. Upon considering the developed space of the residential unit, its correlation coefficient increased to 0.53. In a separate instance, although the correlation between equipment loads and the area is considered, it is observed that the correlation between equipment load and energy consumption is only slightly reduced. When factoring variables of varying strengths, there is a possibility of significant correlation shifts when one variable is strong and the other is weak. However, the resulting correlation shift may be marginal if both variables are strong. The study has identified several key variables that significantly impact energy consumption in residential buildings. These variables include BHK types, occupancy per unit area, income class, built-up area, equipment load, and equipment load per unit area.

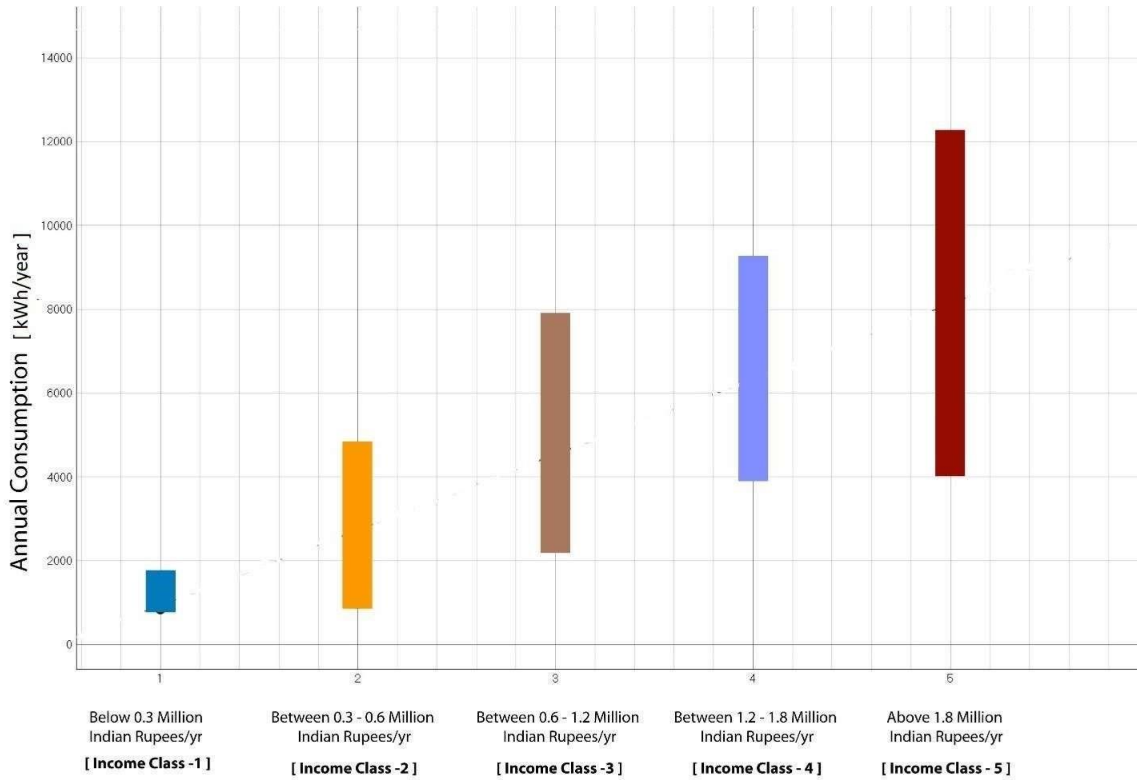

Figure 5: Income groups versus annual energy consumption

EPI and Annual Energy Consumption as an indicator of the energy performance of buildings

Notably, variation exists in the correlation coefficients of each parameter with the annual energy consumption and the Energy Performance Index (EPI), represented as the quotient of total annual energy consumption and the building's area. Remarkably, each parameter demonstrates a more robust correlation with annual consumption than the EPI metric.

Despite this, the EPI has assumed a pivotal role as a primary yardstick for evaluating building benchmarks. A particularly intriguing phenomenon arises when buildings sharing identical energy consumption profiles are assessed through the prism of the EPI metric. Such an analytical shift has the potential to engender divergent perceptions. Consequently, the energy-saving potential intrinsic to larger buildings might need to be more obscured solely due to their representation within the EPI framework.

Moreover, it's noteworthy that a higher occupancy density is accommodated within a confined built-up space within low-income households. Their energy consumption remains substantially lower compared to their counterparts in higher-income brackets. This observation underscores the potential limitations of the EPI as an all-encompassing indicator for capturing a building's comprehensive energy performance. The multifaceted nature of building energy dynamics calls for a nuanced approach when interpreting and selecting indicators. While the EPI has proven valuable, its reliability in portraying overall energy performance is context-dependent, necessitating careful consideration of the specific attributes under evaluation.

Household size

The survey found more individuals living in low-income dwelling units compared to the same dwelling unit with higher income classes. Despite that, the annual energy consumption levels are lower (in low-income units) than in the higher-income units with fewer people. Hence, more people in the household will consume less energy. There were examples of 6-8 people living in a 2BHK unit with very low consumption in low-income houses found during the survey. On the contrary, a similar 2BHK unit with higher income levels consumed more energy.

Household Income and Equipment Ownership

The income levels of households play a crucial role in influencing energy consumption behaviour. While discussing with consumers from various economic classes during the survey, we realized a deep psychological connection between wealth and equipment ownership. People show their economic well-being through new household appliance purchases. Hence, especially among the lower-income classes, the aspiration to own a refrigerator or an air-conditioner is some shot of an economic milestone.

Hence, while looking into the energy consumption aspect of equipment, the aspirational and psychological impact of such ownership must not be discounted. There is a strong consensus among the people for more consumption. Across all economic classes, there is an inherent aspiration to buy more and consume more for better comfort.

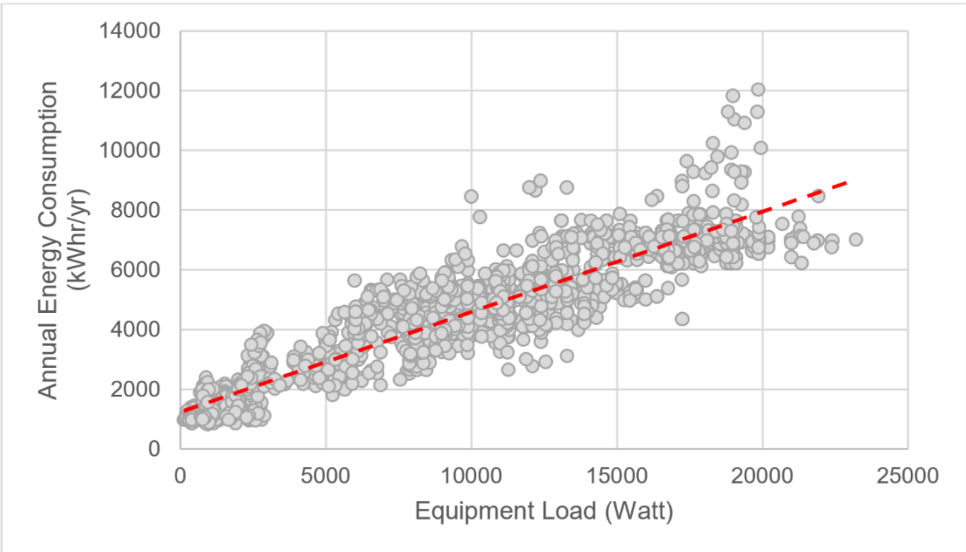

Figure 6: The figure depicts the correlation between equipment Wattage and annual energy consumption

However, higher income and equipment ownership only sometimes generate higher energy consumption. A wide variation in energy consumption is found within higher-income groups with higher equipment ownership.

Limitations and scopes for future studies

The scope of this study is restricted to examining residential buildings exclusively within the city of Jaipur. Consequently, the investigation is limited to a solitary climatic zone. Furthermore, the dataset employed in this research originates from a household survey, whereby information is garnered directly from participants. The operational schedules of appliances and other pertinent end-user details are derived from the responses provided by these participants. The future researcher may undertake similar studies in other geographic locations. It helps compare the impact of various parameters in different contexts. Moreover, IoT-based monitored datasets may be able to unfold the correlations with better accuracy. Additionally, studies may focus on different social groups (ethnic groups, caste-based groups, etc.) to understand their energy consumption behaviours.

Conclusion

Households exhibit varying energy consumption patterns, yet this study underscores the pivotal role of household income as a determinant shaping energy consumption patterns within Jaipur's residences. In the upcoming years, comprehensive large-scale investigations will be imperative to delve into the nuanced intricacies of end-user energy consumption patterns spanning urban and regional contexts. The collection of end-user energy consumption data across multiple strata holds paramount significance.

Amidst the survey, a prevailing aspiration for enhanced comfort resonated across all income brackets. This aspiration, coupled with the advancing efficiency of appliances and the burgeoning household incomes of the aspiring Indian middle class, augurs an exciting trajectory for India's energy landscape in the foreseeable future. Within our survey and subsequent data analysis, three pivotal insights emerged:

1. Establishing a standardized framework for conducting surveys is imperative, fostering data sharing within the research community. This approach is critical as equipment-level datasets are essential for refining statistical models and calibrating simulation outcomes.
2. Contrary to expectation, increased equipment ownership does not necessarily translate to rising energy consumption levels in the same proportion across all income groups.
3. Annual energy consumption is a viable alternative to the Energy Performance Index (EPI) as an indicator for evaluating building energy performance.

This study sheds light on the complexity of energy consumption behaviours and the influence of income, advocating for a holistic approach to data collection and refined metrics for effective energy management.

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Experimental Validation of PCM Integrated Space Heating

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Highlights

- PCM integrated space heating system is a novel off-grid solution.
- Air is used as the heat transfer medium for keeping the room temperatures in optimum range.
- The results validated the space heating solution by maintaining room temperature above 15 °C.
- For 24 hours, while the ambient varied between 0 and 5 °C, the room temperature was controlled in the range 15-20°C.
- The current system needs aesthetical and functional improvements to be commercialized.

Abstract

Phase change materials (PCM) integrated solar-powered space heating plays a crucial role in maintaining thermal comfort in cold regions where the temperature shoots down to -10 °C. This paper presents the experimental results of using PCM HS22 integrated with solar energy to maintain comfortable conditions inside the experimental prototype in the cold ambient. The solar energy is stored in PCM during the daytime to use it for night-time during off-sunshine hours. The results show that the room temperature is maintained in the 10 to 20 °C temperature range when the ambient was between -10 to 0 °C. The room temperature was maintained consistently for 24 hours.

Keywords: Space heating, Thermal energy storage, Phase change materials, Thermal comfort, Cold climate conditions

Introduction

North India alone consumes 364 million GW of electricity in a year, of which 130 million GW is consumed in extremely cold regions and 260 million GW in moderate climates. It is estimated that 30% of this consumption in moderate climates and 70% in cold areas is due to space heating. Not only in India, but 61% of US homes also depend on electricity-based heating systems, and 69% of Europe's total electricity consumption is because of space heating. About 5000 trillion kWh/year of energy is generated over India's land area. Northern India receives solar insolation of 3-7 kWh/m^2/day.

Solar energy plays an important role in responding to the growing demand for energy as well as dealing with pressing climate change and air pollution issues. Solar energy features low density and intermittency; therefore, an appropriate storage method is required [1]. Thermal energy storage (TES) has become very important in recent years since it balances the energy demand and improves the efficiency of solar systems. Thermal energy storage systems must have the necessary characteristics to improve the performance of the storage systems. The usage of PCMs for energy storage provides a great benefit, but their low thermal conductivity becomes a major drawback. This can be compensated with the use of phase change material in an appropriate design for the effective functioning of the system [2]. The most sensitive parameters affecting the performance of the storage unit are the melting point of the storage material, the mass of PCM, and the airflow rate [3]. The usage of TES for storing energy is a favorable technology that is used in current years[4]. Recently, PCM technology improvement has helped the use of different types of PCMs to increase the energy and exergy efficiency of TES. PCMs can also be incorporated into conventional heating or cooling systems so that their capacity can be reduced. Considerable research has been done on the application of PCMs for space heating and cooling, yet at present, there are limited systems in use [5]. Latent heat thermal energy storage (LHTES) is becoming more and more attractive for space heating and cooling of buildings [6]. The advantage of using space heating in buildings is the ability to store the heat during the day and use it continuously later in the night, particularly in the winter, by reducing diurnal temperature fluctuations.

By avoiding conventional methods for thermal storage, PCMs provide heat storage and nearly constant temperature at much higher energy storage densities. This technology can meet up to a maximum of this demand depending on the region's climate. Active and passive systems are used for this purpose [7]. Both the useful energy and the solar fraction of the system are influenced obviously by the amount of solar radiation. The change in the temperature in the heating room is bigger than that of the contrast as the ambient temperature changes [8].

In this experimental work, the discharging of PCM in a specified fabricated room is presented. This paper gives a clear idea about the feasibility of solar heating systems to achieve stabilization temperatures inside a room. The amount of PCM required, the type of PCM to be used, and the Heat Exchanger (HX) design is the important aspect that this paper clarifies with the experiments performed based on theoretical calculations.

The room-in-room model called the test bed, is set up for the testing of solar space heating experiments. The annular space between the rooms is maintained below -5 °C temperature, and the inner room is heated by the hot convecting air from the ETC. The Solid Works 3D model of the test bed with an ETC has been developed for better visualization.

Materials and Methods

The room-in-room model called the test bed, is set up for the testing of solar space heating experiments. The annular space between the rooms is maintained below -5 °C, and the inner room is heated by the hot convecting air from ETC. The SolidWorks 3D model of the test bed with an ETC collector has been developed for better visualization.

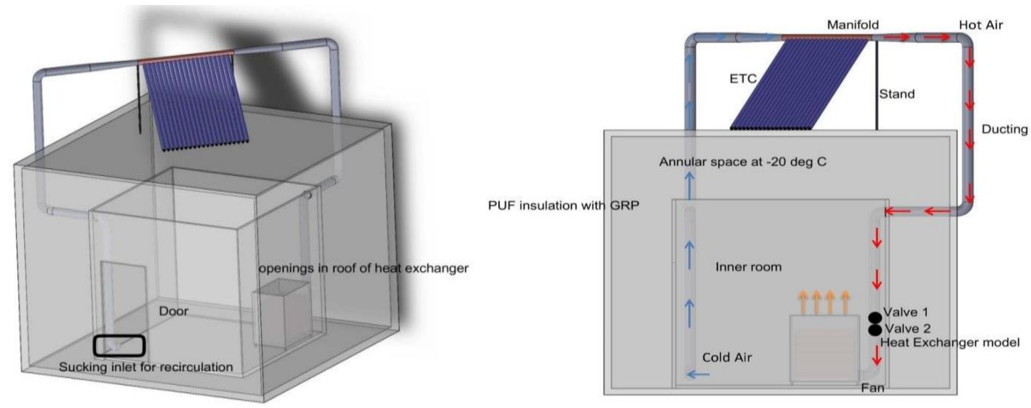

Figure 1: 3D model of test bed (L) Isometric view of model (R) Air flow schematic diagram

The heat transfer from the air to PCM takes place in PCM air HX. The design of the HX is such that the maximum heat transfer takes place by exposing the maximum surface area of the panels to the convecting air. It can accommodate 30 HDPE panels. The insulation is done around the HX to concentrate the incoming heat from the ETC and to prevent heat losses to the room.

Table 1: Test bed specifications

S. No.	Particulars	Specifications
1.	Outer room(mm)	4880x4880x4200
2.	Inner room(mm)	3000x3000x3000
3.	Outer room PUF insulation(mm)	100
4.	Inner room PUF insulation(mm)	60
5.	Inner room and outer room wall material	1.5mm GRP at inner and outer side with PUF insulation
6.	Window (mm)	1000x1000
7.	Window material	Double glazed glass
8.	PVC pipe for ducting(mm)	150Φ
9.	ETC manifold(mm)	100 Φ
10.	ETC manifold material	GI with Aluminum fins

The metal-made roof of the HX is removed and replaced by a foam sheet in which the 5 mm diameter holes are given to exhaust the comparatively less hot air. This is done to increase the residence time of hot air inside HX, which will ultimately increase the heat transfer from the hot air to the PCM panels.

Table 2: HX material specifications

S. No.	Particulars	Specifications
1.	PCM Air HX (mm)	1180x1380x680
2.	HDPE extruded panel (mm)	840x200x20
3.	HX insulation thickness (mm)	25
4.	HX insulation material	Nitrile Rubber Foam
5.	Density of insulation (kg/m^3)	40±2
6.	PCM in each Panel (kg)	3.68
7.	Power capacity of Fan (W)	60
8.	Fan type	Inline Duct fan
9.	PCM type	sav*E*® HS29
10.	Total PCM quantity (kg)	110
11.	Thermocouple type	K-type

Figure 2: (L) PCM air HX closed view (R) Stacking of the HDPE extruded panels inside HX open view

The HX is connected to the ETC of 20 tubes set with the help of ducting. The ducting has been done with a 6” (150 mm) diameter PVC pipe.

Figure 3: (L) ETC solar collector system with ducting (R) PCM air HX with Nitrile rubber foam insulation and dampers to switch the air circulation during night-time.

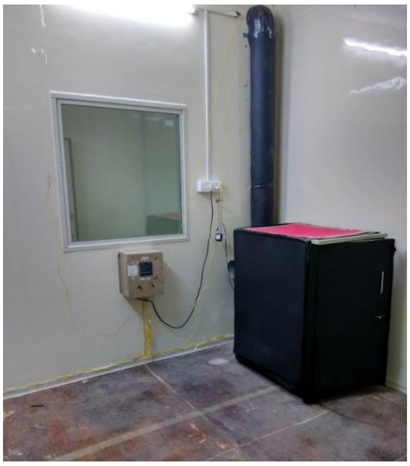

Figure 4: (L) Inside view of the inner room with HX, fan, data logger, and ducting (R) Sucking inlet of the room air

The air suction is created by inline fans connected from the HX in the room to the ETC. The manifold of the collector is made of GI pipe. The copper heat pipes have been inserted in the manifold to transfer the heat to the flowing air through it. To maximize the contact surface area of the air, aluminum fins were inserted into the manifold. The insertion of the fins improves the heat transfer to the air. Successive experiments are performed to achieve the set target of stabilizing the room in the required temperature range.

First, all the equipment, like the data logger and thermocouples, were calibrated, and then the thermocouples were installed at different locations in the setup. The amount of PCM needed was calculated using thermal calculations, and then the encapsulation of the PCM was decided. After this, the design of the HX model was done.

Table 3: Specifications of savE® HS29.

S. No.	Property	Unit	Value
1	Melting Temperature	°C	29.0
2	Freezing Temperature	°C	26.0
3	Latent Heat Melt	kJ/kg	196
4	Latent Heat Cool	kJ/kg	199
5	Liquid Density	kg/m^3	1540
6	Solid Density	kg/m^3	1651
7	Liquid Specific Heat	kJ/kg K	2.53
8	Solid Specific Heat	kJ/kg K	2.27
9	Liquid Thermal Conductivity	W/mK	0.56
10	Solid Thermal Conductivity	W/mK	1.13

First, U is calculated using Equation 2, and then Equation 1 is used to calculate heat conducted through all surfaces of the inner room. Based on this calculation, the net heat load is calculated using Equation 3. Where Q is the heat transferred, U is the overall heat transfer coefficient, A is the area over which the heat transfer occurs, T is the difference in temperature,

$$Q = U \ X \ A \ X \ \Delta T \tag{1}$$

$$U = \frac{1}{R} = \frac{k}{x} \tag{2}$$

$$Q_{net} = Q \ X \ t \ X \ 3600 \tag{3}$$

A negative sign of Q_{net} shows the heat loss from the system. After calculating the net heat load, the quantity of PCM (m) required is calculated using Equation 4. Cp is the specific heat of the PCM, Ti is the initial temperature of the PCM when the heat transfer was initiated, and Tm is the temperature of melting of the PCM.

$$m = \frac{|Qnet|}{(L + Cp \times (Ti - Tm)) \times 1000} \tag{4}$$

Working of the Test chamber – An inline fan installed at the inlet of the PCM air HX creates suction in the pipe connected with the ETC. The convecting air carries the heat generated by the ETC during a good sunny day. The heat carried by the air passes through the barriers created by the aluminum fins, which are in direct contact with the heat pipes. The aluminum fins are installed inside the ETC manifold to increase the contact surface area of the air to maximize the heat gain. Then, the heated air enters the HX through PVC ducting with a force convecting fan installed at the inlet of the HX. The heated air passes over the PCM panels and charges them for later use. The heat gets accumulates in the HX as the inlet of the air into the HX is from the bottom, and the outlet is provided at the top of it. The outlet velocity of the air from HX is very low as the holes' size is very small, through which it escapes to the room space. The air coming out from HX heats the inner room, along with the remaining heat inside it. This air is then recirculated through an extra opening in the room. This process is repeated during the daytime. During the sunshine hours, damper valve 1 remains open, and valve 2 is closed, as shown in Figure 1. But after sunshine hours, the valves are toggled, and valve 1 and valve 2 remain closed and opened, respectively, till sunrise. During off-sunshine hours, the room air is passed through the HX and gets heated up after coming into contact with charged sav*E*® HS29. The PCM slowly starts discharging till the whole energy of the PCM gets exhausted. The experiments were performed in May month of the year 2018-19. The GHI for this month is 6.65 kWh/m^2/day in the geographical location of Bawal, Haryana (Lat, Lon: 28.05, 76.55).

The thermocouples at the inlet, center, and top of the HX are installed to get an idea of the temperature variations inside it. The thermocouples at the ETC collector inlet and outlet, sucking air outlet pipe, inner room volumetric center point, and an annular space between two rooms are also installed.

Results

The results produced for the complete cycle of the PCM inside the test bed are shown in the figure given below. The testing is done for a full day to check the complete charging and discharging of the PCM.

Figure 5 depicts the temperature variations at different locations in the test bed and the HX for the complete 24 hours. The collector inlet temperature is at 15 °C, and the collector outlet temperature is at 30 °C at the start of the experiment. The collector outlet temperature increases to 50 °C at around 02:00 PM, which is the peak time of the beam solar radiation capturing, and annular space temperature is maintained between 0 to -5 °C during sunshine hours and -10 to -15 °C during off-sunshine hours. The collector inlet temperature varies between 20 °C to 35 °C. The collector inlet and outlet temperatures rose to very high temperatures during off-sunshine hours. This is because valve 1 is closed after sunshine hours, and the diffused radiation of the sun captured in ETC increases the temperatures of the collector, and there is no heat transfer from the collector to HX during off-sunshine hours.

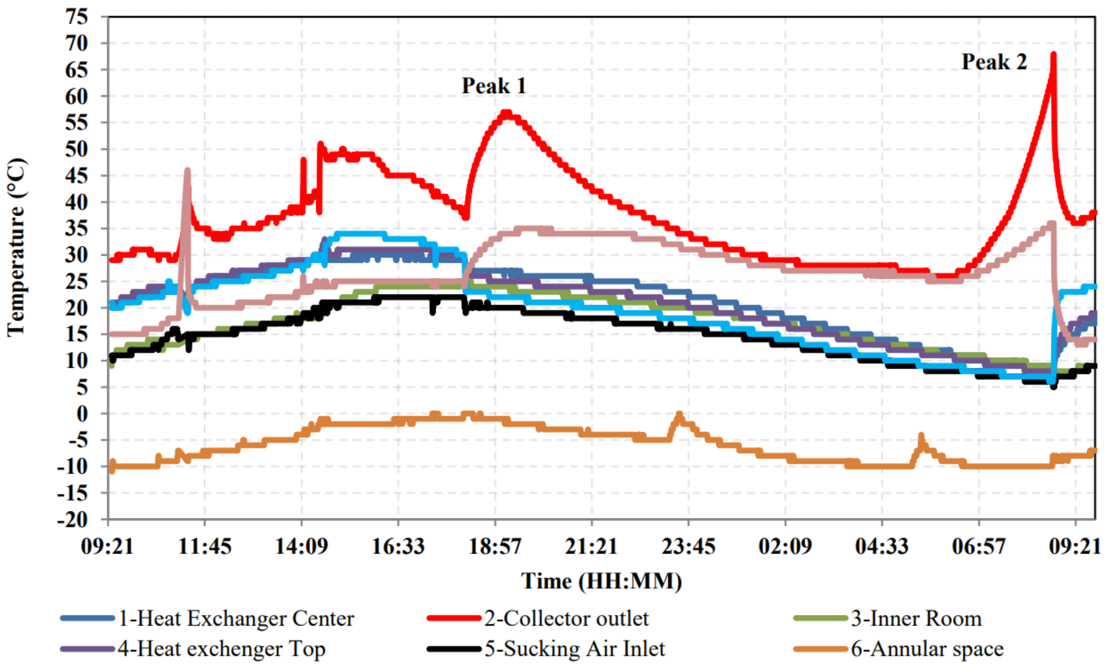

Figure 5: Temperature variations in the inner room and at other locations

The sudden shoot-up of the collector outlet temperature (Peak 1) is due to the solar radiation capturing in the ETC manifold after closing valve 1, which supplies the air from the collector to the room. This results in a rise in collector inlet temperature. Peak 2 is due to the same reason as peak 1, as valve 1 has not been opened till 08:48 AM, which resulted in the rise of the temperature inside the ETC assembly. At the beginning of the experiment, the inner room temperature is around 15 °C and varies between 10 °C to 25 °C temperature for 24-hour span. The inner room temperature is at its maximum of 25 °C at around 05:00 PM, and then it starts decreasing. The room temperature remains above 15ºC till around 05:00 AM and remains between 10-15ºC temperatures for the next 3-4 hours. So, the backup hours for the PCM are approximately 11 hours during off-sunshine hours.

As the temperature at the fan outlet was above 30ºC for more than 4 hours, the PCM melted inside the HX very easily. This molten PCM releases its energy for the next 12 hours and warms up the inner room.

Conclusions

- The results from the scaled-up model indicate that the PCM sav*E*®HS29 is suitable for maintaining room temperature in the range of 15-25 °C.
- The annular space temperature varies from 0 to -5 °C in the daytime and -10 °C to -15 °C at night. During this, the collector outlet temperature varies from 30 °C to 43 °C.
- The temperature is maintained in the required range inside the room till 6 AM and remains between 10-15°C for the next 3-4 hours till the solar collector gets enough radiation that can increase the air temperature above 15°C.
- The heat conducted by the inner room to the annular space maintained at -20°C temperature is balanced by the heat gain in the room through PCM for approximately 12 hours.

The work has not been carried forward because of the installation challenges in the COVID times. The thermal energy storage setup discussed in this paper has the potential to be integrated into Leh. However, there will be several challenges that need to be catered. For example, air density at higher altitudes is low, and hence, heat transfer will be slow. The wind speed has not been simulated in the test chamber. The temperature variation is large in the higher altitudes. To solve all these challenges, some modifications will have to be made to the current setup. To do this, the next step is to undergo simulation studies that take into account the weather conditions at higher altitudes.

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Re-imagining Energy Efficiency in Open-Plan Offices Using Micro-Zonal Occupant Centric Control: Protocols to be Considered

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Highlights

- Need to integrate micro-zoning, thermal zoning and spatial planning of open-plan offices
- Protocols for micro-zoning outlined
- Planned micro-zones save 44% of HVAC energy consumption

Abstract

Air-conditioning energy consumed in buildings can be reduced by cooling only occupied regions. With modern open-plan offices being adaptable with flexible work hours, there is a need to virtually divide thermal zones based on varying thermal requirements. Micro-Zonal Occupant-Centric Control (MZOCC) saves HVAC energy by creating micro-comfort zones around occupants through independent diffuser control. However, research gaps exist between thermal zoning for HVAC design and micro-zoning. There is a lack of clarity on the method of micro-zoning and factors to be considered, such as size and shape of micro-zones. The aim of this study is to delineate protocols for micro-zoning and evaluate the benefits of planned micro-zones. Characteristics of existing Indian open-plan offices are studied, and a method for micro-zoning is delineated. Results indicate that planned micro-zoning saves 44% of energy. The micro-zonal layout acts as the starting point for optimising diffuser allocation and airflow control, which will further improve energy savings.

Keywords: Energy-efficiency, Thermal-zones, Micro-zones, Open-plan offices

Introduction

Micro-zonal occupant centric control (MZOCC) has emerged as a significant method to improve energy efficiency in open-plan offices. This creates micro-comfort zones around occupants, enabling a reduction of energy wastage in conditioning unoccupied regions within a thermal zone. MZOCC acts as an alternative to personalised ventilation (PV) that uses personal fans or air handling units placed very close to occupants. Though PV creates a micro-comfort zone around the occupants, it requires a high initial investment to lay ducts and equipment for bringing airflow to the occupant's face and body [1]. This also causes intrusion to occupants [2], and the conditioned air is concentrated in a very small area [3]. Most importantly, this does not allow flexibility in changing architectural layouts. Hence, there is a need to improve standard HVAC systems so that micro-comfort zones can be created by virtually dividing the thermal zones.

The potential of such virtual sub-zoning to improve energy efficiency [4][5], thermal comfort [6], and air quality in open-plan offices is established in the literature. However, there is a lack of clarity on how micro-zones are to be planned. There is a research gap between micro-zoning and thermal zoning. Current methods of thermal zoning do not consider the parameters required for micro-zoning. In addition, most studies on micro-zoning have chosen arbitrary sizes for micro-zones as per convenience, and inter-micro-zonal interactions are either modelled using steady state models [5] or transient empirical models [4]. Previous studies that used transient CFD models for MZOCC indicated that unplanned micro-zoning can lead to energy wastage and thermal discomfort due to inter-micro-zonal interaction. It can lead to the merging of cool air jets from adjacent diffusers or the clinging of cool air to walls and surfaces, creating heavy thermal gradients [7], [8]. In this regard, there is a need to develop protocols for micro-zoning such that HVAC energy can be saved without violating thermal comfort. The aim of the study is to explore the considerations in micro-zoning by giving recommendations on the size of micro-zones, the shape of micro-zones, the distance between diffusers, etc., and evaluate energy savings due to micro-zonal air-conditioning with respect to standard zone-based air-conditioning.

Literature Review

The method of creating micro-comfort zones for reducing energy wastage has been of great interest to researchers. Personalised ventilation, personal comfort systems [9], and task ambient systems are used to attain comfortable air temperatures around occupants even when the zone is at a higher air temperature. Personalized ventilation (PV), which creates a micro-comfort zone around the occupant by supplying fresh air to the breathing zone of occupants, saves 50%-60% of air conditioning energy [10][11] [12]. The type of airflow and micro-comfort zone created depends on the air terminal device (ATD) used. A few common ATDs are moveable panels (MP), which throw air through a personal air handling unit (AHU); computer monitor panels (CMP), which throw air through an AHU above the computer monitor; vertical desk grill (VDG), horizontal desk grill (HDG), which throws air from an opening near the desk [13], personal environmental modules (PEM) which are placed on partitions [14] [15], air blowers on headsets [2] or their seat [13] etc.

Airflow from each diffuser type can further be controlled by altering air temperature, mean velocity, turbulence intensity, direction of supply air, area of supply vents, the targeted area of supply, activities, and ergonomics of the space [9]. Since PV vents are placed very close to the occupants, the supply air has a higher temperature and lower velocity (approximately 0.25m/s) compared to standard HVAC systems [16]. This restricts the spread of air jets from PV and cools only a small area around the occupant. But this also leads to discomfort due to thermal asymmetry and gradients for occupants who are not near PV vents [3]. Hence, PV is usually operated along with a standard room air conditioner, which maintains a higher setpoint temperature. Strategies linking the control between the micro environment due to PV and the macro environment due to room HVAC systems are developed [17]. Personal comfort systems have cooling mechanisms integrated to personal equipment such as personal chairs, coolers, blankets, mattresses [18], and clothing [9]. The boundary of the micro-comfort zone of PV varies based on the properties of the ventilation system, such as temperature, mean velocity, turbulence intensity, direction of supply air, area of supply vents, and the targeted area of supply. Factors such as occupant movement [19], furniture design and arrangement [14], and other spatial elements in the zone also influence the boundary.

Virtual zoning of thermal zones into sub-zones and controlling airflow in each sub-zone using occupant centric control has emerged as an alternative to PV. Such virtual sub-zoning is mostly done by dividing the thermal zone into geometric grids, with each grid having one air node [5] [4] [6]. 'Fine grained zoning' [20] [6] divides the thermal zone into finer grids of size 7.2mx7.2m. The grid boundaries are considered virtual with a constant air exchange flow, and the grid size is chosen based on separations on the façade[6]. However, with variations in heating and cooling in each fine zone, the thermal coupling between adjacent micro-zones varies; hence, assuming a constant flow may lead to errors. Further, it was observed that while fine grained zoning reduced comfort violations, energy consumption increased in a few cases.

Thermal interactions through the virtual boundary have been modelled in studies that aimed at exploring HVAC energy efficiency using sub-zoning. A steady-state CFD model was developed to model the thermal interaction between the virtual boundary of a zone of size 7mx6.6m divided into two sub-zones of 2.9mx6m [5]. The study leveraged on thermal coupling to cool adjacent sub-zones and was able to reduce 10% energy consumption. To capture the transient variations in thermal coupling, a mathematical model with bi-directional airflow was developed in a study on a co-working office in India [4], [21]–[24]. This model was used to predict the indoor temperature at each sub-zone for a given time in order to allocate workspaces to occupants based on their thermal preferences. The size of each sub-zone was 10mx15.25m. The set-point temperatures of the occupied sub-zone are decided based on the requirements of the users in the sub-zone. But it is also seen that, several unoccupied sub-zones are to be conditioned to reach setpoint in the occupied sub-zones. This is because airflow through the diffusers in the occupied sub-zones is not sufficient and requires thermal coupling from adjacent sub-zones. This highlights the need for connected control of diffusers.

For a detailed understanding of thermal interactions through virtual boundaries, recent studies by the authors used experimentally validated transient state CFD models for MZOCC [7], [8], [25]. These revealed that uncontrolled intermicro-zonal interactions could lead to increased energy consumption due to the merging of adjacent air jets and lead to a deflection of air jets away from occupied regions. Two factors are found critical in controlling this merging: (1) relative location of diffusers and (2) supply velocity [25]. When two supply diffusers were placed at a distance of 2m, air jets were found to merge and move away from the occupied micro-zone. The merging is due to the attraction induced by the low-pressure region created between the diffusers. Low velocity jets were found to deflect towards high velocity jets due to the reduced momentum of the former. The presence of surfaces such as walls or furniture also causes the deflection of air jets due to the Coanda effect [8]. Thus, the diffusers placed in corner regions produce smaller micro-zones than those in the centre of the room. Air movement is also influenced by the type of furniture and height of partitions [8] [26]. Considering the aforementioned properties of air jets, two strategies for controlling air movement and inter-micro-zonal interactions are proposed. (1) setback flow – maintaining a low velocity flow and (2) setback temperature – maintaining a higher setpoint temperature. These are maintained in either all unoccupied micro-zones or only the micro-zones adjacent to the occupied micro-zones such that thermal gradients and draft are minimal with maximum energy savings. MZOCC using setback flow and setback temperature-based control strategies can bring about 60% energy savings [8].

Several strategies for thermal zoning are discussed in the literature, but there is a research gap between thermal zoning and micro-zoning. Thermal zones or HVAC zones are regions with uniform thermal requirements and catered by a single thermostat [27] [28]. The common assumption is that the thermal conditions within a zone are uniform at any point of time. This assumption is used in simulation zoning, where the building is discretized into regions of uniform thermal conditions to reduce model complexity [29]. For zoning in early design stages when room separations or interior loads are unknown, the standard core-perimeter model is used [30] such that externally and internally heated spaces are separated. The prescribed perimeter depth varies in different standards, with a range of 3m to 6m, with 4.5m to 5m being the most commonly used. Further, the cardinal zones are separated as the intensity of solar radiation varies. Thus, the 5 zone model is the most basic form of zoning and is used in several automatic zoning algorithms [29] [31]. Most studies consider room-based zoning, where physical partitions form the zonal boundaries, to be the most granular thermal zoning [32]. In between room-based zoning and core perimeter zoning, several methods of grouping spaces into zones, such as grouping based on function [32], function and orientation [32], thermal loads [29] [33], adjacency of rooms, and similarity in HVAC requirements [34] have been explored. Recently, a cluster-based method of thermal zoning has been proposed, where a large space is divided into finite grids and grouped based on transient heat gained [35].

From the literature, the parameters that influence thermal zoning can be simplified as transient heat gain and source of heat (external or internal), function and activities, schedule of usage, and adjacency of spaces. On the other hand, in microzoning, parameters such as the location of diffusers, inter-micro-zonal interaction, partition heights and air movement, variations in thermal preferences, etc., are important. There is a need to merge this gap between thermal zoning and microzoning and outline a method of micro-zoning. Further, from the literature on micro-zones, it is observed that micro-zonal sizes were decided arbitrarily, with each study having its own grid size. It is suggested in the cluster-based zoning method that the minimum grid size will depend on the area required for the activity and the area catered by a diffuser [35]. In continuation, there is a need to explore minimum grid sizes for common activities and diffuser types found in open-plan offices. In this regard, there is a need to study considerations in the spatial design of open-plan offices from literature as well as built spaces.

Open-plan offices originated with the idea of designing spaces for free communication without the barriers of walls [36]. Important parameters to be considered by planning open-plan offices are work patterns [37], activities [38], organizational hierarchies [39], and the needs of the occupants [40]. The guide on planning open-plan offices prepared in 2010 highlights relevant functional, technical, and financial factors to be considered while planning open-plan offices [39]. Modular planning, plug facilities, and flexible ceilings/partitions upgrade a standard open-plan office to a ‘flexible’ office [41]. Attempts to improve office atmospheres have also led to the emergence of ‘activity-based’ offices, which provide a variety of work settings for occupants to choose from as per the requirement of the assigned work [38].

From literature, the common office types can be categorised as into 5: (1) Bullpen, which is a full open-plan office with no partitions [40], (2) caves and common design [42], where individual cabins surround open workspaces, (3) Team enclosures [40], where each team occupies an open-plan office, (4) flexible offices, which contains a mixed of dedicated workspaces and shared areas [41] and (5) activity-based offices [38]. Similarly, in terms of work culture, open-plan offices can be divided into four [37]. (1) Hive, where one works independently with minimum interaction with the colleagues,

(2) cell, some amount of interaction is present, but most work is done independently, and the worker also works remotely; (3) Den, which requires a highly interactive environment to accommodate group work; and (4) club, which has both concentrated work and group work. A survey of Indian open-plan offices is conducted in this study to explore whether Indian offices follow such characteristics.

Several strategies to improve open-plan layouts to facilitate better communication [43], reduce sedentary time [44], and make the space livelier [45] are discussed in the literature. Inadequate air-conditioning [46], over-conditioning, and lack of control over the thermal environment [37][38] can cause dissatisfaction among occupants. As discussed, this also increases energy wastage. Hence, customisation of the thermal environment with a perceived sense of control is important in open-plan offices. Spatial attributes such as social density (number of occupants in the space) [46], spatial density (size of the space) [46], and office space occupation (number of occupants per enclosed office) [47] are important while creating such personal thermal environments. This gives an estimate of how many people each diffuser serves and how many diffusers are required to serve each activity. This is important in deciding the minimum size of micro-zones.

Listing the common activity spaces and occupant densities (the ratio of social density and spatial density) in open-plan offices for each activity, commonly used air conditioning diffusers, furniture types, and clusters helps in planning microzones. Open-planned offices are often tightly packed to reduce facility costs. Indian offices have occupant densities of 6-8m^2/person [48], indicating crowded work spaces [49]. Further, the occupant densities can vary for different spaces in the open-plan office, such as workspaces, corridors, activity-based work areas, and leisure spaces. Hence, the air conditioning requirement in each region can be different.

To summarise, the location of diffusers, furniture in the space and their arrangement, activities, occupancy in the zone, and other spatial features influence micro-zoning. The need to find optimal virtual boundaries to place thermostats within micro-zones is highlighted in previous studies [7], but there is a need to develop a method for the same. At this point, it is imperative to have guidelines to plan the appropriate size of micro-zones, diffuser location, minimum distance of diffusers from walls, minimum distance between diffusers, furniture height, and arrangement basis the activity and requirement of micro-zones before OCC is implemented in MZOCC. Open-plan offices are diverse, with a variety of activities, and require varying levels of air-conditioning in different regions. Though few studies have proved the efficiency of MZOCC, there is a disconnect between micro-zoning and thermal zoning. The aim of this study is to give guidelines on planning micro-zones in open-plan offices. In this matter, open-plan offices in India are studied to explore how similar these offices are with respect to the characteristics observed in the literature. This also gives insights into the additional factors to be considered for MZOCC. The novel contribution of this study is that it identifies the considerations in micro-zoning Indian open-plan offices, gives guidelines on appropriately planning micro-zones, and evaluates the energy savings due to possible micro-zonal divisions. While previous studies have arbitrarily divided thermal zones into micro-zones [6] or divided considering function planning of the zone [50], this study establishes that planning micro-zones considering the aforementioned spatio-temporal characteristics of the office saves more energy compared to micro-zoning based on function alone.

Method

The study follows a three-stage approach as outlined in Figure 1, wherein the first stage, considerations for micro-zoning open-plan offices, are identified from the literature, following which existing open-plan offices in India are surveyed to identify the similarities of these offices from the ones observed in the literature. From these, considerations for micro-zoning Indian offices are identified.

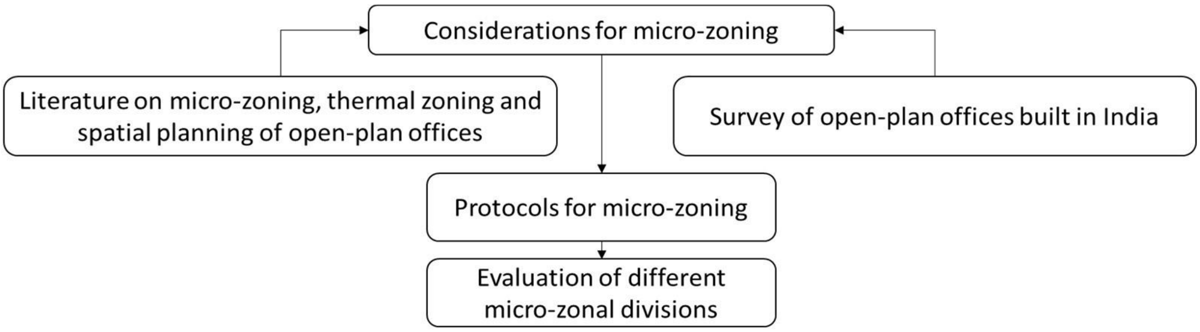

Figure 1: Methodology

A variety of open-plan offices built in the last decade are surveyed to explore the characteristics and existing conditions of Indian open-plan offices. The objective of the survey is to include all possible varieties of open-plan offices to have a holistic understanding. Hence, sampling is terminated when all varieties are studied. Forty-two offices, with a total of 116 open-plan office rooms, are studied, and 65 varieties of open-plan office layouts are observed.

To analyse the characteristics of these offices, the distribution of area of the floor plate, area of open-plan offices, aspect ratio, occupancy, occupant density, activity types, furniture used and their arrangements, etc., are analysed. The additional features in 'flexible' offices and 'activity-based' offices that need to be considered while sizing micro-zones are also explored. The existing conditions in these offices are evaluated in terms of thermal zoning and diffuser allocation. For each activity and diffuser type, the minimum size of micro-zones as per existing office layouts are delineated. In the second stage, protocols for micro-zoning are outlined based on the observed considerations.

The cooling load in the hour with the peak demand is considered the design load. The variations in energy consumed due to changes in occupancy are computed separately after estimating the cooling load. The Radiant Time Series (RTS) method is used to estimate cooling load. The RTS method considers the time delay due to conductive heat gain from building surfaces and delay in radiative heat gain to convert to cooling load [51]. The radiative heat gain absorbed by the interior surfaces adds to the cooling load when it is transferred to room air by convection. Conductive time series (CTS) is used to calculate conductive heat gain at the exterior using equation (1)

$$q_{i,q-n} = UA(t_{e.q-n} - t_{rc}) \quad (1)$$

Where,

$q_{i,q-n}$ is the conductive heat input for the surface n hours ago, (W)

U is the overall heat transfer coefficient for the surface, (W.m^2.K)

A is the surface area, (Wm^2)

$t_{e.q-n}$ is the sol-air temperature n hours ago (K)

t_{rc} is the presumed constant room temperature, (K)

Table 1: U values assumed in the study

Type	Material	U (W/m^2.K)
Roof	4 inch lightweight concrete	1.275
Exterior Wall	8 inch lightweight concrete block	0.8108
Interior Walls	Frame partition with ¾ gypsum board	1.4733
Ceilings	8 inch light weight concrete	1.3610
Floors	Passive floor	2.9582
Slabs	Uninsulated solid	0.7059
Doors	Metal	3.7
Exterior windows	Large double-glazed windows	2.914

Sol air temperature at an hour is calculated using equation (2):

$$t_e = t_o + \alpha E_t / h_o - \epsilon \Delta R / h_o \quad (2)$$

α is the absorptance of the surface for solar radiation

E_t is the total solar radiation incident on surface (W/m^2)

h_o is the coefficient of heat transfer (W.m^2.K)

t_o is the outdoor temperature in K

ϵ is the hemispherical emittance of the surface

ΔR is the difference between long-wave radiation incident on the surface from sky and surroundings and radiation emitted by a blackbody at outdoor air temperature (W/m^2)

The weather conditions are input using weather station data. The U values for different materials are assumed as given in Table 1. The overall U value is estimated by adding the reciprocal of the R-values of the materials.

Hourly conductive heat gain is computed from the conductive heat gained in the past 23 hours using equation (3)

$$q_q = c_o \, q_{i,q} + c_1 q_{i,q} + c_2 q_{i,q} + \cdots + c_3 q_{i,q} \quad (3)$$

q_q is the hourly conductive heat gain for the surface, (W)

$q_{i,q}$ is the heat input for the current hour (W)

c_o, c_1 is the conduction time factors (CTS values for wall and roof are followed as per ASHRAE 2017 [30])

Heat gain through surfaces from adjacent zones is computed using equation (4)

$$q = UA(t_b - t_i) \quad (4)$$

q is the heat transfer rate, (W)

U coefficient of overall heat transfer between conditioned and adjacent space, (W.m^2.K)

A is the area of separating section (Wm^2)

t_b is the average air temperature in the adjacent space (K)

t_i is the indoor temperature

Popular energy simulation tool energy-plus is used to calculate the cooling load, and inter-micro-zonal interactions are modelled using an airflow network [52] with a constant air exchange value of 10 exchanges per hour, as given in previous studies [6]. Though assuming a constant air exchange may overlook the transient variations in inter-micro-zonal interactions, the assumption is made as the objective of this analysis is to plan micro-zones to have a good starting point to further optimize airflow control. Computing inter-micro-zonal interaction using CFD simulations is computationally extensive and is not required at this stage. While planning airflow control, the air jet trajectories can be traced using CFD simulations to further improve MZOCC. The supply air temperature is set at 12 °C, and the setpoint is at 23 °C. It is assumed that the zone is conditioned using a variable air volume system (VAV). On computing the cooling load required in each micro-zone for the peak hour, the total cooling energy consumed for a day is estimated using equation (5)

$$E = \sum (CL_{mz} * Occ) \quad (5)$$

CL_{mz} is the cooling load in each micro-zone, and Occ is the percentage of occupants in a micro-zone at a given hour. It is assumed that the diffusers in the micro-zones are operated following MZOCC protocols formulated in this study.

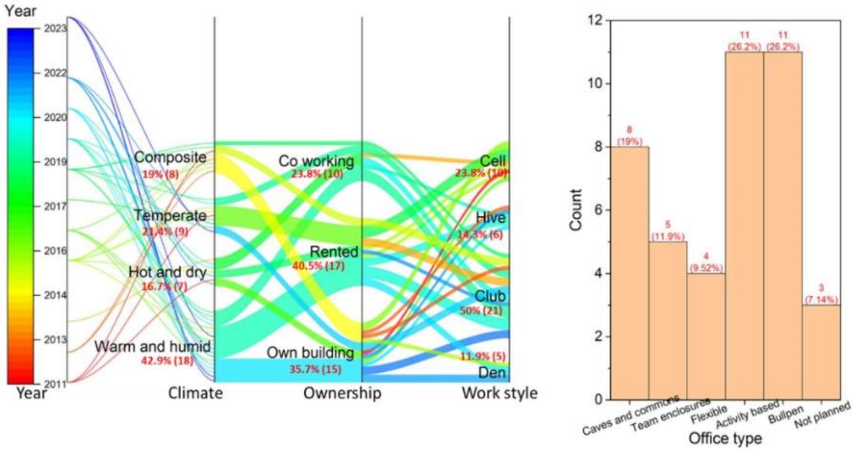

Figure 2: Distribution of year of construction, climate, ownership, work style and office type

Results and Discussion

Stage 1

Characteristics of open-plan layouts in Indian offices

The distribution of climatic zones, building types, work patterns, and layout types of surveyed offices are shown in Figure 2. Offices were surveyed through physical inspection by studying the layouts and interactions with office staff.

The area of floor plates ranges from 15-15000 sqm. The percentage of area allocated for open-plan offices ranges from 8%-90%. Figure 3 shows the distribution of floor plate area, percentage of open-plan offices, and aspect ratio of floor plates. Indian offices are observed to have similar characteristics to those observed in the literature on open-plan offices.

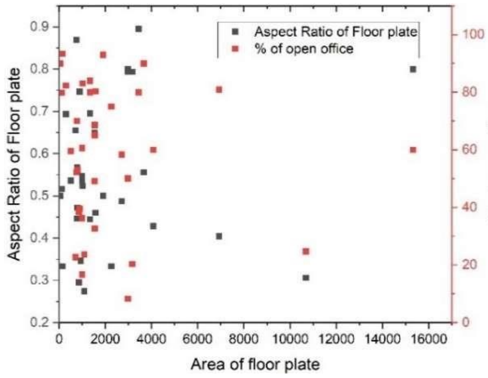

Figure 3: Distribution of office characteristics

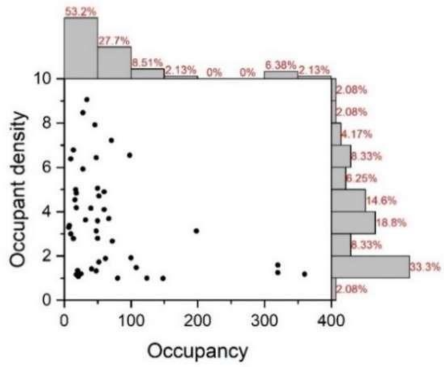

Figure 4: Plot of occupancy vs occupant density

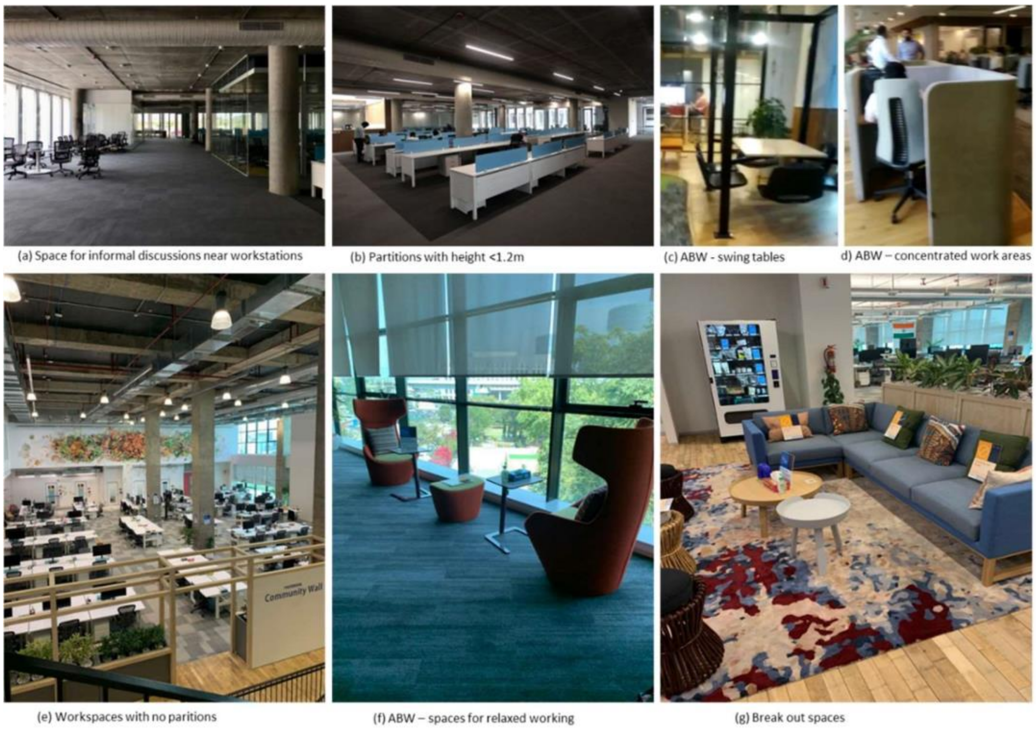

Figure 5: Photos of a few surveyed spaces

Figure 4 shows the distribution of the area of each open-plan office room with the occupant density in the room. The offices where interior layouts are not planned are removed from the distribution. It is observed that more than 50% of the offices have occupant density less than 4, i.e., very low area available per occupant. This contrasts the assumption of taking 6-8 m^2/person in Indian offices [48]. Customising thermal environments in such crowded spaces is challenging. More number of people need to be served by a single diffuser. Thus, people and activities will have to be grouped based on thermal preferences. Most of the offices have rectangular tables (72%), followed by L-shaped tables (18%). Circular tables and other customized furniture types are also seen. On analysing partitions, 3.28% of furniture have partition heights above 1.65m, 47.5% have part partitions between 1.65m and 1.2m, and 49.2% have partition heights below 1.2m. A variety of activity-based work (ABW) environments, leisure spaces, break-out areas, informal discussion areas, spaces with active furniture (e.g., tables with adjustable heights), etc., are found in the offices. Glimpses of a few offices are shown in Figure 5. In a few offices, the common work areas have double-height ceilings with cool air thrown from the ceiling, as shown in Figure 5e. The efficiency of MZOCC under such circumstances has not yet been explored. Considering the spread of jets and the diffusion of air, it can be asserted that MZOCC is challenging under such work settings, and the creation of micro-comfort zones will require personalised ventilation (PV).

Thermal zoning and HVAC systems in Indian open-plan offices

The zoning strategies in each of the floor plates are examined, and the spaces present in the core and perimeter and their distributions are plotted in Figure 6. It is observed that for more than 50% of offices, even the standard core-perimeter zoning strategy is not followed. This indicates that external heat gained is heterogeneous within these offices. Further, for the offices where the perimeter is separated, it is observed that perimeter depths are greater than 10m for cases where open-plan offices are located in the perimeter (as shown in Figure 7). This shows there is a gap between the literature and the implementation of thermal zoning for energy efficiency in open-plan offices.

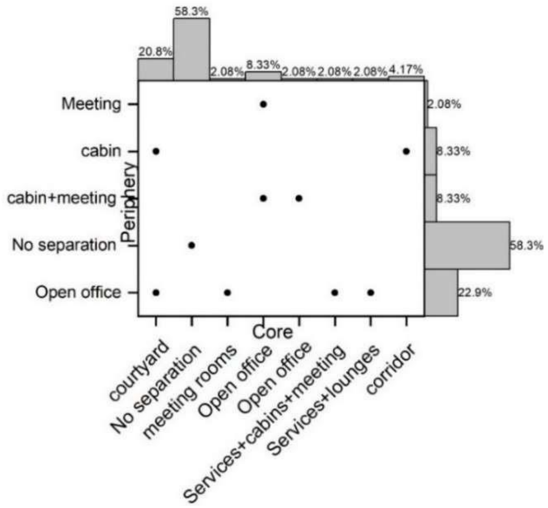

Figure 6: Spaces observed in core vs perimeter

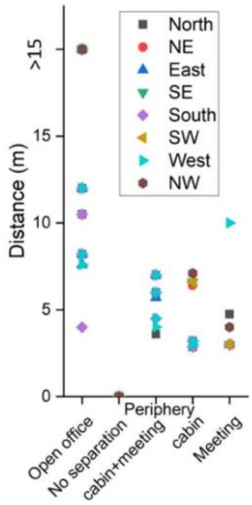

Figure 7: Depth of perimeter zones

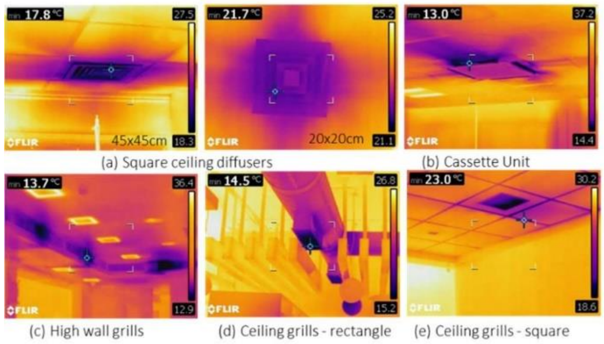

Figure 8: Thermal images of common diffusers

Table 2: Throw of each diffuser type

Diffuser Type	Grid
4-way square ceiling diffuser	3x3
Cassette units	6x6
Rectangular grills	1x4
Circular diffusers	radius of 1.5m

About 95% of the offices have centralised control. Occupants were casually asked how they felt about the thermal environment. Two occupants stated that overcooling is common, and occupants adapt to the thermal environment by carrying jackets to be worn inside the office, even on summer days. This indicates a clear wastage of HVAC energy and discomfort among occupants. Around 4% of office rooms had diffusers with independent control, such as cassette Acs. But in an office that allowed independent control of diffusers, an occupant was observed to relocate to avoid over-cooling. On enquiring, the occupant stated that he feared disturbing other senior staff in the office and hence, decided to adapt to the thermal environment. Though these observations cannot give general conclusions about the office behaviour of occupants, it is observed that MZOCC is needed to maintain thermal comfort in these offices. Most open-plan offices have ducted systems with the throw from either the ceiling or the top portion of the walls. There were instances where diffusers were placed very close to each other. This would lead to air jets hitting each other. Thermal images of the most common diffuser types found in surveyed offices are shown in Figure 8. It is observed that the size of diffusers, CFM, diffuser features, and the presence of a false ceiling, lights, or other installations in the ceiling all influence the throw. Spaces such as corridors are designed to have setback flow or a low-velocity flow. Side grill diffusers have a linear throw, where the region above the occupied zone (above 1.8 m) is at a lower temperature than entrained air in the occupied zone. Hence, these are not suitable for MZOCC. The minimum area catered by various ceiling diffusers is given in Table 2.

Area required for each activity

Common activity spaces found in surveyed open-plan offices are workstations, formal and informal meeting areas, collaborative spaces, waiting areas, queuing areas, lounges, activity-based workstations (ABW) such as couches to work, work cafes, swings with work tables, garden tables, low height seating, furniture with adjustable heights, etc. The unit area required for work station varies based on the furniture type and cluster. Hence, a non-uniform grid prioritizing the activity spaces must be developed. Dimensions of the lowest grid possible for workstations from the survey are plotted in Figure 9. The minimum area required for other activity spaces, as observed from the survey, is given in Table 3. In the absence of a furniture layout, a grid size that can accommodate the planned activity must be used. When furniture layouts are available, the grid should not be overly customized for a given layout, as this will prevent future adaptations. Hence, an optimal grid size, which is also flexible to accommodate other activities in the future, must be chosen.

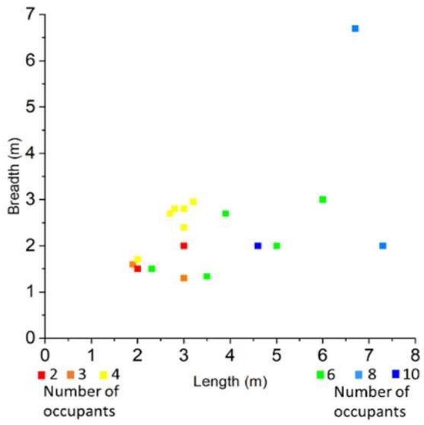

Figure 9: Minimum grid-size for workstations

Table 3: Minimum grid size for each activity

Activity Type	Grid (m)
Rectangular or circular workstations (4seater facing each other)	3x3
Workstations attached to walls or pillars	offset of 2m from surface
Meeting spaces – 12 people	5x4
Collaborative spaces	2x1.5
Waiting area	2x2
Lounges	2x2
ABW – Individual Couches	3x1.5
ABW – Work cafes	6x9
ABW – Swing tables	4x4

Stage 2: Protocols for micro-zoning

Based on the observations so far, an outline of the protocol for thermal zoning can be framed as:

1. Start with standard thermal zoning separation of core-perimeter (perimeter depth can vary from 6m-8m depending on the solar radiation and activities assigned in the perimeter)
2. Further, divide into micro-zones based on planned activities
3. Choose the micro-zonal grid size based on activities. (Table 2 can be used as a reference in this process)
4. Select diffuser type. (Table 1 can be used as a reference for this)
5. Alter the grid size based on area catered by diffusers, minimum distance between diffusers (e.g., at least 3m for 4-way square ceiling diffusers), and minimum distance of diffusers from walls (at least 2m). This has to be further altered while planning airflow control.
6. Alter the grid size to account for flexibility and future activities
7. Choose the grid size and diffuser that gives minimum energy consumption

It is to be noted that this micro-zonal division will not be the optimal one, but a good starting point for further evaluation. This is because transient factors such as occupancy schedule, thermal preference, inter-micro-zonal interaction, air movement, etc., are assumed at this stage observed in the literature. The optimal division will be such that occupied microzones are conditioned without the unwanted merging of air jets, thermal gradients, and drafts. Hence, after micro-zoning and initializing airflow, CFD simulations must be done to adjust micro-zones. This process will be an interesting future study.

Stage 3: Evaluation of micro-zoning in an existing office: A case study

The importance of micro-zoning is evaluated considering an existing open-plan office. The office is located in Hyderabad and is designed for hot and dry climates. Energy consumption under seven zoning layouts is evaluated. Zoning type 'a' is the typical HVAC zoning that currently exists in the studied office space. The entire open-plan office is zoned into a single thermal zone. The meeting room, which is separated by physical partitions, is zoned separately. Since the room has no external walls, core-perimeter zoning is not considered. Micro-zoning layouts 'b' to 'g' are shown in Figure 10. Zoning type 'b' divides each activity space in the open-plan office into different micro-zones. As discussed, the occupancy schedule and thermal preferences for each activity space are different. Hence, they need to be virtually separated. The occupancy in different activity spaces at the given hour is assumed, as shown in Figure 11. A setback temperature of 26 degree C is assumed for the corridors. Zoning type 'c' further divides functional micro-zones into large grids. This division is along the circulation paths observed in between workstations. The occupant density, schedule, and thermal requirements in each micro-zone are updated for cooling load estimation. In zoning type 'd', the functional micro-zones are further

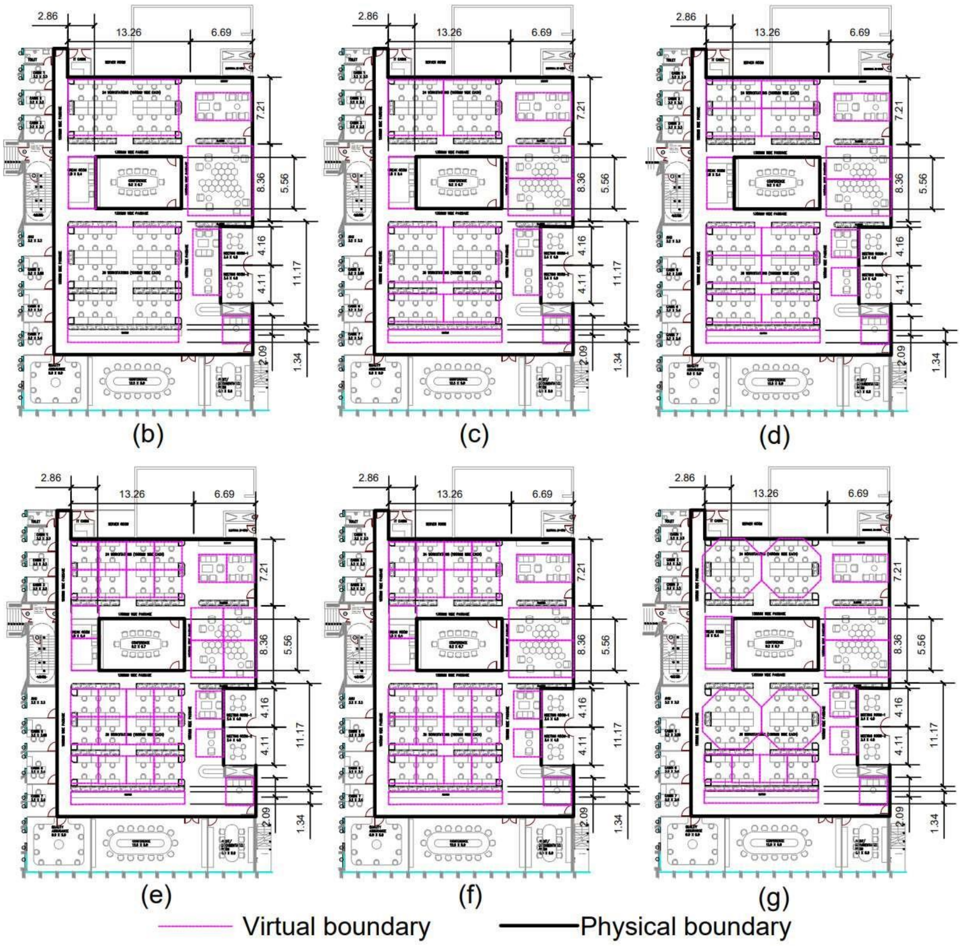

Figure 10: All cases of micro-zoning

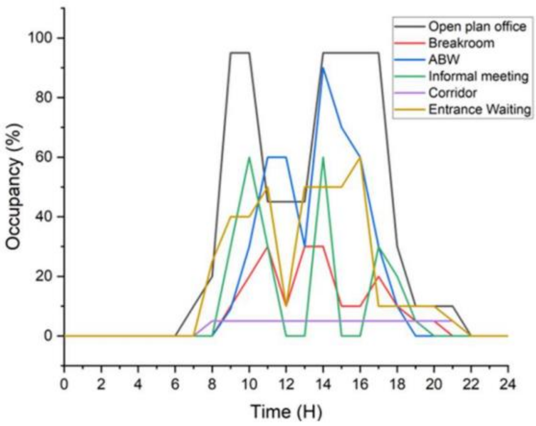

Figure 11: Occupancy pattern

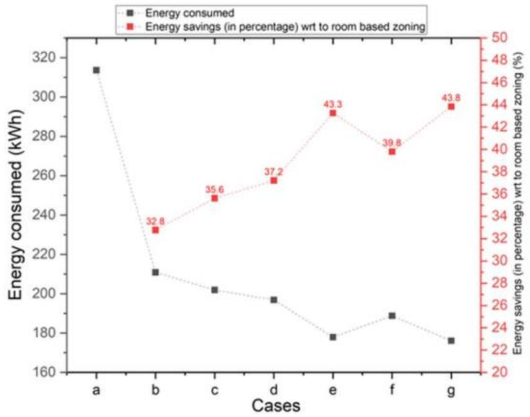

Figure 12: Energy consumption and savings under various micro-zoning

divided to form rectangular grids. Under this division, 2 square ceiling diffusers will be present in each microzone. In zoning type 'e', the micro-zones are further divided such that only one square ceiling diffuser is present in each micro-zone. Considering the area catered by a 4-way square ceiling diffuser of size 45x45cm, the micro-zone is sized 3x3m. Further division of micro-zone will lead to unwanted merging of air jets. But, under such division, in a few microzones (informal meeting spaces), the distance between supply diffusers and the wall is less than 1.5m. As discussed, this will lead to clinging of cool air to the walls. Hence, a larger rectangular grid is taken as shown in case 'f'. Further, it is observed that the corners of the micro-zones containing workstations need not be conditioned. Hence, in zoning type 'g', the shape of micro-zone is altered to an octagon of side 3m. This makes the micro-zone more compact while serving larger occupancy. The total number of diffusers needed is also reduced. Thus, micro-zonal divisions 'c' to 'g' are planned considering the current understanding of micro-zoning, spatio-temporal characteristics of the office, and inter-micro-zonal interaction. Such analysis will give insights on how much more energy is saved through micro-zonal division compared to functionbased division. The energy consumption is computed as discussed in the method section, considering the occupancy schedule given in Figure 11. The results showing the energy consumption and percentage of energy saved in each micro-zonal division with respect to the single zone model are plotted in Figure 12. The results and calculations are uploaded as data [53].

It is observed that energy consumption drastically reduces from room-based zoning ('a') to function-based zoning ('b'). This is because, mostly, activity spaces such as informal meeting areas, activity-based work areas, etc., are unoccupied, and separate airflow control following the occupancy schedule reduces energy consumption. There is only a mild increase in energy savings from function-based zoning ('b') to zoning using large grids ('c') and rectangular grids ('d'). This is because the occupancy pattern does not vary much between these micro-zoning strategies. But, when the most granular square grid ('e') is applied, energy savings increases. This is because, under such granular division, there are several micro-zones that are unoccupied, and air-conditioning can be completely switched off. But, as discussed, such granular division is not feasible considering air jet movement. Micro-zoning 'f', where few micro-zones are merged to prevent clinging of cool air to surfaces, saves about 40% energy consumption and is a suitable micro-zonal division. The grid with a mix of octagonal divisions and granular square divisions ('g') saves 44% energy consumption and abides by all protocols regarding preventing the merging or clinging of air jets. Further, the increased size of micro-zones allows greater flexibility. Thus, improving the size and shape of micro-zones based on the current understanding of micro-zoning helps in reducing 16% more energy compared to function-based zoning. This micro-zonal division is, hence the best starting point to evaluate airflow strategies for MZOCC.

Conclusion

Creating micro-comfort zones around occupants to reduce energy wastage in open-plan offices has been of great interest to researchers. Several methods, such as personalised ventilation, personal comfort systems etc., which use additional 54igeria54g54ture to create micro-thermal environments and diffuser level micro-zonal control of standard HVAC systems, are used in this regard. The latter is preferred due to reduced investment and increased flexibility. Though few studies discuss the importance of planning micro-zones to avoid the merging of air jets to reduce draft and thermal gradients, there is no clarity on how micro-zones are to be planned. The parameters critical in micro-zoning have been identified in this study and are observed to be different from those of thermal zoning. There is a need to establish a link between micro-zoning and thermal zoning. Further, micro-zoning must also be linked to the spatial planning of open-plan offices. This study explored considerations in micro-zoning by performing a survey of existing Indian open-plan offices. It is observed that while Indian offices have characteristics similar to the ones observed in the literature, even standard thermal zoning methods are not employed, indicating huge energy wastage. The area required for each activity and the area catered by diffusers are analysed, and references for minimum micro-zonal grid sizes are outlined in the study. Protocols for micro-zoning are delineated, and an existing open-plan office with different activity spaces is micro-zoned using the protocols. Results indicate that planned micro-zoning reduces energy consumption by about 44% compared to zonal conditioning.

One limitation of this study is that the energy savings were estimated only using simulations, which are based on several assumptions. Field studies can be conducted to get a realistic understanding of the potential of MZOCC by choosing the best micro-zonal planning and strategizing airflow control. Future studies can look into planning airflow control considering micro-zonal divisions and further improve micro-zoning. Transient factors such as occupancy, activity schedule, location of occupants, occupant's thermal preferences, air movement, etc. will be critical in this regard. Based on these, choice of control strategies such as setback flow or setback temperature, whether these are to be employed in all micro-zones or only micro-zones adjacent to occupied micro-zones; and whether similar micro-zones must be combined into one micro-zone are to be decided. Thermal comfort within micro-zones is to be evaluated in the second stage. Thus, a linked bi-level framework with micro-zoning optimized in the first level and airflow control strategies optimised in the second must be framed. Thus, the protocols derived in this study give important contributions to the future development of a bi-level framework for optimised MZOCC.

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Benchmarking Buildings Based on Their Energy Performance in Kerala: A Case Study of Kochi

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Highlights

- Globally, countries are committing to decarbonizing their building stock. Achieving climate mitigation targets requires an understanding of the efficiency levels of existing buildings. Energy performance benchmarking helps establish baseline efficiencies and provides policymakers, building portfolio owners, and managers with the information they need to design and implement building efficiency programs.
- We tested a novel benchmarking methodology for offices in Kochi to understand the availability of data and practical challenges if benchmarking were to be scaled up.
- For each office, we derived a Building Performance Index (BPI) using statistical regression techniques. Twenty-two offices out of 50 had a BPI < 1 or were relatively more efficient than other offices. We also observed an average Energy Performance Index (EPI) of 130 kilowatt-hours per square meter per year (kWh/m^2/year) for sample office buildings, with EPI values ranging from 21.3 to 441.7 kWh/m^2/year.
- Through a qualitative survey, we documented perceptions of the importance of energy efficiency (EE) services in offices of varying ownership and management structures. There were no significant differences in the attitudes and perceptions of owner- and tenant-occupied offices.
- City-level benchmarking can be done in India with minimum data by supporting back-end statistical analysis resources and tools. The benchmarking methodology we have adopted in this study could guide such efforts at national and subnational levels. We recommend India take a more institutional approach to benchmark energy performance.

Abstract

Many developed countries regularly conduct building energy use benchmarking for continuous monitoring and evaluation of energy efficiency (EE) programs and policies to inform the design of new ones. Such activities also provide an opportunity to engage with building owners, tenants, and managers on RE and EE policies and programs. Our study was aimed at developing a methodology for citywide energy benchmarking exercises in India. We tested a novel benchmarking methodology for offices in Kochi to understand the availability of data and practical challenges if benchmarking were to be scaled up. The study was also aimed at documenting barriers to retrofits for different owner-tenant models.

Keywords: Buildings, energy efficiency, benchmarking, energy performance

Introduction

In 2021, the buildings and construction sector accounted for around 37% of energy- and process-related CO_2 emissions and over 34% of energy demand globally [1]. In India, buildings were responsible for 33 percent of total electricity consumption in 2018–19 [2], with more than 60 percent of India's electricity needs coming from thermal power [3]. During 2019-20, in Kerala, buildings with LT connections alone consume nearly 67% of the total electricity consumption in the state [4]. This share will further increase if we consider the data regarding commercial and residential buildings with HT connections, which are not available separately. These numbers highlight the importance of decarbonizing buildings in the state if it wants to achieve its goal of becoming a carbon neutral state by 2050 [5]. Achieving climate mitigation targets requires an understanding of the efficiency levels of existing buildings. Energy performance benchmarking helps establish baseline efficiencies and provides policymakers, building portfolio owners, and managers with the information they need to design and implement building efficiency programs. In this context, we tested a novel benchmarking methodology for offices in Kochi to understand the availability of data and practical challenges if benchmarking were to be scaled-up.

The status quo of building energy performance benchmarking

Many developed countries regularly conduct building energy use benchmarking for continuous monitoring and evaluation of EE programs and policies to inform the design of new ones. Benchmarking provides a baseline of energy use of existing buildings, compares their energy performance with others after homogenizing for physical and operational characteristics, and provides policymakers data on the relative efficiencies of buildings. While building codes and standards speak to new buildings, benchmarking programs specifically address the efficiency of existing buildings. Citywide benchmarking systems can be used by policymakers as a yardstick of energy performance in buildings when benchmarks are disclosed publicly [6]. A citywide benchmarking program where the information is shared publicly serves three purposes [7]: It informs and empowers the real estate market to pay attention to energy efficiency (EE); it motivates building owners to sbenchmarking efforts across a large sample of buildings can inform better building energy codes. Good performers can be rewarded (e.g., US Department of Energy's Sustainability Awards), while low performers can be penalized (e.g., the Minimum Energy Efficiency Standard [MEES] regulations in the United Kingdom).

Benchmarking activities also provide an opportunity to engage with building owners, tenants, and managers on RE and EE policies and programs. These activities provide information to market actors and allow building owners to prioritize measures for improvements. In India, the Bureau of Energy Efficiency (BEE) attempted to collect building energy performance data from 2007 to 2009 through primary and secondary surveys. These results were used to develop and launch a Star Labelling Program for office buildings in 2009. However, this program has not been revised since 2009.

In 2010, the USAID ECO-III project partnered with BEE to conduct a large-scale benchmarking effort involving data from 760 commercial buildings of various typologies [8]. In 2014, with support from the Shakti Sustainable Energy Foundation, BEE launched the EcoBench Tool [9] for benchmarking and rating the energy performance of hospitals using ECO-III Project survey results. No such national benchmarking exercise was repeated in India.

About This Paper

Our research began with the objective of developing a citywide energy benchmarking program. We reviewed the literature, consulted experts with previous experience in benchmarking studies in India, and developed the survey questionnaire. We surveyed 50 offices in Kochi to understand the data available for such a citywide program and to develop a Building Performance Index (BPI) for the offices using statistical regression techniques. Our findings may not be representative due to the small sample size of data fields used in the survey, which had implications on the interpretation of some of the findings (e.g., reasons that some offices performed better than others).

We also conducted a qualitative survey, where we spoke with the office managers to understand their perceptions of EE services and retrofits and their awareness of energy service companies (ESCOs). In several markets globally, ESCOs have been instrumental in driving building energy performance improvements, especially in cases where up-front investments in EE are high. We also asked questions to help assess the applicability of common barriers, like the split incentive and financing barriers facing EE retrofit projects. Split incentives refer to transactions where economic benefits of energy savings do not accrue to those who invest in energy efficiency, such as when building owners pay for investments in energy efficiency while occupants pay the energy bills [10].

Research Objectives

Our research objectives include the following:

1. Assess the feasibility of conducting a citywide benchmarking exercise for office buildings.
2. Develop a BPI for the offices.
3. Document barriers to retrofits for different owner-tenant models as well as enablers to seeking EE services.

Approach and Methodology

We collected data on 50 office spaces in Kochi city. We chose offices because they account for 27 percent of large commercial consumers in Kochi, the second largest category after retail spaces, as per the data we collected from the KSEB. We decided to focus on office buildings also because they are included in BEE's Star Labelling Program typology. Also, office spaces are more amenable to the initial landscape assessment due to more typical operational hours and building design. For defining large commercial consumers, we wanted to follow the threshold based on data on buildings within the Energy Conservation Building Code (ECBC). ECBC applies to commercial buildings with connected load ≥ 100kW or contract demand ≥ 120 kVA. However, since the number of such buildings in Kochi was low, we defined them as those with connected load ≥ 75kW or contract demand ≥ 100 kilovolt ampere (kVA). We adopted a two-part methodology—a quantitative survey to benchmark the energy performance of selected office spaces and a qualitative questionnaire (over the telephone) with managers of the offices.

Scope of Study

The scope of our study is office spaces and the electricity consumed and managed within these boundaries. We have not benchmarked office buildings, which would refer to additional energy services provided as "common services" to all offices within the building in the form of elevators, water pumping systems, and common area lighting. Hereafter, we will refer to the sample as "offices."

Sample Identification

After fixing the sample criteria as offices with connected load ≥ 75 kW, we sought their electricity consumption data from the electric utility, the KSEB. Since the KSEB used a different method to document this information, we had to work with it to clarify the consumer categories and shortlist 91 consumers. We contacted these consumers to seek their willingness to participate in the study. Based on the discussions, 62 joined the survey. Upon further analysis to ensure homogenization, we finalized 50 office spaces for the advanced analysis on benchmarking energy performance and qualitative research to ensure the homogeneity of the sample.

Primary Data Collection

According to Kumar et al. [11], in India, several efforts have been undertaken to collect energy use data of commercial buildings. These have seen only limited success for the following reasons: difficulties in standardizing questionnaire terms with the vocabulary used by office managers; challenges in ensuring data quality; addressing data confidentiality concerns of participating buildings; and inability to strike a balance between depth of data and the ease of collecting information. Keeping these lessons in mind, we developed our survey questionnaire.

This survey sought to collect data on basic energy use to enable comparisons of energy performance. Since this was a first-of-a-kind initiative at a city scale in India, we were also opportunistic and focused on datasets that the office manager could provide without much effort.

We had a letter of support from the Kochi Municipal Corporation (KMC), which immensely helped our data gathering efforts. Primary data was collected over a period of two months, starting in November 2019, by a trained survey agency that used in-person and remote data collection techniques. The survey agency's experience and expertise in data collection, measurement, and verification techniques have helped the researcher obtain quality data from offices. Some data fields were classified as mandatory to enable benchmarking; others were voluntary.

Benchmarking Approach

Energy performance of a building depends on various parameters, including its size, number of occupants, conditioned area, and so forth. While a building is to be compared with other buildings for its energy performance, it is important that we factor in these parameters to warrant a justifiable comparison. Using the Building Performance Index (BPI) as a yardstick to compare buildings for their energy performance allows us the flexibility to factor in these parameters. While the Energy Performance Index (EPI) is one of the most widely used metrics to indicate a building's energy performance, it only considers a building's annual energy consumption and its floor area to assess its performance. Our study was more focused on a detailed assessment that demanded the use of BPI over EPI for benchmarking buildings.

Our methodology for benchmarking is adapted from Sarraf et al. [12], where regression-based statistical methods were used to benchmark the energy performance of 760 commercial buildings. The approach was used to develop India's first national-level benchmarking platform (EcoBench), which we previously mentioned in the paper. Under this approach, a building's energy performance is compared with a "benchmark" building of similar characteristics using a scoring system. Statistical methods were used to estimate the energy consumption of the "benchmark" building and the scores or relative rankings of the buildings on the BPI. Under this approach, a building's energy performance is compared with a "benchmark" building of similar characteristics using a scoring system. Statistical methods were used to estimate the energy consumption of the "benchmark" building and the scores or relative rankings of the buildings on the BPI. The process we followed is delineated below.

Step 1: Homogenizing sample data

First, we looked at office spaces with a connected load ≥ 75 kW. We then collected data on physical characteristics (e.g., floor area, conditioned space) and operations and management (e.g., employee density, working days, and operating hours). We also analysed their impact on the dependent variable—the office's annual electricity consumption. Through this process, we identified 12 buildings that behaved significantly differently from others and decided to remove them from the sample. The parameters, along with the criteria used for the homogenizing sample, are listed in the below table.

Table 1: Independent Variables Considered and Their Contribution to Homogenizing Sample

Parameter	Criteria for removing buildings with heterogeneous behavior from sample
Operating hours	Only single-shift operations were considered. Data points with 24 x 7 operations were excluded.
Operation	Buildings that are not fully occupied/operational.
Year of operation	Buildings that only started operating in the last 6 months.
Additional facilities	Buildings that had additional facilities like laboratories, etc.

Step 2: Estimating energy consumption of benchmark building

Taking guidance from the methodology adopted by Sarraf et al. [11], we used multiple regression techniques to estimate the energy consumption of our "benchmark building." A benchmark building is a hypothetical building with the same characteristics as the building to be benchmarked. There is a standard equation that defines the energy use of a benchmark building.

Energy use of a benchmark building = Function (building type, construction, physical, operational, and location characteristics)

Using the data from the 50 offices, we used multiple regression to derive an equation that calculated the benchmark building's energy consumption, using the coefficients for values of independent variables that impact or drive energy use in a building. A multiple regression predicts a dependent variable's value based on the value of two or more independent variables. Comparing the actual consumption (actual performance) of the building to be benchmarked with that of the benchmark building (expected performance) gives the building's relative efficiency. The small sample dataset limited our choice of functional forms of the regression model. We explored different forms and confirmed through the scatterplots that there were nonlinear relationships between the dependent and independent variables.

This process also helped assess the significance of interactions between the different independent variables. By trying out different regression models and closely examining the coefficients of independent variables, we identified the following variables as significant in influencing the annual electricity consumption of the building: carpet area (m^2), employee density (number of employees/unit area), and conditioned area (percent). Some variables initially assumed to be significant were later removed from the regression analysis. For example, the p-value of the dummy variable for operating hours was not significant and required that we disregard it as a determinant variable for developing the regression model. However, it is likely that with a bigger sample size of buildings, operating hours will play a more significant role in determining the annual electricity consumption of a building. We disregarded it in our analysis because of its statistical insignificance in the regression analysis.

At various stages in our analysis, we tried regression models using different variables to explore their significance before establishing the final regression model. The final model was based on those variables' observed significance (p-value); we have included or disregarded these variables, as appropriate, in further analysis. The final regression model is based on a log-linear functional form in which the log of annual electricity consumption was the dependent variable and the log of carpet area, employee density, and the dummy variable to indicate whether the building is 50 percent air-conditioned or not (variable = 0 if < 50% area is conditioned by ACs; variable = 1 if ≥ 50% area is conditioned) are the independent variables. An R-squared (R^2) value of 0.75 was observed for this model with a residual standard error of 0.1712. The derived equation for predicting the log of the annual electricity consumption of a building is given below.

*Log (Annual electricity consumption) = 2.29532 + 0.83155*Log (Carpet area) + 2.30037*Employee density + 0.21033*dummy variable for conditioned area* (1)

Step 3: Estimating Energy Consumption of Benchmark Building

The results of the multivariate regression provided the equation to estimate the energy consumption of a benchmark building. The next step was to compare actual energy consumption to that of the benchmark office.

The Building Performance Index (BPI) was calculated for each office and used to compare offices with each other. The BPI is defined below.

BPI = Actual energy consumed by the office space / Estimated energy consumed by the benchmarked office space

A BPI of 1 indicates that the building's energy consumption is equivalent to the benchmarked building after normalizing construction and operational characteristics.

Buildings with BPI > 1 indicate that their energy consumption is higher than that of the benchmarked building; buildings with BPI < 1 indicate lower energy consumption. Buildings with a BPI of 2 suggest that they consume twice the energy of a comparable benchmarked building, while a BPI of 0.5 means that the building consumes half the energy of a benchmarked building. So, the lower the BPI, the better the building's energy performance relative to its peers.

Observations

Ownership and occupancy related observations

- Occupancy categories: For each office, we also collected ownership information. Of the 50 buildings, 17 were owned by the central government, 6 by the state government, and 27 by private companies.
- Premise ownership and facilities management: We further classified the buildings into five categories based on facilities management. The details of buildings based on their ownership and management types are given below.

Category	Definition	Number of Offices
Owner-occupied and managing facilities	The owner is also the occupant and manages the facilities in-house	23
Owner-occupied and private management of facilities	The owner is also the occupant of the office premises but has engaged a third party to maintain the facilities wholly or partially. This could include managing of electrical equipment and energy service systems.	9
Multitenant office space, management by owner	Multiple tenants occupy the building, and the owner manages the facilities for them. This owner can be government or private.	8
Multitenant office space, management of individual facilities by tenants	Multiple tenants occupy the building, and they manage their respective facilities. The tenants could be government or, private or both.	7
Single-tenant office space, Facilities management by tenant	A single tenant occupies the office and manages the facilities.	3

- Owners occupied most of the buildings surveyed (32 of the 50 buildings). Facilities in 23 offices were managed by in-house teams, and third parties managed the remaining 27.
- Tenants occupied 18 offices; 15 were present in buildings where there were other tenants as well. In 8, the owner managed the facilities, and in the remaining 10, tenants did.
- None of the leased facilities had third-party facilities managers.

Energy- and equipment-related characteristics

Connected load and annual consumption: Of the 50 offices, 21 had a connected load ranging between 75kW and 100 kW. The remaining 29 had a connected load above 100 kW. There were 11 offices with a load greater than 200 kW. The highest load recorded was 690 kW for a 21-floor office space. The 50 offices had a combined annual electricity consumption of 12 million units and a total connected load of 8.192 MW.

Air-conditioning: Three of the 50 buildings had centralized air-conditioning. The percentage area conditioned by ACs varied from 2 percent to 100 percent, indicating a mixed-mode ventilation practice in many offices.

Rooftop solar: Seven of the 50 offices have rooftop solar plants. Of these, 6 were in owner-occupied offices where the owner also managed the facilities. One multitenant building managed by the owner also had a rooftop solar installation.

Energy performance benchmarks: The benchmarking exercise aimed to collect empirical data to produce statistically robust BPI values and generate a simple ranking of buildings while normalizing for independent variables' impact on individual offices' energy performance. We allotted building IDs to the 50 buildings, calculated their BPIs, and converted them to ranks ranging from 1 to 50. BPI values ranged from 0.34 to 2.19 (Figure 1). Although we could not conduct more in-depth investigations into the reasons behind the different energy performance of the same type of buildings, we are presenting some observations:

The Top 22 ranks are for offices with BPI < 1

- 14 of the 32 owner-occupied offices (44 percent) are in the top 22. Of these, 11 are offices where the owner occupied and managed the facilities, and third parties managed the remaining three.
- There are also 6 office spaces occupied by tenants and managed by the owner (75 percent of this category) in the top 22.
- 2 of the 3 offices where a single tenant occupied the building and managed the facilities are in the top 22, with BPI scores of 0.48 and 0.60.
- 14 of the 22 offices were occupied by private companies (54 percent of private companies), 4 by central government (21 percent of central government buildings), and 4 by state government (80 percent of the state government buildings).

The bottom 28 ranks are for offices with BPI > 1

- Eighteen owner-occupied offices are in the bottom 28. There are 12 offices where the owners occupied and managed the facilities in-house, and third parties managed the remaining 6.

- All 7 offices where multiple tenants occupied and managed facilities are in the bottom 28.
- Fourteen of the 28 offices at the bottom are occupied by central government agencies, 12 by private companies, and the remaining 2 by state government bodies.

Qualitative Survey

We conducted a qualitative survey of the 50 offices over the telephone due to COVID-19 restrictions. The survey's primary respondents were office managers and building supervisors who had provided the quantitative survey data. The interviews focused on two questions:

What are the barriers to implementing EE retrofits in buildings?

Barriers to EE retrofits in buildings are an acknowledged knowledge gap [13]. We wanted to test the applicability of the "split incentives" and other barriers across different buildings.

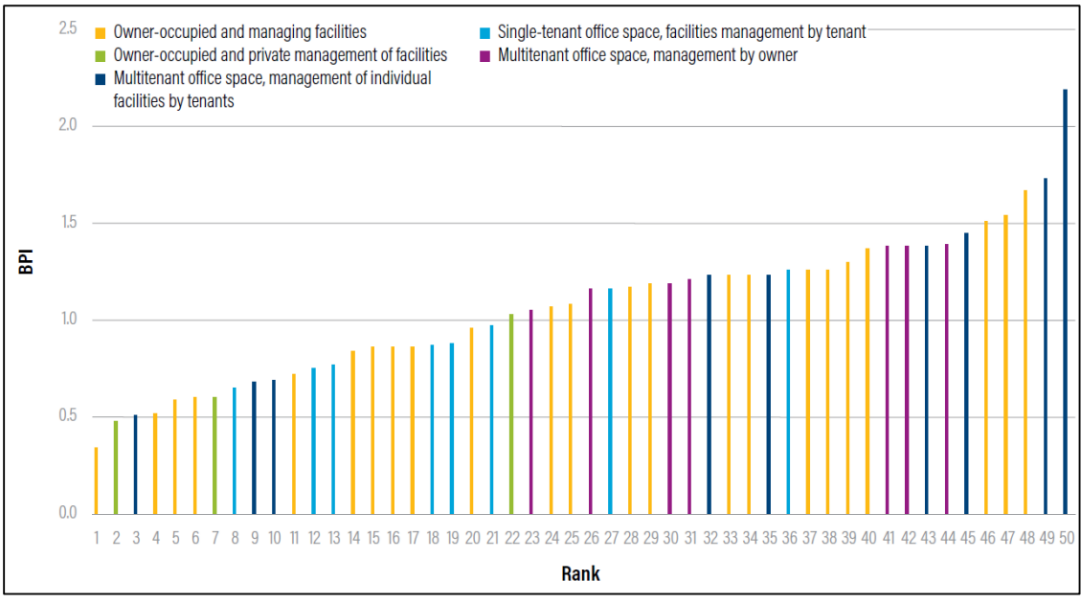

Figure 1: BPIs and Building Ranks by Building Categories

What are the enablers (or drivers) to EE services?

We wanted to document specific drivers of EE services, including retrofit projects. We wanted to see if the benchmarking survey results changed mindsets or receptivity toward EE services in existing offices.

Based on the survey, the findings and inferences are tabulated below.

Barrier Category	Findings from Kochi	Inferences
Split incentives	Most offices were bare when tenants moved in. The tenant had to invest and install cooling equipment (e.g., ACs) and lighting. Although tenants could have installed efficient equipment, most did not, except for Level 1 interventions (replacing broken bulbs with LED lights). [Based on the responses, we classified the replacements and retrofits into three levels: Level 1, referring to no changes or minor replacements (e.g., lights in case of a breakdown to LEDs); Level 2, referring to full-scale retrofits of the lighting system and fixtures to more efficient LEDs; and Level 3, referring to the replacement of higher-cost ACs with higher-efficiency equipment.	Tenants having to invest up-front in efficient equipment typically opt for low-cost equipment and appliances. EE considerations are unlikely to be prioritized unless they are readily available (e.g., LED lights). Also, though tenants could make their own decisions, the owners' management of services may have impacted their decision not to purchase and install more efficient equipment.
Financing	In offices where owners or tenants managed facilities, operations budgets paid for replacements or retrofits, even for new ACs. However, most offices, irrespective of who owns or occupies them, had only carried out Level 1 interventions. When asked, all except one identified financing as a challenge to installing new EE equipment. Interestingly, we found that there is no interest in taking loans to finance retrofits.	Upgrading and retrofitting HVAC systems is generally expensive and may need significant capital (especially in small offices). Given the limited presence of HVAC systems in the study, replacing split ACs with energy-efficient ones is important. ACs or retrofitting efficient fans appears to be easier to implement. However, these do not achieve scale (in terms of cost savings), and more expensive upgrades need

		management approval if they are financed from operational budgets.
Interest motivation saving energy and in	All the surveyed offices ranked energy saving as one of their top five priorities. But beyond stating this, they did not do much to achieve that goal. Their primary need was the presence of a reliable power backup.	Most electrical upgrades or replacements are postponed until there is a breakdown of equipment. Even then, EE is not the first consideration for replacement. Alternatives that are readily available and affordable are prioritized.
Broader information and awareness on the energy services market	Most offices surveyed were aware of energy-saving measures. However, knowledge and awareness of ESCOs were limited across the board.	In mature markets, ESCOs can aggregate smaller projects on behalf of office owners to lower project management and implementation costs [14]. In India, while ESCOs operate in the building sector, awareness of their existence and utility is limited.

Discussion

Findings and Critical Observations

- Benchmarking building energy use is possible in Indian cities with minimal data. We used readily available or collectable data for establishing relative energy efficiency levels of buildings. However, statistical applications for data analysis would require training and capacity-building of program officials.
- Interest and involvement of ULBs are very important. ULBs play a critical role in supporting the data collection exercise.
- There was little evidence of the split incentive barrier. Most tenants moved into offices where the owner provided only basic lighting and core services. Though tenants had the choice of installing efficient equipment and appliances, they preferred purchasing lower-cost and more readily available average efficiency alternatives in the market, except light-emitting diode (LED) lights, because of their ubiquitousness.
- There is no demand for financing high-cost upgrades. None of the offices expressed interest in taking loans or accessing other finance for more expensive retrofits or replacements. They were satisfied with their operations budget for upgrades and replacements.
- Saving energy is considered important to offices even though their actions suggest otherwise. Offices ranked energy savings as one of their top five priorities, but their actions, for example, on energy audits or purchase of high-efficiency equipment, do not back this up.
- Awareness of ESCO models is low. Offices were not aware of energy service companies (ESCOs) and their business models. Those who had heard of ESCOs perceived the business model to be more suited to industries.

Conclusion and Recommendations

- City-level benchmarking exercises are the starting point for evaluating the performance of buildings and identifying opportunities to improve operational performance.
- Regular benchmarking can support the development of outcome-based building codes, elevating India's building efficiency policy efforts.
- Availability of tools and approaches for benchmarking at local levels is necessary to ensure regular improvements.
- Kerala Institute of Local Administration (KILA) can sensitize local bodies on the importance and benefits of energy benchmarking to track the performance of their buildings and encourage energy retrofits afterward.
- Energy Management Centre in Kerala can adopt the methodology attempted in this study to build a benchmarking tool for application throughout the state, thus informing the design of local EE programs and schemes on building stock efficiency improvements in cities.
- The success of EE policies and programs can vary due to local market factors. A deeper understanding of local variations in EE's perceived barriers and opportunities can inform better design and implementation of EE schemes in existing buildings.

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Effect of Thermal Mass and Insulation Position in Walls on the Thermal Performance of Residential Buildings in a Cold Climate

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Highlights

- Thermal mass on the interior side and insulation on the exterior side of walls exhibit better thermal performance in cold climates.
- It reduces the HED by 4% and HDD by 3% across the different climate severities.
- The South orientation is preferred over other orientations.
- Higher WWR leads to higher energy consumption and heat loss.

Abstract

This study investigates the effect of thermal mass and insulation position on the thermal performance of residential buildings in a cold climate. A combination of numerical simulations and field measurements is employed to assess the impact of different wall configurations on heating energy demands and comfort. Configurations with thermal mass placed on the interior side of walls exhibit better thermal performance, reducing temperature fluctuations and enhancing thermal comfort. The study also explores the influence of climate severities, changing the window-to-wall ratio and building orientation on energy savings and comfort for various wall configurations. Wall B (thermal mass inside and insulation outside) reduces HED by 4% and HDD by 3% across different locations. Wall B reduced HED by 9.8% and HDD by 1.4% for a south facing building, and reduced HED by 3.2% and HDD by 2.2% for 10% WWR.

Keywords: Thermal performance, Thermal mass, Insulation, Residential buildings, Cold climate.

Introduction

As the world grapples with the escalating challenges of climate change and the urgent need for sustainable development, it becomes increasingly vital to optimize energy consumption and enhance thermal comfort in residential buildings. In India, a country with diverse climatic zones, the demand for housing is rapidly escalating due to a growing population and urbanization. The energy demand accounted for about 35% of building energy use in 2021, up from 30% in 2010 [1]. In the context of a cold climate, where low temperatures prevail for a significant portion of the year, the key factors influencing thermal performance in residential buildings are the placement of thermal mass and the implementation of proper insulation [2]. Thermal mass refers to the ability of a material to absorb, store, and release heat. Its strategic positioning within a building can help moderate indoor temperatures by absorbing excess heat during the day and releasing it when the ambient temperature drops. Additionally, insulation serves as a vital component in reducing heat transfer between indoor and outdoor environments, effectively mitigating thermal losses during cold weather.

Several studies have already demonstrated that different configurations of insulation and thermal mass have varying effects on both heating and cooling energy consumption and comfort. Kossecka and Kosny [3] carried out a whole-building energy analysis and concluded that the material configuration of the exterior wall could significantly affect annual thermal performance. The best performance was obtained when massive materials were located on the inner side. Al-Sanea and Zedan [4] showed that the insulation layer location had a significant effect on transmission loads. By placing the insulation on inside, the transmission load was reduced to 20% of that of outside insulation. Results also showed that wall orientation had a significant effect on the thermal behaviour of the building. A south-facing wall was most favoured and gave a 12% lower transmission load compared to the least favourable orientation. Changes in WWR in a low and high thermal mass building leads to lower heating and cooling demands for different climates [5]. Furthermore, there is a lack of research focusing on the performance of thermal mass in cold climates [6]. The research that does exist relating to cold climates is patchy and contradictory, and few studies look at its effects in a generalizable, quantifiable sense [6].

The primary objective of this study is to investigate the effect of thermal mass and insulation position on the thermal performance of residential buildings in a cold climate. For this purpose, a residential building is modelled, and simulations were carried out to evaluate the appropriate positioning of thermal mass and insulation required to achieve energy efficiency and improved thermal comfort. The effect of orientation, WWR, and climate severities is also evaluated for the wall configurations with respect to comfort and energy savings. The findings will guide policymakers, architects, and engineers in formulating effective building design strategies, constructing energy-efficient housing, and ultimately contributing to the sustainable development of residential infrastructure in cold climate regions of India.

Methods

A residential building was investigated through real-time field measurement. The reference building was modelled in TRNSYS software and validated using real-time field data. Simulations were carried out in the reference building model to study the variation in comfort and heating energy demand for different wall configurations. Wall configurations with the same U-value but different thermal mass were considered for simulations. The effect of the wall configurations on comfort and heating energy demand is investigated for various orientations, WWR, and climate severities.

Climate and Building Characteristics

The study pertains to Mussoorie city (30.45°N; 78.06°E), located in Uttarakhand state in India, which represents a cold climate zone (Cwb). The dry bulb temperature ranges from -4°C to 18.5°C in winter (January) and 9.8°C to 33°C in summer (May). The diurnal temperature range during winter is around 15°C, and that during summer is about 17°C. A naturally ventilated residential building was chosen to study the thermal performance through real-time field measurements. The indoor and outdoor air temperature and relative humidity are recorded at ten minutes intervals from January 2021 to December 2021 [7]. Table 1 shows the characteristics of House A.

Table 1: Characteristic description of residence.

Parameters	House A
Perimeter	41 m
Floor Area	84 m^2
Volume	235 m^3
Floor-to-floor height	2.8 m
Orientation	South facing
Wall type	230 mm Brick Masonry
Wall U-value	2.18 W/m^2K
Roof type	150 mm RCC Slab
Roof shape	Flat
Roof U-value	3.75 W/m^2K
Window type	Wooden frame with 3 mm Single clear glass
Sill height	0.8 m
Lintel height	2 m
WWR	10%
Overhang depth	0.6 m

Figure 1 shows the floor plan with the location of sensors (grey circle) and the view of House A.

Figure 1: Floor plan showing sensor location and view of House A

Figure 2 shows the real-time indoor environment conditions in the bedroom and drawing room for four consecutive days in the winter month of January, the transition month of March, and the summer month of May. The readings are obtained using a temperature and humidity data logger with a precision of ±0.50C & ±3% RH and a resolution of 0.1°C & 0.1% RH. The outdoor temperature ranges from -0.7°C to 31°C, and relative humidity ranges between 15% to 96% during the recorded period. The indoor temperature ranges from 3.3°C to 33.2°C, and relative humidity ranges between 20% to 95% for the measured period in House A.

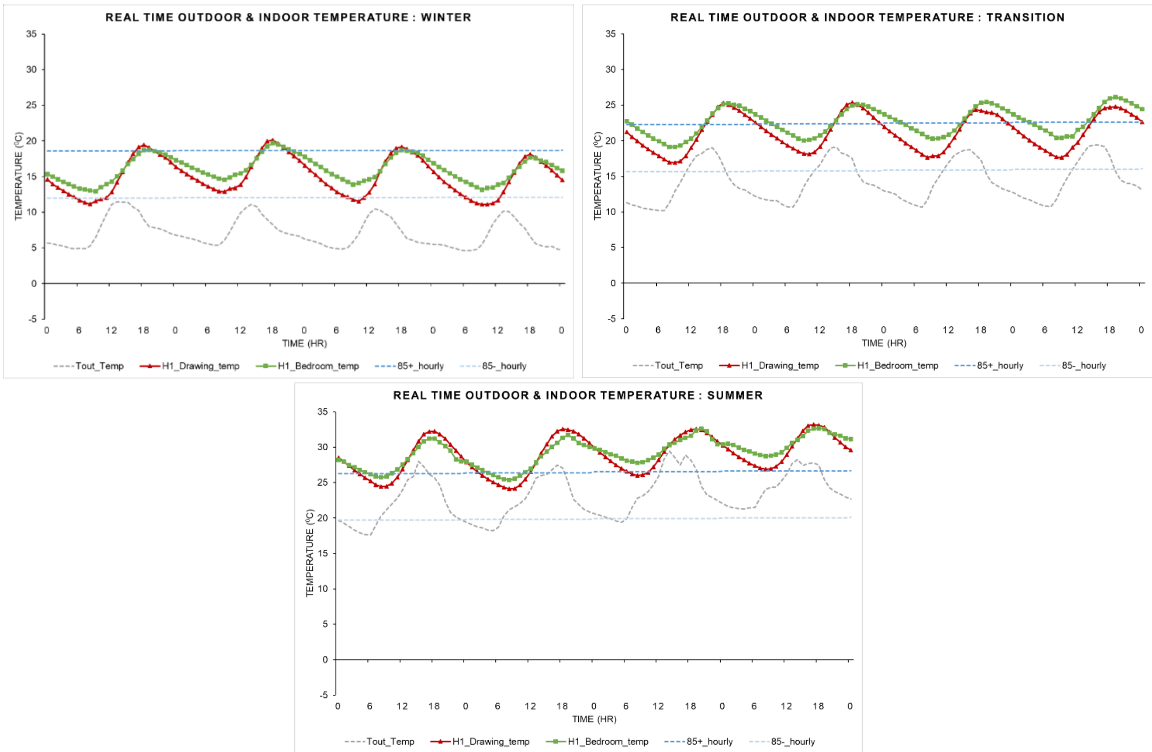
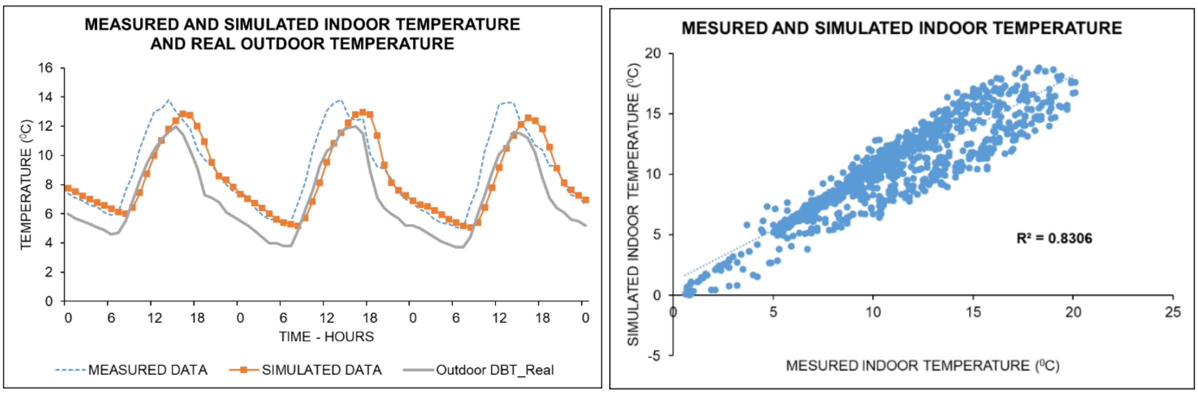


Figure 2: Indoor temperature variation measured in House A in January, March, and June

The indoor temperature of both the drawing room and bedroom remains within the IMAC (Indian Model for Adaptive Comfort) comfort band of 85% acceptability limits [8] in winter. But remains hotter during the transition and summer months. This may be due to the South-West orientation of the drawing room and the absence of external walls and windows in the bedroom. The external windows on the south and east of the drawing room remain open from 8 am to 5 pm in summer and transition months, while in winter, the windows remain open from 10 am to 3 pm. The internal window of the bedroom remains closed throughout the year.



(a) (b)

Figure 3: (a) Validation of measured and simulated indoor temperature data for three consecutive days. (b) Scatter plot showing R^2 value of the measured and simulated data for the measured period

Validation

House A was modelled in TRNSYS, and the simulation results were validated with the actual field measurements under similar conditions comparing the indoor air temperature. The results of a survey on the average and maximum errors recorded in simulation validation studies are presented, whereby the typical maximum error is below 7°C, and the average error is 4.3°C. The CVRMSE (Coefficient of Variance of the Root Mean Square Error) value between modelled and measured indoor air temperature is 9.4%. According to the ASHRAE Guide [9], the models are validated when the CVRMSE values fall within 30%, and the R^2 value is > 0.75 for hourly data. CVRMSE is given by Equation (1):

$$CVRMSE = \frac{\sqrt{\sum_{i=1}^{Ni}\frac{(Mi-Si)^2}{Ni}}}{\frac{1}{Ni}\sum_{i=1}^{Ni} Mi} \tag{1}$$

where Mi – Measured data; Si – simulated data; Ni – count of the number of the data used in the validation. Figure 3 (a) shows the simulated and measured indoor temperature data for three consecutive days in House A. There was a delay in peaks of measured and simulated data due to infiltration. This validated model is used to carry out further simulations. Figure 3 (b) shows the R^2 value of the simulated and measured temperature for the measured period.

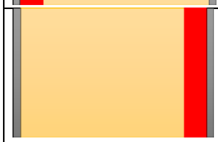
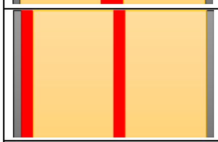
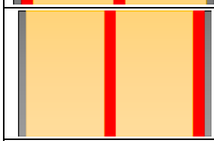
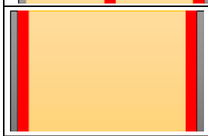
Wall Configuration

Wall assemblies were created to carry out simulations to compare heating energy demand and comfort. Wall assemblies with the same U-value were considered, while they differ with regard to location and number of insulation layers. One, two, and three insulation layers are investigated. The thermal mass comprises either one 300-mm-thick Random rubble masonry or two 150-mm-thick random rubble masonry, as it is practically applicable and locally available material in Uttarakhand [10]. A 10-mm-thick cement plaster on each side encloses the wall assembly. The properties of materials are summarized in Table 2, while Table 3 gives the schematics, U-value, and internal areal heat capacities [11] of wall configurations. The internal areal heat capacity describes the real capacity to accumulate heat on the inner side of a building element. Since the main idea was to investigate the effect of varied thermal mass, the U-values have been kept the same in all the cases, and hence, the conventional brick wall with cement plaster is not included, as its U-value will change with respect to other wall assemblies.

Table 2: Material Properties [12]

Material	Density (kg/m^3)	Conductivity (W/mK)	Specific heat capacity (J/kg K)
Random rubble	1922	1.585	880
Cement plaster	1762	0.721	840
Insulation_EPS	30	0.032	1250

Table 3: Wall configurations with differing locations of insulation and thermal mass [13]

Schematics	Wall	Assembly (Inside to outside)	U-value (W/m^{2}K)	Internal Areal heat capacity (kJ/m^{2}K)
	Wall A	10 mm thick cement plaster + 30 mm thick EPS insulation + 300 mm thick random rubble masonry + 10 mm thick cement plaster	0.75	20.6
	Wall B	10 mm thick cement plaster + 300 mm thick random rubble masonry + 30 mm thick EPS insulation + 10 mm thick cement plaster	0.75	72
	Wall C	10 mm thick cement plaster + 150 mm thick random rubble masonry + 30 mm thick EPS insulation + 150 mm thick random rubble masonry + 10 mm thick cement plaster	0.75	77.5
	Wall D	10 mm thick cement plaster + 15 mm thick EPS insulation + 150 mm thick random rubble masonry + 15 mm thick EPS insulation + 150 mm thick random rubble masonry + 10 mm thick cement plaster	0.75	26
	Wall E	10 mm thick cement plaster + 150 mm thick random rubble masonry + 15 mm thick EPS insulation + 150 mm thick random rubble masonry + 15 mm thick EPS insulation + 10 mm thick cement plaster	0.75	75.4
	Wall F	10 mm thick cement plaster + 15 mm thick EPS insulation + 300 mm thick random rubble masonry + 15 mm thick EPS insulation + 10 mm thick cement plaster	0.75	25.4

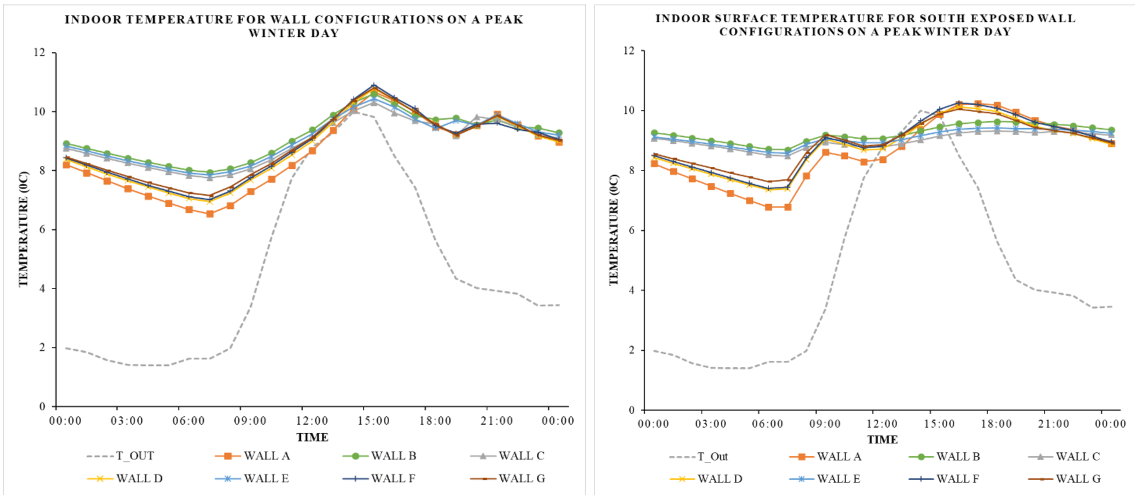
	Wall G	10 mm thick cement plaster + 10 mm thick EPS insulation + 150 mm thick random rubble masonry + 10 mm thick EPS insulation + 150 mm thick random rubble masonry + 10 mm thick EPS insulation + 10 mm thick cement plaster	0.75	31.4
Grey: Cement plaster; Red: Insulation; Yellow: Random Rubble masonry				

The wall configurations were compared to investigate the heating energy savings and reductions in HDD (Heating Degree Days) with respect to climate severities, orientation, and WWR. The Heating Degree Days are calculated in accordance with the EN 15251 standard [14], which provides a comprehensive method for determining the HDD values based on the outdoor temperature. The study includes three locations with varying climate severity levels: MILD: New Tehri (HDD = 2983), COLD: Mussoorie (HDD = 3237), and COLDER: Chakrata (HDD = 3491). The window-to-wall ratio (WWR) ranges from 10% to 40%, and all four orientations (North, South, East, and West) are simulated to evaluate the impact of wall configurations on the thermal performance of the residence. The drawing room facing south west was selected for running simulations on the validated model of House A for assessing the heating energy demand and heating degree discomfort hours.

Results

The paper investigated the effect of thermal mass and insulation position on the thermal performance of residential buildings in a cold climate. Simulations were performed for seven different wall configurations to assess the heating energy demand and comfort. The drawing room was simulated under two conditions: First – naturally ventilated condition, where the windows were programmed to open when the indoor temperature exceeded 24°C and close when the outdoor temperature surpassed the indoor temperature. Secondly – heating conditions, where a heating set point of 22°C is set as per EN 15251 standard to heat the room and maintain a comfortable temperature inside. This provides insight into the thermal behaviour of the room and heating energy requirements for different wall configurations.

Figure 4 a) shows the fluctuations in indoor temperature conditions for different wall configurations on a peak winter day (December 21).



(a) (b)

Figure 4: (a) Indoor air temperature and (b) surface temperature conditions for different wall configurations on a peak winter day

The outdoor temperature ranges from 1.4°C to 10°C on a peak winter day (December 21) considered here. Analysis of indoor temperature reveals that Wall A exhibits an ambient temperature that is 1.4°C lower than Wall B at 7 am when the indoor temperature is lowest. Despite having the same U-value, the variation in the positioning of thermal mass and insulation causes differences in indoor temperature conditions. Based on the decreasing order of preference in terms of indoor temperature, the ranking of walls would be Wall B, Wall E, Wall C, Wall G, Wall F, Wall D, and Wall A. Figure 4 b) shows the indoor surface temperature for a south exposed wall for different wall configurations. The exterior surface temperature of the walls varies between 3.3°C and 9.6°C. The indoor surface temperature for Wall A is 1.8°C lower than Wall B. The ΔT for Wall A is 1.6°C whereas ΔT for Wall B is 1°C only on a peak winter day. This suggests there is less fluctuation in the indoor surface temperature for Wall B than for Wall A. The outdoor temperature ranges from 18°C to 32°C on a peak summer day (June 21). Analysis of indoor air temperature and surface temperature reveals that at 6 pm, when the indoor temperature reaches its peak, Wall A maintains an ambient temperature of 0.1°C cooler than Wall B, while its surface temperature is 0.2°C warmer than Wall B. Since there is no significant difference in indoor air temperature and surface temperature, Wall B remains the preferable choice over Wall A, even during the summer months.

To evaluate the thermal performance of the buildings, various thermal performance indexes like time lag, damping, and decrement factor are used [15]. Table 4 presents the maximum and minimum thermal performance of different wall configurations in terms of decrement factor for surface temperature, damping, and time lag based on indoor and outdoor air temperature for a typical winter month (Dec+Jan).

Table 4: Thermal performance of different Wall configurations in winter month

Wall	Decrement factor		Damping (%)		Time lag (hrs)	
	min	max	min	max	min	max
Wall A	0.3	0.7	40	62	1	4
Wall B	0.1	0.5	42	89	1	5
Wall C	0.1	0.7	23	90	1	5
Wall D	0.3	0.7	22	69	1	3
Wall E	0.1	0.7	31	90	1	5
Wall F	0.3	0.8	21	68	1	3
Wall G	0.2	0.9	10	72	1	3

From Table 4, it is evident that Wall B exhibits the lowest decrement factor, highest damping, and highest time lag among the different wall configurations. This indicates that Wall B outperforms the other configurations in terms of thermal performance. Figure 5 shows the heating energy demand for a peak winter day with different wall configurations.

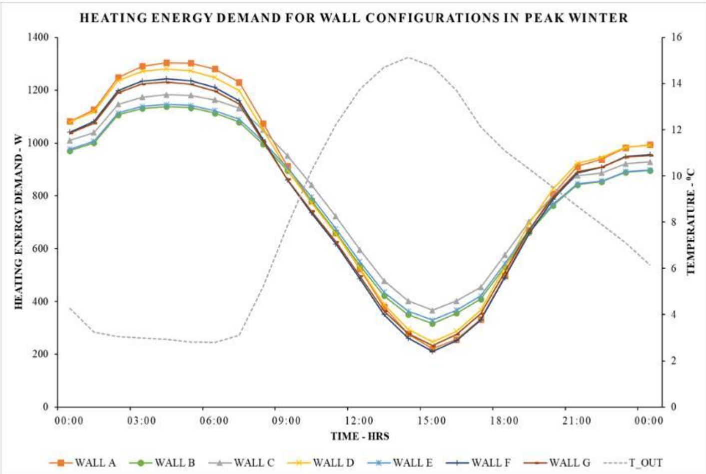


Figure 5: Heating energy demand for different wall configurations on a peak winter day

Analysis of heating energy demand for a peak winter day shows that HED for Wall A is 150 Watts or 12% higher than Wall B. Therefore, Wall A serves as the reference case for comparing the energy savings and reduction in heating degree days among other wall configurations.

Effect of Wall Configuration on climate severity wise thermal performance

The study examined the variations in indoor air temperature and heating energy demand across different climate severities represented by the selected locations, i.e., New Tehri, Mussoorie, and Chakrata. The locations were selected to represent the mild, cold, and colder conditions. The results are for the drawing room with external walls facing south and west. The results demonstrated that buildings located in harsher climates experienced higher heating energy demand and more significant temperature fluctuations. Table 5 shows the reduction in HED and HDD for different wall configurations and climate severities.

Table 5: Effect of wall configurations on climate severities showing reductions in HED and HDD

Wall	New Tehri		Mussoorie		Chakrata	
	HED (% Savings)	HDD % reduction	HED (% Savings)	HDD % reduction	HED (% Savings)	HDD % reduction
Wall A	1642 kWh	2035 hrs	1720 kWh	2150 hrs	2211 kWh	2210 hrs
Wall B	**-4.2**	**-3.1**	**-3.2**	**-2.2**	**-2.8**	**-0.5**
Wall C	-4	-2.3	-3	-1.7	-2.6	-0.4
Wall D	-1.7	-0.6	-1.3	-0.6	-1.1	-0.2
Wall E	-4	-2.7	-2.8	-2.1	-2.6	-0.4
Wall F	-1.7	-1	-1.2	-0.6	-1	-0.1
Wall G	-2.3	-1.2	-1.7	-0.9	-1.4	-0.2

There is an increase of 25% in HED with the increase in climate severity from New Tehri to Chakrata. Among the various wall configurations, Wall B demonstrated a reduction in Heating Energy Demand (HED) ranging from 3% to 4% and a reduction in HDD ranging from 0.5% to 3% across the different locations.

Effect of Wall Configuration on orientation wise thermal performance

The impact of different building orientations on indoor air temperature and heating energy demand was analyzed. The results are for the drawing room in Mussoorie. The results indicated that buildings with favorable orientations, such as south-facing walls, experienced better thermal performance. These orientations allowed for increased solar gain, resulting in reduced heating energy demand and improved thermal comfort. Table 6 shows the reduction in HED and HDD for different wall configurations and orientations.

Table 6: Effect of wall configurations on orientation showing reductions in HED and HDD

Wall	North		East		West		South	
	HED (% Savings)	HDD % reduction	HED (% Savings)	HDD % reduction	HED (% Savings)	HDD % reduction	HED (% Savings)	HDD % reduction
Wall A	1720 kWh	2150 hrs	1591 kWh	2119 hrs	1304 kWh	2045 hrs	1297 kWh	1989 hrs
Wall B	**-3.2**	**-2.2**	**-3.9**	**-1.8**	**-7**	**-1.7**	**-9.8**	**-1.4**
Wall C	-3	-1.7	-3.2	-1.3	-5	-1.1	-7.3	-1
Wall D	-1.3	-0.6	-1.4	-0.5	-2.7	-0.4	-3.5	-0.4
Wall E	-2.8	-2.1	-2.9	-1.4	-5.6	-1.3	-8.3	-1.2
Wall F	-1.2	-0.6	-1.4	-0.5	-1.8	-0.5	-1.9	-0.4
Wall G	-1.7	-0.9	-2	-0.8	-2.7	-0.7	-3.2	-0.6

As the orientation of the building changes from north to south, the HED is reduced by 24%, and the HDD is reduced by 8%. Among the various wall configurations, Wall B demonstrated a reduction in Heating Energy Demand (HED) of 9.8% and a reduction in HDD of 1.4%, specifically for the south orientation. These reductions in HED and HDD indicate that Wall B outperformed all other wall configurations, demonstrating the highest energy efficiency and improved thermal performance for all orientations.

Effect of Wall Configuration on window-to-wall ratio wise thermal performance

In a cold climate, the increase in Window-to-Wall Ratio (WWR) can have a notable impact on building heating energy demand. As the WWR increases, the surface area of windows also increases, leading to higher heat loss from the building envelope. This increased heat loss through windows can result in higher heating energy demand to maintain desired indoor temperatures. Simulations were carried out to study the effect of wall configurations on increasing WWR. The simulations are for the drawing room facing south and west in Mussoorie with a 3 mm single clear glass window with a U-value of 5.6 W/m^{2}K. Table 7 indicates the reduction in HED and HDD for different wall configurations and WWR.

Table 7: Effect of wall configurations on WWR showing reductions in HED and HDD

Wall	WWR 10 %		WWR 20 %		WWR 30 %		WWR 40 %	
	HED (% Savings)	HDD % reduction	HED (% Savings)	HDD % reduction	HED (% Savings)	HDD % reduction	HED (% Savings)	HDD % reduction
Wall A	1720 kWh	2150 hrs	1762 kWh	2162 hrs	1795 kWh	2188 hrs	1886 kWh	2252 hrs
Wall B	**-3.2**	**-2.2**	**-2.5**	**-1.7**	**-2**	**-1.6**	**-1.8**	**-1.3**
Wall C	-3	-1.7	-2.2	-1.3	-1.9	-1.2	-1.7	-1.1
Wall D	-1.3	-0.6	-1.1	-0.2	-1	-0.2	-0.8	-0.1
Wall E	-2.8	-2.1	-2.5	-1.3	-1.7	-1.2	-1.5	-1.1
Wall F	-1.2	-0.6	-1	-0.2	-1	-0.2	-1.3	-0.2
Wall G	-1.7	-0.9	-1.5	-0.4	-1.3	-0.3	-0.9	-0.3

It was observed that as the WWR increased, the HED increased by 8.8% from WWR 10% to WWR 40%, and the HDD increased by 4.5%. This indicates that in cold climates, lower WWR is preferred. Among the various wall configurations studied, Wall B consistently demonstrated a reduction in Heating Energy Demand (HED) and Heating Degree Days (HDD). For a 10% WWR, Wall B exhibited a decrease in HED by 3.2% and HDD by 2.2%. This trend persisted as the WWR increased from 10% to 40%. However, higher WWR with double glazed windows and brick masonry walls will lead to lower heating energy demand [16], which is opposite to the case discussed here.

Conclusion

In conclusion, this study investigated the effect of thermal mass and insulation position on the thermal performance of residential buildings in a cold climate. The research aimed to understand the impact of these factors on energy consumption and thermal comfort conditions in residential buildings. The results of the study demonstrated that the positioning of thermal mass and insulation significantly influenced the thermal performance of residential buildings. By varying the wall configurations, it was observed that different combinations of thermal mass position and insulation had varying effects on both heating demands as well as indoor thermal comfort. The findings indicated that the location of thermal mass played a critical role in regulating indoor temperatures. Configurations with thermal mass placed on the interior side of the walls exhibited better thermal performance by reducing temperature fluctuations and enhancing thermal comfort. In contrast, configurations with thermal mass placed on the exterior side resulted in higher temperature variations and increased energy consumption.

Furthermore, the study explored the impact of climate severities, orientations, and window-to-wall ratio on energy savings and comfort. The study revealed that harsher climates resulted in increased heating energy demand, while changing the orientation from north to south decreased heating energy demand, and increasing the window-to-wall ratio led to higher heat loss and increased heating energy demand. Among the various wall configurations analyzed, Wall B, with thermal mass positioned on the interior side and insulation on the exterior side, consistently exhibited superior performance in terms of energy demand reduction and thermal comfort across all conditions of climate severities, orientation and WWR. The thermal mass layer inside delays the heat loss and maintains the indoor air temperature while the thick insulation layer outside resists the heat loss to outside.

Nonetheless, practical challenges arise when applying insulation on the outer side of the wall rather than the inner side. Additional protective measures must be taken externally to shield the insulation from potential harm caused by sun and rain exposure. Consequently, there is a 10% escalation in costs due to the need for separate scaffolding installation.

Overall, this research highlights the significance of thermal mass and insulation positioning in optimizing the thermal performance of residential buildings in cold climates. The findings of this study contribute valuable insights for architects, engineers, and policymakers in designing energy-efficient residential buildings in cold climate regions. By considering the optimal positioning of thermal mass and insulation, it is possible to create buildings that provide comfortable living conditions while minimizing energy consumption and promoting sustainability in the built environment.

In future research, there is potential for exploring additional thermal mass materials such as dense concrete, heavy-weight hollow concrete blocks, brick, and cavity walls. These materials play a crucial role in the thermal properties of the building envelope, affecting the temperature difference between the indoor and outdoor environments and consequently impacting energy efficiency. Furthermore, conducting a sensitivity analysis on the key thermophysical properties of construction materials with respect to climate severities could be an area of focus for future studies.

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A Control Sequence for Prioritising Ceiling Fan Operation Over Air Conditioners Using Machine Learning to Determine Thermal Comfort

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Highlights

- Machine learning for predicting OT as a scalable approach for adaptive comfort controls.
- Using the corrective power index for cooling to adjust the upper limit of the thermal comfort band based on air speed achieved by ceiling fans.
- Thermal comfort study of comfort votes and energy consumption, compared to a 24ºC constant setpoint.
- Cooling energy savings of more than 97% with higher comfort votes for the demonstrated control sequence.

Abstract

This study aims to use the corrective power of personal comfort systems of -1K to -6K [2] and prioritise ceiling fan operation over AC to reduce energy consumption and implement controls based on Operative temperature (OT). We use a machine learning algorithm that takes indoor air temperature and outdoor values for air temperature, wind speed, and relative humidity as inputs and predicts the indoor OT of a space. The predicted OT is used to determine thermal comfort according to the India Model for Adaptive Comfort (IMAC). We have developed a control sequence that automates ceiling fan speed operation and air-conditioning (AC) set-points. The control sequence is tested in two different rooms; one, a passively designed building with an insulated envelope, and another, a typical uninsulated building, tested against a base case of 24°C set-point suggested by the Bureau of Energy Efficiency (BEE), India, with no ceiling fans operating. The testing shows that the control sequence that prioritises ceiling fan operation has higher comfort votes than the BEE base case, and the control sequence provided more than 80% cooling energy savings compared to the BEE base case.

Keywords: Adaptive thermal comfort, operative temperature, corrective power Index, machine learning, ceiling fans

Introduction

Per capita annual energy consumption for space cooling in India is only 69 kWh compared to the global average of 272 kWh [1]. However, rising temperatures and income levels will increase India's cooling energy requirement, and the India Cooling Action Plan [2] calls for synergistic actions across sectors to provide sustainable cooling that is affordable. Most of the new buildings are air-conditioned, and much of the existing building stock is being retrofitted with AC systems. This has resulted in a wide array of mixed mode buildings and begs a closer look at mixed mode operation.

The existing controls are mostly based on air temperature because the operative temperature is difficult to measure in real-time, while it is a better indicator of indoor thermal conditions [3]. Also, the automation of ceiling fan controls is not explored well since most of the research performed already focuses on providing fan controls to occupants in cases of air speeds higher than 0.8 m/s [4].

This study aims to implement controls based on operative temperature (OT) used in the adaptive comfort model (IMAC) of the National Building Code (NBC) of India. We use the corrective power of personal comfort systems (PCS) of -1K to

-6K [5] and prioritise ceiling fan operation over AC to reduce energy consumption and implement controls based on Operative temperature (OT).

We use a machine learning (ML) algorithm that takes indoor air temperature and outdoor values for air temperature, wind speed, and relative humidity as inputs and predicts the indoor OT of a space. The predicted OT is used to determine thermal comfort according to the IMAC. For this study, the control sequence is tested in two different rooms; one, a passively designed building with an insulated envelope, and another, a typical uninsulated building, tested for these 3 conditions:

- Base case of 24°C (AC set-point suggested by the Bureau of Energy Efficiency, India) with no ceiling fans operating.
- IMAC AC set point at the neutral temperature of the comfort band, without fans.
- Ceiling fan prioritised control sequence

The aim of this research is to develop, implement, and test a control sequence that prioritizes the use of ceiling fans over air-conditioners, integrating products available in the market to provide energy efficient and comfortable cooling while maintaining the thermal comfort of the occupants.

The significant contributions of this work are to demonstrate that OT predicted in real-time with ML can be used in a control sequence that automates the prioritisation of ceiling fans and that in tropical conditions such as those prevailing in India, occupants report higher levels of comfort with ceiling-fan induced air movement and higher temperature set points. The findings of this study point to a method of space cooling that takes full advantage of the IMAC and can be an affordable and sustainable cooling approach.

Additional research can determine the extent to which this method is scalable to other building typologies and climates.

Literature review

Static models of thermal comfort helped in the formulation of thermal comfort standards that were applied universally, but they rely solely on-air conditioning to maintain the thermal comfort of occupants [6]. A location-specific adaptive comfort model, which includes the building's ventilation type, was developed by Manu et al., which will help in not only help in maintaining the thermal comfort of occupants but also help in reducing energy consumption [6], [7]. It allows buildings to operate within a broader range of indoor operative temperatures.

The elevated air speed comfort zone method in the ASHRAE Standard 55 standards allows us to define limits for comfort for indoor operative temperature for defined air speed in the space when other parameters like met value and clo value are held constant. In the 2017 version of the ASHRAE Standard 55, the upper limit of airspeed was increased to 1.6 m/s [8]. Occupants in warmer countries prefer warmer temperatures since they have adapted to high temperatures, especially in naturally ventilated buildings where the outdoor temperature has a significant influence on the indoor comfort parameters [9]. A study by Candido & de Dear [10] also states that occupants who feel hot prefer more air movement. Y. Zhai et al. [11] concluded that the provision of air movement is more important than temperature control in such warm environments.

Ceiling fans are an efficient adaptive comfort strategy to induce air movement, improve comfort, and have a corrective power index (CP) of -1K to -7K when the air speed is as high as 1 m/s, and the ambient temperature is as high as 33°C [12]. Corrective power is defined by ASHRAE 55 as the ability of a PCS to correct the thermal sensation of a person toward the comfort zone. It is expressed as the difference in operative temperatures between two instances where equal thermal sensation is achieved, one with PCS and one without PCS [4]. In a thermal comfort study conducted in California with a hot and dry climate across 10 buildings with air conditioners, ceiling fans provided comfort at 26.7°C with air movement rather than having only air conditioning at 22.2°C [13],[14]. In another study conducted in the tropics, ceiling fans provided comfort up to 27°C, but if given a preference, the occupants chose to have minimal air conditioning along with the ceiling fans as a preference to attain comfort [15]. A study by Bongers et al. [16] in Australia states that the use of ceiling fans can increase the temperature limit when the air conditioning needs to be switched on. The study reports annual energy savings up to 76%. A thermal comfort tool by the Center for Built Environment [17] shows that the upper limit of the comfort model shifts further upwards in response to increased airspeed in space. De et al. [3] used the tool to obtain the upward shift for several conditions and developed an equation to apply the effect of air speed on the IMAC band.

Methodology

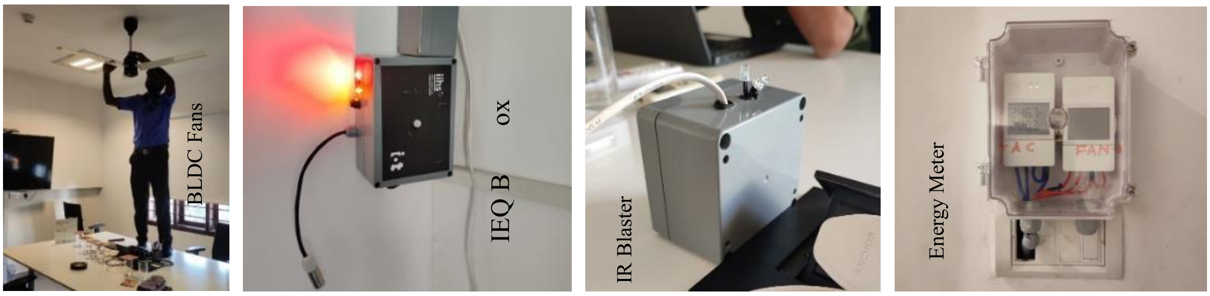
Validation of ML model

The ML model for predicting OT was developed by [3] De et al. for a workstation room in a passively designed building with significant envelope insulation. This model was tested by comparing its predictions for OT with 1-week long hourly data from measurements of the globe temperature, air temperature, and airspeed in the two conference rooms where the control sequence was to be implemented. These measured data were used to calculate the mean radiant temperature and the OT based on ISO 7726-1998. These calculated OT values were then compared with those predicted by the ML model. Mean bias error (MBE) and Root mean squared error (RMSE) were calculated. The RMSE = 4% and MBE = 3%, the accuracy was found to be 96.77 %. With these results, the ML model was then used to predict OT for use in the control sequence.

Equipment installation and setup in spaces

Two conference room spaces in Bangalore were selected for the study. One was in a passively designed insulated office building, and the other was in a typical business as usual, uninsulated office building. Both rooms had split AC units and were operated in mixed mode. Atomberg brushless direct current (BLDC) smart fans were installed in both rooms.

Indoor environmental quality (IEQ) boxes were installed in both rooms to collect air temperature relative humidity data. The boxes also had sensors for CO_2, $PM_{2.5}$, and PM_{10}, but this data was not used in the study. Outdoor weather parameters are collected with a weather station on the building. Energy meters were installed to collect energy consumption data for the AC and the ceiling fans. Infrared (IR) blasters were installed to control the ceiling fans and the AC units. See Figure 1.



(a) **(b)** **(c)** **(d)**

Figure 1. Images of the hardware installed in each room: (a) BLDC ceiling fan, (b) IEQ box, (c)IR blaster, and (d) energy meters

Developing the control sequence

We use the IMAC for determining the thermal comfort band. Based on the National Building Code 2016, Volume 2, the 90% acceptability range for mixed-mode buildings band is calculated as

$$IMAC\_upper = ((0.28 \times \text{outdoor temperature}) + 17.87) + 3.46 \quad (1)$$

$$IMAC\_lower = ((0.28 \times \text{outdoor temperature}) + 17.87) - 3.46 \quad (2)$$

Where IMAC_upper and IMAC_lower are the upper and lower limits, respectively, of the thermal comfort band.

The IMAC_upper is used as the threshold for determining comfort.

The OT prediction ML model runs every minute using the data from the IEQ box and the weather station. The predicted OT is compared with the upper limit of the thermal comfort band.

To determine the upward shift of the upper limit of the band when air speed is introduced as a variable in space, we use the equation determined by De et al. (2022) [3].

$$y = -1.39x^2 + 4.92x - 1.38 \quad (3)$$

where y is the shift in the upper limit of the band and x is the air velocity.

The BLDC fans have 5 speed settings. For each setting, the air speed experienced by the users in the space is calculated as an average for the air speeds experienced by all the users. The air speed experienced by each user is calculated as the average air speed measured at heights of 0.6 m and 1.1 m from the floor level [18]. This approach was used to precalculate the airspeed achieved for each fan speed. The shift of the extended upper limit (extended_IMAC_upper) of the comfort band is calculated using the airspeed achieved at each setting and equation 3.

If the predicted OT is lower than IMAC_upper, the control sequence keeps the ceiling fan and AC off.

If the predicted OT is higher than IMAC_upper but lower than the extended_IMAC_upper, the control sequence turns on the ceiling fan to the appropriate air speed but keeps the AC off.

If the predicted OT is higher than the extended_IMAC_upper for the highest fan speed setting, the fan is switched on at the highest speed to use its full potential, and the AC is switched on with the highest set-point possible. This setpoint is calculated in the following steps:

1. By using the OT formula from ISO 7726-1998 to calculate the MRT in the space using the predicted OT value.
2. Then the air temperature in the space is calculated using the same formula since MRT and the desired OT values are known.
3. The calculated air temperature is sent as set-point temperature to the AC.

Thermal comfort study and energy monitoring

A total of 70 respondents participated in the study, with 34 males and 36 females. The respondents were not compensated for taking part in the study. They signed a consent form for taking part in the study and were part of one session. Each session spanned across 2 hours and 15 minutes. The first 30 minutes were orientation, filling of forms, and acclimatisation. The forms included data related to their age, gender, height, and weight, history of their space cooling adaptations and preferences, recent physical activity, and documentation of the clothing that they were wearing.

The respondents were exposed to 3 different types of conditions for 30 minutes each, with 5-minute break outside the test room between the 3 conditions. The conditions were: *condition 1* - room maintained at a constant 24ºC setpoint without ceiling fans; *condition 2* - room maintained at IMAC band neutral temperature without ceiling fans; and *condition 3* - room comfort maintained using the proposed control sequence.

The thermal comfort study was carried out from 14th March 2023 to 17th March 2023 in the BAU building for a total of 8 sessions with 40 participants, and on the 14th, 27th, and 28th of March in the passive building for a total of 5 sessions with 30 participants. Respondents filled out Google Forms, and their responses were collated in Google Sheets.

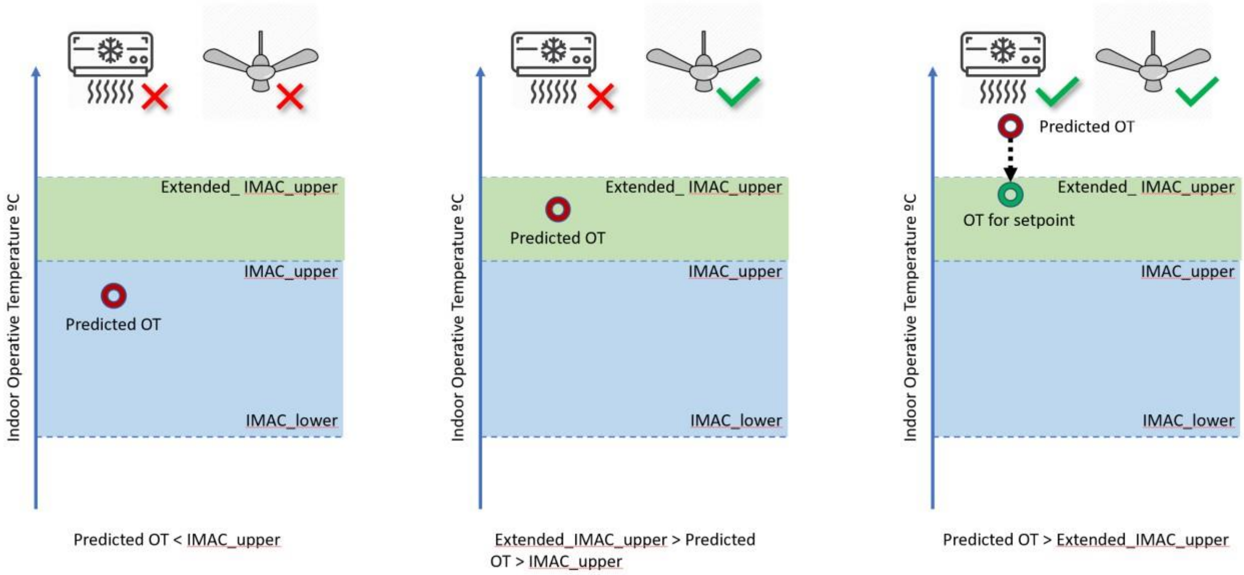


Figure 2: Three scenarios for the control sequence

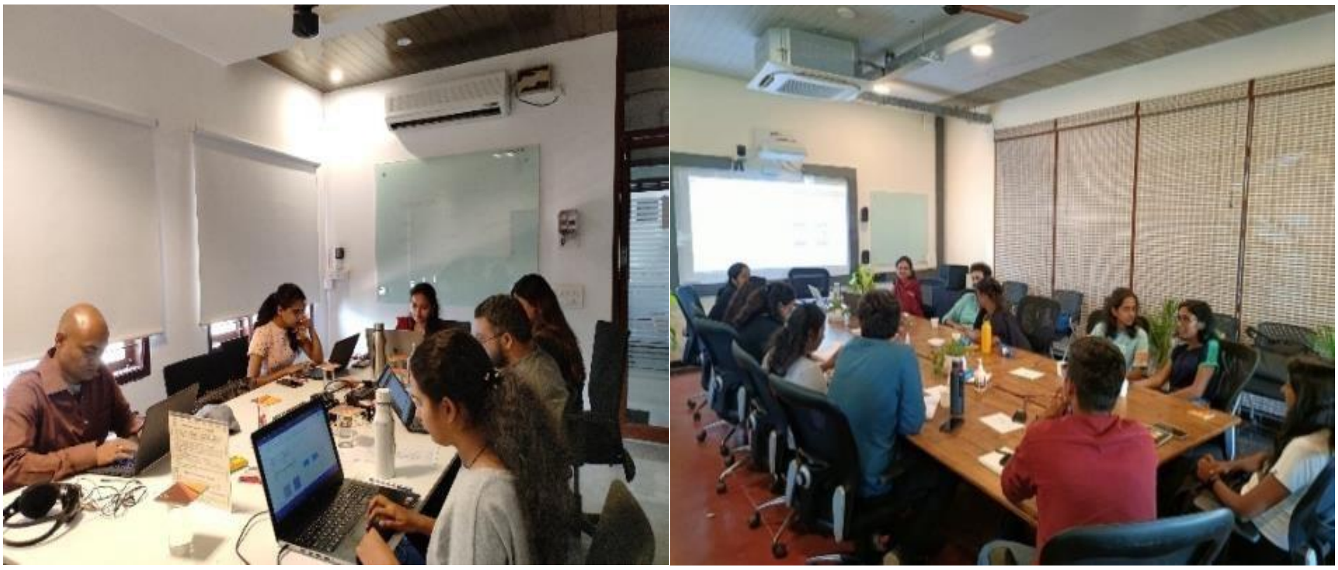


Figure 3: Thermal comfort study in progress

Energy used by the air conditioners and ceiling fans in kWh was recorded by the meters.

Figure 4: Space conditioning data from the survey

Results

Data summary

The outdoor temperature varied between 29ºC and 35ºC during the study. Around 60% of the respondents were in the age group of 20 to 39 years, and the gender ratio was almost equal. (51% male, 49% female). Most of the respondents were involved in sedentary activities before taking part in the survey. Figure 4 shows the space conditioning habits and preferences of the respondents. Almost 98% of the respondents answered that they use ceiling fans for space conditioning in their residence, followed by operable windows and usage of curtains/blinds. But in their workplaces, ceiling fans were used by 68% of the participants, and operable windows and air conditioners were used by about 49% of the participants. The preference for space conditioning methods shows ceiling fans are preferred by 49% and operable windows by 35%, respectively. ACs were preferred by only 15% of the respondents.

During the study period, the IMAC neutral temperature setpoint was calculated at 24ºC. This resulted in identical setpoints for *condition 1* and *condition 2*, and the results for thermal comfort and energy for those 2 conditions are very similar. Therefore, the thermal comfort and energy analysis results below only show *Condition 1* and *Condition 3*

Thermal comfort analysis

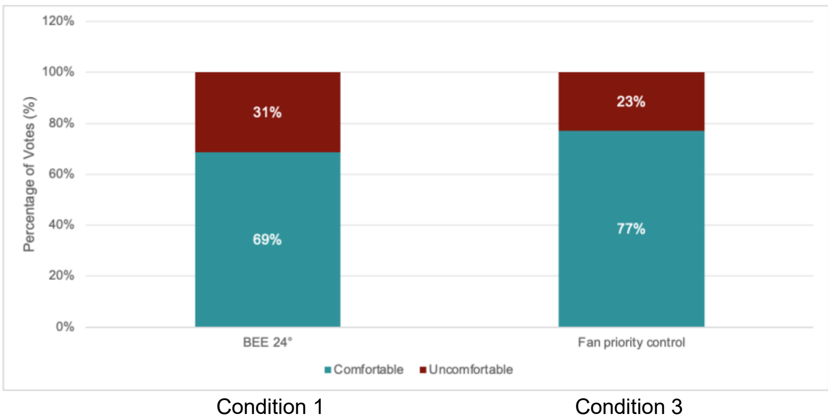


Figure 5: Thermal comfort votes for the 3 conditions tested

About 77% of the respondents reported being comfortable in *condition 3* - fan prioritized control sequence condition compared to about 69% in the other two conditions of the study (see Figure 5). While the study demonstrates that the fan-prioritised control sequence was preferred by the respondents, the statistical significance of these results needs to be determined.

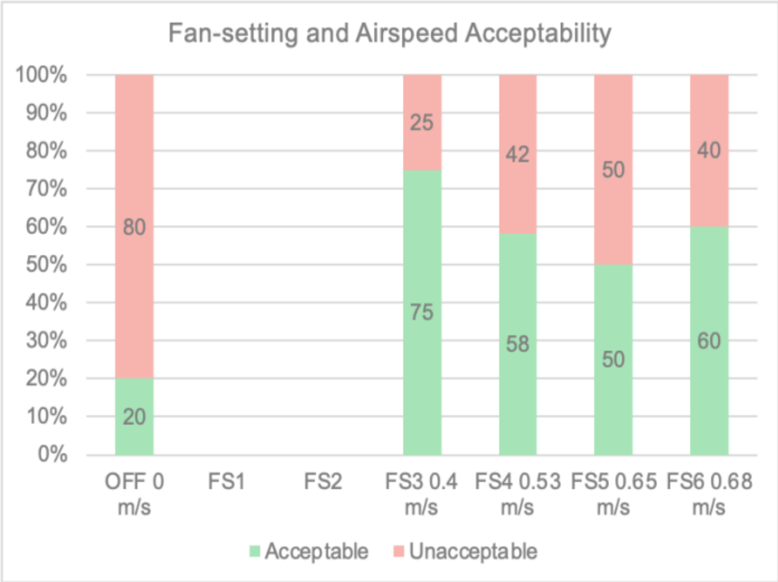


Figure 6: Acceptability of fan speeds

The respondents were also asked whether the airspeeds they experienced were acceptable to them. When the ceiling fan was off, 80% found this unacceptable. Since the fans did not come on at settings of 1 and 2 (FS1 and FS2) during the study, the data on these are not available. The airspeed of 0.4 m/s was acceptable to 75% of the respondents. The acceptability decreases when the air speed is 0.53 m/s and 0.65 m/s but seems to slightly increase again when the speed increases to 0.68 m/s (see Figure 6).

Energy analysis

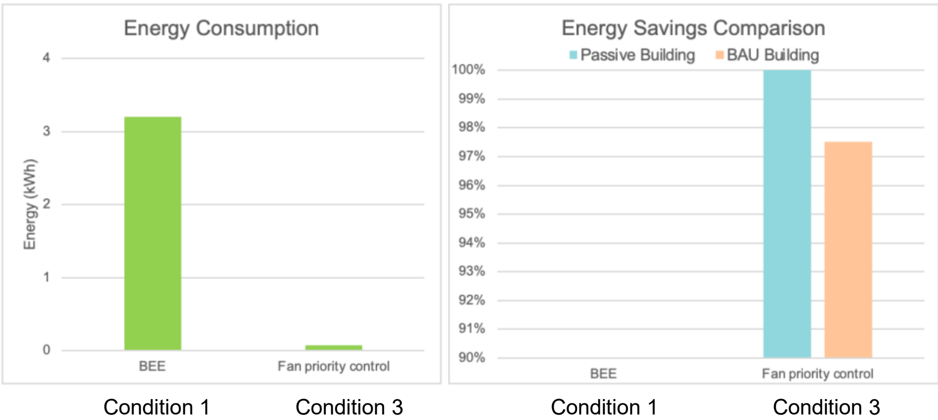


Figure 7: Energy Analysis Results, energy consumption (total during the study period in both buildings), savings for the fan-priority control compared to BAU for each building.

The energy consumption for each condition was calculated as the difference in energy meter readings at the start and the end of the condition. It is to be noted that the BEE 24°C baseline amounted to 3.32 kWh across all sessions while the fan prioritized control sequence consumed up to 0.07 kWh, resulting in a cooling energy savings of 97.9 % (see Figure 7, graph on the left). Please note that the outdoor dry bulb temperature was in the range of 35 °C to 29°C during the study period.

In the typical BAU building, the cooling energy savings were 97.9%, and in the passively designed building, the savings were 100% (see Figure 7, the graph on the right). The savings were 100% in the passive building because the OT was generally in the comfort band, and in the rare cases when it was outside the comfort band, it was lower than the extended_IMAC_upper. Thus, only the ceiling fan was switched on a few times, and the AC was never switched on. Due to the high efficiency of the ceiling fans and the least count of the energy meters, no energy consumption was recorded in the passive building. In the BAU building, while the OT was often greater than the IMAC_upper, it was generally lower than the extended_IMAC_upper, resulting in ceiling fans being switched on quite often. During the entire duration of the study in the BAU building, the AC was switched on for a duration of 5 minutes in condition 3, with the setpoint maintained at 30ºC. Thus, the energy savings for this 5-minute period (compared to the BEE 24ºC condition) was 82%. This shows that significant energy savings are possible with a ceiling-fan prioritised control sequence. This needs to be tested when higher outdoor temperatures are prevalent, where the air conditioner will kick in more often.

Conclusion

This paper shows the use of a machine learning model for predicting operative temperature as a scalable approach to providing comfort based on the adaptive model of the National Building Code of India. The approach that was developed earlier was validated in 2 test rooms for this study.

The control sequence developed in this study uses the CBE approach, where the corrective power index (CP) of ceiling fans was developed as an equation by De et al. [3]. It prioritises the use of ceiling fans in an automated control sequence, and this is tested in two conference rooms, one in a passive and one in a typical BAU building. This approach raises the upper limit of the thermal comfort band based on air speed achieved by the ceiling fan and also raises the AC set points when the ceiling fans are in operation.

The results show that 77% of the respondents found the space comfortable with the fan prioritised control sequence, as opposed to only 69% for the BEE proposed constant setpoint of 24ºC. The fan-prioritised control sequence also resulted in cooling energy savings of 98% during the study period, when outdoor temperatures varied between 29ºC to 35ºC.

The significant cooling energy savings and the fact that ceiling fans were adequate to provide comfort without ACs for several instances in the study period show that the ceiling fan prioritised controls or just ceiling fans for cooling can be a pathway to affordable and sustainable cooling.

Acknowledgement

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Comparative Assessment of a Residential Building's Envelope Based on Embodied Energy

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Highlights

- Determination of life cycle embodied energy for a mid-rise building in the Indian context
- Comparative assessment of the determined embodied energy to existing studies and highlighting the variation in findings
- Comparative assessment of building's envelope based on embodied energy, identifying the most and least efficient materials

Abstract

This paper addresses the estimation of a residential building's embodied energy through real-time data and evaluates the influence of diverse infill wall materials on its embodied energy. The investigation centers on a 10storey residential structure situated in Roorkee, India's composite climate. The study encompasses initial embodied energy from the bill of quantities and recurring embodied energy from maintenance and replacement cycles. Calculated at 11630 MJ/m², the determined lifetime embodied energy comprises 98.6% initial and 1.4% recurrent energy. A comparative analysis is conducted against existing literature and extended to alternative building envelopes. Findings indicate that using fly ash lime brick for infill walls minimizes embodied energy, potentially saving around 515MJ/m² across the building's lifespan. This research provides valuable insights into estimating and comparing the embodied energy of residential buildings and highlights the potential energy efficiency benefits of specific building envelope choices.

Keywords: Life cycle embodied energy, Initial Embodied energy, Recurrent Embodied energy

Introduction

In recent years, the impact of buildings on global energy consumption and greenhouse gas emissions has become a growing concern in the context of climate change. According to the 2019 Global Report for Buildings and Construction [1], buildings accounted for a staggering 36% of global energy consumption and contributed 39% of global emissions. This alarming data highlights the urgent need to address the energy efficiency of buildings to mitigate climate change and global warming.

The energy consumption of buildings occurs in two key domains over their lifetime: operational energy, which is the energy consumed by the building's electrical load, and embodied energy, which is the energy embedded in the construction materials used. To achieve significant reduction in the life cycle energy of buildings, it is crucial to minimize both operational energy and embodied energy. This paper focuses specifically on the determination of the embodied energy in a real-time building situated in the composite climate of Roorkee. Additionally, it undertakes a comparative analysis of embodied energy for the same building, considering a range of nine different building envelopes. Each envelope represents an alternative infill wall material, offering insight into the potential energy savings achievable through the use of different materials in terms of embodied energy.

By shedding light on the embodied energy of buildings and the energy-saving potential associated with alternative materials, this study contributes to our understanding of sustainable practices in the construction industry. Ultimately, it aims to inform decision-makers and stakeholders about the importance of reducing embodied energy as part of comprehensive efforts to create energy-efficient and environmentally conscious buildings.

Methodology

The study was conducted following the methodology outlined in Figure 1. The research consisted of two main parts, each addressing a specific aspect of embodied energy in buildings.

In the first part of the study, the calculation of embodied energy was performed for a residential case building located in the composite climate of Roorkee. To determine the initial embodied energy, the bill of quantities for the building was utilized. This involved quantifying the energy embodied in the construction materials used in the building's construction phase. Additionally, the recurrent embodied energy for a 50-year period was calculated by considering the maintenance and replacement cycles observed in the previous years. The calculated values of embodied energy were then compared to the findings of the existing studies in the field of assessing the relative magnitude of the embodied energy for the case building.

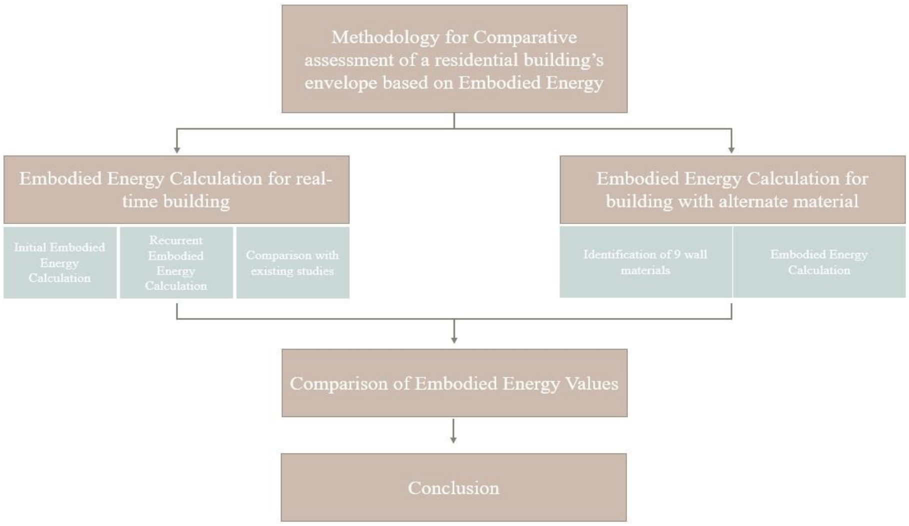

Figure 1: Methodology for the study

The second part of the study focused on investigating the impact of different wall materials on embodied energy. Nine wall materials, identified according to the list provided by NBCC [2], were selected as alternate materials for analysis. For each material, the initial and recurrent embodied energy values were calculated for the residential building, accounting for the specific variation in the building envelope. A comparative analysis of the embodied energy values associated with the different wall materials was performed, allowing for meaningful conclusions to be drawn regarding the energy-saving potential offered by these materials.

By following this methodology, the study aimed to provide a comprehensive understanding of embodied energy in buildings, both in the context of a specific case building and the influence of various wall materials. The findings of this research contribute to the body of knowledge in the field and offer valuable insights for decision-makers and stakeholders seeking to promote sustainable practices in the construction industry.

Introduction to the case study building

The case study building, depicted in Figure 2, is a real-time building situated in the composite climate of Roorkee. Table 1 provides an overview of the specifications for this particular building. Constructed in 2022, the building is a G+10 residential apartment building with a reinforced concrete frame structure and pile foundation serving as its structural system. It is part of an apartment complex consisting of three identical building blocks, as illustrated in Figure 2. The ground floor of each block is allocated for stilt parking.

Table 1: Specifications of the building

Specifications	
Building Name	River View Apartment
Location	Roorkee, Uttarakhand, India
Year of Construction	2022
Climate	Composite (as per ECBC)
Structural System	Reinforced concrete frame structure with pile foundation
Building Typology	Residential building
User Typology	Staff and Faculty Housing for IIT Roorkee

No. of floors	Stilt + 10
No. of blocks	3
No. of residences	60x3 blocks
Typology of residences	3 bhk
Built up area of 1 block	14850 m^2 approx.
Built up area of 1 residential unit	204 m^2 approx.

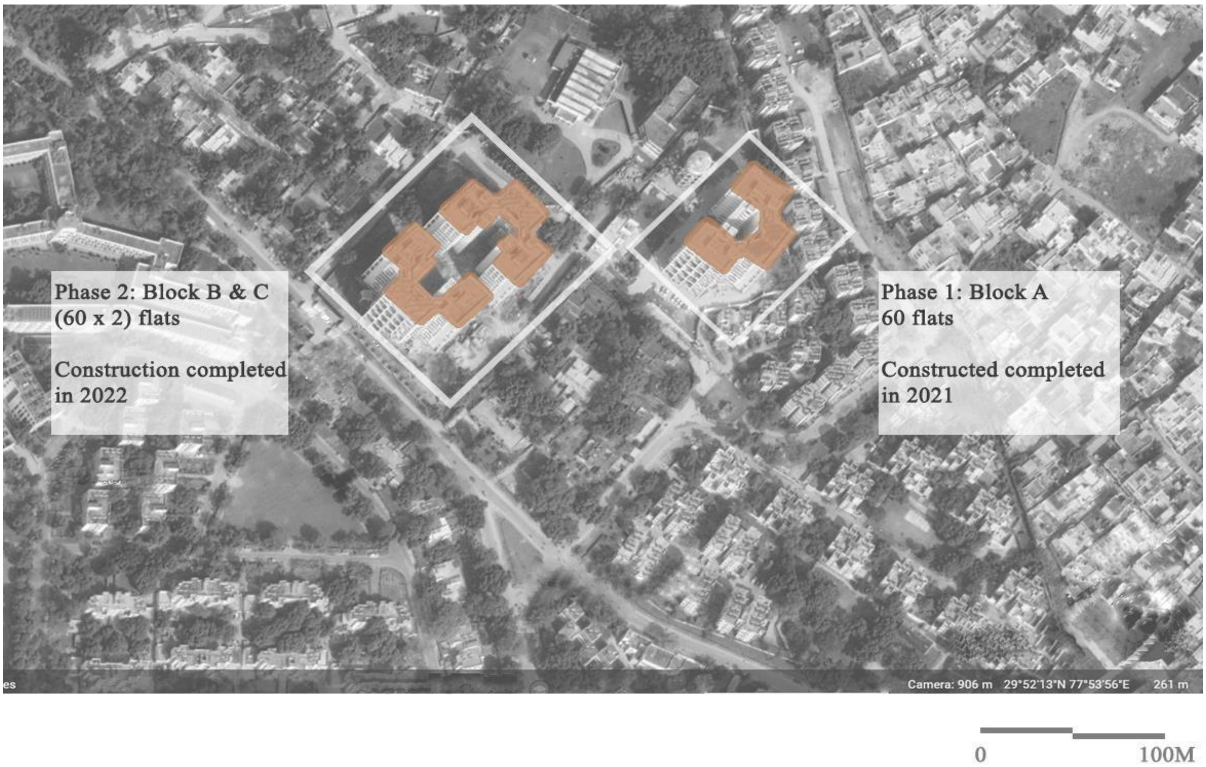

Figure 2: Apartment complex consisting of the case study building

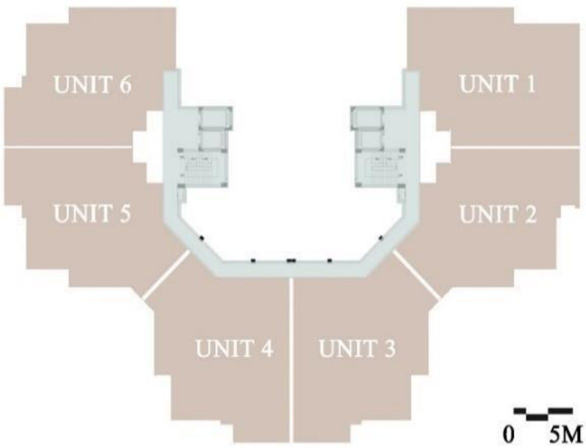

Figure 3: Typical floor plate of the apartment building.

Each typical floor plate of the building contains six residential units, as showcased in Figure 3. The total area of a typical floor plate is approximately 1485m^2, with approximately 18% of the space dedicated to circulation. Each residential unit is a 3 bhk apartment encompassing an area of around 204 m^2 and featuring balconies on three sides. A visual representation of a typical residential unit layout can be seen in Figure 4. For the purposes of this study, the anticipated life span of the building is considered to be 50 years, aligning with established industry standards [2].

Embodied Energy Calculation for the real time building

Initial Embodied Energy Calculation ($EE_{initital}$)

The $EE_{initital}$, which represents the embodied energy of the construction materials, is determined for the case study building. The bill of quantities is used to calculate the $EE_{initital.}$ The embodied energy values are sourced from the "Indian Construction Materials Database of Embodied Energy and Global Potential" [3], a report published in 2017 by the International Finance Corporation and European Union. The embodied energy values consider the "cradle to gate" system boundaries and do not include transportation from production to the building site. All embodied energy values are expressed in Mega Joules per unit area.

The calculation of embodied energy covers various aspects of civil work, including concrete work, reinforced concrete work, masonry work, marble and granite work, wood and PVC work, steel work, flooring, roofing, finishing, pile work, and aluminum work. The specific scope for calculating embodied energy is outlined in Table 2.

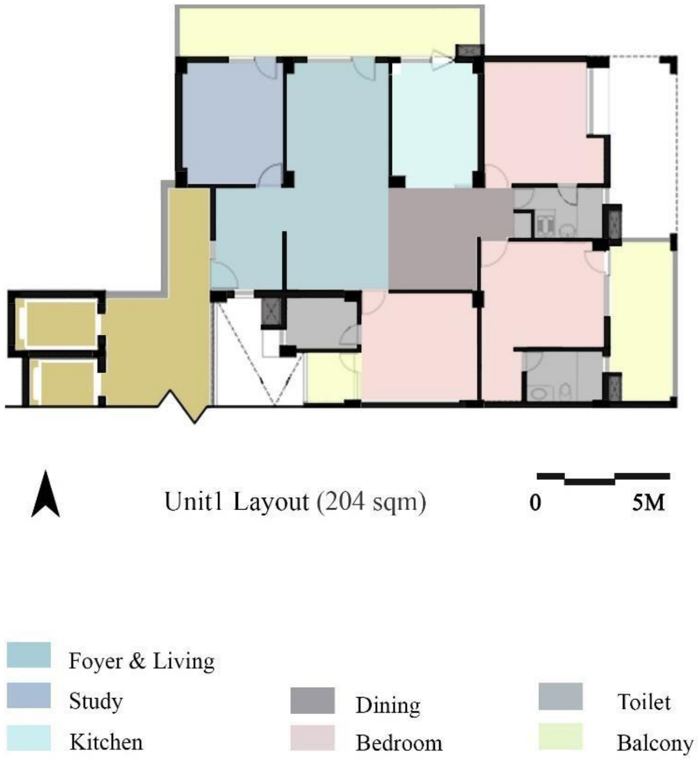

Figure 4: Typical layout of the residential unit

Table 2: Scope of embodied energy calculation

S.No.	Works considered for Embodied Energy Calculation	Works not considered for Embodied Energy calculation
1	Concrete Work	Earthwork
2	Reinforced Cement Concrete	Road work
3	Masonry/ brick work	Sanitary Installations
4	Marble and granite	Water Supply
5	Wood and PVC	Drainage
6	Steel Work	Water Proofing
7	Flooring	Extra (New technology/materials)
8	Roofing	Horticulture and landscape
9	Finishing	Lightings
10	Pile Work	Fire Alarm and PA System
11	Aluminum Work	Lifts/ Elevators
12		Sub-station
13		DG Set
14		Earthing and Miscellaneous Items

15		CCTV Surveillance
16		Fire Fighting Work
17		Pumps, Solar Hot Water System and Equipment

The $EE_{initital}$ for each block of the case study building is determined to be 170321035.50 MJ, equivalent to 2838683.92 MJ per residential unit. The calculated $EE_{initital}$ per unit area is approximately 11469.43 MJ. Table 3 provides details on the amount of building materials and the associated energy consumed per unit area. It is worth noting that cement and steel account for nearly 90% of the initial embodied energy consumption despite comprising only 31% of the total material quantity.

Table 3: Initial Embodied Energy consumed per unit area

S.No.	Building Material	Quantity (kg/ m^2)	Embodied Energy values reported in the database (MJ/kg)	$EE_{initital}$ (MJ/m^2)	Percent $EE_{initital}$ consumed by the material
1	Cement	1052.96	6.40	6738.98	58.76%
2	Steel	108.00	24-30	3255.08	28.38%
3	AAC	42.45	11.5	488.17	4.26%
4	Aluminum	0.64	330.00	211.52	1.84%
5	Tile	21.30	7.8-8.2	174.63	1.52%
6	Bricks	42.87	3.6-4.4	154.32	1.34%
7	Sand	1383.64	0.11	152.20	1.32%
8	Stone Aggregate	1069.00	0.11	117.59	1.02%
9	Kiln Dried Timber	7.81	15.00	117.21	1.02%
10	Cement based plaster	8.43	4.80	40.45	0.35%
11	Float Glass	0.60	17.00	10.10	0.08%
12	Stone Floor Tile	13.53	0.44	5.95	0.05%
13	Glass Reinforce Concrete	2.71	1.30	3.52	0.03%
		3753.94	**-**	**11469.43**	

It is important to recognize that there is currently no globally accepted standard or method for determining embodied energy [4]. Consequently, an attempt is made to benchmark the calculated values of the case study against existing studies conducted within the Indian context. Table 4 presents a compilation of such studies that have estimated the initial embodied energy in various buildings. Notably, Figure 5 illustrates the absence of a clear pattern or relationship between the height of the building and the initial embodied energy per unit area. The wide variability observed in different studies can be attributed to the use of different databases, inventories, methods, and scopes employed when determining the initial embodied energy. Achieving consistency in study outcomes demands the adoption of a shared boundary and standardized embodied energy value. However, practical implementation poses challenges due to the substantial material diversity inherent in various construction projects. Buildings draw materials from diverse sources, spanning both local and international origins. Furthermore, the manufacturing processes for identical products can diverge significantly based on geographical context. Consequently, deriving a universal embodied energy value for the same material, produced across distinct locations, risks oversimplification in the face of intricate contextual nuances.

This underscores the inherent unpredictability and breadth of variations observed in studies. It accentuates the call for standardized methodologies in assessing embodied energy within construction—an endeavor rife with practical complexities, yet ongoing efforts strive for advancements in this realm.

Table 4: Initial Embodied Energy per unit area of existing studies in Indian scenario

S.No.	Number of floors	Structural System/ Specifications	$EE_{initital}$ (MJ/m^2)	Climate	Source
1	1	Load bearing	4550.00	-	[5]
2	2	Load bearing system with alternate or low energy materials	1610.00	-	[6]
3	2	Load bearing system with conventional materials	2920.00	-	[6]
4	2	Load bearing system	3950.00	-	[5]
5	2	Load bearing system with alternate materials	4700.00	Warm-Humid	[7]
6	2	Load bearing system with conventional materials	5600.00	Warm-Humid	[7]
7	4	Reinforced concrete frame system	3700.00	-	[5]
8	4	Reinforced concrete frame system	7358.00		[8]

9	7	Reinforced concrete frame system	10800.00	Warm-Humid	[9]
10	8	Reinforced concrete frame system	4210 .00	-	[6]
	8	Reinforced concrete frame system	4250.00	Moderate	[2]
11	River-View Apartments (S+10)	Reinforced concrete frame system	11138.6	Composite	
12	14	Reinforced concrete frame system	3472.22	Warm-Humid	[10]
13	34	Reinforced concrete frame system	10510.00	Moderate	[2]

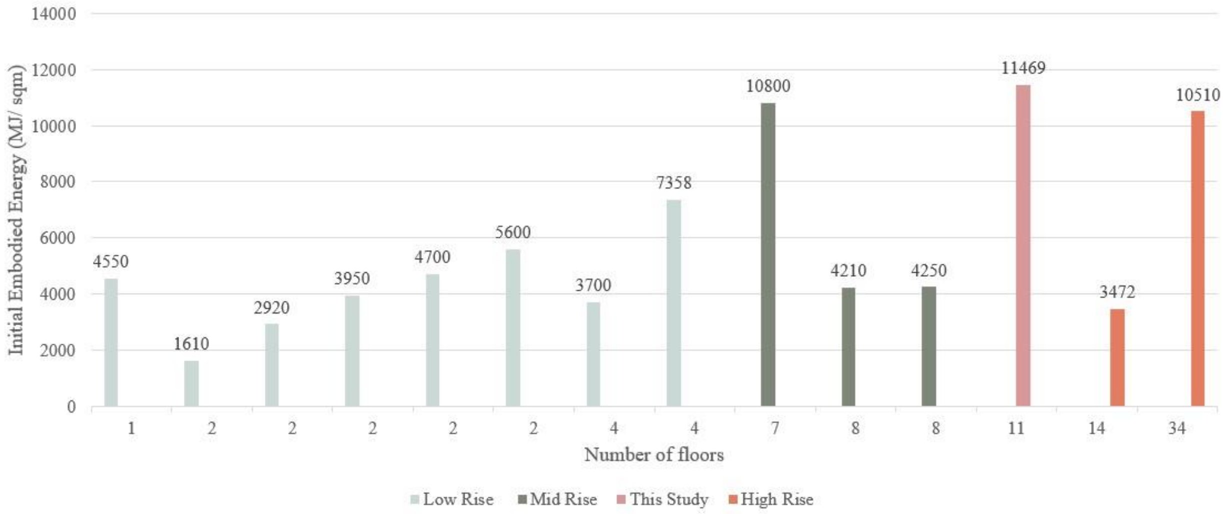

Figure 5: Initial Embodied Energy per unit area of existing studies in Indian scenario.

Recurrent Embodied Energy Calculation ($EE_{recurrent}$)

The $EE_{recurrent}$ is determined by the embodied energy associated with the maintenance work carried out on similar buildings within the campus that have been constructed in the past. Specifically, three apartment buildings – HillView Apartment, Canal-View Apartment, and Shivalik Apartment- are selected for this analysis. These buildings share similarities with the case study building in terms of resident type, floor area, and maintenance practices. Detailed specifications of these buildings can be found in Table 5.

Table 5: Specifications of buildings considered for recurrent embodied calculation

S.No.	Building's Name	Year of Construction	Built up area per block (m^2)	Number of floors	Floor area of a typical residential unit (m^2)
1	Hill View Apartment	2005	15192.50	Still + 7	181.12
2	Shivalik Apartment	2012	12126.75	Stilt + 6	163.08
3	Canal View Apartment	2014	12126.75	Stilt + 6	163.08
4	River-View Apartment	2022	148500.00	Stilt + 10	200.00

The calculation of $EE_{recurrent}$ incorporates the embodied energy of both scheduled and unscheduled maintenance works. Scheduled maintenance activities, such as internal painting, external painting, and varnish work, are performed at regular intervals. On the other hand, unscheduled maintenance works encompass civil work carried out based on specific requirements. By averaging the embodied energy values of the maintenance work performed on these similar buildings, the recurrent embodied energy for the case study building is determined. The results, as presented in Table 6, indicate an annual $EE_{recurrent}$ per unit area of approximately 3.27MJ. It is noteworthy that the $EE_{recurrent}$ accounts for only 1.40% of the $EE_{initial}$ over the building's lifetime.

Table 6: Annual Recurrent Embodied Energy consumed per unit area

S.No.	Building's Name	Type of maintenance work	$EE_{recurrent}$ (MJ/m2/year)		Average $EE_{recurrent}$ for the case study building (MJ/m^2/year)
1	Hill View Apartment	Painting Work	1.97	3.29	3.27
		Civil work and maintenance work	0.87		
		Tiling work	0.45		
2	Shivalik Apartment	Painting Work	1.97	2.73	
		Tiling work	0.76		
3	Canal View Apartment	Painting Work	2.06	3.77	
		Tiling work	1.71		

Comparing the findings with existing studies [4], it is important to note that the range of recurrent embodied energy reported varies widely, spanning from 0.6 to 294.3 MJ/m^2/year. In this context, the $EE_{recurrent}$ for the case study building falls on the lower end of the spectrum, showcasing relatively efficient maintenance practices and lower embodied energy requirements. This observation highlights the significance of appropriate maintenance strategies and their potential to minimize the recurrent embodied energy, contributing to the overall energy efficiency and sustainability of the building.

Comparison of embodied energy with varying building envelope using alternative building material

In order to explore the impact of different wall materials on the embodied energy of the building, the study considers a set of nine alternative infill wall materials. Given the potential for a considerable shift in a building's operational energy due to changes in infill wall materials, the study delves into the extent to which such adjustments impact embodied energy. These 9 materials endorsed by NBCC [11] are thoughtfully curated for their lower embodied energy values, making them viable options for building construction in the Indian context. For determining the Life Cycle Embodied Energy with alternate infill material, $EE_{initial}$ is derived for each material, followed by the determination of $EE_{recurrent}$. $EE_{recurrent}$ for the alternate materials is determined considering recurrent embodied energy at 1.4% of the initial embodied energy (established for the reference building). Table 7 provides an overview of the life cycle embodied energy for the building envelope using the selected set of alternative materials, as well as the life cycle embodied energy for the case study building.

Table 7: Life cycle Embodied Energy consumed per unit area for different building envelopes

S.No.	Alternate Material	$EE_{initial}$ (MJ/m^2)	$EE_{recurrent}$ (MJ/m^2)	Life cycle Embodied Energy (MJ/m^2)	Savings in life cycle Embodied Energy compared to the real time building (MJ/m^2)
1	Machine molded modular clay bricks, designation 7.5	11363.60	159.09	11522.69	107.31
2	Machine molded non-modular clay bricks, designation 12.5	11199.78	156.80	11356.58	273.42
3	Machine molded modular clay bricks, designation 12.5	11148.59	156.08	11304.67	325.33
4	Hollow concrete block	11765.45	164.72	11930.17	-300.17
5	Sand lime bricks	11036.82	154.52	11191.34	438.66
6	Clay Fly Ash Bricks	11024.88	154.35	11179.23	450.77
7	Solid concrete block	11714.26	164.00	11878.26	-248.26
8	Fly Ash lime bricks	10959.18	153.43	11112.61	517.39
9	Aerated Autoclave Concrete Block	11808.11	165.31	11973.42	-343.42
10	Brick and AAC block (Case Study Building)	11469.43	160.57	11630.00	-

By evaluating the embodied energy associated with these different wall materials, the study aims to quantify the potential energy savings that can be achieved by making informed choices regarding the building envelope. Comparing the life cycle embodied energy of the case study building with the alternative wall materials; the result shed light on the energy efficiency benefits that can be achieved by opting for lower embodied energy materials. The findings in Table 7 highlight the variations in embodied energy values across the different building envelope options, allowing for a comprehensive understanding of the potential energy savings achievable through the material selection.

Conclusion

In conclusion, the life cycle embodied for the G+10 real-time building is determined to be 11630MJ/m^2, comprising approximately 98.6% initial embodied energy and 1.4% recurrent embodied energy. The analysis reveals that the initial embodied energy is higher compared to existing studies, while the recurrent embodied energy is relatively lower. The research also emphasizes the wide variation in embodied energy found across different studies, which can be attributed to the absence of a globally accepted standard method or determination along with different system boundaries and embodied energy values considered while determining the embodied energy.

By examining nine different building envelopes based on their infill wall materials, the study demonstrates the significant impact of the building envelope on embodied energy. Among the investigated envelopes, the use of fly ash lime bricks is found to be the most favourable, resulting in a minimum life cycle embodied energy with a savings of approximately 517.39MJ/m^2 (equivalent to 4.45% of the total life cycle embodied energy of the actual building). Conversely, the building envelope utilizing aerated autoclave concrete blocks is identified as the least efficient, contributing an additional 343.42 MJ of embodied energy per unit area (representing an extra 2.95% of the total cycle embodied energy).

These findings underscore the importance of carefully selecting building envelope materials to achieve significant energy savings. It is crucial to note that changes in embodied energy through the building envelope will inevitably impact the operational energy consumption of the building. Therefore, a comprehensive approach is necessary to optimize life cycle energy and reduce embodied energy simultaneously in order to achieve sustainable building practices.

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Decarbonizing India's Residential Building Sector: Insights and Pathways from a System Dynamics Model

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Highlights

- Strategic pathways for sustainable development in India's residential sector.
- Study focuses on reducing carbon impact, which is crucial for achieving the net-zero target.
- Practical implications for energy-efficient interventions, aiding informed decision-making.
- Sectoral connections and resource considerations emphasized for effective net-zero transition.
- Incorporating thermal comfort enhances the potential for significant operational energy savings.

Abstract

This study analyzed potential low-carbon pathways to achieve net-zero residential buildings in India. With the building sector contributing to 33% of global energy-related CO_2 emissions, decarbonizing it is crucial for a net-zero economy. The study used a system dynamics model—Sustainable Alternative Future for India—to capture sectoral interlinkages and explore the implications of meeting India's development goals related to energy, resources, materials, and emissions. Three scenarios were developed, constituting interventions from the building, power, and material industry sectors. The business-as-usual scenario assumes that existing policies will persist, whereas the other two decarbonization scenarios consider different levels of realistic interventions, such as electrification and behavioural shifts. The study discusses the residential cooling demand and transition cost to high-efficiency appliances. Furthermore, it highlights the importance of considering sectoral interlinkages and resource constraints in achieving net-zero energy residential buildings.

Keywords: Residential Sector, Greenhouse Gas Emissions, System Dynamics, Operational Energy, Embodied Energy

Introduction

India's building sector

India's building sector is growing rapidly, contributing to approximately 24% [1] of the nation's greenhouse gas (GHG) emissions. According to the Bureau of Energy Efficiency, the building sector is solely responsible for 30% [2] of India's energy consumption, with the residential segment accounting for 25% of total energy demands [3]. A report by the National Institute of Urban Affairs and Rocky Mountain Institute (RMI) on India's building sector—"From the Ground Up: A whole-system approach to decarbonizing India's buildings sector"—states that most of the building stock that is to exist in 2050 has not been built [4], warranting a considerable increase in emissions and energy consumption in the coming years. Since the majority of the country's building stock is yet to be built, it presents a unique opportunity for designing sustainable decarbonization pathways for the sector and to adhere to the Sustainable Development Goals (SDGs), such as SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action).

India is a developing country with challenges in several areas, such as housing, education, and healthcare. Amongst these, challenges related to the two core areas of housing and thermal comfort are addressed by national policies. The Pradhan Mantri Awas Yojana Scheme (PMAY) operationalizes affordable housing for all by 2024 [5]. Moreover, the Indian Cooling Action Plan (ICAP), released in March 2019 by the Ministry of Environment, Forest and Climate Change (MoEFCC), addresses thermal discomfort due to increasing heatwaves and rising temperatures and highlights the importance of access to sustainable cooling. The plan has incorporated cooling demands from different sectors and established actions to reduce cooling requirements by promoting energy efficiency and stressing passive cooling through the Energy Conservation Building Code (ECBC) [6]. Some of the targets set to be achieved by 2037–38 are to reduce cooling demand by 25–30% and cooling energy requirements by 25–40% [6].

This paper aims to present different decarbonization pathways of India's building sector to assess the impact on energy consumption, GHG emissions, and resource implications. The study draws valuable perspectives from a system dynamics model—Sustainable Alternative Futures for India (SAFARI), developed by the Centre for Study of Science, Technology and Policy (CSTEP) [7]. The SAFARI's housing sector (residential) module was used to develop three realistic scenarios, considering India's development objectives, resource constraints, and climate targets. The first scenario is a business-asusual (BAU) scenario, the second is based on moderate-level technology-based interventions on buildings and interlinked sectors, and the third includes more stringent interventions than the second one. These scenarios represent a balanced approach between India's climate targets and development goals.

Several studies have attempted to model decarbonization pathways for India's building sector, with the most significant study being based on the high-efficiency building model of the Central European University [8]. The study explored energy demand scenarios, highlighting the significance of high-efficiency buildings. The study findings indicate a possibility of halving global building thermal energy demand by 2060 through ambitious policies, while a lack of support could lead to a 34–83% increase in thermal energy demand. Furthermore, the RMI report integrates solutions and innovative financing mechanisms to transform India's building sector, addressing embodied carbon reduction, energy demand curtailment, and efficient energy utilization [4]. Unlike the previous studies, this study presents a novel perspective—introduced through the lens of a system dynamics model—and offers an alternative approach to model India's building sector.

Modeling logic

In this study, SAFARI was used to model potential decarbonisation pathways for India's building sector till 2100. The model focuses on the demands arising from achieving India's development goals pertaining to different economic sectors. Socio-economic parameters, such as population and gross domestic product (GDP), are also considered. The GDP output is obtained from a macroeconomic computable general equilibrium model that is soft-linked to SAFARI, thereby ensuring macroeconomic consistency. The model works in a bottom-up manner to provide a more comprehensive and nuanced understanding of the interdependencies between sectors and the trade-offs that must be made to balance development objectives with climate action [7].

By using the modeling software Stella Architect, SAFARI estimates sectoral demand in a dynamic and non-linear manner, capturing the synergies and feedback loops that exist between different variables over time. The model explores the implications of meeting development goals on materials, energy, resources, and emissions.

The residential building sector in SAFARI has a housing shortage, new construction, material, appliances, and cooking modules causally connected with each other, along with interlinkages in industry, power, land, and the transport sector, as depicted in the causal loop diagram in Figure 1.

Framework and Assumptions

Housing module

The "Housing for All" development goal was set to meet the housing shortage by 2024 through PMAY Urban and Rural (PMAY-U and PMAY-R). Under PMAY-R and PMAY-U, 2.95 crore [5] and 1.20 crore [9] houses have been sanctioned respectively.

Shortage calculation

The housing module examines the dynamic housing shortage in India, taking into account a timeline till 2100 with the base year as 2011. The housing type for urban areas is divided on the basis of the income group—Economically Weaker Section (EWS), Low Income Group (LIG), Middle Income Group (MIG), and High-Income Group (HIG). The existing housing stock for both urban and rural is classified into various age groups: less than 1, 1–5, 5–10, 10–20, 20–40, 40–50, 50–60, 60–80, and more than 80 years. Furthermore, the structural condition of the existing houses within each age group is considered as good, satisfactory, and bad [10], [11]. For the new stock projected by the model, the age groups are 0–30 and 30–50 years, which are structurally considered as good.

The following are the factors considered for calculating the housing shortage:

1. ***Obsolescence/Dilapidation***: As houses pass through age cycles, they become dilapidated and contribute to a housing shortage. In this model, the shortage caused by aging housing stock consists of the following houses:
    - All those houses that are more than 80 years old and houses between 40 to 80 years old that are structurally in bad condition from the housing stock of 2011 are considered as obsolete.
    - Newly constructed houses will become part of the aging housing stock once they reach the age of 50 years.
2. ***Congestion factor*** indicates the percentage of households with no separate rooms for couples. According to the 2011 population census data, the estimated congestion factor is 18.42% in urban (EWS/LIG) and 6.5% in rural areas [11].
3. ***Homelessness*** is estimated to be around 0.53 million in urban and 0 in rural areas [11].
4. ***Others***:

Percentage of housing stock reconstructed annually due to natural disasters. Voluntary reconstruction by MIG/HIG households.

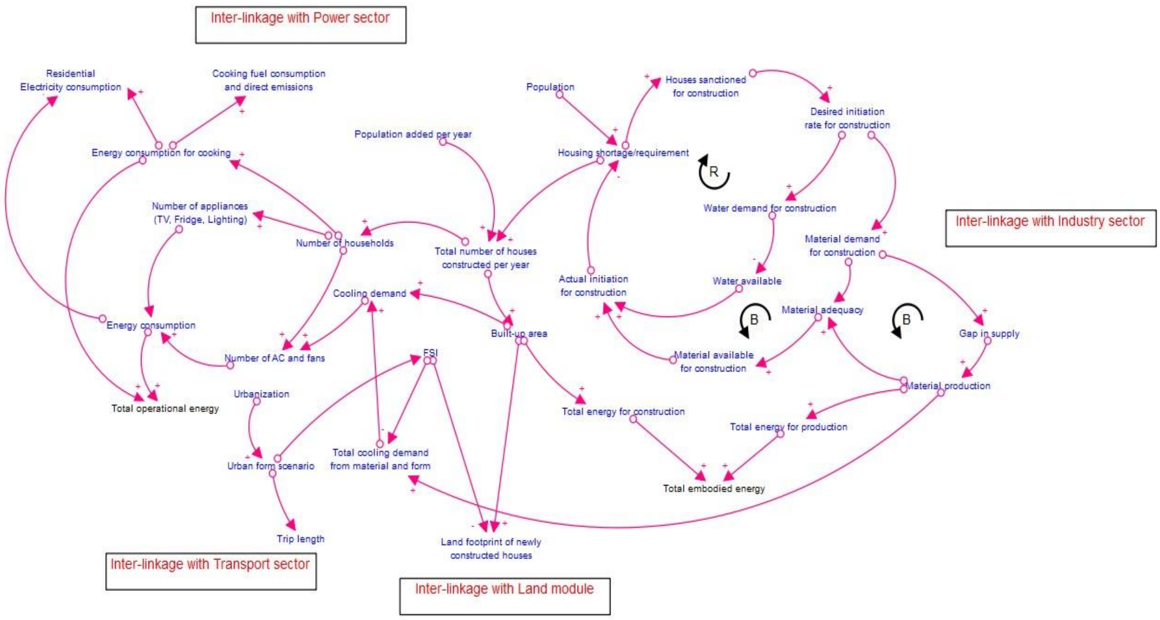

Figure 1: Causal loop diagram for the residential building sector

Shortage filling

The sanction rate to meet the housing shortage is a user input function that acts as a policy lever. The sanction rates are based on four different scenarios, namely, rent sanction rate based on the PMAY scheme, user input sanction rate, and SDG 2030 sanction rate.

Built-up area

The total built-up area is calculated on the basis of the existing housing stock, the total houses added from shortage filling and multiplied by the average built-up area for each housing category. The built-up area considered for each housing type is listed in Table 1.

Table 1: Built-up area assumption

Housing category	Built-up area per house (m^2)		Remarks
	2011	2100	
Urban (EWS–LIG) [12]	30	100	Linearly interpolated for intermediate years
Urban (MIG–HIG) [13]	100	180	
Rural	60 across all years		

Materials

Demand calculation

The SAFARI model takes into consideration the demands for cement, steel, sand, aggregate, and water. In addition to accounting for conventional materials, such as burnt clay bricks (BCBs) and solid cement concrete (CC) blocks, SAFARI accounts for alternative construction materials, such as hollow CC blocks, fly ash blocks, fly ash–lime–gypsum blocks (FaLG), autoclaved aerated concrete blocks (AAC), and stabilized earth blocks (SEBs). The user interface of SAFARI allows one to select from two alternative material scenarios with a predefined proportion of these materials. Users can also try different combinations by changing the proportion of these materials to obtain the desired outcome [14].

Embodied energy estimation

The total required quantity of each material (M_i) is computed as a product of material requirement per square meter floor area (M_a), residential floor area (A), and percentage of floor area under that material (P_i).

$$M_i = M_a \times (P_i \times A) \quad (1)$$

The total embodied energy of all materials is calculated using the following equation:

$$E = \sum_i^n (M_i \times e_i) \quad (2)$$

Where e_i is the embodied energy of each material type per unit.

Cooking

The calculation for cooking energy is based on different types of fuels and their subsequent emissions in all urban and rural households. The following formula is used:

$$\boldsymbol{Number\ of\ households\ (HH)\ using\ a\ fuel\ type} \times ((\boldsymbol{Average\ useful\ cooking\ energy\ required\ per\ HH})/(\boldsymbol{Cooking\ efficiency\ of\ that\ fuel})) \quad (3)$$

The five types of fuels considered in this model are liquid petroleum gas (LPG), electric, pressurized natural gas, biomass, and others (inclusive of coal, kerosene, and biogas).

1. Number of households using a fuel type is calculated by multiplying the cooking percentage share of a fuel type and the total number of households. Historical percentage share of fuel type data is sourced from India Energy Security Scenarios (IESS) [15] and Council on Environment, Energy and Water (CEEW) [16] and calibrated accordingly.
2. Cooking efficiency data for different fuels are adopted from IESS [15].
3. Useful cooking energy is assumed as 7.09722e-7 TWh, as per a CEEW report [17].
4. Emissions from fuel are calculated using the following formula:

$$\boldsymbol{Fuel - wise\ cooking\ energy} \times \boldsymbol{Emission\ factor\ of\ that\ fuel} \quad (4)$$

Appliances

The energy consumption of each appliance is calculated separately for urban and rural households by using the following formula [15]:

$$Total\ number\ of\ appliances \times Hours\ of\ use \times Power\ consumption \times Efficiency\ of\ appliance \quad (5)$$

The appliances considered in the model are TV, fridge, fan, air conditioners, and lighting.

1. Number of appliances is obtained by multiplying the number of households and appliance penetration for urban and rural households, wherein the penetration values are adopted from IESS [15].
2. Hours of use of a particular appliance.
3. Power rating is classified as low, medium, or high on the basis of the energy efficiency of the appliance, which is sourced from IESS [15].
4. Efficiency of appliance has four different scenarios of efficiency shares—A, B, C, and D, with each having a different percentage mix of low, medium, and high efficiency. Of these, A is the lowest efficiency scenario with a maximum number of low-efficiency appliances, whereas D is the most desirable scenario with a maximum number of high-efficiency appliances. The four efficiency trajectories are shown in Table 2.

Table 2: Efficiency trajectories

	Efficiency A			**Efficiency B**			**Efficiency C**			**Efficiency D**		
Year	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
2011	0.98	0.01	0.1	0.98	0.01	0.1	0.9	0.01	0.1	0.98	0.01	0.1
2022	0.79	0.105	0.105	0.79	0.105	0.105	0.79	0.105	0.105	0.79	0.105	0.105
2047	0.79	0.105	0.105	0.45	0.275	0.275	0.35	0.3	0.35	0.03	0.05	0.92
2070	0.79	0.105	0.105	0.45	0.275	0.275	0.2	0.4	0.4	0.02	0.03	0.95

Cost of transition to high-efficiency appliances

The cost of transition to high-efficiency appliances is inclusive of CAPEX and OPEX. The model has four different efficiency trajectories: A, B, C, and D. These signify different percentage shares of low-, medium-, and high-efficiency appliances, wherein trajectory A has a large number of low-efficiency appliances and D has a maximum of high-efficiency appliances. The cost is calculated for all four efficiency trajectories of different appliances considering their entire lifecycles. CAPEX costs are estimated using the cost of appliances sourced from IESS. The calculation for OPEX costs is based on average electricity tariff rates for tier 1 cities, tier 2 cities, and rural towns, as sourced from tariff booklets. The difference between the total cost for low-efficiency and high-efficiency trajectories discounted over the modeling timeline gives cost savings.

Cooling demand

Cooling demand is calculated for both urban and rural households by adding cooling demand due to sensible and latent heat. The sensible heat gain is the result of the changing inside and outside temperatures and occurs through building envelopes and roofs, whereas the latent heat gain occurs due to humidity present in the air. The acceptance level of both these heat gains is responsible for maintaining a thermally comfortable environment. The total cooling load is calculated by assuming the setback temperature as 26°.

Sensible heat gain: Cooling demand from building envelopes

This is calculated using the Residential Envelope Heat Transmittance (RETV) formula adopted from Eco-Niwas Samhita (ENS) 2018 [18].

$$RETV = \frac{1}{A_{envelope}} \times \left[\{a \times\times \sum_{i=1}^{n}(A_{oppaque_i} \times U_{non-oppaque_i} \times \omega_i)\} + \{b \times \sum_{i=1}^{n}(A_{oppaque_i} \times U_{non-oppaque_i} \times \omega_i)\} + \{c \times \sum_{i=1}^{n}(A_{oppaque_i} \times SHGC_{eqi} \times \omega_i)\}\right] \quad (6)$$

The variables in the RETV formula carry the same meaning as defined in the ENS code. Four climatic zones—warm and humid, hot and dry, composite, and temperate—are considered, and the RETV calculation is performed by equally dividing the housing land area under the warm and humid zone (50%) and the combined zone of hot and dry and composite zones (50%). As India has a small proportion of temperate area, it is considered negligible in the calculation. Similarly, weighted averages are taken for orientation and latitude factors to provide a nationally relevant estimate. Subsequently, RETV is converted to a cooling load by using linear regression from the energy simulation model [19].

Sensible heat gain: Cooling demand from roofs

Cooling demand from roofs is calculated through linear regression of thermal transmittance due to roofs. Thermal transmittance of a roof is calculated using the following formula sourced from ENS 2018:

$$U_{roof} = \frac{1}{A_{roof}}\left[\sum_{i=1}^{n}(U \times A)\right] \quad (7)$$

The variables carry the same meaning as described in the ENS code. Considering the scale of the study, an aggregate U value based on different materials from all states is derived for rural and urban data sourced from CENSUS 2011 [20]. The average height considered to obtain roof area is 1.25 floors for rural areas [21]. The number of floors for urban areas is dependent on Floor Space Index (FSI) scenarios, which are further segregated into HIG/ MIG and EWS/LIG.

Latent gain

Energy simulations were performed to calculate latent loads for different climatic zones by using the energy simulation model [21]. The latent load per unit built-up area obtained from these simulations was kept the same for urban and rural areas and constant for the modeling time horizon.

Cooling demand estimation

The total space cooling requirement is calculated by adding sensible heat gain and latent heat gain, multiplied by 70% of the total built-up area, to exclude kitchen and washroom spaces. The cooling requirement is converted into cooling electricity demand by using the following equation:

$$Cooling\ electricity\ demand\ (KWh) = (Space\ cooling\ Requirement\ (KWh)) / COPe \quad (8)$$

The equivalent coefficient of performance (COPe) gives the efficiency of the cooling technology used. It is considered as 2.75, with an increase of 2% per annum reaching a maximum of 5 [21].

Interlinkages with Other Sectors

Transport sector

The interlinkage between the transport and building sectors is defined through urban forms, where FSI plays an important role. For urban sprawls, the FSI considered in the model is 0.75, which extends the city boundary limit and increases the trip length, thereby impacting transport sector emissions. For a compact city scenario with an FSI of 8, the city infrastructure tends to densify. This results in shorter trip lengths, leading to fuel and energy savings.

Industry sector

The housing module interacts with the cement and steel segments of the industry module through its resource demand, influencing resource availability. The industry module assesses the available resources and determines the actual construction rate achievable based on this availability. If there is excess demand that surpasses the current production capacity, the industry module incrementally increases cement and steel production to meet the demand.

Land

The total built-up area in the housing module depends on two factors—the number of houses owned per household and the average size of each house (Table 1). The total land needed for residential construction includes the built-up area per unit and effective common space. The net new land required is determined by subtracting the land recycled from dilapidated housing (calculated using SAFARI) from the total land required for construction.

Power sector

Power sector linkages with the housing module are through electricity demand and consumption. Lower emission factor from grid supply tends to reduce operational emissions from the sector. Moreover, higher penetration of renewable sources and nuclear power in the energy mix will generate clean power sources to fuel housing appliances, resulting in reduced emissions.

Scenario Development

The BAU scenario incorporates India's current policies and guidelines, such as PMAY, ICAP, ENS, Minimum Energy Performance Standard, and National Energy Policy. Table 3 lists the combination of policy interventions used to build two decarbonization scenarios DS-A and DS-B, wherein DS-A is a more pessimistic scenario than DS-B. Furthermore, these scenarios are a mix of technological interventions, electrification, and behavioural-based shifts.

Table 3: Scenario assumptions

Sector	Intervention	DS-A	DS-B
Buildings	Electric cooking penetration	50% LPG and 50% electric in urban households; 60% LPG and 40% electric in rural households by 2070	100% electric in urban and rural households by 2070
	Appliance efficiency	Switching from Efficiency B to C	Switching from Efficiency B to D
	Alternative construction material usage	Predominantly AAC and Fly-ash blocks	Predominantly AAC, Fly ash, and SEB blocks
	Urban form	Sprawls with 0.75 FSI	Compact cities with 8 FSI
Interventions in other sectors having interlinkages with the building sector			
Industry	Electricity met by low-carbon grid for the production processes of cement and steel by 2070	100%	100%
Cement	Type of cement production	40% Portland Pozzolana + 40% Portland Slag + 20% Ordinary Portland by 2070	100% Portland Pozzolana
	Fuel share in the cement production process	1/3rd Hydrogen +1/3rd alternative fuel + 1/3rd electric by 2070	50% Hydrogen + 50% electric by 2070
	Cement efficiency target year	2050	2050
	% Electricity intensity reduction due to efficiency	50% by 2050	50% by 2050
Steel	Fuel share in the steel production process	BF-BOF(blast furnace): 40%, hydrogen: 20%, and scrap steel: 40% by 2070	Hydrogen: 50% and scrap steel: 50% by 2070
Power	No new coal power plant to be sanctioned after	2025	2025
	Nuclear power capacity by 2070	15.5 GW	292 GW (high uptake due to policy targets)
Land	Land recovered from the demolition of dilapidated houses	Reclaimed for constructing new houses	

Results and Findings

The annual energy consumption and GHG emissions for the three scenarios are presented in Figures 2 and 3, respectively. Moreover, the space cooling requirement for both urban and rural residential sectors is shown in Figure 4.

BAU scenario: This scenario accounts for policy interventions focused on the development goals of the country and a decent quality of life. In this scenario, high embodied emissions were observed in the building sector because of the high percentage share of conventional materials, such as BCBs. Operational energy includes energy consumed by appliances and cooking within households. Most appliances in this scenario are low efficient, leading to increased energy consumption. In urban and rural households, LPG is the primary cooking fuel used, and the penetration of electric fuel remains low. Moreover, rural households have a large share of biomass fuels. In the power sector, electricity supply is driven by coal. Similarly, production processes for cement and steel plants are driven by coal and blast furnaces, respectively, thereby increasing embodied emissions of the building sector.

DS-A: In this scenario, a reduction in energy consumption by 12% (2.16 EJ) was observed compared with the BAU scenario by 2070. The operational energy was 12% (1.9 EJ) less, and embodied energy was 15% (0.26 EJ) lower than those in the BAU scenario. A reduction in emissions by 16% (0.26 $GtCO_2e$) was observed compared with the BAU scenario by 2070, wherein operational and embodied emissions account for 14% (0.21 $GtCO_2e$) and 34% (0.05 $GtCO_2e$) reductions, respectively. This can be attributed to the moderate electrification level in cooking and industry production processes. Embodied emission reduction is primarily due to the replacement of BCBs with alternative construction materials, such as AAC and Fly ash bricks. Most appliances considered in this scenario have medium efficiency.

DS-B: A reduction of 41% (7.37 EJ) in energy consumption was observed in this scenario compared with the BAU scenario by 2070. Wherein, the reduction in operational energy is 42% (6.74 EJ), and that in embodied energy is 37% (0.63 EJ) compared with the BAU scenario. A total emission reduction of 51% (0.82 $GtCO_2e$) was observed compared with the BAU scenario by 2070. Operational and embodied emission reduction account for 49% (0.72 $GtCO_2e$) and 74% (0.11 $GtCO_2e$), respectively. Operational energy and emissions decrease significantly due to high electrification in cooking and an increased share of highly efficient appliances. Industry production processes are also highly electrified in addition to the high usage of hydrogen fuel and the high percentage of recycling for steel plants, which drive down the embodied energy of cement and steel. Furthermore, the material composition in this scenario comprises of AAC, Fly ash, and SEB bricks.

Net-zero potential: The realistic interventions for both decarbonization scenarios, while similar, are implemented in higher capacities for DS-B than for DS-A. While these interventions can cut back energy consumption and emissions to a certain extent, reaching net zero will involve high dependency on aggressive scenarios for buildings and interlinked sectors. Operational emissions are contributed by the electricity consumption in buildings. Therefore, a push for policy and the implementation of supplyside interventions in the power sector, such as solar rooftop solutions, increased renewable mix in the grid supply, battery storage, and carbon capture, utilization, and storage, will nullify operational emissions from the building sector. Assuming a zero-emission grid by 2070 would reduce the overall emissions by 75%. Embodied emissions of the main building materials can be reduced by incorporating a high percentage share of green-hydrogen-based cement and steel plants. Extensive electrification of the industry has also been a widely discussed lever for decarbonization, which in turn is dependent on the extent of the greening of the grid. Apart from these, more technology advancements to replace energy-intensive materials would reduce embodied emissions, paving the way for a net-zero residential building sector.

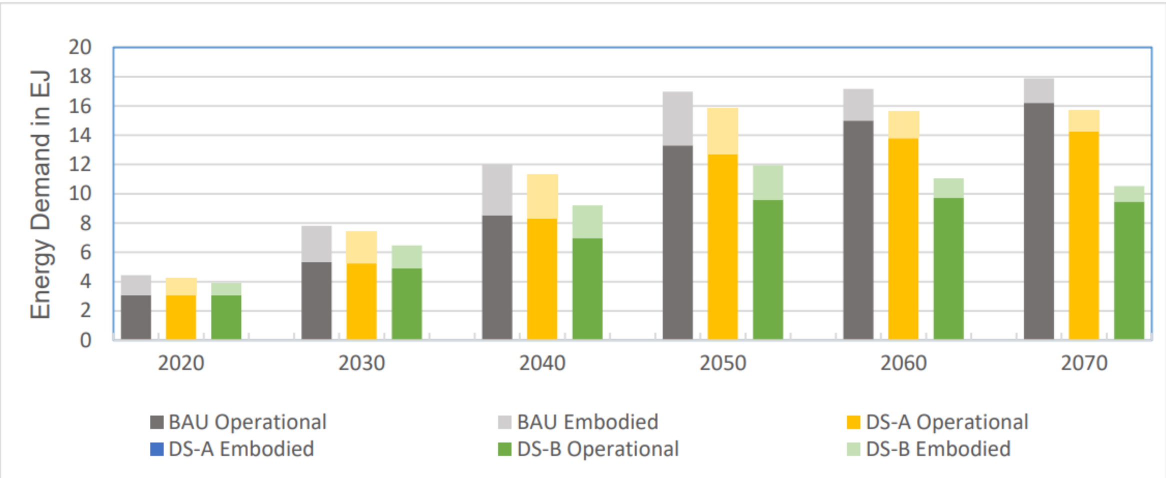

Figure 2: Energy demand from the residential building sector

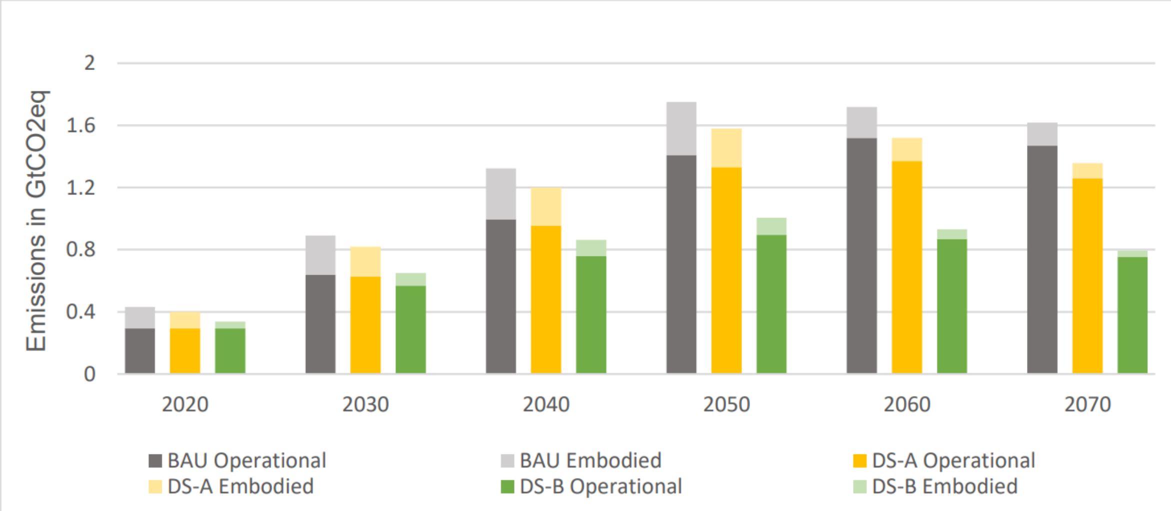

Figure 3: GHG emissions from the residential building sector

Cooling Demand Projections - BAU

The total space cooling requirement for thermally comfortable homes across India was 2388 TWh in 2020, which may reach 4411 TWh in 2070 (Figure 4). The corresponding electricity demand for cooling will increase from 878 TWh in 2020 to approximately 882 TWh in 2070, owing to a 2% per annum increase in COPe value from 2.75 for the base year. The space cooling requirement for urban households will increase from 758 TWh in 2020 to 3630 TWh in 2070, whereas for rural households, it will decrease from 1630 TWh in 2020 to 781 TWh in 2070. This is attributable to the decadal decrease in rural built-up areas and increases in urban built-up areas, owing to the swift urbanization. By considering higher COPe for the base year, this electricity demand would be further reduced. This indicates that switching to high-efficiency appliances will lower the electricity consumption for maintaining a thermally comfortable environment. In 2020, driven by the average number of cooling appliances per household, the annual electricity consumption for cooling was 207 TWh—47% of the total electricity consumption for the residential sector. This means that only 24% of the 'thermal comfort' requirements were met for the aggregate population. However, with rising incomes and urbanization, appliance ownership trends are projected to increase exponentially, which will drive the residential sector's electricity demand in the future. As per our projections based on appliance ownership trends, the electricity demand from cooling appliances will overshoot 'thermal comfort' requirements by 2035 and continue to burgeon to 2.5 times the requirement by 2050. This indicates a huge opportunity for energy savings in the sector, arguably with a shift in regulation to incorporate the 'thermal comfort' aspects. In terms of avoided emissions, it will amount to 640 million tCO_2e in 2050.

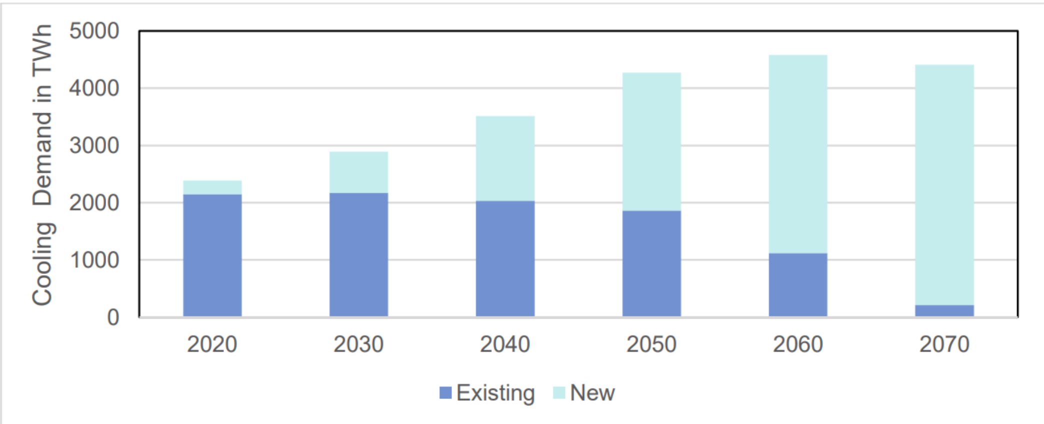

Figure 4: Cooling space requirement for the residential building sector

Cost of transition to high-efficiency appliances

Although high-efficiency appliances have a high purchase cost, they would lower the electricity consumption and maintenance cost, thereby reducing the operating cost. Switching to high-efficiency appliances would result in cost savings in the long run. The SAFARI cost module assesses the cost of transition to highly efficient appliances. Factoring the discount rate, the cumulative cost saving from the transition would be approximately INR 51.68 trillion by 2070. The CAPEX of appliances will reduce over time as the technology matures, resulting in increased cost savings.

Conclusion

In this study, SAFARI was used as a modeling tool because it is based on a system thinking approach, which allows for capturing interlinkages and complexities of dynamic systems. As per the Intergovernmental Panel on Climate Change classification, the building sector is considered as a small category under 'other fuel combustion', which in the Indian context, contributes to less than 8% of emissions directly. The 'emissions value chain' of the building sector was mapped using SAFARI, with the results indicating that buildings are responsible for 11–13% of the country's GHG emissions. The study, therefore, highlights the need for cross-sectoral collaboration to achieve net-zero emissions. Deep decarbonization of the building sector is impossible without aggressive mitigation action in the construction sector, as well as in the manufacturing industries. Policy instruments, such as carbon pricing, can perhaps drive the market toward alternative low-carbon materials and green cement and steel, as mentioned in the previous sections.

Cooling demand has emerged as an important driver to reduce operational emissions because it is expected to increase substantially in the future with rising population, incomes, and lifestyle changes. While only 40% of the 'thermal comfort' demand is being met currently, cooling appliance ownership trends point to a scenario of probable overconsumption and, thus, increased emissions in the future. A policy-based regulation tied with the building codes—with a lens of 'thermal comfort for all' as a development goal to be achieved equitably—can potentially help reduce electricity consumption from the residential sector and, consequently, the emission load on the power sector.

This study only explored cooling demand from building typology and climatic zones and did not consider the effect of urban heat islands (UHIs may be significant in the coming decades) on cooling demand. Urban densification, when coupled with increasing temperatures, will lead to a pronounced UHI effect in cities, thereby causing thermal discomfort. This will, in turn, drive up the use of air conditioners, leading to more GHG emissions and ultimately creating a ripple effect on urban heat. The DS-A and DS-B scenarios are also in line with policy developments that are expected to happen in the coming years. However, the target of net-zero buildings can only be achieved by shifting to more aggressive interventions in the power and industry sectors, which will directly drive down the building sector emissions.

The study accounts for the residential building segment, which has a major contribution to the building sector. However, the commercial building segment also accounts for approximately 9% of India's total electricity demands [22]. Thus, this also needs to be modeled to understand holistically and aim for net-zero pathways for the building sector.

Acknowledgement

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Hybrid Solution for Solar Passive Architecture in the High-Altitude Cold Climate of Leh

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Highlights

- Climate Responsive Hybrid Technology for High Altitude Cold Climate
- Nil-to-very less carbon footprint
- Improvised thermal performance

Abstract

The study aims to establish a research directory of passive techniques in the field of building construction. It would provide local practitioners the necessary skills to improve and innovate building construction technology for Leh's harsh, high-altitude cold climates. The research focuses on understanding the cold highland climate of Ladakh, integrating cultural elements into the built environment, and identifying the latest innovative construction technologies. It will help to determine the existing architectural or structural development issues. The study extends to finding possible solutions to the non-renewable indigenous approach and gathering the new trends in the building environment or modern building techniques. Further, the research proposes adapting modern technology that efficiently works in high-altitude, cold climates. It aims to improve indoor environmental quality in harsh climatic conditions by using local materials and developing hybrid solutions. Passive solar techniques can take advantage of the available energy source.

Keywords: Solar-passive, High-altitude, Hybrid Construction Technique, Thermal comfort, Vernacular Architecture

Introduction

Human civilization has evolved and survived throughout history by integrating with the surrounding environment and relying on preserving nature. Each region developed distinct features that distinguished it from other places over time and via the diverse interaction of evolution and human adaptation to the ambient environment, which is unique [1]. Vernacular architecture has always been a way of building locally in response to a region's cultural, social, and microclimate [2]. It is indigenous to an area and contributes to the community's and environment's long-term viability. With the shifting approach to the built environment, understanding the state of vernacular sustainability is more important than ever [3]. Sustainability is an essential component of vernacular architecture, which has grown over time by using local materials and technologies to create a harmonious relationship between humans and their surroundings.

This paper aims to propose suitable indices for assessing the long-term viability of vernacular architecture in Ladakh, a region in northern India known to be the world's highest and coldest region that humans have continually inhabited. The communities are known for their monasteries and palaces, which testify to the indigenous people's outstanding building ability despite the harsh environment and topography [4]. Aside from its unique and rich cultural history, any study of architecture and settlement studies is fascinated by human survival in difficult weather conditions, with temperatures as low as - 30°C, posing a threat to human survival and other life forms. Ladakh's residents have harnessed the sun's energy through traditional architecture incorporating climate-controlling passive techniques [4]. Apart from using native building materials such as mud bricks, quartzite stones, poplar, grass, timber, etc., and construction techniques, the buildings have a distinctive spatial arrangement to deal with the climatic circumstances.

Most of the building components used in technology come at a cost to the environment or our immediate surroundings. In addition to using a lot of energy and natural resources, construction operations generate many by-products. It indicates that the world's resources are being used up far more quickly than they are being restored. Similarly, producing tons of by-products causes the environment to be further harmed by releasing undesired elements. Numerous problems exist in the modern world, such as resource shortages and pollution (including air, water, land, and noise). Everything here emphasizes how crucial it is to protect the environment and keep it that way for future generations and how essential it is to use sustainable building and architectural practices.

Hence, their study focuses on understanding the cold highland climate and identifying the latest innovative construction and technologies. To create a directory of indigenous architectural technologies and identify existing architectural and structural development issues. This study aims to find a possible solution to the non-renewable indigenous approach. This study aims to find a possible solution to the non-renewable indigenous approach.

Methodology

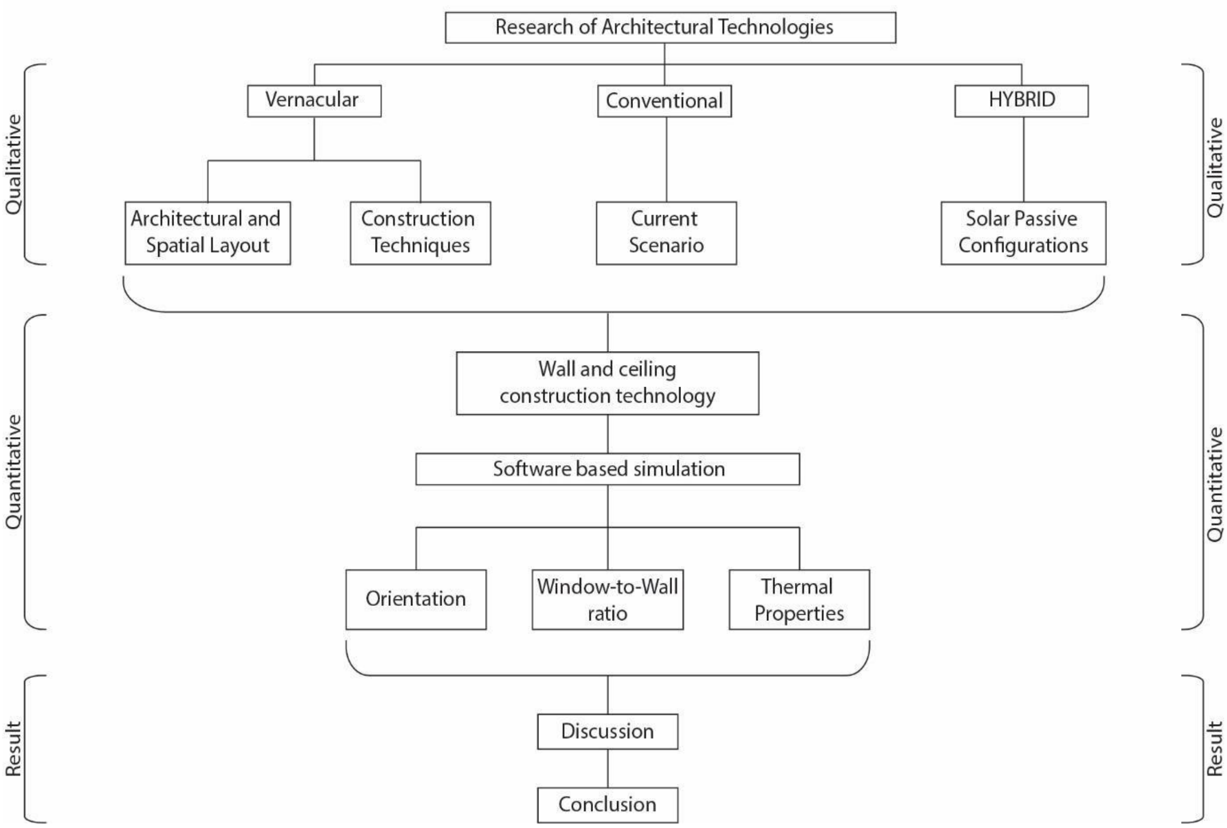


Figure 1: Methodology of the Research

This methodology provides a structured approach to researching solar passive techniques and fusion technologies in high-altitude regions. It involves gathering information from multiple sources, analyzing data, proposing solutions, and validating findings through simulations and real-world tests.

Ladakh: The Study of Context

After the removal of section 370 in 2019, Ladakh became UT. It occupies the largest area of this region, even if it is the least populated one. Ladakh is surrounded on the east by the Tibet Autonomous Region, on the south by the Indian state of Himachal Pradesh, and on the west by Pakistan's Gilgit-Baltistan. It also stretches southward from the Siachen Glacier to the main Great Himalayas.

Ladakh is a high-altitude desert with extremely little vegetation for the most part due to a lack of precipitation. Natural vegetation thrives along waterways and higher elevations, with more snowfall and lower summer temperatures.

Traditional buildings in Ladakh, like those in Tibet, are made of stones, timbers, and mud in various forms, such as sun-dried mud bricks and rammed earth for floor and roof plastering. The structures

reflect the people's way of life, with cow pens on the ground floor and Buddhist altar chambers on the top [5].

Climate of Ladakh

Temperature variation is substantial both diurnally and seasonally, with temperatures ranging from 35°C in the summer to -35°C in the winter. The annual average rainfall in Leh is 100 mm, most falling between May and September, and snowfall in the winter (November to March) is typical. The harsh climatic conditions of India's cold desert region are characterized by dry and cold weather, heavy snowfall, and low temperatures, reaching as low as -30°C in the late evenings. During the summer, the average temperature can get + 30°C in the afternoon [6]. According to a 35-year analysis of meteorological data, the minimum temperature at Leh has been rising by roughly 1 degree Celsius in the winter and 0.5 degrees Celsius in the summer [7]. Rising temperatures and more precipitation have transformed this harsh and dry Himalayan desert into a warmer and wetter environment with shorter winters and pleasant summers over the last few years [8].

Architectural Technologies - Vernacular, Conventional, and Hybrid

Vernacular technologies of the High-Altitude Cold Climate of Leh district

Vernacular architecture is the constructed environment (city, architecture, and interior spaces) created to meet the demands of civilization. It is constructed by the natural environment (geography, terrain, site, climate, local building materials, labor experience, and construction techniques), ensuring that people's physical, economic, social, and cultural needs are met.

Due to transportation constraints, vernacular architecture relied on local materials, which helped to save resources while also giving each region's architecture a distinct personality [9]. Each material had its own physical and aesthetic properties, which governed the architectural technology that was appropriate for it.

Earth and Timber, are the oldest and most often used materials in dry places like Ladakh, necessitating specific technologies due to their shape, size, and durability. The proportions of most sun-dried earth blocks are designed to fit the palm of a human's hand; this was useful for constructing walls and piers, as the thickness of these vertical elements varied depending on their constructional location, height, and structural loads. Builders had to construct new forms by the physical qualities of brick to solve the roofing problem; the trunk of native poplar trees as beams was the creative solution. These innovative forms were both aesthetically and functionally compatible with the surrounding environment and climate. These structural materials received symbolic importance beyond functionality and aesthetics over time, and they formed part of the "culture memory." In terms of aesthetics, the long sunny days in scorching dry locations complemented the brick's particular charm. Through the juxtaposition of shade and shadow, the sun and clear sky highlighted the aesthetics of mud bricks. Even though some of these forms were designed for structural and practical reasons, the aesthetic and creative aspects were not overlooked [1].

Architectural and Spatial Layouts

Typical residences are two-story structures. Larger homes are built around a courtyard, whereas smaller homes are not. The Ground Floor is usually a dwarf floor that is not intended for human use. It serves as a holding area for cattle, as well as a storage facility and a collection point for lavatory waste [4]. (Refer Figures 2 and 3) The top levels have lavatories, whereas the lower stories have a chamber where the excreta are collected and composted. Since the kitchen and sleeping areas are adjacent, the heat generated during cooking contributes to the overall warmth of the interior during the night [4]. In addition, the main hall is carpeted and equipped with a furnace and a smoke stack for warmth in the winter. The upper floor is used for residential purposes and includes a prayer room, store, and toilet, and a relatively big space as a drawing room, kitchen, and bedroom [10]. A typical timber decorative Ladakhi post in the center of the main room serves as a focal point.

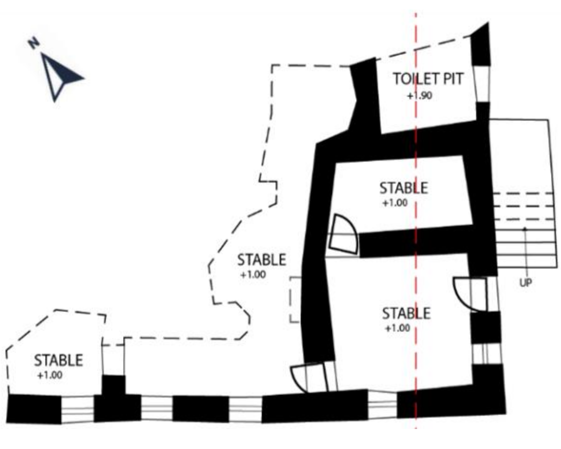


Figure 2: Typical Ground Floor Layout [11]

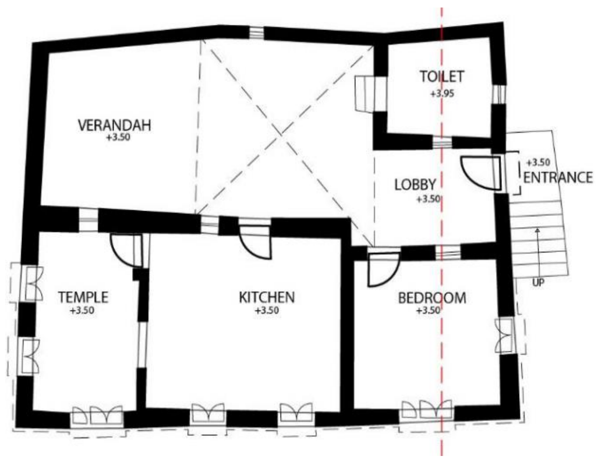


Figure 3: Typical First Floor Layout [11]

The terrace is used for family meetings and drying items. The main living area has a large window facing the sun. Dry materials like grass, straw, and sticks are stored on the roof for insulation. Other rooms typically have less volume, keeping the interior warm and comfortable. Larger rooms tend to cool off quickly, and smaller windows in rooms not exposed to the sun help maintain heat [12] [13] [14] [4].

Construction Techniques and Technology

The fundamental unit of a masonry building is sun-dried earth blocks (Figure 6a). They are used to construct 300 or 450-mm thick walls, usually 300 x 150 x 150 mm. Alluvial material along the banks of the Indus River was used to create these earth bricks. Most earth blocks are manufactured in Shey, which is around 15 kilometers from Leh [15].

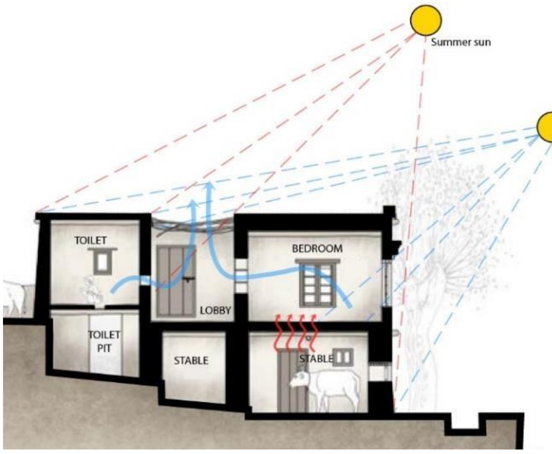


Figure 4: Typical section [11]

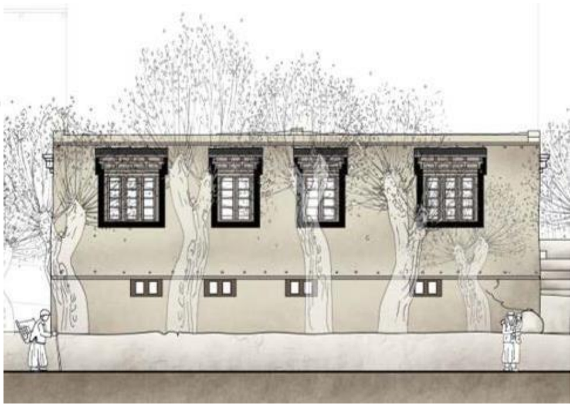


Figure 5: Typical Elevation [11]

Stone blocks are sometimes used in the lower courses of walls for extra strength and water resistance, especially in low-lying areas. Finally, mud plaster is used to complete the wall. Roofs are built with flat spans utilizing the trunks of native poplar trees as beams, spaced 50-60cm apart. The trunks have an average diameter of 15 centimeters and a length of 3 to 4 meters [15]. Poplar willows spread in the other direction are used to cover these timbers. Willows usually have a thickness of 20 to 30 mm. Over the layer of willows, a 15 to 20-cm layer of dried grass, hay, etc., is laid and finished with clayey mud plaster.

Figure 6 (a): Traditional Façade (b) Sun-dried Earth Block (c) Traditional ceiling [23]

The bottom story on the ground has mud floors, while the upper level has timber floors. Along with outfitting rugs, timber flooring provides improved thermal comfort [16]. Timber from Kashmir is used for the doors and windows. The lintels of the doors and windows are ornately corbelled elements. The plaster band, which is commonly red or black in color, articulates the sills and jambs. The distinctive features of Ladakhi architecture are the timber lintels and plaster bands. Their growth, however, is not solely for symbolic or aesthetic purposes [17].

Shift from traditional to modern architecture - Conventional building techniques

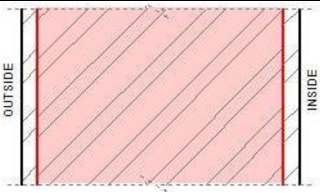
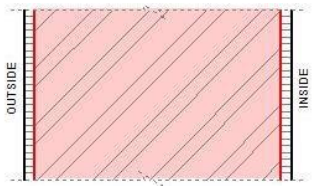
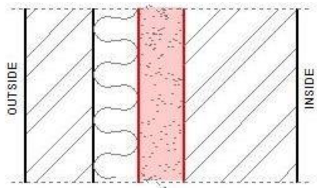
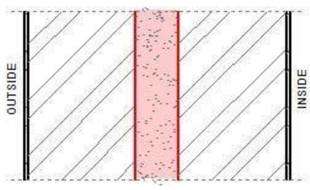
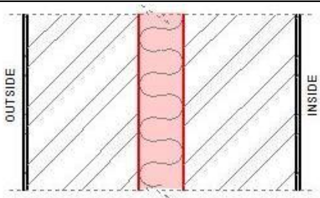
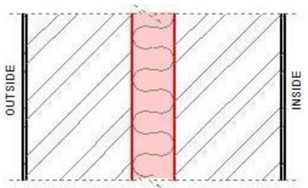
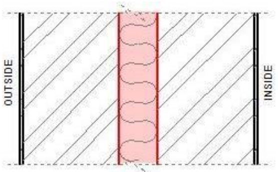
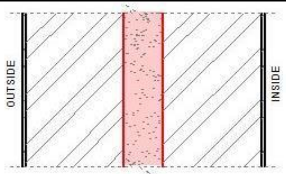
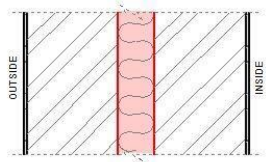
After releasing the movie 3 Idiots, starring Aamir Khan, in 2009, Leh experienced a boom in national tourism. The city's floating population increased multiple folds, and many guest houses started being built to accommodate such a high number of tourists. Due to the absence of a city master plan, the growth was never planned, leading to building encroachment on roads and traffic congestion. Almost everyone had a home in Leh where they stayed during the summer and a home in their nearby village where they spent the off-season. After the major floods of 2010, a misbelief rose among the locals that traditional mud construction is not stronger than concrete.

Identifying the features that attracted people to move towards brick and concrete houses was essential. After studying traditional earth homes and modern brick homes, it was inferred that users found brick construction faster, more durable for rain, cheaper, and easier to maintain. Brick houses were also found to be a status symbol. Users also pointed out that villagers themselves traditionally built an earth home. However, modern-day lifestyles do not allow people to pursue the construction of their homes. In this regard, it is easy to find a contractor to construct a conventional home rather than an earth building. With this perception in mind, the focus of the research was to rethink the technique of designing and executing earth homes to make them more palatable to present-day user needs, both aesthetically and economically [16].

Climate Responsive Hybrid Architecture using Passive Solar techniques

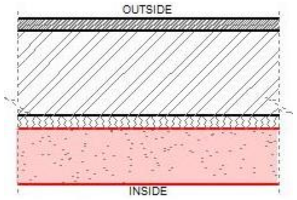
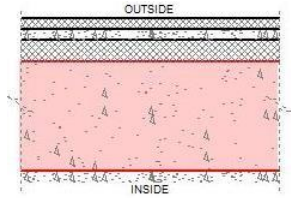
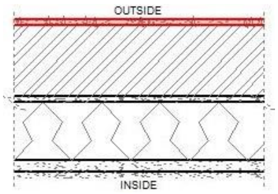
Combining traditional knowledge with modern technologies is essential to arrive at an environmentally friendly solution that uses local resources and harvests indoor thermal comfort through passive means. Climate-responsive hybrid architecture using solar passive techniques could be the answer to the sustainable architecture approach in Ladakh's harsh, arid climatic conditions.

Table 1: Wall Design (The thermal conductivity for each material is referred from AutodeskEcotect, and λ value is cross-checked by the CBRI material list)

1. **Traditional Wall (TW)** 320mm thick	2. **Contemporary Wall (CW)** 250mm thick	**3. Hybrid Wall Option 1 (HWO1)** 600mm thick
		
Mud Plaster (l = 0.01 m, λ = 0.75 W/m.K) + Mud Brick (l = 0.3 m, λ = 0.75 W/m.K) + Mud Plaster (l = 0.01 m, λ = 0.75 W/m.K)	Cement Plaster (l = 0.01 m, λ = 0.9 W/m.K) + Brick (l = 0.23 m, λ = 0.7 W/m.K) + Cement Plaster (l = 0.01 m, λ = 0.9 W/m.K)	Mud Plaster (l = 0.01 m, λ = 0.75 W/m.K) + Mud Brick (l = 0.15 m,) + λ = 0.75 W/m.K) + Wool (l= 0.1m, λ = 0.03 W/m.K)) + Sawdust (l= 0.1m, λ = 0.05 W/m.K) + Mud Brick (l = 0.25 m, λ = 0.75 W/m.K) + Mud Plaster (l = 0.01 m, λ = 0.75 W/m.K)
U-Value = 1.685 W/m²K	**U-Value = 2.038 W/m²K**	**U-Value = 0.163 W/m²K**
4. Hybrid Wall Option 2 (HWO2) 620mm thick	**5. Hybrid Wall Option 3 (HWO3)** - 620mm thick	**6. Hybrid Wall Option 4 (HWO4)** - 620mm thick
		
Mud Plaster (l = 0.01 m, λ = 0.75 W/m.K) + Mud Brick (l = 0.15 m,) + λ = 0.75 W/m.K) + Sawdust (l= 0.1m, λ = 0.05 W/m.K) + Mud Brick (l = 0.25 m, λ = 0.75 W/m.K) + Mud Plaster (l = 0.01 m, λ = 0.75 W/m.K)	Mud Plaster (l = 0.01 m, λ = 0.75 W/m.K) + Mud Brick (l = 0.15 m,) + λ = 0.75 W/m.K) + Wool (l= 0.1m, λ = 0.03 W/m.K)) + Mud Brick (l = 0.25 m, λ = 0.75 W/m.K) + Mud Plaster (l = 0.01 m, λ = 0.75 W/m.K)	Mud Plaster (l = 0.01 m, λ = 0.75 W/m.K) + Mud Brick (l = 0.15 m,) + λ = 0.75 W/m.K) + Straw (l= 0.1m, λ = 0.07 W/m.K) + Mud Brick (l = 0.25 m, λ = 0.75 W/m.K) + Mud Plaster (l = 0.01 m, λ = 0.75 W/m.K)
U-Value = 0.355 W/m²K	**U-Value = 0.241 W/m²K**	**U-Value = 0.445 W/m²K**
7. Hybrid Wall Option 5 (HWO5) - 620mm thick	**8. Hybrid Wall Option 6 (HWO6)** - 620mm thick	**9. Hybrid Wall Option 7 (HWO7)** - 620mm thick
		

Mud Plaster (l = 0.01 m, λ = 0.75 W/m.K) + Rammed Earth (l = 0.25 m,) + λ = 1.8 W/m.K) + Wool (l= 0.1m, λ = 0.03 W/m.K)) + Rammed Earth (l = 0.25 m, λ = 1.8 W/m.K) + Mud Plaster (l = 0.01 m, λ = 0.75 W/m.K)	Mud Plaster (l = 0.01 m, λ = 0.75 W/m.K) + Rammed Earth (l = 0.25 m, λ = 1.8 W/m.K) + Sawdust (l= 0.1m, λ = 0.05 W/m.K)) + Rammed Earth (l = 0.25 m, λ = 1.8 W/m.K) + Mud Plaster (l = 0.01 m, λ = 0.75 W/m.K)	Mud Plaster (l = 0.01 m, λ = 0.75 W/m.K) + Rammed Earth (l = 0.25 m,) + λ = 1.8 W/m.K) + Straw (l= 0.1m, λ = 0.07 W/m.K)) + Rammed Earth (l = 0.25 m, λ = 1.8 W/m.K) + Mud Plaster (l = 0.01 m, λ = 0.75 W/m.K)
U-Value = 0.265 W/m²K	**U-Value = 0.399 W/m²K**	**U-Value = 0.516 W/m²K**

Table 2: Ceiling Design (The thermal conductivity for each material is referred from AutodeskEcotect))

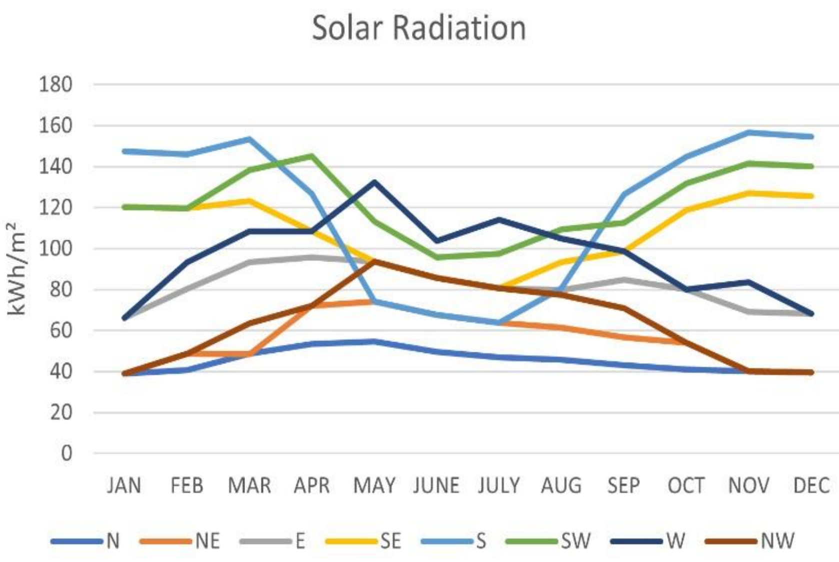
1. Traditional Roof (TR)	**2. Contemporary Roof (CR)**	**3. Hybrid Roof (HR)**
		
Mud Plaster (l = 0.03 m, λ = 0.75 W/m.K) + Rammed Earth (l = 0.25 m,) + λ = 1.8 W/m.K) + Straw (l= 0.3m, λ = 0.07 W/m.K)) + Timber (l = 0.13 m, λ = 1.4 W/m.K)	Tile (l = 0.01 m, λ = 1.2 W/m.K) + Cement motar (l = 0.1 m, λ = 0.14 W/m.K) + RCC Slab (l= 0.1m, λ = 0.8 W/m.K)) + Cement Plaster (l = 0.01 m, λ = 0.9 W/m.K)	Mud Plaster (l = 0.03 m, λ = 0.75 W/m.K) + Mud Brick (l = 0.3 m,) + λ = 1.8 W/m.K) + Wood batten (l= 0.025m, λ = 0.14 W/m.K)) + Insulation (l = 0.25 m, λ = 0.03 W/m.K) + Wood batten (l= 0.025m, λ = 0.14 W/m.K))
U-Value = 0.607 W/m²K	**U-Value = 2.810 W/m²K**	**U-Value = 0.108 W/m²K**

For cold climates, a passive solar building is a building in which the various components are arranged to maximize the collection of solar heat. It is then stored and finally distributed into the space without any expenditure of conventional energy [17]. The two primary types of solar heating systems, active and passive, can be distinguished by how they retain heat after it has been produced from sunshine. Active systems use an additional energy source to pump a liquid or blow air over the absorber. The passive system has absorbers that also store heat but require no other energy source [18]. Instead of being purchased as a finished good, passive solar systems are carefully measured and sized before being planned, produced, and manufactured. This section discusses the use of sunlight for home heating in cold climates and describes several passive solar heating systems.

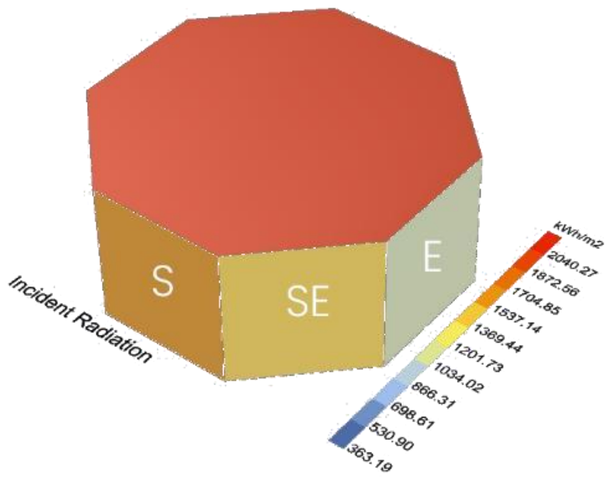
Passive Solar Building Configurations

Layout, Orientation, Shape, and Opening

Knowledge of the sun's path and the intensity of global solar radiation falling on rooves and different walls at different times of the day at a particular location is essential for determining the location and orientation of the building. The building should be located where adjacent buildings or tree cover do not impose shade on it. As explained earlier, the roof and the south-facing wall receive maximum solar radiation in the northern hemisphere during winter. Therefore, the plan of the building should be rectangular, with its length running east-west to allow for maximum opening on the south face. [19]. The surface and roof area of the building should be at a minimum to reduce heat loss and also the location from which snow will have to be removed. For example, double-storied structures are preferable to single-storied ones. The emphasis should be given to minimizing internal volume, i.e., the height between the floor and ceiling should be as little as possible to lessen the heating load. It is also desirable to identify heated (kitchen), unheated (staircase, store, bathrooms), and transition zones (bedrooms) and locate them to maximize thermal comfort and minimize heat loss [20,21,22]. Windows should be on the south-facing walls, and the percentage of opening required for floor area depends on the outside temperature during winter. Windows on the north side should be kept to a minimum.[19]



(a)



(b)

Figure 7: (a) Graph showing solar radiation of 8 sides in a monthly period (b) visual of Octagon with annual solar radiation data (Data and visual from Rhino with Grasshopper and Ladybug)

Traditional, Contemporary, and Hybrid Technologies

Inferences: Due to their lower u values, which equate to lower thermal conductivity, hybrid wall and ceiling designs function more effectively.

Performance analysis – Based on software analysis

Orientation of Building

An octagon shape (3 m in length and 2.4 m in height) with eight radiation sides is modeled in Rhino software. With the help of Grasshopper and Ladybug, solar radiation on different facades is derived for performance analysis based on orientation.

Inferences: One needs maximum radiation in winter to harvest maximum heat and minimize radiation in winter to maintain a comfortable temperature. Figure 7 indicates that the south façade of any building gets the maximum exposure to radiation (Minimum to the north). The south wall gets maximum radiation in winter (Oct, Nov, Dec, Jan, Feb) and minimum radiation in peak months of summer (May, June, July).

Fenestration Design

One of the significant factors affecting solar radiation to promote solar heat gain or loss is the window-to-wall ratio. A matrix for Performance efficiency analysis with variable orientation and window-to-wall ratio with the deciding factors are Direct Radiation and diffuse radiation for performance analysis. Data were taken for the entire year, from 8 AM to 6 PM, for a size 5m x 5 m room. The variable for WWR is 5% (0.7 m x 1 m), 10% (1.3 m x 1 m), 15% (1.8 m x 1 m).

Table 3: Matrix for Energy efficiency analysis with variable orientation and window-to-wall ratio. The deciding factors are Direct, Diffuse, and Total radiation (Simulation done in Ecotect)

Orientation ▼	Window-To-Wall ratio ▼	Direct Radiation (kWh)	Diffuse Radiation (kWh)	Total Radiation (kWh)
North	5%	0.123	111.1	112
	10%	0.2	116.1	116.4
	15%	0.28	119.7	120
North-East	5%	2.6	111.8	114.5
	10%	4.9	116.1	121.1
	15%	6.7	119.7	126.5
East	5%	12.9	111.8	124
	10%	24.1	116.1	140.3
	15%	33.2	119.7	153
South-East	5%	21.4	111.8	133.3
	10%	39.1	116.1	153.3
	15%	54.2	119.7	174
South	5%	23.6	111.8	135.5
	10%	43.3	116.1	159.5
	15%	59.5	119.7	179.3
South-West	5%	17	111.8	128.9
	10%	32.1	116.1	148.3
	15%	44.3	119.7	164
West	5%	10.7	111.8	122.6
	10%	19.6	116.1	135.8
	15%	27.1	119.7	146
North-West	5%	3.4	111.8	115.3
	10%	6.4	116.1	122.6
	15%	8.8	119.7	128.6

Inferences: From the matrix, cross-referenced from various orientations, WWR to Direct, Diffuse, and total radiation infer that building WWR 15% gives the best performance in high altitude climatic conditions. It also suggests that a longer wall oriented towards the south is best regarding Direct and Diffuse Radiation. (Avoid the north side window.)

Thermal Performance

Further, to compare the thermal performance based on the insulation in Vernacular, Conventional, and Hybrid building envelope, modelling and simulation was done in Ecotect software. The deciding factor is the temperature difference between outside and indoors. (Ecotect)

Inferences: Conventional Walls/Roofs are efficient for summer seasons. The kitchen is a good source of heat. Hybrid Wall (HR) and Traditional Roof (TR) or Hybrid Wall (HW) and Hybrid Roof (HR) are performing efficiently.

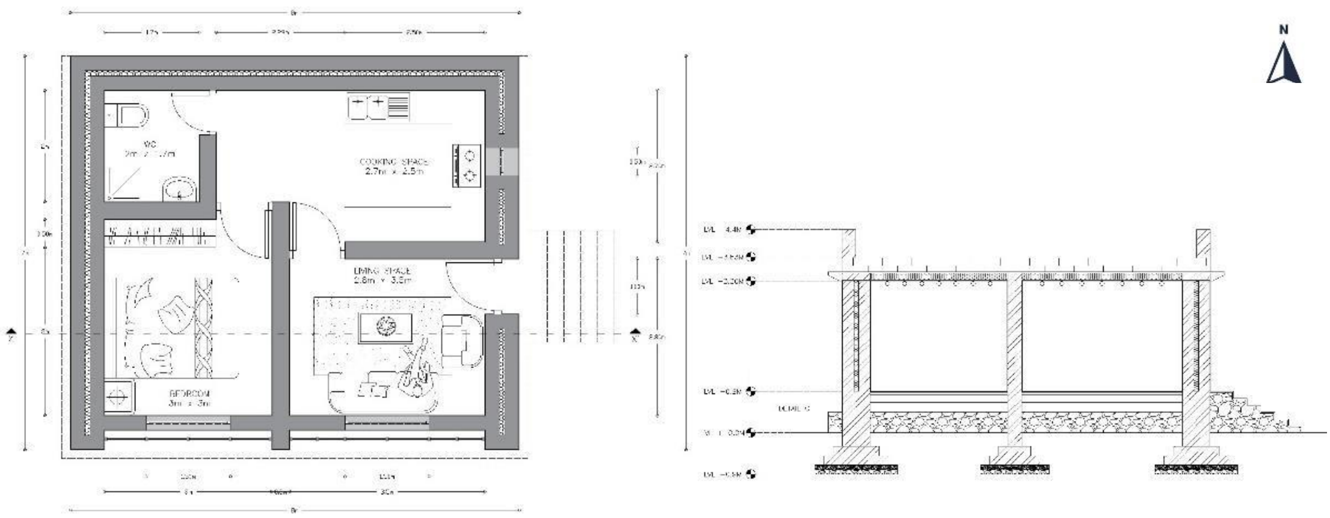


Figure 8: (a) Plan (1 BHK 8m x 7m) (b) Section AA

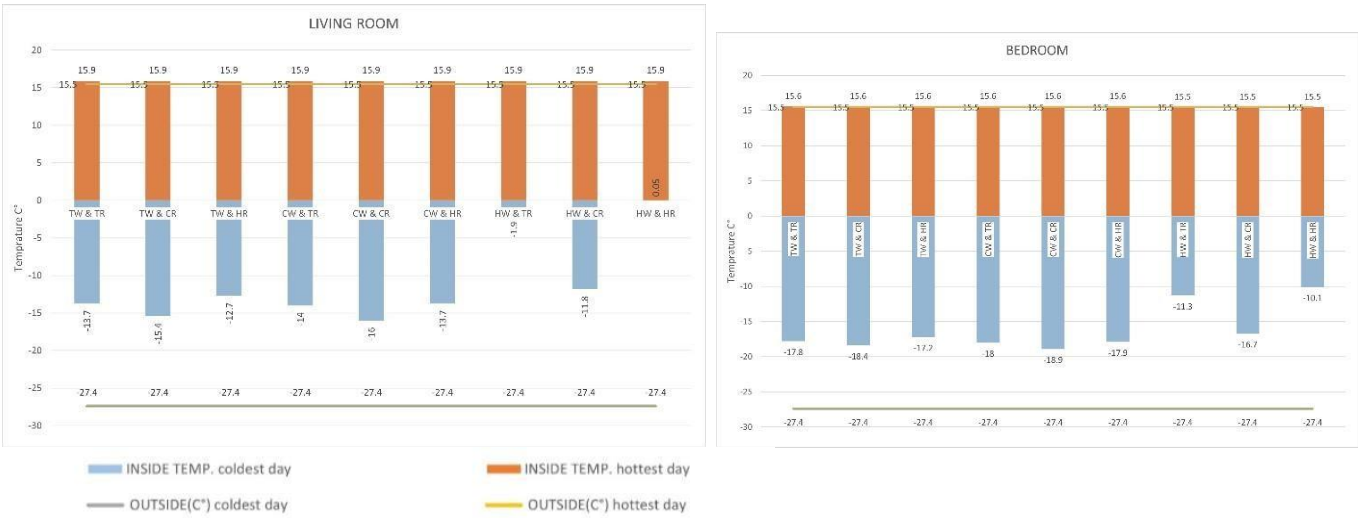


Figure 9: (a) Living room (b) Bedroom

Discussion

- For climate efficient design in high altitude climate., one needs maximum radiation in winter to harvest maximum heat and minimize radiation in winter to maintain a comfortable temperature. The south wall gets maximum radiation in winter (Oct, Nov, Dec, Jan, Feb) and minimum radiation in peak months of summer (May, June, July).
- To get maximum solar radiation in summer, the building with WWR 15% gives the best performance in high altitude climatic conditions. It also suggests that a longer wall oriented towards the south is best regarding Direct and Diffuse Radiation. (Avoid the north side window.)
- Conventional Walls/Roofs are efficient for summer seasons. The kitchen is a good source of heat. Hybrid Wall (HR) and Traditional Roof (TR) or Hybrid Wall (HW) and Hybrid Roof (HR) are performing efficient discussion.

Conclusion

- After completing the studies mentioned above, we learned about the architectural practices used in Ladakh. Based on this knowledge, the contemporary architectural style is inappropriate for that environment due to resource constraints, lack of water, and the growing carbon footprint of moving construction materials. While 80% fewer carbon emissions are produced during construction, the hybrid has 80-90% local materials and vernacular techniques.
- In 2009, comparing costs between conventional construction and passive solar earth homes, TPDS mentor Sonam Wanchuk found that while conventional construction costs Rs.750 per square foot, earth homes only cost Rs.500 [16].
- Passive solar technology is advantageous in areas like Ladakh, where thermal radiation is more abundant and can generate more heat in cold climates.
- After comparing u-values, hybrid walls and ceilings with a lower u-value have less thermal conductivity, which is beneficial for maintaining internal comfort in a climate like Ladakh. In a hybrid wall, the u-value is five times traditional and seven times contemporary. The hybrid ceiling is six times lower than the traditional one and 28 times lower than the modern one.
- Due to the need to maintain heat in the winter, the sun is naturally at a 30-degree angle, allowing the most sunlight and heat to enter the room. In contrast, the sun is at an 85-degree angle in the summer, preventing sunlight from entering the room and resulting in lower summer radiation on the south wall. As opposed to this, 15% WWR will operate effectively in the south, 5% in the east, 5% in the west, and 5% in the north, which is only optional for ventilation after simulating the three analyses.

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Role of Energy Recovery Ventilators on the Indoor Airborne Disease Transmission

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Highlights

- Impact of energy recovery ventilators (ERV) on the probability of infection in a multi-room office building is studied
- ERV slightly increases the probability of infection only in the connected rooms (rooms without infection source)
- Bypassing ERV increases the probability of infection in both source and connected rooms

Abstract

Energy recovery ventilators (ERVs) are commonly used in HVAC systems to reduce energy consumption. ERVs transfer the energy from the exhaust air and use it to precondition the incoming outdoor ventilation air. According to literature evidence of non-biological contaminant transfer, it is suspected that the bioaerosols (with pathogen) may be transferred from exhaust to ventilation air during energy transfer in ERVs. This may lead to disease transmission indoors. Consequently, without any experimental/field evidence, ERVs are often bypassed in the HVAC systems during pandemic operations. To address this research gap, this study numerically analyzes the effect of ERVs on indoor airborne disease transmission in a multi-room office building. It is identified that the ERV slightly increases the infection risk only in the connected rooms (rooms without the source of infection), whereas bypassing ERV increases the infection risk in both source and connected rooms.

Keywords: Energy recovery ventilator, HVAC system, pandemic ventilation, probability of infection

Introduction

Pandemic is not new to the world. A recent study listed that the world faced at least 17 major pandemics before COVID-19. For example, a human plague outbreak by the flea-borne bacteria Yersinia pestis killed around 100 million people in the Roman Empire between 541 and 543 [1]. Hence, developing the infrastructure to curb disease transmission for future pandemics is essential. When applying the traditional hierarchy of hazard control strategies, the engineering control measures are more effective than the common pandemic control measures (namely using masks, handwashing, and social distancing), which mostly fall in the last two categories of the control hierarchy, as shown in Figure 1 [2]. Hence, engineering measures for controlling airborne transmission have been considered to be a high priority since the last pandemic outbreak. It was found that the airborne transmission of infectious diseases, including COVID-19, mostly occurs indoors rather than in outdoor settings [3]. Hence, it is vital to develop measures to control disease transmission in indoor settings.

Engineering control measures are majorly classified into three types, namely filtration, inactivation, and ventilation. Both filtration and inactivation technologies are somewhat specific to the characteristics of pathogens, such as size, concentration, etc. Moreover, some of the inactivation technologies have safety constraints. For example, ultraviolet germicidal radiation is a widely adopted technology in which irradiation and inactivated contaminants might risk human health. Similarly, the bipolar ionization system may release ozone during disinfection, which concerns the occupant's health. However, increasing ventilation to reduce airborne disease transmission is applicable to all types of infectious diseases and doesn't have safety concerns [4].

In the ventilation technique, the outdoor ventilation rate is increased to dilute the concentration of infectious aerosols indoors, thereby minimizing disease transmission. However, increasing the outdoor air supply is not feasible if outdoor climatic conditions are far from human comfort conditions. For example, the average monthly temperature in Saskatoon, Canada, is -9°C in January [5]. Supply of ventilation air in these extreme outdoor conditions will lead to an uncomfortable indoor environment, which can cause thermal stress to the occupants, may be life-threatening, and can also lower human resistance to infection [6]. Hence, it is essential to first condition the outdoor air before supplying it to an indoor environment. This increases the energy consumption of heating, ventilation, and air conditioning (HVAC) systems. The increase depends on the climatic conditions and operational conditions of the building. A study of the climatic conditions of China predicted that the increase in energy consumption of buildings was likely to be as high as 140% [7].

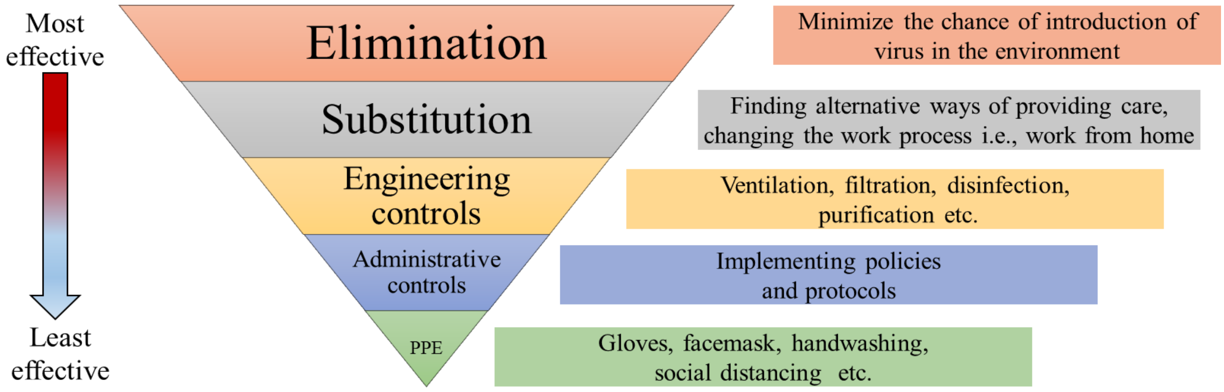


Figure 1: Hierarchy to control the pandemic outbreak (adopted from the hazard control hierarchy in the workplace by the Centers for Disease Control and Prevention, United States)

Energy recovery ventilators (ERVs) are commonly used in HVAC systems to reduce energy consumption and operating costs, especially during pandemic operations when the required ventilation rate is substantially higher than normal operating times. Figure 2 shows the schematic of providing ventilation to a building using the HVAC system with an ERV. As shown, the energy from the exhaust air is used to precondition the incoming outdoor ventilation air. The operation of ERVs may lead to the transfer of bioaerosols (a type of airborne material with microorganisms or biological items that originate from living organisms) from the exhaust to the fresh ventilation air entering the building. Consequently, it may lead to disease transmission in the building. As a result, all the pandemic guidelines [8] are recommended to bypass or operate ERV with constraints to reduce the disease transmission risk. Table 1 lists the recommendations about ERV in pandemic HVAC guidelines [8]. As a result, ERVs are mostly bypassed by HVAC systems during the COVID pandemic operation.

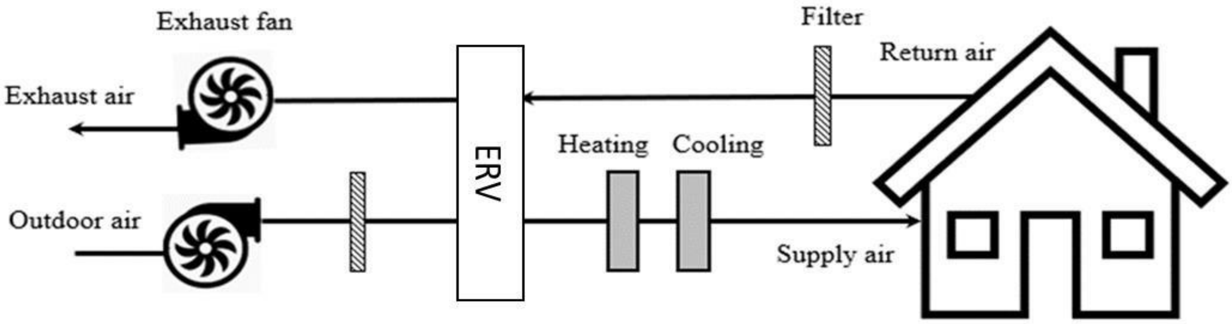


Figure 2: Schematic of the ventilation to a building by the heating, ventilation and air conditioning system with an energy recovery ventilator (ERV)

There is no experimental/field evidence of bio-aerosol transfer in ERV, and thus, the recommendations listed in Table 1 to bypass ERV or operate ERV with constraints are not sustainable. This research gap forms the primary motivation for this research work. When the ERV is bypassed, HVAC systems must operate with a lesser ventilation rate to maintain the designed thermal comfort conditions indoors. Providing a lower ventilation rate indoors may increase the risk of disease transmission. Hence, bypassing ERV has two simultaneous effects: (i) decreases the disease transmission risk by avoiding the bioaerosols transfer across air streams and (ii) increases the disease transmission risk due to the decrease in ventilation rate. The consolidated influence of these effects has not been studied so far. Hence, the present study numerically analyzes the impact of ERV on indoor airborne disease transmission of infectious pathogens.

Table 1: Recommendations about ERV in the pandemic HVAC guidelines [8]

Agency	Recommendation related to ERV
• American Society of Heating, Refrigerating and Air-Conditioning Engineers	Heat recovery devices can be utilized if the leakage percentage is acceptable
• Federation of European Heating, Ventilation and Air Conditioning Associations • European Centre for Disease Prevention and Control • Society of Heating, Air-Conditioning and Sanitary Engineers of Japan	Heat recovery devices can be utilized when leakage is below 5%
• Canadian Committee on Indoor Air Quality	Cross-contamination between outdoor air and exhaust air should be avoided with the application of heat recovery devices
• ASHRAE Singapore Chapter • Indian Society of Heating, Refrigerating and Air Conditioning Engineers	Rotary heat exchangers should not be applied

Method

The study is performed for a building with three medium-sized enclosed office rooms and an HVAC system, as shown in Figure 3. Each room contains two adults, and only one adult in the source room got infected with COVID-19. Each room is considered a standard enclosed office of approximately 42.3 m^2 and a height of 2.7 m. The office schedule is assumed to be 8 hours, and the work is regarded as sedentary. The study assumes that the room air is well mixed due to its circulation, i.e., the concentration of any pollutants or pathogens in the room is the same. In addition, the concentration of pathogens in the rooms and ducts is assumed to be uniform in space. The concentration of pathogen is measured in terms of "quanta". A quantum is defined as the dose of airborne droplet nuclei required to cause infection in 63% of susceptible persons. The estimated infection risk of the pathogen is generally presented as "probability of infection", which depends on the number of quanta inhaled by the susceptible person. The conservation of pathogen concentration in a room can be expressed as [9, 10]:

$$V\frac{dC}{dt} = A_sN_s - A_rN_r - A_dN_d + \oiiint R_{generation}dV + \oiiint R_{decay}dV \quad (1)$$

Where C is the volume-averaged concentration (m^{-3}), V is the volume of the room (m^3), A_jN_j is the flux of the pathogen to or from the room (s, r, d and f denotes the supply air duct, return air duct, door leakage area and floor settling), $R_{generation}$ is considered as a constant generation term that accounts for coughing, sneezing etc. Various environmental factors such as humidity, temperature, and sunlight can inactivate the virus and are represented by the first-order term R_{decay}.

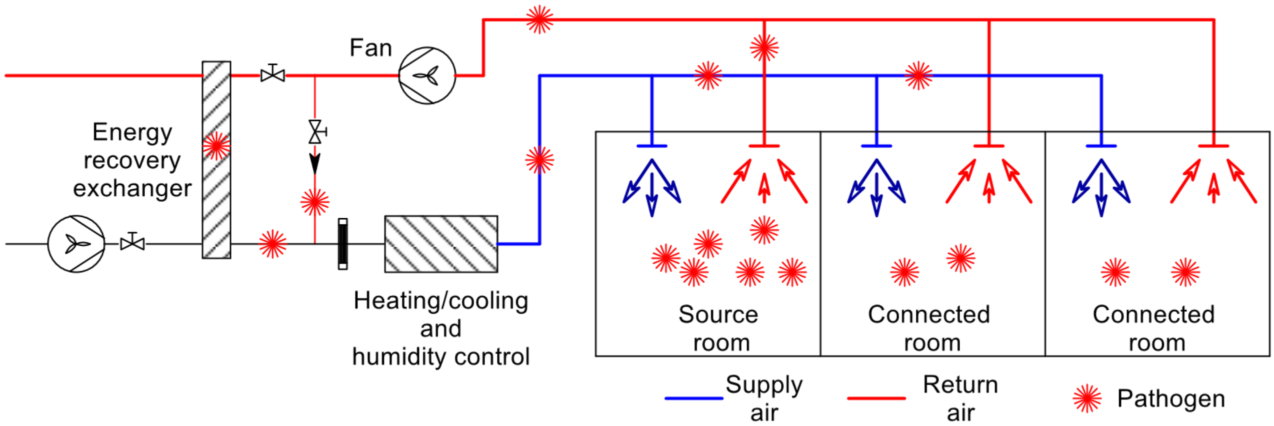


Figure 3: Disease transmission due to the pathogen transfer in ERV in an office building with one source and two connected rooms

Equation (1) can be normalized for the source room (C_{SR}) with respect to the volume of the rooms and considering the order of various terms above gives:

$$\frac{dC_{SR}}{dt} = \left(\left[\frac{\lambda.A\cdot m_{RA}}{m_{SA}}\right]\cdot[C_{SR} + (N\cdot C_{CR})]\right) + \dot{C}_g - \Lambda C_{SR} \quad (2)$$

Where λ is the air change per hour of the room (h^{-1}), which includes the effect of door leakage, m_{RA} and m_{SA} are the recirculation and supply air flow rates normalized to the volume of the room (h^{-1}), N is the number of connected rooms, C_{CR} is the volume averaged virus concentration in the connected rooms, $\dot{C}_g$ is the virus generation rate, which could be evaluated as per equation (3):

$$\dot{C}_g = \frac{q}{V} \quad (3)$$

Where q represents the quantum generation rate (h^{-1}), which is a function of the pathogen species, hazard control effectiveness, etc. q is estimated using a Monte Carlo approach to solve the piecewise volume integral of the virus concentration and is taken as 58 h^{-1} in this study for sedentary office work. A is a constant expressed as:

$$A = \frac{1-\eta_f}{(N+1)} \quad (4)$$

Where η_f is the efficiency of the filter used in the HVAC system. Λ is the effective ventilation rate (h^{-1}), which takes into account the effect of virus inactivation and settling and is written as:

$$\Lambda = \lambda + \frac{v_f}{H} + k_{decay} \quad (5)$$

Where H is the height of the room (m) and k_{decay} is the virus decay rate (0.63 h^{-1}), v_f is the floor settling velocity (ms^{-1}), which is calculated as per Stokes' terminal velocity approximation:

$$v_f = \frac{\rho_d - \rho_f}{18\mu_f} g d^2 \quad (6)$$

ρ_d and ρ_f are the densities of the droplet (1000 kgm^{-3}) and air (1 kgm^{-3}), μ_f is the viscosity of air ($1.8 \cdot 10^5$ Pa s), g is 9.81 ms^{-2} and d is the geometric mean diameter of the virus in size ranges at 0.55 µm (0.3-1 µm), 1.7 µm (1-3 µm) and 5.5 µm (3-10 µm). The distribution of the virus generated in these ranges was observed to be 15%, 25%, and 60%, respectively. The virus distribution in these size ranges was also considered in the settling velocity term.

If ERV is included in the HVAC system, then the rate of change of concentration of pathogen in the source room is given as

$$\frac{dC_{SR}}{dt} = \lambda\left(\frac{(A\cdot[C_{SR}+(N\cdot C_{SR})]).(m_{RA}\cdot EATR)}{m_{SA}}\right) + \dot{C}_g - \Lambda C_{SR} \quad (7)$$

Where EATR is the exhaust air transfer ratio of ERV. Similarly, the concentration of the pathogens in the connected room (C_{CR}) without ERV is given as

$$\frac{dC_{CR}}{dt} = (A\cdot m_{RA}\cdot[C_{SR} + (N\cdot C_{CR})] - C_{SR} \quad (8)$$

With ERV,

$$\frac{dC_{CR}}{dt} = \lambda\left(\frac{(A\cdot[C_{SR}+(N\cdot C_{CR})]).(m_{RA}\cdot EATR)}{m_{SA}}\right) - \Lambda C_{SR} \quad (9)$$

Equations 2, 7, 8 and 9 are solved using the Runge Kutta 4th order method to obtain the concentration of pathogen in the source and connected rooms at different time steps. The probability of infection to an uninfected individual (P) at a particular time step is evaluated based on the equations:

$$P_{SR}(t) = 1 - e^{-C_{SR}\cdot b\cdot t} \quad (10)$$

$$P_{CR}(t) = 1 - e^{-C_{CR}\cdot b\cdot t} \quad (11)$$

Where t is the time step, and b is the breathing rate for an adult executing sedentary office work (0.3 m^{-3}/h).

Results and Discussion

The pathogen transfer possibility through any ERV can be related to its performance characteristics,

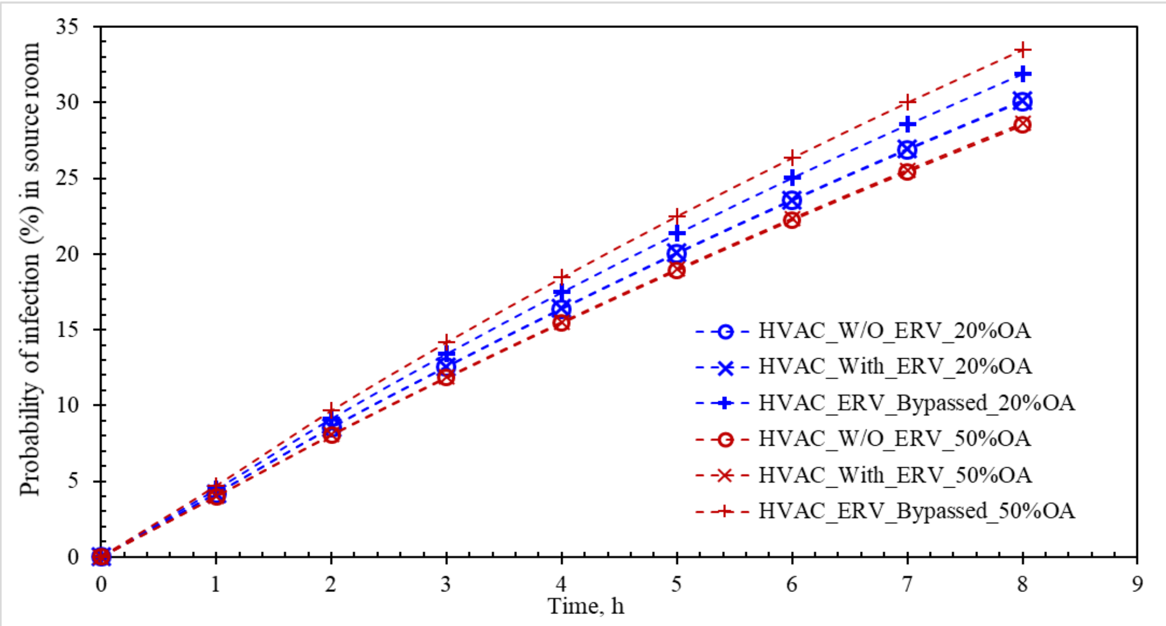
"Effectiveness (ε)" and "Exhaust Air Transfer Ratio (EATR)". According to ASHRAE [11], effectiveness is defined as the ratio of the actual energy transfer to the maximum possible energy transfer across air streams in ERV. Similarly, EATR is the ratio of the concentration increase (of any contaminant) in supply air (including ventilation air) relative to the maximum concentration difference between supply and exhaust air streams. The effectiveness and EATR of ERVs generally vary between 40 to 90% and 0 to 10%, respectively. Hence, an effectiveness of 70% and EATR of 5% is considered for the present study. The thumb rule for the outdoor air (OA) fraction in the supply air to meet the ventilation requirements (prescribed in the standards, e.g., ASHRAE Standard 62.1) generally varies from 20 to 50% (i.e., the total supply air constitutes 20 to 50% outdoor air). Thus, the study also analyses the effect of ERV with the OA fractions of 20 and 50%.

Infection risk due to ERV

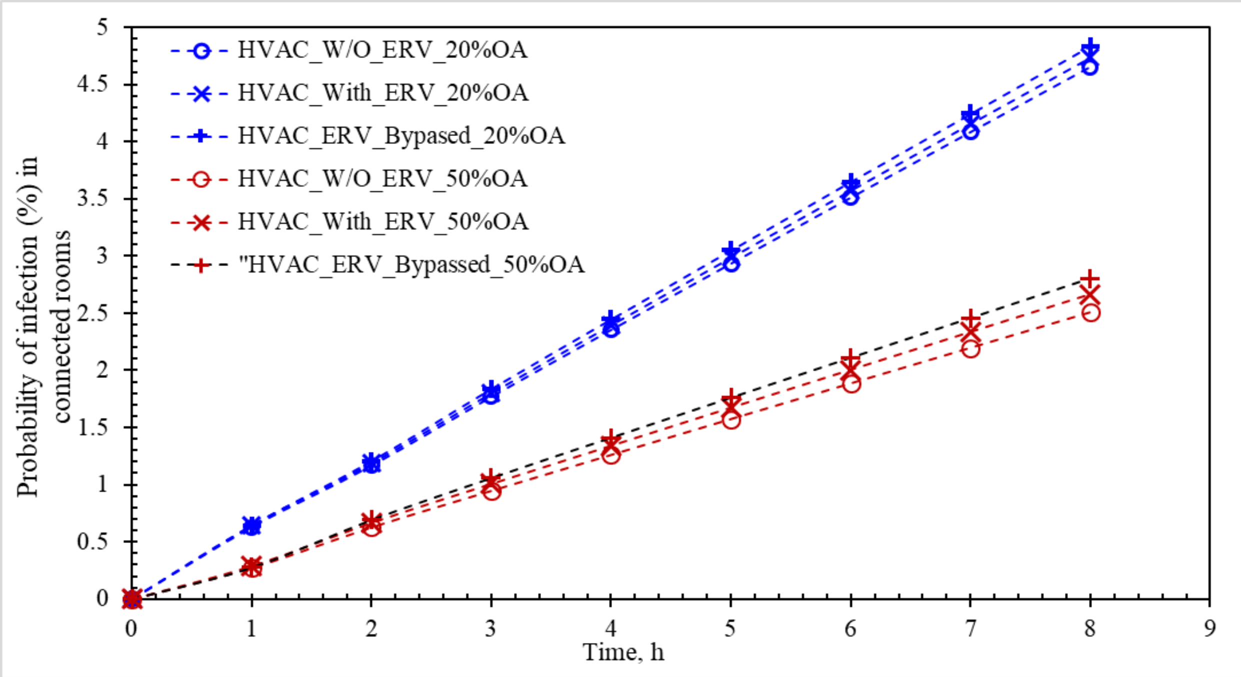
Figure 4 shows the effect of ERV in the HVAC systems on the probability of infection in the source and connected rooms. When the susceptible person is exposed to the infected person for a longer duration, the likelihood of getting infection increases. Hence, the probability of infection increases linearly with the time in the source room, as shown in Figure 4(a). Similar observations are found in the connected rooms (Figure 4(b)), except the probability of infection in the connected rooms is significantly lower than in the source room since there is no infected occupant, i.e., no source of the pathogen. When the HVAC system is operating with ERV, the pathogens from the exhaust air can be recirculated to the rooms through return air and also through ventilation air due to ERV, as shown in Figure 3. Consequently, the pathogen transfer in ERV increases the concentration of the pathogen in the source and connected rooms. However, due to the significantly higher emissions of pathogens from the infected person, the increase is negligible in the source room for both OA conditions. Hence, there is no noticeable effect on the probability of infection due to ERV in the source room, as shown in Figure 4(a). However, since there is no source of infection, ERV slightly increases the probability of infection in the connected rooms. The increase is high when the HVAC system operates with a higher OA fraction. This is because, at the same EATR, the amount of pathogen transferred from the exhaust air to the supply air through ERV is higher for the higher OA fraction. The increase in the probability of infection is 6% in the connected rooms at 50% OA fraction, as shown in Figure 4(b).

Infection risk due to bypassing ERV

When the ERV is bypassed, HVAC systems must operate with a lesser ventilation rate to maintain the designed thermal comfort conditions indoors. The lower the ventilation rate, the higher the probability of infection due to insufficient dilution of pathogens by the fresh outdoor air. Hence, the probability of infection increases in both source and connected rooms. The increase in the probability of infection is higher for 50% OA conditions. This is because bypassing ERV at a higher OA fraction leads to a significant increase in the load of the HVAC system. Consequently, the ventilation rate to the source and connected rooms decreases substantially to achieve the required indoor thermal comfort conditions. Hence, the increase in the probability of infection is significant for a 50% OA fraction when compared to a 20% OA fraction when the ERV is bypassed. As shown in Figure 4(a), the increase in the probability of infection in the source room is 6 and 17% for the OA fraction of 20 and 50%, respectively. Similarly, as shown in Figure 4(b), the corresponding increase in the connected rooms is 4 and 12%. Hence, bypassing ERV is a highly inefficient practice that promotes indoor airborne disease transmission.



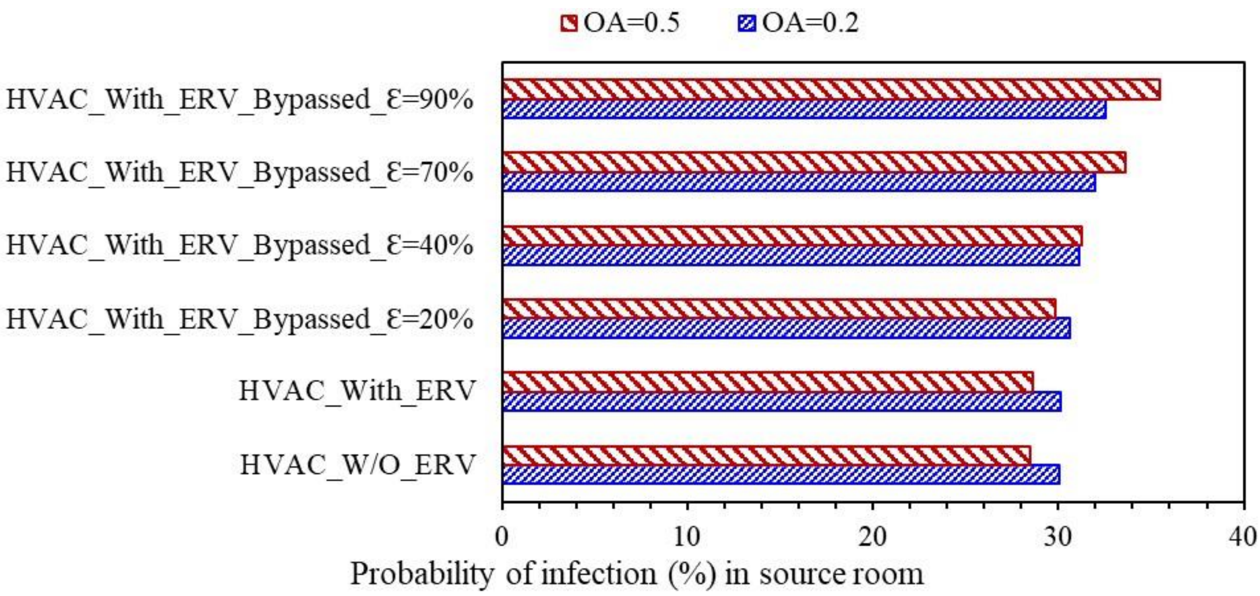
(a)



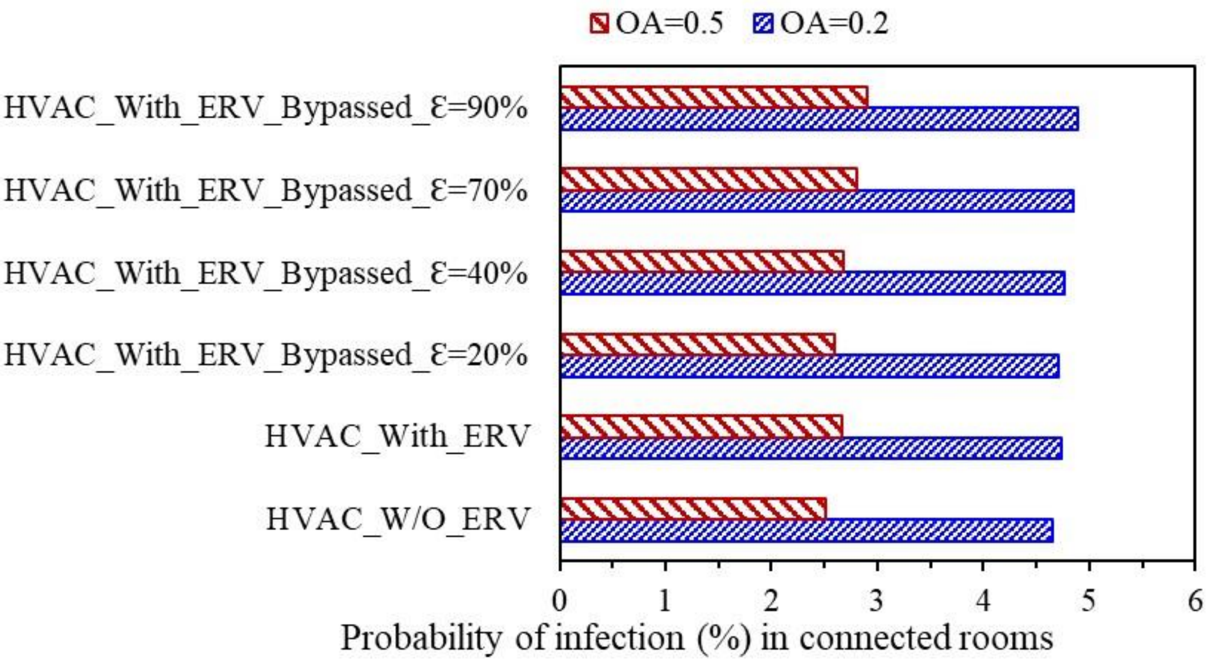
(b)

Figure 4: Effect of ERV of HVAC systems on the probability of infection in (a) source and (b) connected rooms of an office building. An HVAC system is considered with 20% and 50% outdoor air (OA) conditions

The effect of the increase in the probability of infection when bypassing ERV is highly dependent on the reduction in the ventilation rate, as discussed earlier. The reduction, in turn, depends on the effectiveness of ERV. Hence, the present study analyzed the effect of effectiveness on the probability of infection while bypassing ERV, and Figure 5 depicts the corresponding results. As expected, an increase in the effectiveness increases the probability of infection in both source and connected rooms. As shown in Figure 5(a), the increase in the probability of infection in the source room is 8 and 24% for the OA fraction of 20 and 50%, respectively. Similarly, as shown in Figure 5(b), the corresponding increase in the connected rooms is 3 and 9%. It is also inferred from the figure that bypassing ERV with an inferior effectiveness of 20% (which is the least possible condition) increases the probability of infection. Hence, bypassing ERV is a highly inefficient practice in any operating condition.



(a)



(b)

Figure 5: Effect of the effectiveness of ERV on the probability of infection in (a) source and (b) connected rooms of an office building. An HVAC system is considered with 20% and 50% outdoor air (OA) conditions

Conclusion

The effect of ERV on indoor airborne disease transmission is analyzed for a medium-sized office building with one source and two connected rooms. The transmission risk is quantified using the probability of infection. The study considers an ERV with an effectiveness of 70% and EATR of 5% and includes the influence of OA fraction (20 and 50%). It is identified that the ERV slightly increases the probability of infection only in the connected rooms and at a higher OA fraction. The increase in the probability of infection is only 6% at 50% OA fraction. Hence, bypassing or operating ERV with constraints as per the pandemic HVAC guidelines is not necessary for single enclosed space applications like common hospital wards, church prayer halls, etc. Moreover, it cannot be concluded that the slight increase in the probability of infection in connected rooms leads to disease transmission. This is because the metal and/ or chemical coating of ERVs may deactivate the viability of the pathogen. The study also shows that bypassing ERV increases the probability of infection in both source and connected rooms at any operating condition. The increase in the probability of infection in the source room is 6 and 17% for the OA fraction of 20 and 50%, respectively. Similarly, the corresponding increase in the connected rooms is 4 and 12%. Therefore, bypassing ERV, even with inferior effectiveness as per the pandemic HVAC guidelines, is a highly unsustainable practice.

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Nomenclature

EATR	Exhaust Air Transfer Ratio
ERVs	Energy recovery ventilators
HVAC	Heating, ventilation and air conditioning
OA	Outdoor air
Ɛ	Effectiveness

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Developing an Embodied Energy Database for Construction Materials in India

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Highlights

- Framework for developing an Embodied Energy Database.
- Using Pedigree matrix -data scoring method to reduce the uncertainties in the data.
- Integrating crowdsourcing for data collection to help the stakeholders.
- Optimizing environmental impacts and developing policy guidelines.

Abstract

Optimizing operational energy in buildings can increase the significance of embodied energy and associated carbon emissions. Promoting low embodied energy materials and construction processes is crucial for achieving low-carbon development while reducing operational energy. However, accessing reliable embodied energy data for construction materials in India poses a major challenge for conducting Life Cycle Assessments (LCA) to quantify the environmental impact. The proprietary nature of these datasets limits their availability in LCA studies, leading to uncertainties in building LCA results. Thus, this study aims to develop a construction material embodied energy database in India. A uniform data collection framework adapted for the building and construction sector and confidence level measurements for the embodied energy datasets will be used. This database will help reduce uncertainty in LCA studies and support informed decision-making.

Keywords: embodied energy, life cycle assessment, crowdsourcing database, construction materials

Introduction

According to the IEA report, 8% of the global energy-related and process-related CO_2 emissions result from using fossil fuels in the building, 19% from generating electricity, and 6% related to manufacturing building materials [1]. Buildings consume energy during all the lifecycle stages, including construction, use, maintenance, renovation, and demolition. The research conducted by CSIRO reveals that the typical household encompasses approximately 1,000 gigajoules (GJ) of energy embedded in the construction materials used to build it, which is equal to 15 years of normal operational energy use [2]. Embodied emissions encompass the significant environmental impact of various building life cycle stages. Additionally, all activities and processes throughout the supply chain that contribute to building construction also contribute to embodied emissions. These embodied emissions play a crucial role in understanding the overall carbon footprint of a building [3].

India's rapid urbanization and population growth have led to significant demand for residential spaces [4]. However, there is a concerted effort to construct buildings that are less intense on energy consumption and have reduced operational carbon emissions. As most of the residential buildings in India are either Naturally Ventilated or Mixed mode, the operational energy in the residential buildings is comparatively lesser. Additionally, the Government of India has also introduced codes like ENS – Eco Niwas Samhita, and initiatives like Pradhan Mantri Awas Yojana (PMAY) enhance the usage of sustainable materials and locally available materials, which helps to reduce embodied energy and emissions ultimately. There is a growing trend towards using sustainable and low-carbon materials to reduce embodied carbon in residential buildings. Materials like fly ash bricks, autoclaved aerated concrete (AAC) blocks, and bamboo composites are being promoted as alternatives to conventional high-carbon materials like red bricks and concrete. Apart from the material selection, the BEE has also introduced the standards and labelling problem through which the appliances are rated, and the energy savings potential of the appliances is informed [4]. Additionally, passive design strategies that optimize natural lighting and ventilation are being incorporated to reduce the energy demand of residential spaces [5] [6]. On the other hand, the commercial building sector is also undergoing a transition towards more energy-efficient practices and technologies. This includes adopting advanced building management systems, energy-efficient lighting, and HVAC (Heating, Ventilation, and Air Conditioning) systems, and integrating renewable energy sources. The Indian government, along with organizations like the Bureau of Energy Efficiency (BEE), has introduced energy efficiency codes and rating systems for buildings, such as the Energy Conservation Building Code (ECBC) and rating systems like the Indian Green Building Council (IGBC) certification. By implementing and adopting these measures, the operational energy consumption of commercial buildings can be significantly reduced [7] [8]. On the other hand, the operational versus embodied carbon ratio is changing due to efforts to reduce the embodied carbon in construction materials. This involves utilizing low-carbon or carbon-neutral materials, optimizing the design to reduce the required materials, and sourcing materials locally to reduce transportation emissions.

While demand-side measures, such as energy-efficient practices at the building and community scales, have been gaining momentum in improving energy efficiency in the built environment, there is also a pressing need to address supply-side measures for achieving substantial carbon reduction. Additionally, renewable energy continues to grow despite global uncertainties, which take a larger part of the operational energy of the building sector [9]. Building codes, energy regulations, and similar building rating systems primarily prioritize the reduction of energy consumption during building operation and the transition to low-carbon electricity sources, whether generated onsite or obtained from external sources. However, they have not made it a specific requirement to reduce embodied energy due to the inherent challenges of calculating it [10]. Focusing on less carbon-intensive production processes and materials is crucial. The supply-side measures emphasize the importance of considering the entire life cycle of buildings, from material extraction to manufacturing and transportation. Significant carbon emissions can be attributed throughout these stages to the production of building materials, such as cement, steel, and glass, and the energy consumed during manufacturing and transportation [11] [12]. The quantification of carbon emissions throughout the production of building materials and the energy-intensive manufacturing and transportation processes highlights their significant environmental impact. Hence, understanding the embodied energy of construction materials is crucial for assessing their overall carbon footprint and identifying opportunities for sustainable alternatives.

Thus, this study aims to develop a database of embodied energy of construction materials in India. This is achieved through a tool that serves three purposes:

- Generation of embodied energy database through crowdsourcing
- Quantification of the confidence level of the datasets
- Access point of the openly available database

The tool's scope includes a framework for collecting embodied energy data based on the "Fit-for-purpose" approach.

Context – Literature study

The embodied energy or carbon of a building considers the energy and carbon emissions associated with the extraction, processing, manufacturing, transportation, and assembly of building materials, as well as the energy used during construction and the disposal of waste materials. It also considers the potential for recycling or reusing materials and the environmental impact of demolition or removal. It refers to the total energy consumed throughout the life cycle phases of a building [13] [14].

Conducting a Life Cycle Assessment (LCA) study, which involves a systematic analysis of the environmental impacts of a product, process, or system throughout the entire life cycle of the building. The standard ISO/EN 15978 international standard is titled "Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method." It provides a standardized methodology for assessing and reporting the environmental performance of buildings throughout their life cycle. The standard focuses on calculating the environmental impacts associated with the construction, use, and end-of-life stages of buildings. It provides guidelines for evaluating various aspects such as energy consumption, greenhouse gas emissions, resource depletion, water consumption, and waste generation. ISO 15978 outlines a life cycle assessment (LCA) framework for analyzing the environmental impacts of buildings. This includes considering the extraction and processing of raw materials, manufacturing of building products, transportation, construction activities, operational energy consumption, maintenance and repair, and the eventual demolition or disposal of the building. It provides guidelines and requirements for conducting an LCA, including data collection, impact assessment, and reporting. This standard enables stakeholders in the building industry to evaluate and compare the environmental performance of different building designs and materials, facilitating more informed decision-making towards reducing embodied carbon and improving overall sustainability [15].

Furthermore, the principles and framework for conducting Life Cycle Assessment (LCA) the fundamental concepts, terminology, and structure for LCA studies established in the ISO 14040:2006 standards. This standard ensures consistency, transparency, and credibility in the assessment process by providing guidelines for goal definition, scope setting, inventory analysis, impact assessment, and interpretation of results [16]. The four components of LCA are described in the ISO /EN 14040 are as follows:

1. Goal and Scope Definition: Clearly define the purpose, boundaries, functional unit, and system limits of the LCA study to establish the scope and context.
2. Life Cycle Inventory (LCI): Compiling a comprehensive inventory of inputs (resources, energy, materials) and outputs (emissions, waste) associated with each life cycle stage to quantify the environmental inputs and outputs.
3. Life Cycle Impact Assessment (LCIA): Analyzing the inventory data to evaluate the potential environmental impacts of the assessed system in specific impact categories such as climate change, human health, ecosystem quality, and resource depletion.
4. Interpretation: Analyzing and summarizing the LCA results, including comparing impact categories, identifying hotspots, assessing uncertainties, and drawing conclusions to provide insights for decision-making and improvement opportunities [17].

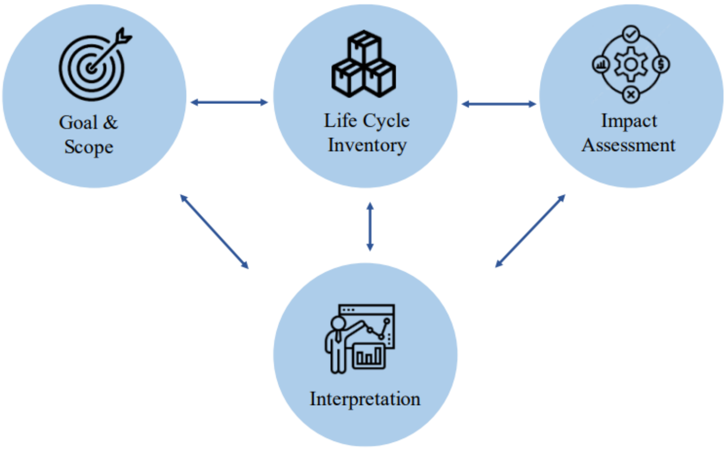

Figure 1: Life Cycle Assessment Phases

Furthermore, ISO 14044:2006 complements ISO 14040 by detailing the requirements and guidelines for conducting LCA studies. It provides a comprehensive methodology and technical guidance for each assessment stage. ISO 14044 specifies the data requirements, methods, and tools to collect and analyze life cycle inventory data, assess environmental impacts, and interpret the results. This standard promotes the use of reliable data, systematic analysis, and peer review to ensure the accuracy and validity of LCA studies. This standard helps to conduct robust LCA studies and make informed decisions to improve the environmental performance of their products and systems [17].

LCA can be easily calculated with the help of software, which can carry out detailed environmental assessments based on integrated databases. Numerous commercial tools are available in the market that facilitate the calculation of Life Cycle Assessment (LCA) as well as the estimation of both embodied and operational energy. These tools simplify the process and make it more accessible to users. Some tools include ATHENA, ACE, Boustead Model, EcoPro, EcoScan, EPS 2000, eToolLCD, GaBi, One Click LCA, Simapro, Umberto, etc. These tools allow using many databases and environmental impact assessment methods. Additionally, these tools follow ISO standards for assessments [18] [19] [20]. However, when it comes to commercial tools that incorporate LCA data for building assessment, there can be limitations regarding the reliability of data sources. Some tools are considered "black box" or "grey box" tools, meaning that the underlying data and calculations are not transparent, and it may be challenging to verify their accuracy or assess the reliability of the data used. For example: Ecoinvent, GaBi allows and supports black box modelling by offering data on the input and outputs of processes without detailed data [21] [22]. This lack of transparency and uncertainty in data sources can limit the widespread adoption of these tools, especially when developing national codes or regulations that rely on consistent and trustworthy data for assessing building performance [23].

In terms of research and development, there have been numerous papers focused on LCA methodologies and applications.

The methods include Life cycle costing, life cycle inventory, life cycle analysis and optimization [24] - [30]. However, a common and comprehensive method that is a universally accepted approach has yet to emerge. The field of LCA is still evolving, and researchers are continuously working on improving methodologies and addressing challenges, such as data reliability and standardization.

Additionally, it is worth noting that some countries are making attempts to incorporate embodied carbon. For example, the United Kingdom has introduced the "Redefining Carbon" initiative, which aims to establish a new framework for measuring and reporting embodied carbon in construction projects. The United States and the Netherlands have adopted a material-scale approach, which focuses on the performance of materials. Denmark has taken a more progressive approach than the building-scale method by establishing an embodied carbon budget of 12 kg CO_2 equivalent (CO_2-eq) per square meter per year for new buildings larger than 1000 square meters [31].

Regarding the building code, Marin County - United States, has successfully incorporated embodied carbon into its Marin Country code Chapter [32]. The Netherlands has introduced limits on embodied carbon in buildings through building regulations applicable to residential and non-residential buildings. France has introduced regulations "RE2020", which is relevant to the new buildings, that govern operational and embodied carbon. Countries like Finland are trying to develop legislation for low-carbon construction [33].

In India, the Energy Conservation Building Code (ECBC) is undergoing a restructuring process to introduce a new chapter called the Building Materials in the Energy Conservation Building Sustainable Codes Standards (ECBSC). This new chapter will focus on addressing building materials' embodied energy and carbon. Including embodied carbon considerations will be applicable to structural and envelope systems, excluding building finishes and electrical, mechanical, plumbing, and non-structural elements. The additions to the code will consider factors such as seismic zones and the availability of floor space index or floor area ratio. The embodied energy or carbon will be reported in kilograms of carbon dioxide equivalent per square meter ($KgCO_2e/m^2$). The benchmark for embodied carbon will be calculated using a CSV file and is subject to annual revisions, making it a dynamic benchmark that can change over time. Overall, restructuring the code in India aims to incorporate embodied carbon considerations into the regulatory framework, providing guidelines and benchmarks for reducing carbon emissions associated with building materials in buildings' structural and envelope systems.

Similar Crowdsourcing Databases:

Crowdsourced data collection offers a cost-effective method for researchers to delegate straightforward tasks or surveys, enabling them to gather data in real time. This approach allows for a significantly larger and more geographically diverse set of observations than traditional data collection methods, keeping costs relatively low. The crowdsourcing database is popular and used in many fields. Some of the popular crowdsourcing databases are listed as follows:

Table 1: Crowdsourcing Databases - Examples

Crowdsourcing Database	Description	Usage Examples
Autodesk Revit Families	A category within Autodesk Revit where manufacturers, designers, and architects can upload their BIM files for users to download and incorporate into their own BIM projects [34].	Architectural design, building modelling, component sourcing
ASHRAE DB II	A specialized database for collecting and compiling Thermal Comfort data worldwide, ensuring proper attribution and referencing. Data is structured for consistency and easy analysis. Rigorous validation checks maintain data integrity [35].	Research, analysis, and exploration of thermal comfort conditions
3D Warehouse-Sketchup	A cloud-based platform within Autodesk SketchUp where users can share their 3D models. Professional companies, including furniture manufacturers, can upload their products for designers to incorporate into their projects [36]	Architectural visualization, product design, collaboration
Open Street Map	A collaborative mapping project that relies on crowdsourcing for data collection, validation, and maintenance. User-contributed data is reviewed and verified through peer review, cross-referencing, and automated technologies [37].	Mapping, navigation, geographic information systems
Google Maps	Google Maps allows users to contribute crowd source data, which is validated through a structured process. Users can submit updates, corrections, reviews, and additional information to improve the accuracy and completeness of map data [38].	Navigation, local business information, real-time traffic updates
Wikipedia	Wikipedia is a collective platform for sharing structured knowledge. Quality control is maintained through community engagement, moderated discussions, and secondary processes such as arbitration committees [39].	General knowledge, research, reference

Methods

The proposed methodology for developing the embodied energy database of building materials involves the creation of a user-friendly tool. This tool allows users to input their data related to the embodied energy of various building materials. Once the data is collected, it undergoes analysis and verification to ensure its accuracy and reliability. The verified fit datasets are then saved into the database for further utilization.

The database's final dashboard will provide users with valuable information regarding the embodied carbon of different building materials. Users can access this dashboard, which will present the data comprehensively and easily understandable. The dashboard will visually represent the embodied energy database, enabling users to explore and analyze the embodied carbon of specific building materials.

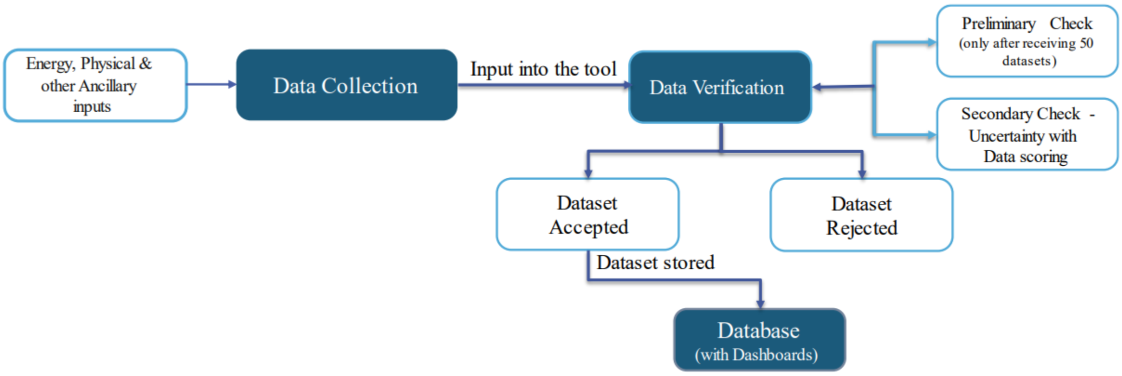

Figure 2: Process flow of the Embodied Energy Database Too

Data collection: Collecting embodied energy data is indeed a complex task due to the lack of consensus on the specific details, units, metrics, and data format. To set up an embodied energy database, the initial crucial step is to formulate a comprehensive data collection format capable of storing and validating the collected information. We propose creating a standardized database format designed to collect material carbon emissions during the A1 to A4 life cycle processes – Cradle to Gate. These processes, including raw material extraction, procurement, manufacturing, and transportation, form the foundation of the overall life cycle assessment. By focusing on these core processes, the proposed format can effectively capture the essential data needed for assessing building materials' embodied energy and carbon emissions. This standardized format will establish a consistent framework for data collection, enabling efficient storage, validation, and analysis of the gathered information, laying the groundwork for developing a robust and reliable embodied energy database. The following points were considered while finalizing the data collection format:

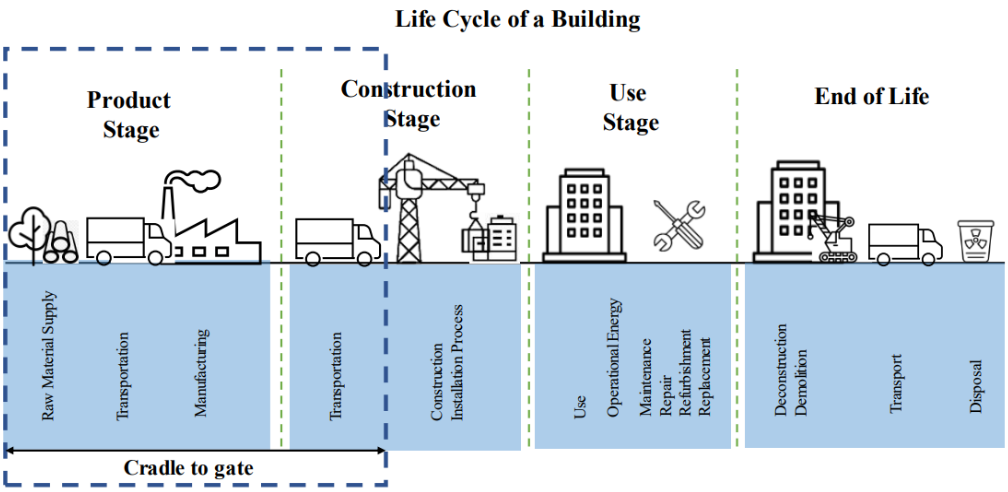

Figure 3: The life cycle of a building

1. ***Data Collection*** – The data being collected includes both embodied energy and carbon emissions. The units used are MJ (megajoules) for embodied energy and kg CO_2 or kg CO_2eq (carbon dioxide equivalent) for carbon emissions.
2. ***Life cycle process*** – The proposed granularity of the life cycle process data collection is at the individual process level. The database aims to collect data for each specific activity within a life cycle process. For example, if Process A1 includes activities such as "Raw material extraction" and "Raw material procurement," contributors would be encouraged to enter data for each activity separately to achieve the highest level of granularity.

3. ***Data source*** – The data sources can be primary and secondary. Preliminary data may be obtained directly from material suppliers, scientific publications, or material-specific Environmental Product Declarations (EPDs). Secondary data is information gathered from existing databases or literature that compiles relevant life cycle assessment data.
4. ***Age of data*** – The age of the data can vary. Contributors may enter the age of the data directly, or it can be categorized into time slabs, such as 1-2 years old, to indicate its recency.
5. ***The geographical region of data*** – The region from which the data was collected should be specified. For example, contributors would be prompted to provide information on the location of material extraction for Process A1 or the manufacturing location for Process A3. This helps to account for regional variations and specific environmental conditions that may influence the life cycle assessment.
6. ***Who would be able to enter the data*** – Contributors can range from PhD scholars to material manufacturers. The database aims to be inclusive and welcomes data contributions from a wide range of stakeholders who possess relevant knowledge and information regarding the life cycle processes of materials.
7. ***Level of technical rigour of the database***– The database will be maintained with a high level of technical rigour. While data can be collected from various sources, it will undergo rigorous validation checks to ensure its fitness and reliability. The validation checks will be applied at the individual process level, meaning that data for each specific process will be evaluated separately. For instance, if a contributor provides data for Processes A1, A2, and A3, the validation checks will assess the confidence intervals for each process. This means that data for A1 and A2 might fall within a 95% confidence range, while data for A3 may fall within an 80% confidence interval. All data will be integrated into the database but will be differentiated based on their associated confidence intervals, indicating their reliability.

We propose the establishment of a centralized database that will be interconnected with multiple data collection files. Each contributor will receive separate data collection files tailored to their specific contributions. The data collection file will be structured into four sheets corresponding to the A1, A2, A3, and A4 life cycle processes. The following data is proposed to be collected for each life cycle process:

- **For the A1 life cycle process:** In the case of the A1 life cycle process, contributors are encouraged to provide data at the most detailed level possible, if available. They can enter specific information related to the activities involved or provide comprehensive data for the embodied energy or carbon of the process. Background information is crucial for establishing the context of the data, while some details are specific to embodied energy or carbon. It also requires the contributors to indicate the source of the data, which can be either primary data from the contributor or data obtained from material manufacturers, scientific literature, reports, and other sources. Data sources indicate the data type, specifying whether the data was directly measured by the contributor, calculated indirectly, or derived using conversion factors. For example, indirect calculations or conversions can be used to estimate the data if certain information is unavailable, such as the total weight of coal used. This approach ensures an accurate and comprehensive collection of embodied energy and carbon data for the A1 life cycle process by emphasizing granularity and providing relevant context.
- **A2/A4 life cycle process:** In the case of the A2 and A4 life cycle processes, contributors will be requested to provide information regarding transport-related carbon emissions or embodied energy. The data collection format for these processes will be similar. Contributors will have the opportunity to enter details related to transport for as many vehicles involved in the process as necessary. Detail 10 in the format will indicate the vehicle category, distinguishing between Light Duty Vehicle (LDV), Medium Duty Vehicle (MDV), or High Duty Vehicle (HDV). This information will enable comprehensive data collection and analysis for transport-related aspects of both the A2 and A4 life cycle processes.
- **A3 life cycle process:** In this stage, contributors will provide data on the embodied energy or carbon emissions resulting from the manufacturing process. The data collection will capture information about all the raw materials utilized in the manufacturing process and the specific method or technology employed.

We propose to have the data collection of each stage with four levels of detail; the above-mentioned information is further broken down into four levels according to its availability.

Table 2: Lifecycle stages process breakdown into four levels of details

	Raw Material Acquisition	Transport	Manufacturing	Transport
LOD 1	Manufacturer, Raw materials, Quantity	Vehicle used, Distance from the mine to the manufacturing site	Manufacturing process, Quantity of the raw materials	Vehicle used, Distance from the mine to the manufacturing site
LOD 2	Equipment type, Fuel type of the equipment	Number of vehicles, Vehicle type, Fuel type of the Vehicle	Equipment used, Energy used (Fuel and electricity)	Number of vehicles, Vehicle type, Fuel type of the Vehicle
LOD 3	Manufacturer and model of the equipment, Embodied energy	Manufacturer and Number of vehicles, Number of trips, Embodied energy	Manufacturer and model of the equipment embodied energy	Manufacturer and Number of vehicles, Number of trips, Embodied energy
LOD 4	Waste	Waste	Waste, Material Production Quantity	Waste

We propose implementing an online data collection method for this database. The data collection template will be available for download, allowing contributors to access and complete it. Once the contributors have filled out the template with the relevant data, they can share it with the designated database manager(s) via email. The database manager(s) will then review and validate the data for its quality and accuracy. This process ensures that the collected data undergoes a rigorous quality control check, enhancing the reliability and credibility of the information stored in the database. By providing an accessible and straightforward method for data submission, we aim to encourage widespread participation and collaboration from various stakeholders, ultimately enriching the database with comprehensive and diverse life cycle process data. The data validation process is explained in detail in the further sections. Note that in case of data scarcity, we may propose the users use syntenic data for their calculation.

Data Verification:

The data checking and verification will consist of two phases: the Primary Check and the Secondary Check.

1. Primary Check: This phase occurs after the tool submits the data. The dataset is compared with similar datasets that have been previously accepted. The dataset is deemed unfit and excluded from further analysis if any major errors or discrepancies are identified. The Primary Check phase commences once sufficient datasets, such as 50, have been gathered to enable effective comparisons. The distribution range will be fixed with the obtained dataset, and if the new dataset doesn't fit into the distribution range, it will be rejected.
2. Secondary Check: This is a mandatory phase. During this phase, the selected datasets undergo scoring based on the pedigree matrix method outlined in ISO 14044. The scoring considers regionality, time relevance, and units used. The uncertainty of the dataset about the identified scoring parameters is also assessed. The Secondary Check helps evaluate the quality and reliability of the datasets, considering their alignment with specific criteria and the level of uncertainty associated with the provided data.

By following these two comprehensive checking phases, the database ensures that only reliable and high-quality datasets are included for further analysis and utilization. The primary check eliminates major erroneous data, while the secondary check evaluates datasets based on predefined scoring parameters and uncertainty assessments, providing a robust framework for data validation.

Data Scoring

The scoring system can consider various factors, such as data source reliability, data age, geographical coverage, completeness, and consistency. Each criterion can be assigned a score based on its importance and relevance to the analysis. For this study, we have used the Weideman and Wesnaes (1996) proposed framework for scoring based on five parameters:

The parameters for scoring are as follows:

Data source: The data source refers to the origin or provider of the information used for scoring. It is crucial to consider the data source's reliability, credibility, and validity. High-quality data sources, such as reputable research institutions, government agencies, or well-established organizations, are generally preferred as they are more likely to provide accurate and trustworthy information.

Age of the data: The age of the data indicates how recently the information was collected or updated. More recent data is generally preferred because it reflects the current state of affairs and is likely to be more relevant. However, the importance of the data's recency may vary depending on the specific context.

Geographical coverage: Geographical coverage refers to the extent to which the data represents different geographic areas. Depending on the application, it may be necessary to have data that covers a specific region, country, or even the entire globe. The geographical coverage should align with the scope of the analysis or decision-making process.

Lifecycle stages: The lifecycle stages parameter considers the different phases or locations of the assessed phenomenon. The inclusion of data from different lifecycle stages provides a more comprehensive understanding of the phenomenon and allows for better decision-making across the entire lifecycle.

Units/Indicators: This parameter refers to the measurement units or indicators used to quantify and assess the phenomenon of interest. The choice of appropriate units or indicators depends on the specific context and the scoring goals. It is important to use indicators that are meaningful, valid, and aligned with the objectives of the analysis. The units or indicators should capture the relevant aspects of the phenomenon and enable meaningful comparisons and evaluations.

The obtained datasets are scored with the help of the pedigree matrix provided above, and with the data quality score obtained, the dataset's quality will be assessed. The pedigree matrix is carried out to determine the data uncertainty.

The overall uncertainty will be calculated once the Data Quality Indicators (DQI) are scored. The general uncertainty is computed by calculating the coefficient of variation, which is obtained by taking the square root of the sum of the squares of the individual coefficients. The formula for calculating the overall uncertainty is given below:

$$\text{Uncertainty (Co-efficient of the Variation)} = \sigma / \mu$$

The Uncertainty value is calculated for the individual process in the system. It is said that a low score on the data quality indicator often leads to higher uncertainty and changes in the mean value. The uncertainty value helps to decide on the data quality and its acceptance into the database.

Table 3: Scoring of data sources based on data quality indicators (adapted from Weidema & Wesnæs, 1996) [40]

	1	2	3	4	5
Data Source	Life Cycle Database or Manufacturer or EPD	Peer-Reviewed Journal Paper	Government Report or Conference Paper	All other sources	-
Age of the data	<3 years	<6 years	<10 years	<15 years	Unknown or more than 15 years
Geographical Coverage	City/State	India	South Asia	Asia	World
Units/Indicator	$KgCO_2e$	$kgCO_2$	kWh or MJ	-	-
Lifecycle stages covered	A1-A4	A1-A3	A1, A2, A4/A3	A1, A2	Anyone lifecycle stage

Uncertainty information can guide further data collection efforts, improve data quality, or prioritize uncertainties for future research. Clearly communicate the uncertainties associated with the LCA results to stakeholders and decision-makers, sensitivity plots, probability distributions, confidence intervals, or other appropriate means. Transparently conveying the uncertainties enables stakeholders to make informed decisions, understand the limitations of the assessment, and identify areas where further data collection or research may be needed.

To ensure the accuracy and relevancy of the dataset, users and manufacturers need to update the data on a yearly or biyearly basis regularly. This periodic updating process helps maintain the dataset's dynamic capability by incorporating any changes or advancements in the embodied energy or carbon data over time. By encouraging users and manufacturers to provide updated information regularly, the dataset can effectively reflect the latest industry standards and practices, providing users with reliable and up-to-date information for their analysis and decision-making processes.

Discussion

The proposed framework for data collection of embodied energy will introduce uniformity and comparability of LCA data pertaining to stages cradle to the gate of the building life cycle. Further, the adopted methodology for database generation can ensure continuous availability of the most recent and relevant embodied energy data.

Each dataset's confidence level measure can help reduce uncertainty in LCA studies that refer to or use the database during the process. At the same time, crowdsourcing of data will ensure that the database is rich in terms of geographical specificity. Hence, it could be used to understand geographical trends in the energy impacts of construction materials during the lifecycle stages cradled to the gate across different parts of India. The database can also be extended to include embodied carbon emissions of these materials. The study focuses on developing a continuously updating embodied carbon database specific to Indian construction materials. This is achieved with the help of a uniform data collection framework adapted for India's building and construction sector. The database also measures and provides the confidence levels of various embodied energy data sets, which is crucial to reducing the uncertainty in LCA studies.

The study aims to create a crowdsourcing database for the embodied energy of the building materials of India. The embodied energy database benefits the Indian built environment in many ways. Some of the benefits are listed as follows:

Understanding environmental impact: By having a comprehensive embodied energy building database, we can better understand the environmental impact of different building materials, construction methods, and design choices. This knowledge enables us to make informed decisions to minimize energy consumption and reduce carbon emissions.

Comparative analysis: An embodied energy buildings database will compare different building materials, products, and construction techniques. With access to such a database, architects, engineers, and builders can evaluate various options' energy efficiency and environmental performance. This will facilitate informed decision-making during the design and construction phases, helping select materials and methods with lower embodied energy and reduced environmental impact.

Performance optimization: The embodied energy buildings database will serve as a resource for optimizing the energy performance of buildings. By analyzing the embodied energy data, designers and developers can identify areas where improvements can be made. This includes exploring alternative materials, assessing the energy efficiency of different building components, and optimizing the construction processes to minimize energy consumption.

Policy development and regulation: A comprehensive embodied energy building database will provide a foundation for developing energy policies, regulations, and certifications related to sustainable construction practices. Governments and regulatory bodies can use this data to set standards, incentivize low-energy and low-carbon construction practices, and promote environmentally friendly building materials.

Research and innovation: An embodied energy building database will facilitate research and development efforts focused on reducing energy consumption and environmental impact in the building sector. Researchers can use the data to analyze trends, identify opportunities for improvement, and develop innovative solutions. This knowledge-sharing platform will encourage collaboration among stakeholders, foster innovation, and accelerate the adoption of sustainable practices in the construction industry.

In summary, an embodied energy buildings database will provide a valuable resource for understanding, analyzing, and optimizing buildings' energy performance and environmental impact. It will enable informed decision-making, support policy development, foster research and innovation, and promote the transition towards more sustainable built environments.

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Evaluation of Thermal Performance of Agro-waste Material for Team SHUNYA Building

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Highlights

- Thermal performance of wall panels made up of bagasse was analyzed.
- Lower thermal conductivity compared with the traditional brick.
- 28 % decrease in the thermal cooling load of the house.
- A 16.4 % increase in the thermal comfort hours is obtained.

Abstract

Using brick-concrete for building envelope is a common practice in India. These envelopes have high heat gains and experience large embodied energy. Agro-waste panels made up of sugarcane waste can significantly reduce cooling load for new construction due to its better u-value and also reduce carbon emission since it is produced from sugarcane waste, i.e., bagasse. A double storey naturally ventilated building has been simulated for Mumbai climatic conditions to understand the performance of agro-waste materials. The total cooling load and temperature profile for a year have been simulated using EnergyPlus software. Thermal comfort hours are calculated using the India model for adaptive comfort (IMAC) band to show the potential of the agro-based panel. The thermal cooling load of the simulated building incorporated with an agro-waste panel decreased by 28 % as compared to the brick-concrete envelope. There is a 16.4 % increase in annual thermal comfort hours compared to brick-concrete envelope.

Keywords: IMAC band, Thermal cooling load, Agro-waste material, EnergyPlus

Introduction

The International Energy Agency's research indicates that the construction and operation of buildings were responsible for 35% of global final energy consumption and 38% of energy-related CO_2 emissions in 2019 [1]. This highlights the significance of addressing energy efficiency and decarbonization in the building sector to reduce greenhouse gas emissions and contribute to global efforts to mitigate climate change. The building envelope is one of the essential factors contributing to the energy efficiency of a building. Furthermore, the embodied energy of the material accounts for 20 % of the total life cycle carbon emissions of the building [2].

The building envelope consists of walls, roof, floor, windows and doors. Bricks and concrete are usually used for wall construction; concrete is used as the structure for roofs and floors. Walls contribute to 30% of the total heat gain of the building, which is second after roof.

The existing building material i.e., brick and concrete, have high embodied carbon emissions and operational carbon emissions [3-4]. Researchers have looked into alternate possible materials with low carbon footprints and better thermal performance. Agro-waste material is one of the found options having low/negligible embodied carbon [5-6]. Thus, some studies are performed to look at the possibility of using agro-waste as a building material. Straws are one of the most common agro-waste found in India. Around 2 billion tonnes of various straw varieties are generated globally [7].

Straws are burned in fields in many poor nations, releasing hundreds of greenhouse gases or air pollutants such as particulate matter, elemental carbon, organic carbon, and ions. [8]. Instead of burning, such waste straws can be used as building materials since they have strong thermal insulation, good sound insulation [9-10], and good shear performance

[11-12]. To substitute the single insulation layer, straws may be mixed with hollow bricks, a core wall material in the building component market [13]. Ahmadi et al. investigated the heat transmission coefficient of wheat straw-filled hollow bricks at various levels of compaction. The thermal transfer coefficient first increased and subsequently declined as the degree of compaction increased [14]. Hu et al. investigated how the filling location affected the thermal transmission coefficient of straw-filled hollow bricks at the same rate. The outcomes demonstrated that the straw stuffing performed admirably on both sides [15].

With the increase in the use of agro-waste panels, it becomes important to evaluate the thermal performance of the material. This paper aims to analyze the thermal performance of agro-waste wall panels and flooring. A specific case of products provided by Ecoboard Industries Limited is taken as an agro-waste material for the case study. The materials provided are made up of bagasse, which is a sugarcane waste, and used as wall panels and flooring for the building. A comparative analysis is also performed to inspect the performance of agro-waste panels against typical brick-concrete structures. This is a simulation-based study using EnergyPlus software. The validation of the conduction transfer function module used in EnergyPlus for evaluating conduction through components of the building has been performed by P. C. et al. [16]. Also, several researchers have performed simulation-based studies to evaluate the thermal performance or energy consumption of the material using EnergyPlus [17-19].

From the comparative analysis for the thermal performance, it has been concluded that the agro-waste material has higher numbers of hours within IMAC band compared to the brick-concrete envelope. Also, the thermal cooling load of the building is reduced by 28 % with the use of agro-waste material.

This paper starts with the description of the building taken for the simulation and the assumptions. The methodology section explains the background equation used by EnergyPlus to generate the temperature profile and thermal cooling load. Also, the Indian Model of Adaptive Comfort (IMAC) band is described in the same section. Then, the results and discussion section show the outcome of the simulation with proper reasoning. In the end, conclusions with some future work to further enhance the thermal performance of building envelope are mentioned.

Model description

For analyzing the thermal performance of a bagasse-based wall panel, we consider a G+1 unit with a carpet area of 1367 ft², as depicted in Figure 1. The drawings of the building are provided by Team SHUNYA, and they are using it for U.S. Solar Decathlon Build Challenge 2023 [20]. The building has 2 bedrooms, a double-height living room, a dining room, a kitchen, 2 toilets, a utility area, and a battery area. The building has a plinth height of 750 mm. To restrict the scope of the analysis to building envelope related thermal loading and performance, the building is considered in its unoccupied condition with no lighting, computers, or office equipment. The building is naturally ventilated with no heating and cooling air conditioning. The deep ground surface temperature has been assumed to be 2 ℃ below the monthly mean outdoor air temperature.

Figure 1: Floor plan of ground floor and first floor of the building

The envelope details and their thermal properties have been given in Table 1 for a typical construction case and Table 2 for new construction with the agro-waste material case. Therefore, two envelopes are simulated, i.e., typical construction (details in Table 1) and agro-waste construction (details in Table 2) made up of bagasse and provided by Ecoboard Industries Limited. The properties of the Ecoboard are provided by the supplier after conducting the experiment test using the ASTM C518 method for thermal conductivity and IS: 3087-2005 method for density. The insulation used in the wall and roof assembly is provided by Owens Corning Composite Material Company and is made up of fiberglass wool. The overall U-value is calculated on the basis of the parameters provided by the suppliers. The infiltration through the building envelope is assumed to be 0.7 ac/h. It is assumed that the occupants' metabolic rates are within the range of 1-1.3 met, and occupants are free to adapt their clothing value in the range of 0.5-1 clo.

Table 1: Material details of typical construction

Components	**Description**	**U-value** (W/m^2-K)
External wall	Plaster (12 mm) Brick (105 mm) Plaster (12 mm)	1.3
Roof	Concrete (200 mm)	2.4
Floor	Concrete (200 mm)	2.4
Partition wall	Plaster (12 mm) Brick (105 mm) Plaster (12 mm)	1.6
Window	Sgl Clr (6 mm)	4.2

Table 2: Material details of agro-waste construction

Components	**Description**	**U-value** (W/m^2-K)
External wall	Fibre cement board (8 mm) Ecoboard (9 mm) Insulation (100 mm) Ecoboard (9 mm)	0.2
Roof	Concrete (100 mm) Metal deck Insulation (100 mm)	0.3
Floor	Metal deck	1.6
	Ecoboard (38 mm)	
Partition wall	Ecoboard (9 mm) Insulation (50 mm) Ecoboard (9 mm)	0.2
Window	Dbl Clr/Air (6 mm)	2.6

Methodology

The building is modeled in Design Builder and simulated in EnergyPlus V22-2-0. The hourly simulation was performed in EnergyPlus with outputs such as indoor temperature profile and cooling load.

EnergyPlus model

To analyze the thermal properties of the dwelling unit, it has been simulated in EnergyPlus. EnergyPlus is a building energy simulation tool that works on the fundamental principle of energy balance. Each zone (volumetric space of each zone) is assumed as one node containing uniform properties of state variables, e.g., temperature, pressure, and density. For the one node temperature T_z of the air inside the zone, an energy balance can be given as

$$m_z c_z \frac{dT_z}{dt} = \sum_{i=1}^{N_s} Q_i + \sum_{i=1}^{N_{surface}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} m_i c_p (T_{zi} - T_z) + m_{inf} c_p (T_\infty - T_z) + Q_{sys} \quad (1)$$

where the L.H.S. represents the energy stored in zone air. For the R.H.S., the first, second, third, fourth, and fifth term represents the sum of the convective internal loads, the sum of convective heat transfer from the envelope, heat transfer due to interzone air mixing, heat transfer due to infiltration of outside air and air system output, respectively. The above equation results in the calculation of the temperature T_z of the air inside each zone.

After the calculation of zone temperature, the system energy provided to the zone for meeting cooling or heating load is calculated from the difference between the supply air enthalpy and the enthalpy of the air leaving the zone, as shown in Equation (2)

$$Load = m_{sys}C_p(T_{sup} - T_z) \quad (2)$$

where, T_{sup} is the supply air temperature, and T_z is the indoor air temperature.

IMAC MODEL

India Model for Adaptive Comfort (IMAC) model is the standard for adaptive thermal comfort, based on Indian specific climatic conditions. It is applicable for naturally ventilated, mix-mode and air-conditioned buildings and remains valid for the wide range of outdoor temperatures of Indian climatic zones. The indoor operative temperature is calculated using the equations given below.

For Naturally ventilated building:

$$\text{Indoor operative temperature} = (0.54\times\text{outdoor temperature}) + 12.83 \quad (3)$$

For Mixed-mode building:

$$\text{Indoor operative temperature} = (0.28\times\text{outdoor temperature}) + 17.87 \quad (4)$$

For Air-Conditioned building:

$$\text{Indoor operative temperature} = (0.078\times\text{outdoor temperature}) + 23.25 \quad (5)$$

The indoor operative temperature obtained from the above equation is comfortable for most people. 90 % acceptability range is derived as ± 2.83 °C, ± 3.46 °C, and ± 1.5 °C in naturally ventilated, mix-mode and air-conditioned buildings, respectively. Similarly, for the 80 % acceptability band, the comfort band is ± 4.1 °C, ± 5.9 °C and ± 3.6 °C for naturally ventilated, mix-mode and air-conditioned buildings, respectively. The acceptability band's narrowness increases when we move from a naturally ventilated building to an air-conditioned building.

Results and Discussion

For the thermal performance analysis, a simulation has been performed for a warm and humid climatic condition. The simulation is performed by turning off the air conditioner and using only natural and mechanical ventilation. The Indian model of adaptive comfort (IMAC) band for mixed mode building with a 90% acceptability range is calculated for each day of the year.

Figure 2 shows the hourly simulation of the maximum outdoor temperature day in Mumbai, i.e., 16 March. Agro-waste construction has only 4 hours out of the band, whereas typical construction has 13 hours out of the IMAC band. To quantify the discomfort hours further, the area under the curve, i.e., outside the IMAC band for both cases, has been calculated using the trapezoidal rule. It is found that for typical construction and agro-waste construction, the area outside the IMAC band is 32 and 1.55, respectively. This shows that agro-waste construction is marginally out of the comfort band as compared to typical construction. The diurnal temperature range of maximum temperature day is 16.7 °C. The temperature swing of agro-waste construction is 4 °C approximately, while the temperature swing of typical construction is around 10 °C.

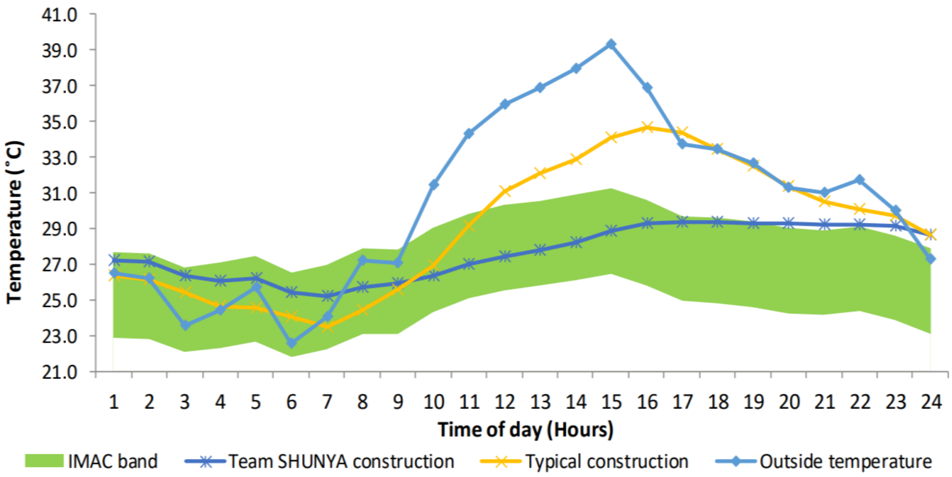

Figure 2: IMAC comfort band for Mixed Mode building (90% acceptability range)

Figure 3 shows the diurnal temperature of the peak temperature day of each month for outdoor temperature and indoor temperature of agro-waste construction and typical construction. It can be seen from the graph that the maximum temperature swing for outdoor temperature is 16.7 °C in the month of March, and the maximum temperature swing for typical construction and agro waste construction is 11.16 °C and 4.15 °C, respectively, in the same month. It can also be concluded that for agro waste construction, the diurnal temperature ranges between 1.0 °C to 4.15 °C, whereas the temperature swing of typical construction ranges between 2.63 °C to 11.16 °C. The reason for the lower diurnal temperature of agro-waste construction is the lower thermal conductivity and lower u-value of agro-waste materials used. Even the thickness of both construction types is equivalent for most of the building components, but lower diurnal temperature swings show that the agro-waste construction has better thermal mass and performs better in all the seasons for warm and humid climatic conditions.

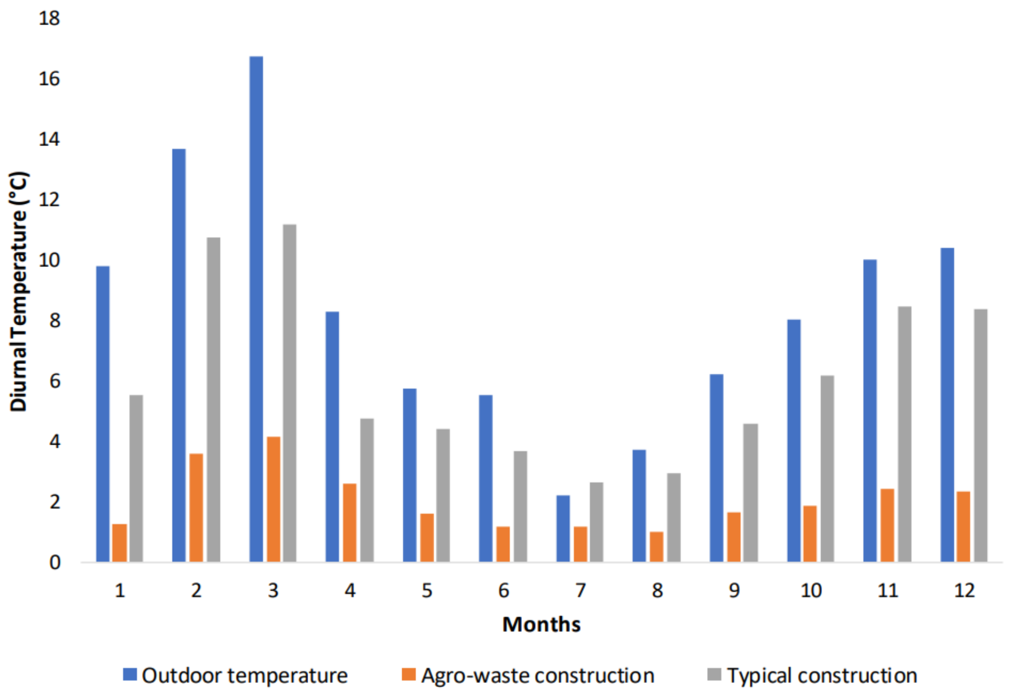

Figure 3: Diurnal temperature for all the months of Mumbai

After looking at the temperature profile of the maximum temperature day, the indoor temperature for the whole year is analysed, and the number of hours within the comfort band is calculated. Figure 4 shows the number of hours within the comfort band for each month for both construction types. The comfort hours for agro-waste construction are greater than the typical construction every month. The number of comfort hours is maximum for the month of May and minimum comfort hours are observed in February. The reason for less comfort hours in February is the low outdoor temperature, due to which the lower temperature of the IMAC band is above the indoor temperature. In the case of May, 96 % of the indoor temperature is within the thermal comfort band. Quantitatively, it is observed that 8154 hours and 7000 hours are within the IMAC band for agro-waste construction and typical construction, respectively. This indicates that when the construction material is changed from typical construction to agro-waste construction, a 16.4 % increase in comfort hours is obtained.

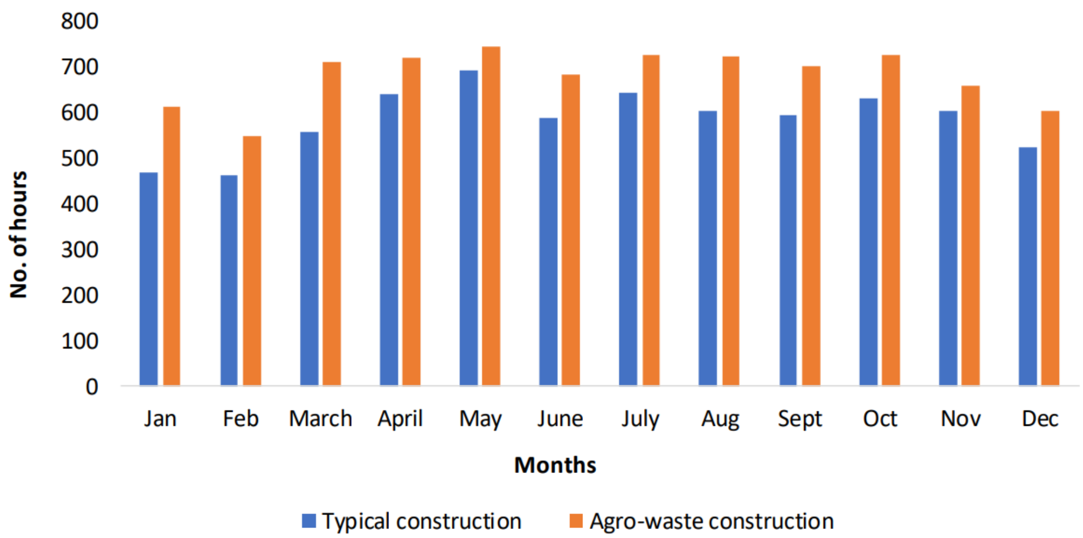

Figure 4: IMAC comfort hours of Mumbai

Figure 5 shows the comparison of cooling load for agro-waste and typical construction. The total cooling load of agro-waste construction is 28 % less than that of typical construction. The highest cooling load of typical construction and agro-waste construction is 2247 kWh and 1182 kWh, respectively. For the peak month, the cooling load is reduced by 45 % using agro-waste construction. The low cooling load of agro-waste construction is due to the low u-value of material used in the building.

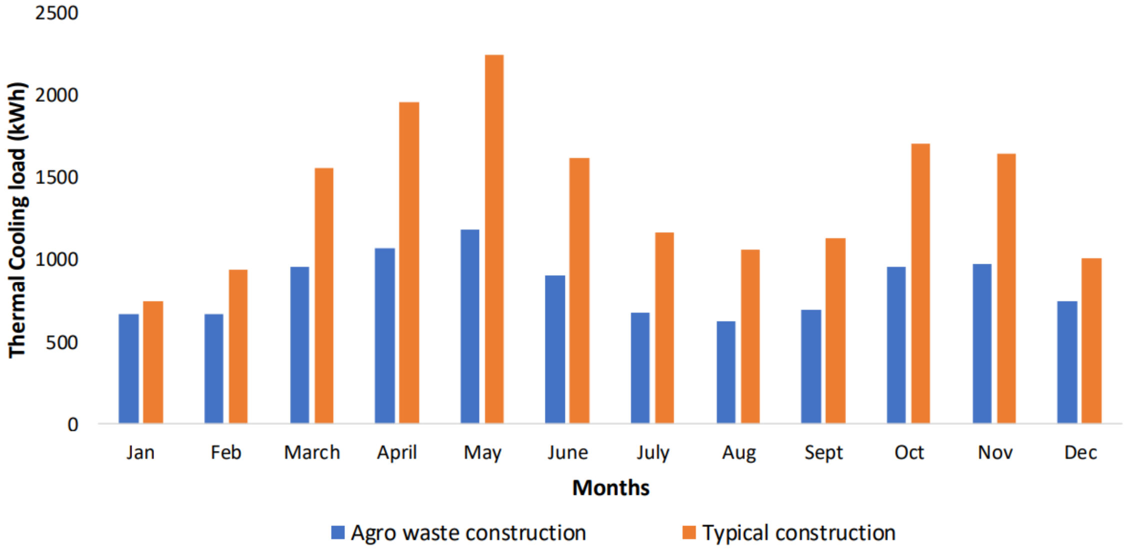

Figure 5: Monthly thermal cooling load of Mumbai

Conclusion

This study compared the thermal performance of the G+1 dwelling unit using agro-waste construction and typical construction. It has been concluded that the agro-waste construction performed better in terms of thermal comfort and thermal cooling load of the building as compared to the typical construction. Then, the monthly cooling load of the building is calculated, which shows a 28% reduction in yearly consumption.

The use of agro-waste panels for wall assembly and floor has minimal carbon emission as the product is in its second life. As the panel is pre-fabricated, this could fasten the construction as compared to the brick-concerte structure. However, strength and waterproof tests should be performed to further implement it in the future.

In the future, the wall gain and cooling load can be decreased with the use of advanced materials such as phase change material (PCM), green roof, and skin green façade. The agro-waste panels would behave differently in different climatic condition, so it becomes important to simulate the performance of agro-waste panel before using it for any climatic zone. A simulation of the agro-waste panel with advanced materials such as phase change materials becomes important as it would reduce the u-value of the assembly, and a very low u-valued material could restrict the internal heat load to decapitate outside, resulting in a rise of indoor temperature. Also, a techno-economic analysis of the product should be performed according to different income groups of India.

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Empirical Examination of Trends in Indoor Air Quality in a Sample of Urban Indian Residences

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Highlights

- Pioneering empirical study that combines time-series data on IAQ with contextual data on household characteristics.
- Middle-income group residences were found to experience better IAQ than those with high and low incomes.
- Daily mean indoor temperature was 4.8°C warmer than the recommended acceptable temperature prescribed by ISHRAE (Class C).
- An online interactive dashboard (RIAQ) for visualising IAQ was developed for academics, policymakers, and industry to enable further research.

Abstract

Indoor air quality (IAQ) in residences is a complex phenomenon determined by many factors. IAQ in homes has been studied far less than air quality outdoors, especially in urban India, where outdoor air pollution frequently exceeds recommended levels. This paper empirically examines daily trends and variations in IAQ parameters measured across a sample of eight urban Indian residences located in three cities, representing the warm-humid and composite climates. Using internet-enabled Airveda devices, time-series monitoring data at 30' intervals were gathered for indoor temperature, relative humidity, CO_2, $PM_{2.5}$, and PM_{10} for 10 days during the monsoon season when air conditioning was prevalent. Contextual data about the physical and household characteristics of residences were gathered using household surveys. The results were compared against the recommended ISHRAE and WHO standards to observe any deviations. Given the paucity of empirical data, an online interactive dashboard (RIAQ) for visualising IAQ was developed for academics, policymakers, and industry to enable further research.

Keywords: Indoor air quality, particulate matter, residences, monitoring, visualization

Introduction

Over the past two decades, there has been a rapid increase in urbanization in many cities in India [1], resulting in a significant increase in the number of residences, together with an increase in household activities (such as cooking, heating, cooling) and associated indoor air pollutants such as particulate matter. About 10 of the world's top 15 most polluted cities are located in India [2]. The number of deaths due to air pollution was 1.67 million, of which 0.61 million deaths were attributable to household air pollution (HAP). This has resulted in an economic loss of $36.8 billion, accounting for 1.36% of India's gross domestic product (GDP) [3]. In contrast to the attention paid to ambient air quality, indoor air quality (IAQ) research has recently received attention from Government authorities and researchers due to the COVID pandemic and the adverse health impacts of poor IAQ related to Sick Building Syndrome.

Several studies have indicated the need for having appropriate thresholds for IAQ and a standardized measurement approach for producing reliable results [4-8]. Rawal et al. proposed an India Model for Adaptive Comfort-Residential (IMAC-R) based on year-long thermal comfort field surveys across the five climatic zones of India and showed that existing models (like the PMV model) and standards (ASHRAE) had under-predicted thermal adaptive capacity of Indian occupants in both mixed-mode and naturally-ventilated residential buildings [8]. To address these concerns, IAQ standards have been recently published for the Indian context. The Indoor Environmental Quality Standard ISHRAE Standard-10001: 2016 as India's first Indoor Environmental Quality (IEQ) standard, defines recommended threshold values, methods of measurement, and technical specifications of the measuring instruments for IAQ, thermal, lighting, and acoustic comfort [9]. It is hoped that the ISHARE standard will help to increase the number of empirical studies on indoor air quality for different types of building typologies (residential, public, commercial, institutional) in India.

Most studies have focused on office buildings [4] and institutions like schools [10]. The number of studies on measuring IAQ in residential buildings is scarce [11-13]. A recent study by Greenstone et al. [14] used low-cost indoor air quality monitors to measure indoor $PM_{2.5}$ concentrations across thousands of homes in Delhi and found that average indoor $PM_{2.5}$ concentration levels were 23 and 39 times higher than the WHO [15] recommended limit of 10 $\mu g/m^3$ respectively. Garg & Ghosh measured the conventional air pollutants of $PM_{2.5}$, SPM, NO_2, and SO_2 across diverse socio-economic zones and revealed better IAQ in middle-income group households in comparison to the high- and low-income groups [16]. The study pointed out that ventilation (air exchange) plays a critical role in improving IAQ, which was substantiated by the calculation of indoor/outdoor (I/O) ratios.

Despite these recent studies, IAQ in residences has received limited attention from policymakers and researchers due to the limited use of established protocols for long-term measurement of IAQ to pick up seasonal differences [17-18] and lack of awareness of the link between poor IAQ and health [14,17,19]. This has resulted in a lack of accessible data on the variation in IAQ in residences (with different income groups, locations, and construction) across India [18]. In addition, national guidelines on IAQ monitoring and management in residences may need to be varied given the outdoor pollution levels in cities across India that influence indoor-outdoor air exchange.

Against this context, this study empirically investigates daily trends and variations in indoor temperature, relative humidity (RH), CO_2, and Particulate Matter ($PM_{2.5}$ and PM_{10}) across a sample of eight urban Indian residences located in three cities, representing the warm, humid and composite climates of India. Contextual data about the physical and social aspects of residences were gathered using face-to-face household surveys. The results were compared against the recommended ISHRAE standards to observe any deviations. An online and interactive dashboard (RIAQ) for visualizing IAQ was developed for academics, policymakers, and industry to enable further research.

Methods

The study adopted a mixed methods approach combining IAQ monitoring with household surveys across a sample of eight urban Indian residences located in three cities, representing the warm, humid, and composite climates. Using internet-enabled Airveda devices, time-series monitoring data at 30' intervals were gathered for indoor temperature, RH, CO_2, $PM_{2.5}$, and PM_{10} for 10 days (6th-15th August 2022) during the monsoon season when air conditioning was prevalent. The IAQ conditions were monitored in the most occupied space - the living room of the case study residences. The technical specifications of Airveda devices are detailed in Table 1 below. To investigate the relationship between indoor and outdoor air quality, outdoor air quality data (temperature, RH, CO, $PM_{2.5}$, and PM_{10}) of studied cities were obtained from the Central Pollution Control Board (CPCB) online portal run by the Ministry of Environment, Forest and Climate Change, Government of India [11].

Table 1: Specifications for Airveda devices

	Parameter	Range	Accuracy	Resolution
 **Device Model: PM2510CTH**	Temperature (°C) RH (%) CO_2 (ppm) $PM_{2.5}$ ($\mu g/m^3$) PM_{10} ($\mu g/m^3$)	10 – 60 0 – 90 0 – 5000 0 - 999 0 - 1999	±1 ±3 ±50 ±3% ±10% ±10%	1 1 -- < 0.3 < 0.3

Contextual data about dwelling and household characteristics of the residences were gathered using face-to-face interview-based surveys with householders. The survey questionnaires were implemented using online Google Forms and included details about the building (size, orientation), household (number of occupants, occupancy pattern, activities), cooling systems (set point temperature), appliance ownership and usage, and thermal comfort.

Table 2: Residence characteristics

Cities	Dwelling ID	Dwelling type	No. of AC units	Floor area (m²)	No. of occupants	Income group	Weekly occupancy
Pune	P01	Row house	0AC	135	2	MIG	Evenings and Weekends
	P03	Apartment (<4 story high)	3AC	125	5	HIG	All the time (24/7)
		Apartment (<4 story high)	2AC	125	8	HIG	All the time (24/7)
Pondi cherry	PD2	Stand-alone house	2AC	112	4	MIG	Most of the time
	PD5	Stand-alone house	0AC	121	7	LIG	All the time (24/7)
Patna	PT7	Stand-alone house	0AC	102	3	LIG	All the time (24/7)
	PT8	Row house	0AC	65	5	LIG	All the time (24/7)
	PT10	Apartment (<4 story high)	2AC	139	2	HIG	NA

Overview of case study residences

The eight sample residences were categorized as three low-income group (LIG, income up to INR 6 lac per annum), two middle-income group (MIG, income between INR 6 lac to INR 12 lac per annum), and three high-income group (HIG, income more than INR 12 lac per annum). The residences were grouped as three apartments, two-row houses, and three stand-alone houses. They were located in the following cities - Pune (P01, P03, P04), Pondicherry (PD2, PD5), and Patna (PT7, PT8, PT10), representing the warm-humid and composite climates, as shown in Table 2. The residences varied in size from 65m^2 to 139m^2. The majority of case study residences were constantly occupied and had more than two occupants, with P04 having eight occupants (highest). AC ownership varied across the sample - as 50% were MIG, there was no ownership of AC across LIG residences, and all the HIG residences owned two or more AC units. Throughout the monitoring period, the frequency of AC usage was about 7-9 hours per day among the four AC-equipped residences.

To better explain the reasons behind IAQ trends, outdoor air quality data were examined. During the monitoring period, Pondicherry experienced the highest mean outdoor temperature of 31.8°C, with the lowest mean values of outdoor $PM_{2.5}$ and RH at 13.8µg/m³ and 67.6%, respectively. Pune experienced the lowest mean values in temperature (24.5°C) and PM_{10} (29.6µg/m³). Patna experienced the highest mean values for RH, $PM_{2.5}$, and PM_{10} at 74.3%, 30µg/m³, and 61.5µg/m³.

Results

Temperature and Relative Humidity

Table 3 summarises, by each residence, the measured mean, maximum, and minimum concentrations of IAQ parameters during the monitoring period of 10 days in August 2022. Indoor temperature was found to vary across the residences, with daily mean temperature ranging from 28.3°C in P01 to 35.2°C in PT10.

Table 3: Descriptive statistics for indoor Temperature, RH, CO_2, $PM_{2.5}$ and PM_{10}

	Cities	Pondicherry		Pune			Patna		
Date Range:6-15 August	**Dwelling**	**PD2**	**PD5**	**P01**	**P03**	**P04**	**PT7**	**PT8**	**PT10**
	Temperature (°C)								
	Mean	32.1	33.4	28.3	30.7	30.2	30.1	34.2	35.2
	Min	28	31	26	29	29	29	32	32
	Max	34	35	30	33	33	32	38	38
	Humidity (%)								
	Mean	48.3	53.2	64.0	60.9	63.4	58.0	50.8	56.1
	Min	28	43	56	49	55	51	40	49
	Max	62	65	71	68	68	67	60	67
	CO_2 (ppm)								
	Mean	577.2	586.6	420.1	551.8	1119.3	502.7	461.4	421.9
	Min	392	440	384	398	526	406	391	382
	Max	1112	891	554	1090	2000	724	632	554
	$PM_{2.5}$ ((µg/m^3)								
	Mean	30.6	44.9	10.6	7.0	14.5	29.1	67.8	26.5
	Min	7	7	0	0	0	3	7	7
	Max	476	786	214	88	133	229	994	80
	PM_{10} ((µg/m^3)								
	Mean	59.6	98.5	33.5	34.4	45.5	55.0	97.6	59.2
	Min	19	24	1	2	6	12	14	14
	Max	671	1091	369	176	307	414	1590	338

The boxplot of temperature in Figure 1 shows the monitored mean indoor temperature for each residence compared against the upper limits of indoor operative temperature prescribed by ISHRAE, which is 27°C (Class C). At the sample level, the mean indoor temperature was 31.8°C, which was 4.8°C warmer than the acceptable temperature recommended by ISHRAE. More specifically, at the individual dwelling level, the temperature difference between the mean indoor temperature of each dwelling and the maximum specified by the ISHRAE threshold varied from 1.3°C to 8.2°C. Residence PT10 had the largest temperature variation from the ISHRAE threshold at 8.2°C, while P01's mean temperature was 1.3°C higher than the ISHRAE threshold.

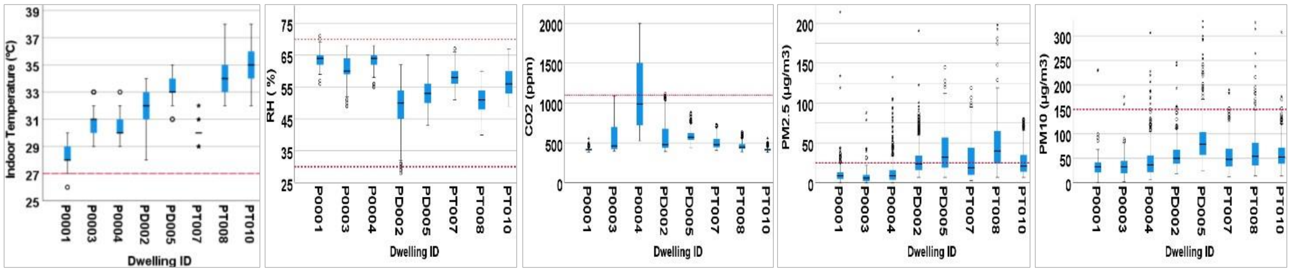
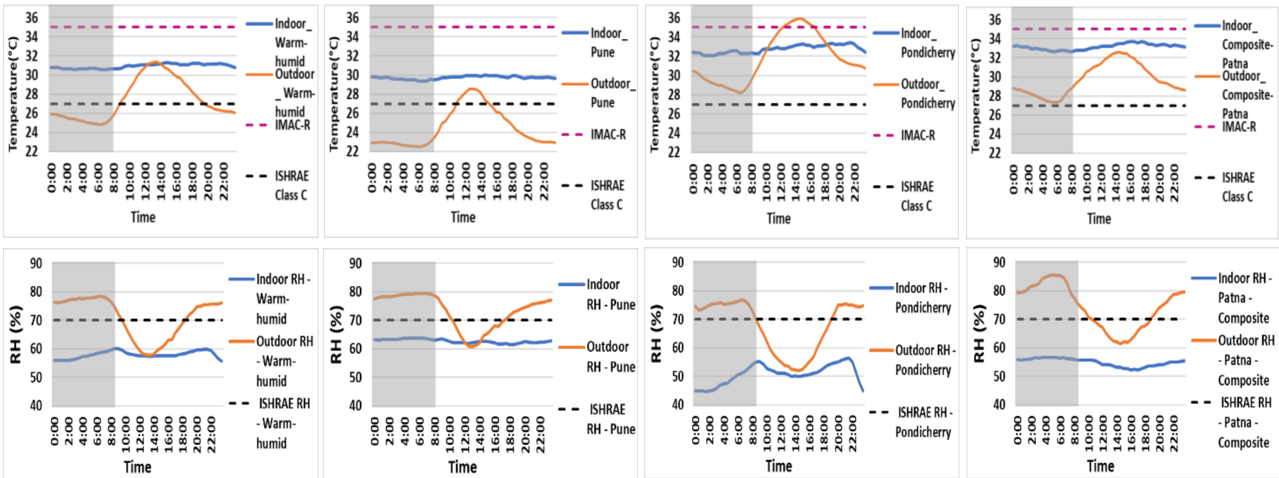


Figure 1: Boxplots showing the distribution of (left to right) indoor temperature, RH, CO_2, $PM_{2.5}$ and PM_{10} of each individual residence compared against ISHRAE standard

Figure 2 shows the indoor and outdoor temperature profiles during the sleeping (00:00-08:00) and awake hours (08:0024:00) by different dwelling cities and climates. In this case, the monitored indoor temperature was compared against the Class C indoor operative temperature (27°C) prescribed by ISHRAE IEQ standard [9] and the upper limit of the neutral temperature range prescribed by IMAC-R [8]. According to the IMAC-R model, more than 80% of the Indian residents experienced a neutral thermal sensation in the indoor operative range of 16.3°C–35°C. Overall, the mean indoor temperature measured in this study was in line with the operative temperature range prescribed by the IMAC-R model.

In general, Patna, in the composite clime, had higher outdoor and indoor temperatures than cities in the warm-humid climate. Even though Pune and Pondicherry have a warm-humid climate, the daily indoor temperature profiles show a difference of 3°C between them. While the correlation between indoor-outdoor temperature for residences in the composite climate was found to be weak (Pearson correlation r =0.164, R^2 = 0.027), a moderate correlation was observed in residences located in the warm-humid climate (Pearson correlation r = 0.58, R^2 = 0.338), both statistically significant at 0.01 level. Moreover, indoor temperature is also influenced by local environmental conditions, which is why a higher indoor temperature was found in residences with 2 AC units than those without AC units.



(a) Warm-humid climate (b) Pune (c) Pondicherry (d) Composite climate-Patna

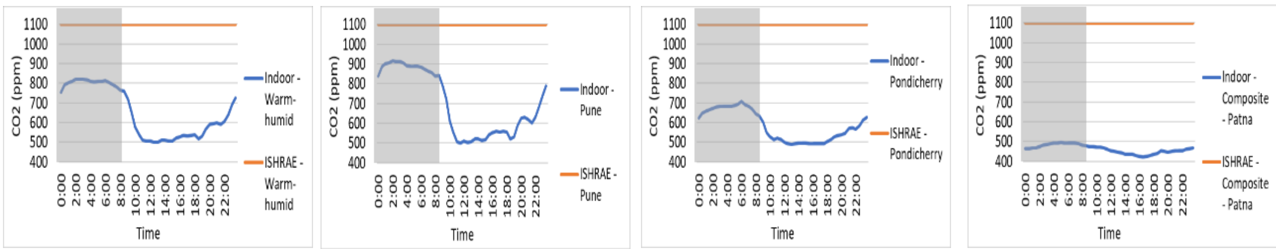
Figure 2: Indoor and outdoor temperature (top) and RH (bottom) profiles averaged over 10 days by Warm-humid and Composite climatic zones. The shaded area represents sleeping hours.

Profiles of indoor RH showed less daily variation over the course of the monitored period. Although daily mean RH ranged from 48% in PD2 to 64% in P01 (Table 1), they were in line with ISHRAE's recommended acceptable range of 30-70%. Indoor RH showed a weak correlation with external RH with Pearson correlation r = 0.288 and 0.314 for the composite and warm-humid climates, respectively, both significant at the 0.01 level.

CO_2 levels

Since indoor CO_2 is mainly emitted by building occupants, CO_2 levels can be a useful indicator of occupancy patterns. Excessive CO_2 indoor concentrations can indicate inadequate ventilation levels in homes, with possible accumulation of other indoor pollutants [20]. Throughout the monitoring period, CO_2 concentrations varied across case study residences due to diversity in residents' window opening behaviours and the number of occupants. The ISHRAE recommended maximum value for CO_2 is 1100ppm [9]. Except for residence P04, all other residences experienced lower CO_2 levels ranging from 400ppm to 700ppm, as shown in Figure 3. Low CO_2 concentration levels could be due to the frequency of window openings by the residents to remove smells due to cooking activities. Residence P04 experienced the highest CO_2 level at 1119ppm due to a high number of occupants – eight residents occupying the residence constantly (Table 2).

The correlation between indoor CO_2 concentration levels and the number of residents was moderately strong, with the Pearson correlation value at 0.6 and significant at the 0.01 level.



(a) Warm-humid climate (b) Pune (c) Pondicherry (d) Composite climate -Patna

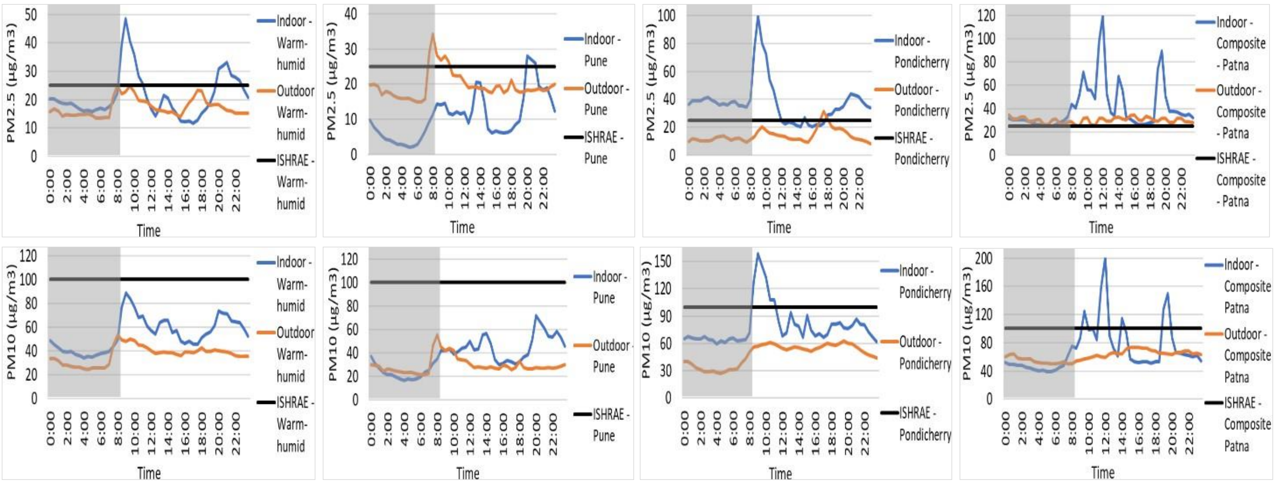
Figure 3: Indoor CO_2 daily profile averaged over 10 days by climate. The shaded area represents sleeping hours.

CO_2 levels varied during the sleeping hours and waking-up hours, as observed in the daily CO_2 profiles. The peak CO_2 concentration occurred during sleeping time. While in residences located in composite climatic zones, CO_2 concentration was stable between 400 to 500ppm, the CO_2 profile in the residences of warm-humid climate varied significantly during the daytime and between sleeping and waking up hours (Figure 3, left figure). This is likely to be due to the difference in the window opening behaviours of residents.

Particulate matter ($PM_{2.5}$ and PM_{10})

Particulate matter (PM) consists of tiny solid or liquid particles found in the air. Pollutants from combustion processes, such as $PM_{2.5}$ and $PM_{10,}$ are generated from outdoor sources, such as traffic and industrial processes, as well as indoor sources, such as cooking and cleaning. The indoor levels of $PM_{2.5}$ and PM_{10}, in the presence of indoor sources of PM, are usually higher than the outdoor PM levels [21]. Exposure to $PM_{2.5}$ is known to induce oxidative stress and is the leading cause of cardiovascular mortality [13, 22]. High $PM_{2.5}$ levels could lead to death in the worst-case scenarios.

The concentrations of particulate matter $PM_{2.5}$ and PM_{10} were found to vary significantly across the residences throughout the monitored period. As shown in Table 3, mean concentrations of $PM_{2.5}$ in residences P01, P03, and P04 were found to be below the ISHRAE recommended limits of 25µg/m^3 ($PM_{2.5}$), while residence PT8 experienced the highest mean $PM_{2.5}$ levels at 68µg/m^3. Mean PM_{10} levels varied between 34µg/m^3 in residences P01 and P03, 45µg/m^3 in P04, 55µg/m^3 in PT7, 59µg/m^3 in PT10, 60µg/m^3 in PD2, 98µg/m^3 in PT8 and PD5. Across all case study residences, PM_{10} levels were found to be below the ISHRAE's recommended limit of 100µg/m^3 for PM_{10} [9].



(a) Warm-humid climate (b) Pune (c) Pondicherry (d) Composite climate -Patna

Figure 4: Indoor and outdoor particulate matters ($PM_{2.5}$ (top) and PM_{10} (bottom)) profiles averaged over 10 days by climate: Warm-humid, Composite. The shaded area represents sleeping hours.

The daily profiles of $PM_{2.5}$ in residences of warm-humid and composite climates varied significantly throughout the daytime because of the relationship with occupant activities. Spikes in $PM_{2.5}$ levels were observed around the cooking time in the evening, as shown in Figure 4. As other studies have shown, cooking fuels are the biggest contributor to high PM concentration levels in Indian households, which explains why PM peaks occurred during the cooking time in this study. While in the warm-humid climate residences, more than 70% of the monitored $PM_{2.5}$ concentrations were below the ISHRAE recommended range, this proportion was 50% in the residences located in composite climate.

Interestingly, non-AC residence PT8, with the smallest internal floor area of 65m^{2,} was constantly occupied by five residents (Table 2) and experienced higher PM levels. In contrast, residence P03, with three AC units and a bigger floor area of 125m², experienced the lowest PM levels. As shown in Table 1, residence PT8 experienced the maximum range of mean $PM_{2.5}$ and PM_{10} compared with the rest of the sample residences.

Cross relating IAQ parameters

The strength of the relationship between indoor and outdoor IAQ parameters across different cities, climates, and dwellings was determined using Pearson's Correlation. As shown in Table 4, at the sample level, the correlation between outdoor and indoor temperature was moderate (Pearson correlation r=0.556), and the correlation between outdoor and indoor RH was weak with a Pearson correlation value of 0.254; both sets of correlations were statistically significant at 0.01 level. The Pearson correlation values of $PM_{2.5}$ and PM_{10} were both less than 0.2, indicating a weak correlation between indoor and outdoor PM. Indoor temperature was found to have a moderate correlation (r=0.43) with outdoor PM_{10}, which was statistically significant at 0.01 level. The household survey revealed that most residents chose to keep windows closed because of dust and high outdoor temperatures. Dust is one of the main contributors to PM_{10} [13, 22], which might explain the moderate correlation.

Table 4: Pearson's Correlation Coefficient between indoor and outdoor air quality parameters at the sample level

	Outdoor Temp	Outdoor RH	Outdoor $PM_{2.5}$	Outdoor PM_{10}	Indoor Temp	Indoor RH	Indoor CO_2	Indoor $PM_{2.5}$	Indoor PM_{10}
Indoor Temp	.556	-.099	.172	.430	1	-.589	-.224	.185	.149
Indoor RH	-.553	.254	.067	-.320	-.589	1	.227	-.145	-.096
Indoor CO_2	-.374	.161	-.118	-.240	-.224	.227	1	-.069	-.057
Indoor $PM_{2.5}$	.243	-.028	.138	.200	.185	-.145	-.069	1	.964
Indoor PM_{10}	.205	-.109	.082	.171	.149	-.096	-.057	.964	1

Interestingly, indoor temperature and indoor humidity had a moderate negative correlation with a correlation coefficient of around –0.6. Generally, as air temperature increases, air can hold more water molecules, and its relative humidity decreases. When temperatures drop, relative humidity increases, and vice versa. Levels of CO_2 and indoor humidity showed a positive weak correlation with the Pearson Correlation value of 0.227. In addition, indoor CO_2 and indoor temperature had a weak negative correlation of -0.224. There was no correlation observed between indoor PM ($PM_{2.5}$, PM_{10}) and CO_2, implying that measuring CO_2 alone may not be a suitable proxy for assessing IAQ in Indian residences. Occupant activity affects indoor PMs as the value increases significantly during waking hours. Most of the PMs were generated due to household activities such as smoking, cooking, cleaning, and use of air fresheners. The relationship between CO_2 and PMs is still under researched.

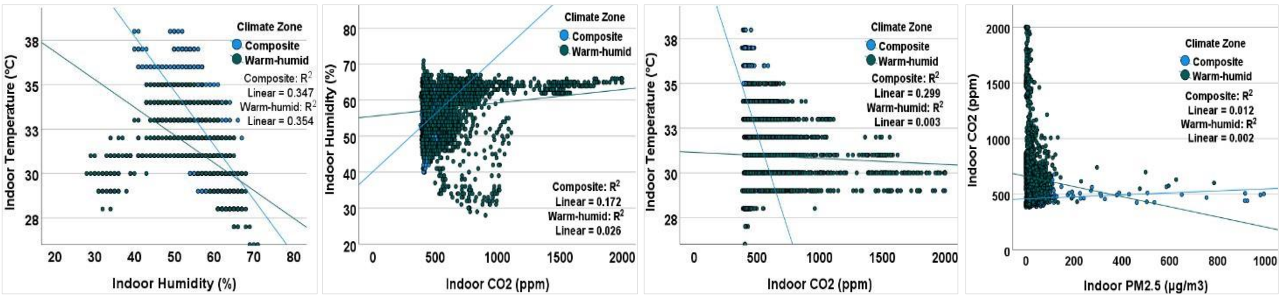


Figure 5: Scatter plots showing a relationship between IAQ parameters across two climates

IAQ parameters and household characteristics

The monitored IAQ variables were analysed based on dwelling and household characteristics that included built form, income group, number of AC units, and number of residents. At the building typology level, the apartment residences showed higher indoor temperature, RH, and CO_2 levels than the house residences but with better air quality in PMs levels. The row houses (with two sides covered) had the lowest indoor temperature.

As seen in Figure 6, daily profiles of IAQ parameters varied by number of AC units. Evidently, the residents experienced lower levels of $PM_{2.5}$ and PM_{10} as the number of AC units increased. Residences with three AC units were found to have the lowest indoor temperature, $PM_{2.5}$, and PM_{10} levels while also having the highest indoor RH during the monitoring period. Residences with two AC units experienced fluctuations in daily mean indoor RH and had the highest indoor temperature and CO_2 levels. Residences without AC performed well in terms of indoor RH and CO_2 concentrations in homes, but had the highest levels of $PM_{2.5}$ and PM_{10} levels during the monitoring period. The mean concentrations of $PM_{2.5}$ were up to four times more than the ISHRAE $PM_{2.5}$ safe limit of 25µg/m³.

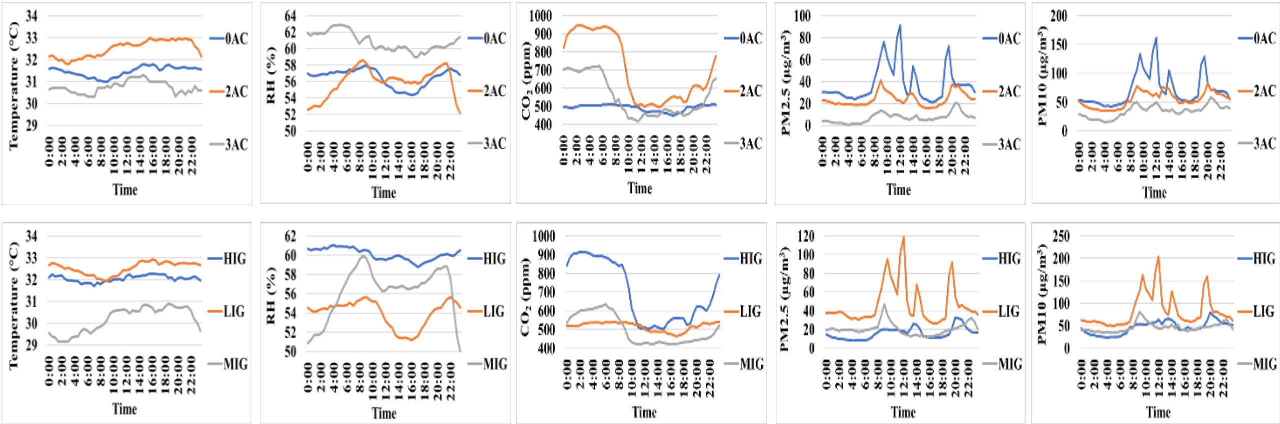


Figure 6: Distribution of daily IAQ parameters across different physical household characteristics: Number. of AC (top), income groups (bottom)

The study also found that daily indoor temperature and $PM_{2.5}$ and PM_{10} levels were found to be high during the monitoring period. As presented in Figure 6 (bottom), non-AC LIG residences were observed to have the lowest indoor RH, while the monitored daily average temperature, $PM_{2.5}$ and $PM_{10,}$ were highest during the study period. The MIG residences were observed to have the lowest indoor temperature, as well as lower levels of CO_2 during waking hours. In contrast, high levels of CO_2 concentration and indoor RH were observed in HIG residences. This may be due to inadequate ventilation, possibly driven by closing windows during the use of air-conditioning, as indicated in the household survey with HIG residences, wherein residents preferred to use AC or fans instead of opening windows. No major differences were observed between the MIG and HIG residences in terms of the concentrations of $PM_{2.5}$ and PM_{10}. The indoor $PM_{2.5}$ had a weak negative correlation with the floor area of residences (Pearson Correlation $r = -0.228$, significant at the 0.01 level). Higher indoor CO_2 levels were observed in residences with a high number of occupants. The peak CO_2 concentration occurred during sleeping time (00:00-08:00) when there were more people in homes. This is why a moderate correlation was observed between indoor CO_2 levels and the number of residents, with a Pearson correlation value of around 0.6.

Data analytics and visualisation dashboard

To provide access to the empirical data gathered and raise awareness about exposure to poor IAQ in homes, IAQ data gathered in the study has been made available to the academic, policy, and business communities through an online data analytics and visualisation dashboard called RIAQ (RESIDE Indoor Air Quality Dashboard). RIAQ dashboard is designed to be an online interactive platform that has the capability to rapidly analyse and visualise IAQ parameters for individuals or a combination of case study urban Indian residences. RIAQ can also generate IAQ profiles and cross-relations between different IAQ parameters for any time scale in the monitoring period and relate them to key building and household characteristics.

The RIAQ dashboard presents the outputs in the form of a bar graph, line graph, box plot, and scatter plot, while allowing users to filter the outcome data based on the typology, time period, dwelling ID, and IAQ parameters. It brings together technical monitoring data on IAQ performance and contextual data on building attributes, household characteristics, and appliances ownership and visualises data at different levels, including the *sample level* (all residences), *typology level* (by climatic zone, built form, dwelling size, income group and the number of AC units), and the *individual residence* level.

The RIAQ dashboard includes five elements (tabs) - *Characterising, Profiling, Distribution, Correlation,* and *Benchmarking*. Characterising presents information on the contextual characteristics of the residences through a series of line graphs and bar charts, including built form, dwelling size, income group, and appliance ownership. These can be filtered by typology and by individual residences. The daily trends and variations in IAQ parameters across the sample are visualised on the Profiling page as presented in Figure 7 (left figure), which can be filtered based on by typology and by individual residences, as well as the IAQ parameters and time period. The default visualisation displays results at the sample level.

The distribution of IAQ parameters can be explored through the box plots presented in the *Distribution* section of the EIAQ dashboard. The IAQ parameters are characterised by the number of residents, built form, income group, and the number of AC units. The strength of the relationship between IAQ parameters data and contextual characteristics of the residences can be explored in the *Correlation* section four scatter plots, as shown in Figure 7 (right). Grouped by AC and non-AC residences, the relationship between indoor humidity and indoor temperature, indoor CO_2 and temperature, indoor CO_2 and humidity, and indoor CO_2 and $PM_{2.5}$ are shown in this section. Users of RIAQ can identify the strength of the relationship through positive and negative linear trend lines in each scatter plot.

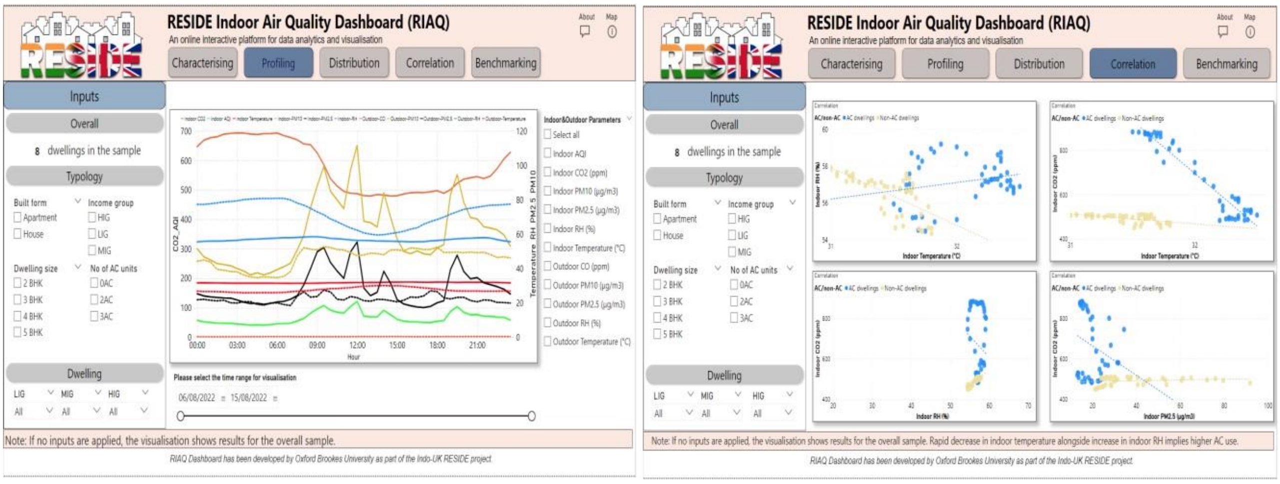


Figure 7: RIAQ dashboard profile examples: Profiling page (left) and Correlation page (right)

In the *Benchmarking* section, IAQ parameters are compared against the corresponding recommended levels by standards to observe any deviations. The ISHRAE IEQ standard [9] is used to visualise maximum values (Class C) for the indoor temperature at 27°C, RH at 40% -70% range, CO_2 at 1100ppm, $PM_{2.5}$ at 25µg/m^3 and PM_{10} at 100µg/m^3. Users can select appropriate IAQ parameters and associated benchmarks simultaneously to visualise results.

To our knowledge, there is no freely-available online and interactive dashboard that has the capability to rapidly analyse and visualise IAQ in urban Indian residences. The RIAQ dashboard developed in this study can generate user-determined IAQ profiles, show cross-relations between different IAQ parameters for any time scale in the monitoring period, and relate them to key building and household characteristics. This allows academics, researchers, policymakers, and building practitioners to better understand how IAQ varies daily in Indian residences with different numbers of residents. This can potentially enable further research related to improving IAQ in residences.

Discussion

This study has discovered interesting findings through an empirical approach combining monitoring (indoor IAQ) with household surveys (context) for eight urban Indian residences located in three cities covering two climatic zones. Despite the small sample, variation in the levels of IAQ parameters was observed during the monitoring period (6th-15th August 2022). Daily mean temperatures ranged from 28.3°C to 35.2°C, which were slightly warmer than the operative temperature prescribed by ISHRAE. Mean indoor RH levels varied from 48%-64%, which remained within the acceptable range of the ISHRAE standard. Apart from one residence (P04), all other residences experienced lower levels of CO_2 ranging from 400ppm to 700ppm, much below the upper benchmark of 1100ppm prescribed by the ISHRAE standard. Residences in apartments experienced higher indoor temperature and CO_2 levels than stand-alone houses since apartments are likely to have smaller areas for windows (for ventilation) in relation to floor area.

The measurements of $PM_{2.5}$ and PM_{10} showed interesting trends. While $PM_{2.5}$ and PM_{10} levels remained low, under 50µg/m^3 and under 80µg/m^{3,} respectively, during sleeping hours, they varied significantly throughout the daytime. Monitored $PM_{2.5}$ levels (arising from combustion and cooking) varied across the study sample, with mean $PM_{2.5}$ levels ranging from 11µg/m^3-68µg/m^3, with half of the residences experiencing $PM_{2.5}$ levels above the upper threshold value of 25µg/m^3 set by ISHRAE. Mean PM_{10} concentration ranged from 34µg/m^3-98µg/m^3, which was below the ISHRAE prescribed upper threshold value of 100µg/m^3. Overall, PM levels were related to occupant activities such as cooking.

Indoor air quality is also influenced by outdoor pollution through air exchange. This is why indoor $PM_{2.5}$ and CO_2 levels correlated with corresponding outdoor levels. A moderate correlation was observed between indoor temperature and outdoor PM_{10}. The fact that no correlation was observed with CO_2 levels, $PM_{2.5,}$ and PM_{10} implies that simply monitoring CO_2 levels in residences may not be a suitable proxy for assessing IAQ in Indian residences. Monitoring of PMs also needs to be encouraged to get a true picture. Even though high-income households have more modern amenities, they experienced poor levels of IAQ, followed by the low-income group, while residents in the middle-income group experienced better levels of IAQ. This finding is similar to the study by Garg & Ghosh [16], wherein they used the calculation of indoor/outdoor (I/O) ratios to compare the IAQ across the three income groups.

Given the paucity of empirical data, this research developed an online interactive platform, i.e., the RIAQ dashboard, to help users understand how indoor air quality varies daily in Indian residences that have different built forms and are occupied by different income groups. Insights from this study can help policymakers understand the trends of residential IAQ and support the development of regulations, with the ultimate aim of improving IAQ in Indian homes.

Conclusion

Indoor air quality is a global issue being associated with health, economic, and sustainable development goals, yet there is limited research on measuring IAQ in Indian residences. This study has adopted a field study-based approach to empirically examine the trends and concentrations of IAQ in a sample of urban Indian residences and explore the relationship between contextual characteristics and IAQ. Empirical evidence gathered in the study suggests that even for a small sample of eight residences, there was wide variation observed in indoor temperature, relative humidity, and PM_{10} levels, possibly due to occupancy patterns and personal activities of occupants. Interestingly, although the high-income group living in apartments are equipped with more AC units, their overall indoor air quality was found to be poorer, followed by the low-income group, while the middle-income households were found to have better IAQ.

To raise awareness about the exposure to poor IAQ in homes, IAQ data gathered in the study has been made available to the academic and policy communities, as well as industry, through the online RIAQ Dashboard. This interactive dashboard has the capability to rapidly visualise IAQ parameters for individuals or a combination of case study residences. RIAQ can also generate IAQ profiles and cross-relations between different IAQ parameters for any time scale in the monitoring period and relate them to key building and household characteristics.

Since the research presented is based on a small sample, there are limitations in drawing generalisations on the relationship between IAQ and household characteristics in urban Indian residences. Nevertheless, the methodological approach adopted in the study can be rolled out nationally to provide a more comprehensive coverage of urban Indian residences across different types and locations.

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Quantifying the Demand Response Potential of Residential Loads in India

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Highlights

- Smart meter data from residences in Pune City is analyzed for estimating urban residential load in India.
- Appliance ownership data is exploited to infer electricity usage and peaks in the load curve for each household.
- Potential of demand response (DR) programs is studied using this data set to shave peaks by load shifting.
- Load composition of residences contributing to system peak is studied to estimate their DR potential.

Abstract

The paper investigates how residential loads in India contribute to grid peak load and how to manage such peaks. Algorithms that process smart meter data from residential loads and compute attributes that capture their contribution to the system peak are devised and demonstrated in the paper. Specifically, a distribution system is considered based on a study on households in Pune, India. To enhance the household dataset for analysis, a synthetic data generation technique is employed. The algorithms developed here are applied to this system to showcase their capabilities. Results show how simple attributes such as peak amplitude and peak duration can extract sufficient information to ensure households that contribute to system peak are appropriately identified. Moreover, these attributes offer insights into appliance ownership, supporting the development of effective DR programs. A demonstration of how shifting of individual peaks can significantly impact system peak is also provided. The results lay the foundation for designing meaningful DR programs leveraging the smart meter data.

Keywords: demand response, residential loads, peak load shaving, load shifting

Introduction

The residential consumption in India accounts for about 24% of the total electricity in the country [1]. There are multiple categories of appliances owned by these households. Understanding the appliance penetration in individual households and studying their load curve can help the utility to manage the efficient dispatch of power for the system. For instance, when a few households consume high power at the same time, it could result in high demand. This demand is met by activating high-cost generators, leading to increased generation costs for the utility and, thus, higher electricity bills for consumers. Managing the system peak is a concern for all utility operators; it can be managed via an effective generation dispatch, leveraging storage and/or demand side management. This paper is concerned with the last category.

Demand side management and demand response (DR) programs motivate the consumers of households to reduce or shift their electricity usage from peak periods to off-peak periods by providing financial incentives or by responding to time-varying electricity prices. DR programs are an intelligent way used by the system operator to balance supply and demand to make decisions to operate low-cost generators to fulfill the estimated household demand. There are multiple methods by which end users are engaged in DR programs. Time-based electricity pricing, like time-of-use (ToU) pricing, critical peak pricing (CPP), and real-time pricing (RTP), is a way in which the consumer is motivated to shift the appliance operation based on electricity tariff information. Direct load control programs provide flexibility to the utility to control high consumption loads like air conditioners (ACs) and water heaters (WHs) by turning ON and OFF during intervals of system peak in lieu of financial incentives.

The potential for DR among residential consumers increases with the growing penetration of flexible and controllable loads like electric vehicles (EVs) and cooling and heating appliances such as ACs and WHs. DR programs, leveraging advanced metering infrastructure (AMI) and other innovative technologies, can alter the electricity consumption patterns of households by shifting, shedding, or shaping the load curve [2]. However, engaging consumers in DR programs can be challenging, especially in terms of which consumers to enrol. DR implementation requires the installation of smart meters and communication capability to enable the exchange of information between the grid and the end user. Smart meters allow improved management and control over the electricity grid. Meter data can help utilities to identify appropriate residential consumers for the DR program.

Residential DR programs that show a reduction in peak load by controlling operations of WHs [3] have been studied in the literature. Experimental results covered in [4] show a drop in peak demand by 3% to 6% when using ToU pricing and a 13% to 20% drop in peak demand when using CPP. The survey presented in [4] for the United States mentions a change in metering infrastructure for implementing DR in the retail electricity market and emphasizes that about 60% of the investment can be covered by savings in distribution system costs. The remaining amount could be recovered by reducing power generation costs which could be achieved by DR. A survey conducted in [5] has assessed appliance use behaviour and DR preferences to simulate DR potential by using the survey data in a Home Energy Management System (HEMS) optimization tool. A peak reduction of 33% was observed with the use of HEMS for DR.

The success of electricity DR programs is found to be correlated with the extent of urbanization of the area where it is implemented and annual economic growth rates. The DR programs in the future can be made more effective by deploying DR programs in urban areas with the capability to afford infrastructure and coupling the program with economic policies and urban development planning [6]. To address the potential of implementing DR for large industrial and commercial customers, a bottom-up engineering approach that assesses the individual user's peak load is studied in [7]. The customer survey-based approach reported in this paper uses the responses to evaluate the likelihood of end users participating in DR programs. Evaluation of the DR potential of heating, ventilation, and air conditioning (HVAC) systems is studied in [8], which considered a DR event period, and load adjustment in the DR period was evaluated by ensuring consumer preferences. A simulation tool for estimating DR potential from residential loads is presented by modelling occupant behaviour relating to residential activity patterns and residential loads [9]. A study in [10] estimates the impact of change in the setpoint of HVAC in implementing DR programs. The household information available in [11] is leveraged to build a demand curve for individual households. Their behavioural patterns and appliance ownership information are used to create a demand curve for individual households. The case study focuses on peaks generated in the utility demand curve and observes the peaks of households to study the appliance level contribution on individual peaks and harness the information to save during peak price periods by shifting the operations to low pricing intervals.

From the literature reviewed above, it can be concluded that smart meter data analysis can be leveraged to assess DR potential. Due to the absence of sufficient smart meter data for residential DR in the Indian context, this paper leverages information on household type and appliance ownership along with recorded smart meter data from select houses in Pune to generate representative synthetic household consumption data. A hypothetical total system load is computed using the recorded data from the select houses and synthetic data. This time series system load, along with individual household time-series load data, is analysed to understand the DR potential of households having high-consumption appliances such as WHs and ACs. The role such houses play in shaping the system load peak is comprehensively studied using easily computable metrics: peak amplitude and peak duration. Finally, the appliance ownership information available [11] is leveraged to infer appliance usage and contribution to individual peaks, and a rudimentary load-shifting application is presented to potentially shave the peak by load-shifting intervals.

Preliminary Data Analysis

Dataset

eMARC dataset [11] is used to construct the load data for the analysis presented in this paper. The dataset encompasses power consumption information of 5 cities having 115 households for a period of two and half years from Jan 2018 to June 2020. The data includes both the daily consumption power as well as 15-minute block aggregate power consumption dataset for individual households in each city. The 15-minute block dataset for all the cities is considered for this paper. This dataset includes the basic as well as high power rating appliance ownership information like the number of lights, fans, WHs, ACs, and other appliances present in each household. From the review literature, the DR potential of residential appliances like WH and AC is established. Therefore, for this study, load data from households with AC and WH appliance ownership are considered, and hence data from Pune & Pune City comprising of 67 households are used. To avoid having to tackle with large volumes of missing data, only 55 households having less than 30 days of missing data are included in this analysis. Information on the income of households is unavailable and may not be disclosed due to privacy issues.

Data Pre-processing

The raw data of the considered households has missing data points for some intervals. Every household is expected to have 96 data points showing aggregate load power for each day. For each household, daily load curves having at least 90 data points are considered for the analysis. The remaining days with fewer data points are replaced with the data of the day having the nearest temperature of that corresponding day. For the days that have up to 6 missing data points, the linear interpolation method [12] is used to impute the missing data. After data pre-processing, the dataset comprises 15-minute interval power consumption profiles of 55 households over 365 days, starting from 1 January 2019 until 31 December 2019.

Appliance Usage and Synthetic Data

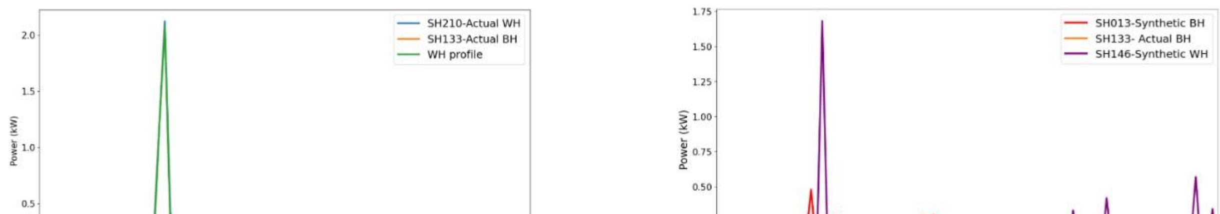
The initial dataset comprising of 55 households is used to generate a collection of 245 synthetic household data to enrich the analysis of the study. From the eMARC dataset [11], the shortlisted 55 households are categorized based on ownership of WHs and ACs: 6 households have AC ownership only, 12 have WHs only, 8 households own both WH and AC, and 29 basic households (BH) have neither AC nor WH ownership. The appliance ownership information allows for appliance usage patterns to be inferred to aid the synthetic data generation.

The synthetic data generated for this work is derived from an adaptation of the Generative Adversarial Network (GAN) model [13]. The adapted model takes as inputs the original daily load curves of basic households from the eMARC dataset and typical daily appliance usage patterns for WHs and ACs. Through statistical techniques, the load curves are reproduced with suitable time shifts and scaling as needed, with appliance usage patterns superimposed on them if necessary. In this way, basic household load data can be processed to generate load data for another hypothetical house that is either basic or has WH, AC, or both appliances.

To illustrate the synthetic data generation process, consider WH household (SH210) and basic household (SH133) from the eMARC dataset. The appliance ownership of both is presented in Table 1: it is evident that the households are nearly similar in all aspects, such as number of occupants, house area, and number of appliances, except for the WH presence in SH210. Assuming that the energy consumption of both households is only differentiated by WH appliance operation, the two datasets are subtracted and suitably rounded off to derive the WH energy consumption patterns as shown for a typical day in Figure 1(a). The load data of SH133 can then be processed along with appliance consumption data, thus derived in the adapted GAN model to generate data for a basic synthetic household and a synthetic household with WH. Figure 1(b) shows the typical daily load curve for all three households: SH133, synthetic WH house SH146, and synthetic basic house SH013.

Table 1: Appliance data and other relevant information of two example households

H.No.	Area	Rooms	People	ACs	Air cooler	WH	Fans	Lights	WM	Mixer	Iron
SH133	575	3	2	0	0	0	3	11	1	1	0
SH210	600	3	2	0	0	1	3	9	1	1	1



(a) Extracting appliance consumption pattern *(b) Generating synthetic load curve*

Figure 1: Daily load profile and load duration curve

The AC usage patterns are harder to extract from real data; rather, these are simulated using ambient temperature, occupancy, and rated power of AC for each house along with an assumed setpoint temperature using the standard equivalent thermal parameter model such as the one proposed in [14]. This way, the power consumption of the AC for each time interval is derived by making suitable assumptions on the time of the day and months of the year when the AC would be ON. With AC and WH consumption profiles thus generated, the original dataset comprising of 55 households is processed to generate synthetic data for an additional 245 hypothetical households. Table 2 shows the description of actual and synthetic datasets with respect to appliance ownership. The household distribution is approximately informed by the original distribution of household ownership types, effectively capturing the diverse proportions of basic, WH-only, AConly, and AC-WH ownership configurations.

Table 2: Household information for the complete dataset

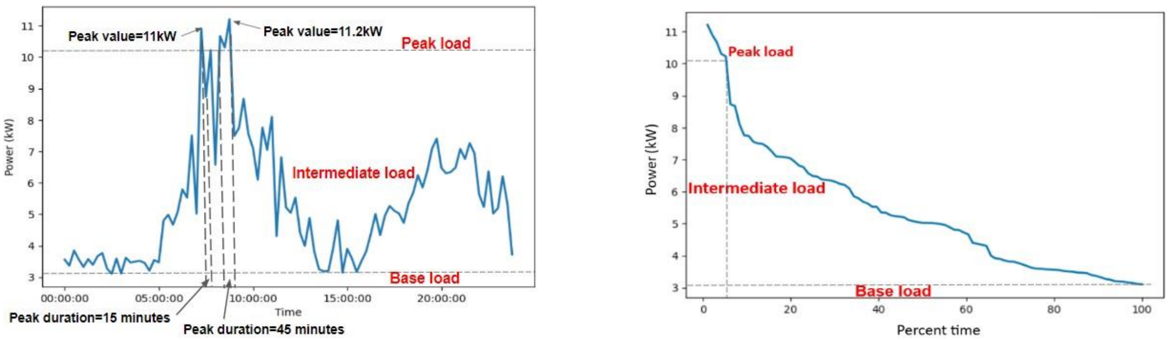
Dataset (Count)	Basic (Count)	WH only (Count)	AC only (Count)	WH & AC (Count)
Actual (55)	SH109-SH137 (29)	SH205-SH216 (12)	SH240-SH242 (3)	SH287-SH297 (11)
Synthetic (245)	SH001-SH108; SH298-SH300 (111)	SH138- SH204 (67)	SH217- SH239 (23)	SH243-SH286 (44)

Methods

Load duration curve (LDC)

Suppose the load is recorded for T samples each day. The LDC represents the statistical distribution of the load over a specified period. For instance, consider a typical daily load curve based on 15 minutes of sampled data, as shown in Figure 2(a). The LDC is obtained by rearranging the recorded load values in descending order and translating the X-axis to percent time [15], as shown in Figure (b). The minimum demand needed to supply is termed the base load. The peak load is assumed to occur 5% of the time. The power between peak load and base load is known as intermediate load. Figure 2(b) shows the base, peak, and intermediate load values.

Load curve can be plotted for a year also. It helps the utilities to identify the day and time during which the system load was at peak values in that year. If this peak load can be reduced or shifted, then it can help the utilities to reduce the burden on their generating stations.



(a) Daily load profile *(b) Load duration curve*

Figure 2: Daily load profile and load duration curve

Peak Associated Attributes

The following are the peak associated attributes are considered based on LDC and time-series data:

1) Peak value: The magnitude on the y-axis on the LDC for 5% time represents the peak value. 2) Peak duration: The duration for which this peak occurs is defined as the peak duration.

For the load curve in Figure 2(a), these peak attributes are plotted for reference. The peaks that are generated for individual households and the entire system can be studied to identify the appliance level contribution. The days and intervals that contribute to the top 5% of time are considered. Two algorithms are proposed to study the peak attribute information for these days. Algorithm 1 is proposed to identify the contribution of households to the peaks and infer the dominant appliance operating at the peak day. Algorithm 2 calculates the duration of peaks that occur for households with and without AC.

Algorithm

Consider H number of households for D days. Each day, D has T data points at timesteps of 15 minutes. Here, H, D, and T are 300 households, 365 days, and 96 data points, respectively. Let the notation for household be h. Let P be the peak load of the total system load in kW and $p \in P$ be the subset of the 0.5% time of the LDC. Considering i as the instance of date and time, p_i represents the i^{th} instance of p. Let h_{ji} be the household $j \in \{1,2,\ldots,H\}$ at i^{th} instance of date and time. The peak load in kW of household j at instance i is given by $p(h_{ji})$. Let δ be the allowable threshold in kW that captures the power consumption of ACs and WHs. Typical values of δ are obtained from [16] and observed to be over 1.5 kW.

Algorithm 1 shows the steps to identify the households that contribute to the high demand peak for 0.5% time. Algorithm 2 is used to calculate the duration of peaks for households with and without AC. For households with AC, the threshold Δ is introduced to capture any drop in power consumption of AC due to a change in the setpoint and duty cycle of the AC. These algorithms are used to analyse the data set.

Algorithm 1 Identifying contribution of peak load

Require: H, D, T, p_i, $p(h_{ji})$, δ

for $p_i \in P$ do
    Identify the households h_{ji}, $j \in \{1,2,\ldots,H\}$, that are the highest contributors of p_i
    Arrange h_{ji} in decreasing order of $p(h_{ji})$
    Calculate the total percentage contribution of the households as $\left(\sum p(h_{ji})/p_i\right) \times 100, p(h_{ji}) \geq \delta$
    Based on the ownership information of h_{ji}, the appliance operating at i^{th} instance are inferred
end for

Algorithm 2 Identifying peak instances and duration for households with and without AC

Require: H, D, T, p_i, $p(h_{ji})$, δ

for $h_{ji} \in H$
    for $p_i \in P$ do
        Consider the timeseries data for the same date of i^{th} instance
        Consider the k consecutive instances of p_i such that $p(h_{ji}) \geq \delta$
            if ownership is AC then
                Define threshold Δ as the allowable decrease in power from p_i
                The peak duration is calculated as the k consecutive instances of p_i such that $p(h_{ji}) \geq \delta p_i - \Delta$
            else
                The peak duration is calculated as the k consecutive instances of p_i such that $p(h_{ji}) \geq \delta$
            end
        The peak duration in minutes is obtained by multiplying k with 15
    end for
end for

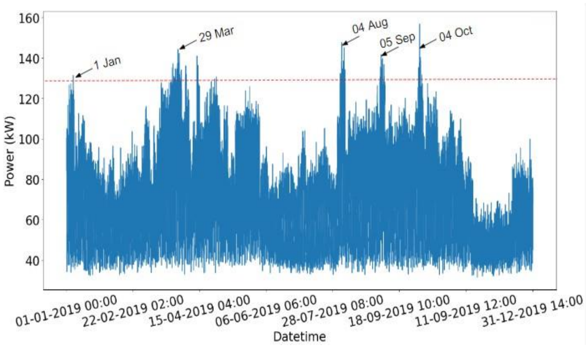
Results and Discussions

Daily consumption profile

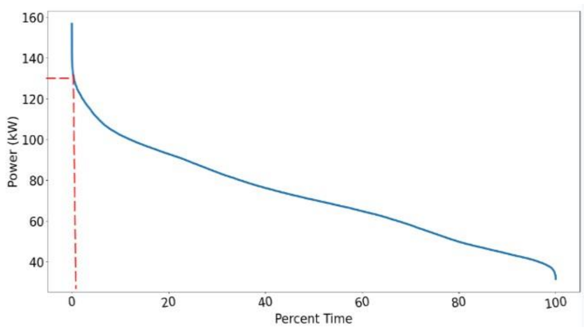
The daily load profile for all the households in the dataset is added to compute the total system load of the utility servicing these households. The system losses are ignored, and the utility is assumed to be supplied to these residential households only. Figure 3(a) shows the daily system load curve for the whole year under study (2019).

Load duration curve

To identify the peak days and time, the yearly system load time series is rearranged in descending peak load values to generate the LDC, as shown in Figure 3(b). The highest peak load of 155.86 kW occurs on 4th October 2019 at 5:15 am. Using Algorithm 1, the peak value corresponding to 0.5% time is observed to be 130 kW and marked as in Figure 3(b). A few days with load values above 130 kW are marked in Figure 3(a): the second highest peak load of 152.97 kW also occurs on 4th October at 7:00 am, followed by peak load instances recorded for 4th August, 7:45 am with 146.97 kW, and so on.



(a) Daily load profile



(b) Load duration curve

Figure 3: Daily load profile and load duration curve for complete dataset

Peak load contribution

Using the peak information obtained from the system LDC and yearly time series data, the contribution of individual households in the considered peaks in total demand is analysed for the date and time corresponding to peak load instances.

As per the LDC shown in Figure 3(b), 4th Aug. 2019 at 7:45 am shows one of the highest peak load values. During the system peak of 146.97 kW at 7:45 am, households SH280, SH283, SH285, SH282, SH290, SH250, and SH138 also show a high load value for the same interval. Figure 4 shows the daily load curve for these households and the system load curve for this day. The peak load contribution of these households is shown in Table 3 in descending order.

Table 3 includes the appliance ownership information of the peak contributing households. The load values for the selected households show that WH and AC usage play a major role in causing the system to peak. The consumption of all the households mentioned in Table 3 contributes to 27.49 kW in aggregate, implying that these 10 households, out of 300, contribute to 18.7% of the total peak load value.

From the LDC in Figure 3(b), the prominent days of peaks are noted on the time series load curve in Figure 3(a). Observing the power consumption of individual households during these peak intervals, the contribution of appliances to system peak can be studied, and the potential of DR of these loads can be estimated.

To observe the impact of ownership of appliances, peak durations corresponding to different dates of the year are considered. The date of the year and time of the day can be used to draw inferences on the status of appliances for each household. For the system peak intervals, the households with the highest load values are considered. The peak attributes for these households are computed; these along with the appliance ownership information, are studied to understand the DR potential.

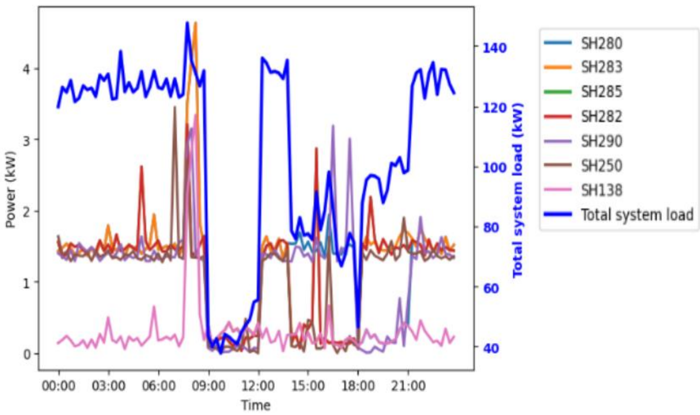


Figure 4: Load curve of households on 04 Aug 2019

Table 3: Peak load of households on 04 Aug 2019

Household No.	Ownership	Peak load (kW)
SH280	WH, AC	3.514
SH283	WH, AC	3.514
SH285	WH, AC	3.207
SH282	WH, AC	3.207
SH290	WH, AC	2.928
SH250	WH, AC	2.718
SH138	WH	2.237
SH207	WH	2.171
SH258	WH, AC	2.011
SH256	WH, AC	1.982

Table 4: Household information for peak intervals

Month	January 2019	March 2019	September 2019	October 2019	October 2019
Date-time	01 Jan, 7:30 am	29 Mar, 7:15 am	05 Sep, 7:45 am	04 Oct, 5:15 am	04 Oct, 8:00 am
Peak (kW)	130.60	143.15	139.1	155.86	150.14
Individual household load (kW)	SH253 (4.4) SH158 (3.27) SH283 (2.80) SH191 (2.12) SH251 (2.30) SH138 (2.01) SH270 (1.91) SH207 (1.87) SH215 (1.74) SH241 (1.70)	SH287 (5.09) SH285 (4.89) SH142 (3.79) SH282 (3.56) SH264 (2.97) SH291 (2.77) SH246 (1.92) SH169 (1.64) SH228 (1.63) SH260 (1.62)	SH283 (3.52) SH280 (3.51) SH278 (3.02) SH268 (2.97) SH291 (2.59) SH138 (2.43) SH207 (2.42) SH215 (2.29) SH183 (1.93) SH273 (1.88)	SH243 (4.23) SH287 (4.14) SH285 (4.09) SH282 (4.02) SH253 (3.22) SH148 (2.91) SH142 (2.83) SH140 (2.75) SH185 (2.26) SH247 (2.01)	SH280 (4.81) SH283 (4.65) SH281 (4.52) SH284 (4.31) SH207 (3.22) SH224 (1.74) SH225 (1.71) SH226 (1.69) SH217 (1.66) SH229 (1.60)
Percentage contribution	18.5	20.8	19	20.83	19.92
Ownership (majority)	WH, AC	WH, AC	WH, AC	WH, AC	WH, AC

Table 4 shows the analysis for a few peak instances shown in Figure 3(a). Each column shows the total peak load and the contribution of households to the peak for the days that experience high consumption. The total percentage contribution of high-consumption households shows that they contribute dominantly to the corresponding peaks. Based on the ownership information, the appliances that are responsible for generating the peaks are inferred in Table 4. It can be observed that a few of the households frequently operate at their peak when the system experiences peak load values for the corresponding date and time. As mentioned in Table 3 and Table 4, SH283 and SH207 contribute significantly to system peaks. SH283 has the appliance ownership of WH & AC, while SH207 has ownership of WH only. Similarly, SH280, SH287, and SH285 are observed to contribute to the highest peak load instances. These households have ownership of WH & AC. The other households contributing to the peaks have a majority of WH & AC ownership. On analysing the daily load curve of these households for the date and time mentioned in Table 4, it is observed that the peak values are mainly due to the coinciding operation times of WH & AC.

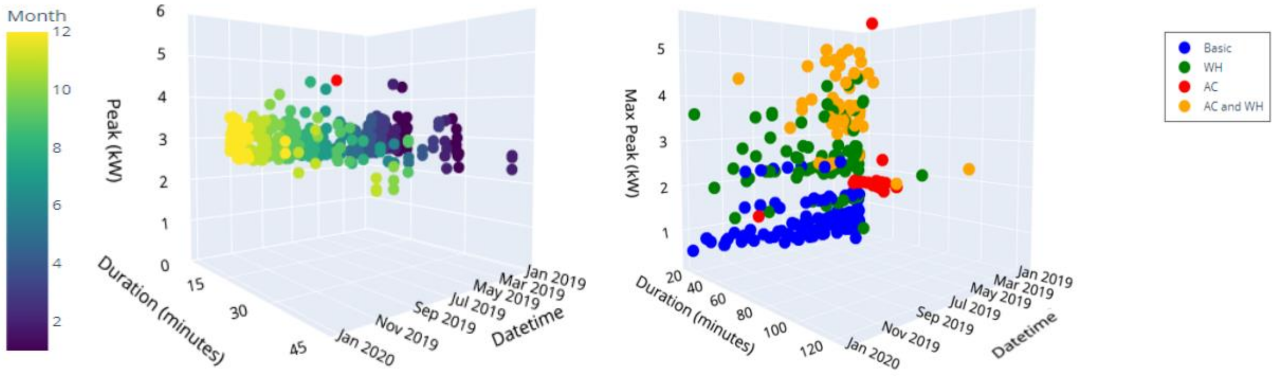
From Table 4, it is clear that households with high-consumption appliances contribute significantly to the system peak. Deferring the operation time of high-rating appliances can potentially reduce the peaks and help flatten the system load curve.

Peak amplitude information

The scatter plot for household SH291 is shown in Figure 5(a). The x-axis represents the peak duration, the y-axis represents the timing of the peak, and the z-axis represents the amplitude of the peak. The plot gives information on the variation in the highest 1% peak values of the household occurring throughout the year, along with the duration of peaks. The data points in the plot are coloured in accordance with the month of the year. The resultant projection point for this household considering maximum peak amplitude is shown in red colour in Figure 5(a). Since SH291 has ownership of both appliances, AC and WH, the duration of peaks on different days is scattered. The short-duration peaks can be attributed to the usage of WH, and longer-duration peaks can be the result of AC consumption.

The households that frequently show high load demand for system load greater than 130 kW are obtained from the LDC. The projection points using the maximum peak amplitude of the highest contributing households in LDC are marked in Figure 5(b). The colour of the data point represents the appliance ownership type of the household. This plot gives us insight into the power consumption behaviour based on appliance ownership. Some clusters within households of similar ownership types can be observed in the scatter plot, which indicates the prominent usage pattern of appliances with similar duration and peak power consumption behaviour. From Figure 5(b), it can be observed that basic households are not significant contributors to system peak and experience short peak durations. Households having ownership of only AC show high peaks in wide ranging amplitudes and duration in the month of May. However, peaks of the households with only WH are evidenced across the year, show a wide range of power consumption values, and persist for shorter durations between 15 and 45 minutes in line with expected usage of WH. Finally, for households with both AC and WH, high peaks for shorter durations that can be attributed to WH usage and peaks with longer durations that occur due to the operation of AC are seen.

A similar plot can be obtained by considering the maximum duration of the peak for all households. Analysis of the scatter plot in Figure 5(b) can be done by suppressing the datetime axis and obtaining the 2D plot of the peak amplitude and duration of the households. Figure 6 shows the resultant 2D plot containing projection points of the maximum amplitude and duration of peaks for all the households. The households with ownership of only WH have clustered at short peak duration intervals. Households with AC have a relatively higher duration of appliance usage and contribute highly to power consumption. Basic appliances, excluding AC and WH, do not have high power ratings, and the duration of operation of the appliances also varies across the day. The clustering observed amongst households containing both AC and WH gives a high indication of the usage of the appliance. Households with WH contribute to shorter duration peaks occurring for less than 45 minutes, while AC operation may be prominent for a longer duration that may be indicative of households with AC.



(a) Peak projection point for household SH291 *(b) Peak projection point for all households*

Figure 5: Peak projection using maximum peak amplitude for households.

The information on the date and time of peaks can be used as in Figure 5(b) to verify the category of appliance used in the household. Inferences can be made on ownership of households that contribute to peak amplitude and duration using Figure 5(b) and Figure 6.

This analysis can help to identify the households to perform DR to shave the system peak and avoid using high-cost generators. The projection points for individual households using the information on peak amplitude, duration, and datetime can be calculated by considering maximum peak amplitude and maximum peak duration, similar to Figure 5(b). Considering both the duration and amplitude of the projection points, Figure 7 provides added information on the duration of peaks. This can be used to infer information on the duration of the peaks of the households that are considered in Figure 6. The dominant factor that contributes to the peaks in households with ownership of both AC & WH can be estimated using the plots. Households like SH282 and SH285 have short-duration peaks with high amplitude, as shown in Figure 6. This may be a result of operating WH only, while households like SH250 and SH295 have peaks with higher duration, as shown in Figure 7, that may occur due to the operation of AC & WH.

In the subsequent section, the algorithm introduced is applied in a case study, utilizing ownership information to implement DR.

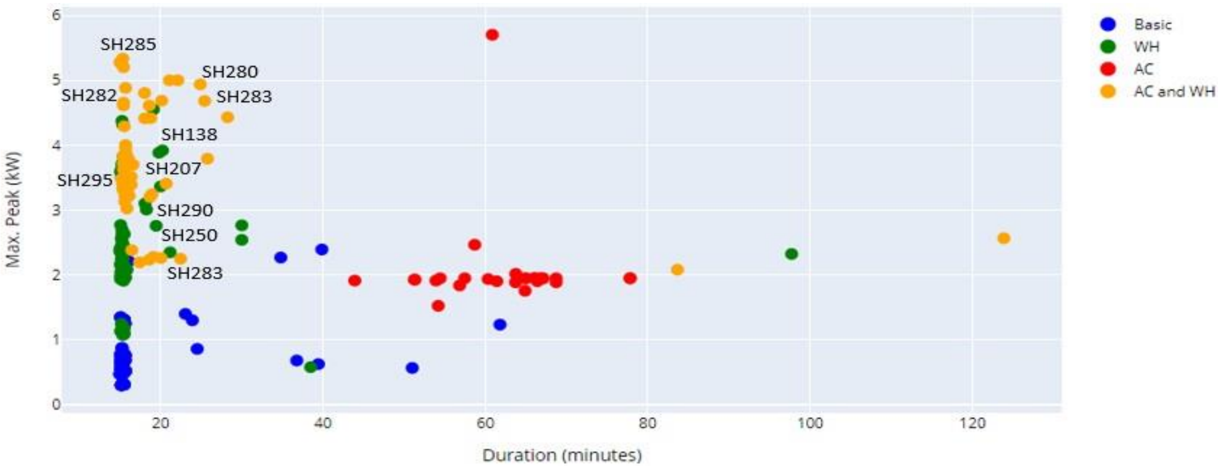


Figure 6: Scatter plot for households using projection on maximum peak amplitude

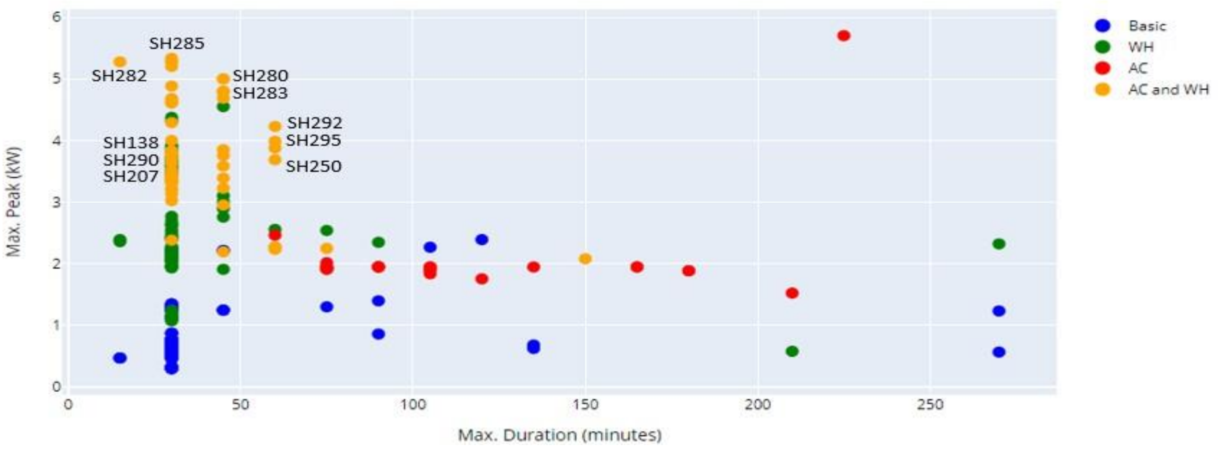
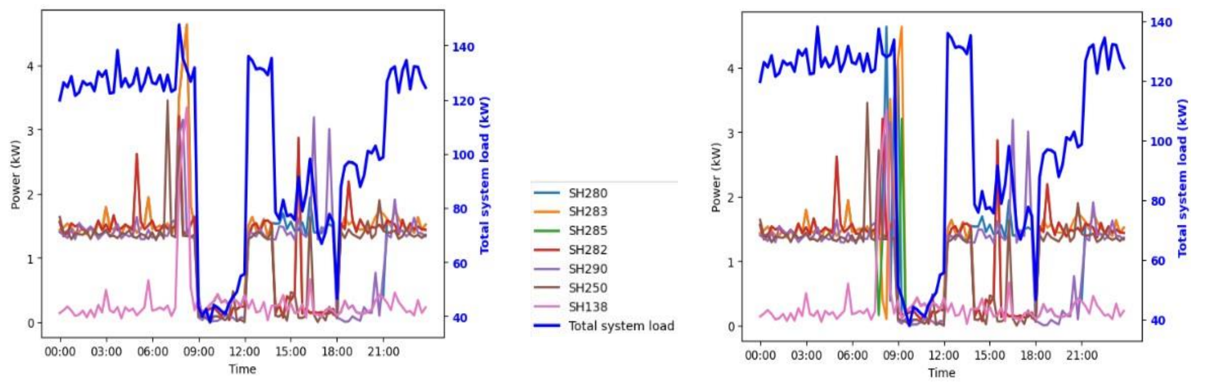


Figure 7: Scatter plot for households using projection on maximum peak amplitude and duration

DR potential of WH to remove peaks

Figure 8(a) shows the households that contribute to the system peak on 04 Aug. 2019 at 07.45 am. Table 4 shows that the top 10 households for the same interval account for 18.7% of the system peak. Considering the morning time and with the knowledge of ownership of WH in these households, the potential of eliminating the peak by shifting the operating intervals of the WH is explored. According to the survey in [5], WH offers a great DR possibility due to significantly high energy consumption. The turn ON time of WH can be shifted to off-peak intervals, ensuring the least loss of comfort for the consumers [5]. Assuming that only the WH was ON at 07.45 am in the households, the total power consumption of the household is assumed to be equal to the power consumption of the WH in this interval.



(a) Household load profiles with WH without DR *(b) Household load profiles with WH with DR*

Figure 8: Peak reduction using DR for households with WH

The load profile of households with WH without the implementation of DR is shown in Figure 8(a). By constraining the shifting time of WH to at most 30 minutes, the system peak at 07.45 am can be reduced by almost 6.5% by deferring 5 WHs operation as can be observed in Figure 8(b). Table 5 shows the potential reduction in system peak on 04 Aug. 2019 at 07.45 am by shifting the operating time of WH if DR is implemented with the objective to reduce peaks. The deferral period ensures minimum loss of comfort and also results in significant peak reduction. Peak reduction can be achieved by designing DR objectives carefully to ensure that households do not shift the operating time of appliances to low price periods together, which may result in a shift in peak.

Table 5: DR potential in WH

Peak values (kW) on 04 Aug 2019 07.45 am							
Strategy	SH280	SH283	SH285	SH282	SH290	SH250	System peak
Without DR	3.514	3.514	3.207	3.207	2.928	2.718	146.97
DR using 1 WH	1.474	3.514	3.207	3.207	2.928	2.718	144.61
DR using 5 WH	1.474	1.836	1.410	1.410	1.346	2.718	137.48

DR programs are implemented by either publishing the time-varying prices of electricity a day ahead of time or by providing incentives to the consumers to shift the consumption from peak intervals to off-peak intervals. The pricing information can be exploited to schedule the appliance operation to ensure the minimum electricity consumption cost and reduce peaks in the system. This can be realized using an HEMS that is integrated into smart meters installed in households by fetching the electricity prices from the utility. An analysis of the change in consumption patterns of household appliances using the system load information and time-varying prices can be conducted to study the effect of different pricing schemes used in DR programs.

Some Remarks

The analysis performed herein leads to two findings: First, high-consumption appliances such as WHs and ACs may contribute to nearly a fifth of the peak. Second, analysing the peak amplitude and peak duration of individual households may lead to the discovery of a cluster of households that are significant contributors to the system peak load. For more conclusive results, the analysis should be performed for the top 5% system load values – in this case, it is loads over 110.27 kW. Due to page limits we skip this detailed analysis here.

Conclusions and Future Work

The study presented in this paper focuses on households from Pune region in India. A hypothetical system load is constructed based on data from actual houses as well as synthetically generated data. The algorithms presented in this paper use the information encapsulated in the system load curve and the individual household load curves to identify the households that are suitable candidates for DR programs. Our results show that the households contributing to system peak load possess high-consumption devices such WHs, ACs, or a combination of both. We also observe that the peak loads lasting for shorter durations can be typically attributed to the households having WH ownership, while those with longer durations can be attributed to households with AC ownership. Both WH and AC loads exhibit inherent flexibilities that can be exploited to implement DR. In this paper, a simple load-shifting possibility is demonstrated to affect a peak shaving of 6.5%.

The dataset with some missing information for households in Pune & Pune City has been considered for the study. A richer dataset containing information on appliance ratings and user preferences can be used to quantify savings at the appliance level. The study of the frequency of occurrence of the peak would add more information to this analysis.

Similarly, using other attributes like mean values and peak-to-average ratio can lead to a more detailed analysis. The paper can be scaled to a larger set of households to study the potential savings using DR programs. This is future work and is out of the scope of this paper.

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An Educational Framework for a Net Zero Future

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Highlights

- The primary objective of the paper is to evaluate the current state of education curricula to build capacity in students to design net zero resilient buildings with the literature review of formal education curriculum, continuing education programs, and competitions aimed towards building capacity for designing climate resilient buildings.
- This paper finds that building sector education needs to be interdisciplinary with competencies and knowledge in three areas - Climate Literacy, Climate Justice, and Climate Action.
- This paper also finds that among the curricula and education programs reviewed, the ten contests of the Solar Decathlon India and the education resources provided in the challenge form a robust framework that could be used in education curricula in India.

Abstract

This paper evaluates the current model curricula in India for architecture and engineering colleges as well as education policy documents that will influence the coursework taught across the country to determine if the undergraduate and post-graduate education system is aimed at creating future professionals who can respond to India's Nationally Determined Contributions and net-zero by 2070 goal. It uses literature review and survey data to identify gaps in graduate attributes and competencies that result from these curricula and policy documents. While over fifteen years of codes and rating systems, and longer for industry-led practices, have introduced standards and best practices, the market has not moved towards future-proof net-zero buildings. The findings show that the model curricula do not address climate change and that comprehensive frameworks, as well as transformative education at scale, are being done through other programs like Solar Decathlon India (SDI).

Keywords: Net Zero buildings, education, curriculum, Climate change, evidence-based design

Introduction

At COP26 in 2021, India committed to achieving net-zero by 2070 and followed it up with an update to the Nationally Determined Contribution in August 2022 [1]. It is a challenging task for India to manage the emission targets amidst population growth, rapid urbanization, increased manufacturing, mining, and infrastructure development activities, as well as unprecedented growth in energy demand over the next few decades. Amidst these challenges, ensuring climate justice becomes imperative, as marginalized communities should not bear the disproportionate burden of transitioning to net-zero while facing the impacts of industrial growth and urban development.

An integral aspect of urban development is embodied in buildings, and this sector alone contributes 33% to carbon emissions [2]. This presents an opportunity for the building sector to future-proof infrastructure in the decades to follow. Net-Zero Energy Buildings (NZEBs) can help reduce energy demand in buildings as they are energy-efficient and give back clean electricity to the grid. However, the uptake and enforcement of energy codes and rating systems are weak, and the building sector largely operates in a business-as-usual mode [3]. Therefore, it is crucial to tighten and target these codes and standards towards achieving net-zero energy and net-zero water to meet India's 2070 goal.

There is also a capacity gap among building professionals in designing and implementing NZEBs. Out of over 500,000 students graduating annually from courses related to the built environment in India, a meagre 50 receive formal training to deliver NZEBs [4]. To address this gap and foster sustainable development, climate literacy, climate action, and climate justice (henceforth called the climate trifecta) must be seamlessly integrated into the education system for building professionals.

A review of the current status of the education system for building professions shows that students are not given the training and resources necessary to address climate change in their careers [5]. In higher education, there is currently no coursework related to climate change or net zero energy buildings. Moreover, the coursework offered is not comprehensive and not mandatory [6]. The All India Council for Technical Education (AICTE) and the Council of Architecture (CoA), which are national statutory bodies responsible for the development of the technical educational curriculum for engineering and architecture, only offer coursework on concepts of climate, thermal comfort, and passive design for the architecture curriculum [7], [8], [9]. In engineering courses, coursework on energy efficiency in electrical systems is provided.

Other educational programs that are not formally a part of the curriculum, such as education modules provided by the green building rating system authorities and the Solar Decathlon India (SDI) challenge, may be able to fill the gap. Therefore, the objectives of this paper are to:

- Assess the state of the curriculum for higher education and its gaps through a literature review.
- Assess the capacity building efforts outside the formal undergraduate and post-graduate coursework.
- Identify a possible comprehensive educational framework for the climate trifecta.

Method

Our method contains five steps to research:

1. The first step is a literature review to identify any recent updates to higher education curricula internationally in response to climate change imperatives.
2. The second step is to review any changes included or proposed at a national level by the CoA or the AICTE. This review looks beyond changes to individual course content or new courses focused on climate change that were introduced in isolation. Rather, the review is conducted to identify structural changes in the curricula or systemic changes to the curricula related to the education of building design, construction, and operation.
3. Next, a review of the educational content provided for professional accreditation and continuing education in the building industry by various Green Building Councils and rating organizations. First, it was assessed if the content was intended for and accessible to students. If yes, then it was reviewed whether individual courses and the systemic curricula were relevant to climate change.
4. The fourth step is to assess distance learning or hybrid learning programmes and competitions that aid in building capacity toward net-zero building design. NPTEL, Green Rating for Integrated Habitat (GRIHA) Trophy, Indian Green Building Council (IGBC) Green Design competition, and the SDI Net-Zero Building Challenge are some of the platforms/programmes that enable capacity building for climate action.
5. Within these learning programmes, the paper identified SDI as the most comprehensive and accessible one and assessed its robustness and its role in building capacity for the climate trifecta. This is done in two parts:
    a. Assessing the scores given by the Jury members of SDI and analyzing if the scores of the teams meet the expectations of the Jury based on the evaluation criteria given by SDI.
    b. Assessing a self-evaluation test given to faculty on how they rate their areas of expertise before and after participating in the SDI program.

Results

1. Literature Review of architectural curriculum internationally

A recent study investigated architectural curricula in select international educational institutions outside

India, as directed by the CoA subcommittee, focused on integrating climate change syllabi into India's architectural education. Institutions studied included UCLA, Cornell University, MIT, University of Melbourne, University of Sydney, and National University of Singapore's College of Design and Engineering. Results indicated no dedicated climate change syllabi at the undergraduate level, though building science courses like passive environmental design, energy and water conservation, indoor environmental quality, and energy modelling were integrated across academic levels. Several governing bodies and institutions were reviewing their architectural curricula.

Notably, the Australian Institute of Architects recommended adding Climate Literacy and Action in Architecture Education. RIBA stated that climate change awareness is a core competence for chartered architects, while the Technological University of Dublin emphasized curriculum reform with climate-related subjects. Arch4Change, a collaboration supported by the Erasmus+ Programme, created a forward-looking climate emergency curriculum for 21st-century architectural education. Emphasizing restorative, inclusive design and climate justice, this curriculum aims for radical transformation toward carbon neutrality.

In conclusion, certain universities and institutions are already in the process of developing undergraduate architectural curricula that include climate change courses. These endeavors signify a growing recognition of the need to equip future architects with the knowledge and skills to address climate challenges in their practice.

2. Review of architectural curriculum in India

The CoA, responsible for architectural education standards in India, recently updated minimum standards in the 'Council of Architecture (Minimum Standards of Architectural Education) Regulations, 2020' [8]. These changes emphasize compulsory studies in building sciences and applied engineering.

Among the ten subject areas, only 3 are loosely related to climate action. The document also outlines 20 optional professional elective courses, with only 3 relevant to climate action - green buildings, sustainable cities, and building performance. While these courses offer insight into climate change mitigation, they lack a comprehensive understanding of its causes, impacts, and effects on vulnerable groups. This reveals a deficiency in the architecture curriculum's approach to addressing climate change in an integrated and multi-disciplinary manner. Similar to the CoA, the All India Council for Technical Education (AICTE), which is the national statutory body governing higher education for engineering courses, the coursework includes concepts of thermal comfort and passive design for those with an electrical and mechanical engineering background. These courses are, however, not comprehensive, nor are they compulsory.

Recognising the reform proposed in the National Education Policy of India 2020 (NEP 2020), the CoA prepared an 'Interim Report - Architecture Education Way Ahead, in Pursuit of Education Reforms' [10] to revamp architectural education in India. While the report proposed subject areas and competencies, it overlooked climate change as the biggest environmental, economic, and equity challenge. It lacked subject areas in context to climate action, climate justice, climate literacy, interdisciplinary collaboration, and building performance. A sub-committee has been established by the CoA to develop and prepare a syllabus for climate change to be added to the architecture curriculum and also to suggest ways and means to sensitise architects on the issue for achieving Net Zero Carbon Targets by India [11].

The sub-committee conducted an online survey with all registered architecture colleges in India to assess the gaps and strengths in their architectural education related to climate change. CoA curriculum reviews show that climate analysis, thermal comfort, passive design, and energy efficiency courses are not mandatory or comprehensive for architecture and engineering programs. Further, specific coursework related to Building Performance Simulations (BPS) is not offered.

Nalla et al. (2023) [12], in their review of curricula in India for adaptive pathways for resilient infrastructure for economic development, poverty reduction, and climate action, stress the importance of interdisciplinarity, critical thinking, and reflexivity, reflected in the elements of content, pedagogy, and delivery. They note that while some master's programs in Civil Engineering or Water Resource Engineering build an understanding of water distribution and result in requisite skills to design a drainage system to address the issue of flooding, their training only equips them to address the physical vulnerabilities. They argue that the education content does not build responsiveness and sensitivity to the vulnerabilities and needs of the most disadvantaged and marginalised communities and that education on climate action needs to be underpinned with an appreciation for equity and differential vulnerability in the form of climate justice.

3. Review of continuing education programs

Various green building rating systems like EDGE, LEED, GRIHA, and IGBC offer accreditation programs to professionals for a deeper understanding of the system and project facilitation. Accreditation exams evaluate broad green building comprehension and specific rating system knowledge. Only LEED's Green Associate (GA) credential is available to students. Preparing for the GA exam enhances green building knowledge within the rating system framework, particularly in site, water, energy, materials, and indoor quality aspects. However, it lacks comprehensive skills for designing net-zero energy-water buildings and resilient design and falls short on climate literacy and justice, limiting its climate action scope.

The United States Green Building Council (USGBC) provides over 1,000 e-learning courses for continuing education for LEED professionals, which are accessible to students too. Courses span basic, intermediate, and advanced levels, covering energy efficiency, materials, carbon, comfort, air quality, and more. While valuable for climate literacy and justice, these courses inadequately address skills crucial for climate action, especially resilient, carbon-neutral design. The platform's curated playlists by discipline and topic offer a starting point but lack a structured learning path.

Table 1. Review of continuing education programs aimed at capacity building for students and professionals

Organization	Program/platform	What is offered by the program/ platform
USGBC	Education@USGBC	e-learning platform of more than 1000 courses on green buildings and sustainability concepts aimed at continuing education for green building professionals, which is also accessible to students. 2 colleges in India have Campus subscriptions that give their students free access to all the courses on the platform
IFC	Design for Greater Efficiency (DfGE)	DfGE covers the fundamentals of energy and resource efficiency measures in building design from a technical and commercial perspective. The course also introduces the IFC EDGE online tool to assess the energy, water, and carbon metrics of a building. 5 day program to train the faculty, who will, in turn, train the students.

The International Finance Corporation (IFC) offers a Train-the-Trainer certification program for faculty of architecture, structural, and building services engineering colleges called 'Design for Greater Efficiency' (DfGE). The week-long program covers the fundamentals of energy and resource efficiency measures in building design, HVAC controls, lighting, and photovoltaics from a technical and commercial perspective. The program also introduces the IFC EDGE online tool to assess the energy and carbon emissions of a building design, using which the learners demonstrate their understanding of a sample project. When faculty train the students, it is expected to have a secondary effect in building capacity for climate action. DfGE is a good resource for faculty, but it too largely ignores climate literacy and climate justice while addressing climate action with issues that relate to the EDGE rating.

4. Review of the distance/hybrid learning programs and competitions

Massive Online Open Courses (MOOC) developed by seven Indian Institutes of Technology (IIT) under the National Programme on Technology Enhanced Learning (NPTEL) offer certified online courses to students across the country in various disciplines, including architecture and civil engineering (Table 2). These distance learning courses cover topics such as building science concepts, sustainable design guidelines, materials, daylight, and others. While the individual topics are relevant to climate change, they do not cover the entire gamut of skills required to design a net-zero building, such as building performance simulation and evidence-based approach to design, among others.

The Indo-Swiss Building Energy Efficiency Project (BEEP) organised an annual hands-on educational event for students called the BEEP Camp over the last several years to build capacity for designing energy-efficient buildings through an integrated design process. The program emphasises fundamentals of building physics, passive strategies, thermal comfort, cooling processes, ventilation, daylighting, building simulation, and monitoring in a hands-on, immersive learning experience. All these topics are relevant to building competencies for climate action related to net-zero buildings. However, it appears that there is less emphasis on resilient design and climate justice, which includes competencies in assessing vulnerability, risk, and resilience. The BEEP programme has now been turned over to the Bureau of Energy Efficiency, and its continuity in its past form is uncertain.

Table 2: Review of distance/hybrid learning programs for building capacity among students

Organization	Program/platform	What is offered by the program/ platform
National Programme on Technology Enhanced Learning (NPTEL)	MOOCs on various disciplines developed by seven Indian Institutes of Technology (IIT)	• *Courses under Architecture discipline:* Strategies for sustainable design • *Courses under Civil engineering discipline:* Sustainable Materials and Green Buildings, Sustainable Engineering Concepts And Life Cycle Analysis, Principles and Applications of Building Science Energy Efficiency, Acoustics and daylighting in Building Glass in buildings: Design and Application
Indo-Swiss Building Energy Efficiency Project (BEEP)	BEEP camp	• Annual hands-on educational event to build capacity in students. • Content covers fundamentals of building physics with multi-disciplinary working sessions. • Program brings leading practitioners and educators from the building energy efficiency sector to teach the students the latest and relevant skills and knowledge.

GRIHA, India's Green Building Rating System, hosts an annual net-zero design competition awarding the GRIHA Trophy. Held at the National Association for Students in Architecture Convention, it targets Indian undergraduates in Architecture. The design brief expects sustainable, climate-responsive designs, excluding resilience and climate justice. Organizers offer no resources, leaving students to self-learn climate trifecta aspects, excluding engineering students.

The IGBC organizes the Green Building Design competition for Indian undergraduates and post-graduates in architecture, planning, and design. It evaluates sustainable strategies, feasibility, and scalability, not requiring comprehensive or evidence-based entries. IGBC lacks green design resources, excluding engineers.

The SDI Net-Zero Building Challenge targets multi-disciplinary teams of Indian post-graduates and undergraduates, partnering with developers for real projects. SDI provides learning resources like modules, webinars, and mentors. They encourage various disciplines, providing education and competition criteria linked to the climate trifecta.

Table 3: Review of competitions for building capacity among students

Competition	Participating criteria	Learning resources offered
GRIHA Trophy	• Background: Undergraduates in Architecture • No. of participants: 2 Students per institution	-
IGBC Green Building Design	• Background: Undergraduates or pos-tgraduates in Architecture, Planning and Design • No. of participants: 2 per team + Faculty	-
Solar Decathlon India Net-Zero Building Challenge	• Background: Undergraduates or Post-graduates (all backgrounds) with at least 1 architecture, 1 engineering student • No. of participants: 5-15 per team + Faculty Lead + Real Estate developer	• Online Self-Learning Modules • Live Webinars • Simulation workshops • FDP

5. Assessment of SDI

Apart from the educational resources mentioned above, the SDI challenge has ten contests for participating teams, and these contests are the framework for evaluating student work. The ten contests include issues of energy, water, embodied carbon, resilience, affordability, building operations, and innovation, among others. These contests and their evaluation criteria have evolved over three years of the SDI challenge in the following key phases:

1. Year 1: Review of metrics to design net-zero buildings worldwide to develop the first version of the ten contests.
2. Year 2: Focus group discussions with experts, including industry and educators, and feedback from the Jury to revise the contests and develop detailed criteria for each contest.
3. Year 3: Learning from Year 2 and feedback from the Jury to refine the contests and and criteria.

The 10 contests in year 3 are shown in Table 4. SDI commnuciates the contests and their requirements to the participants as well as the Jury and revises its educational resources each year to ensure that students and faculty are supported in their learning to be successful in developing net-zero and resilient building solutions. Since each contest holds equal weightage and teams need to perform well across all 10 contests for a successful submission, SDI ensures a balanced approach to the climate trifecta at a team level.

Table 4: Ten contests and their evaluation criteria as of year 3

Contest Name	Contest Description	Evaluation Criteria
Energy Performance	Evaluates net-zero building design as a super-efficient building that generates renewable energy on-site as well as the capability of the building systems to interact with an electricity grid, with on-site or stored power. Teams are evaluated based on their solutions to achieve a low energy performance index and net-zero annual energy use.	• Reduction of loads demonstrated with annual energy analysis • Integration of low energy comfort systems • Integration of sufficient renewable energy generation on site • Smart grid interaction capabilities
Water Performance	Evaluates a net-zero water building regarding the design and management of on-site water resources towards a fully watersufficient development. Teams should provide a water-cycle design supported by detailed water calculations. Teams are evaluated based on their solutions to achieve low per capita water demand and net-zero annual water performance.	• Minimizing water usage • Sufficient use of harvested rainwater, recycled water, and treated wastewater returned to a public source • Optimisation of on-site storage and recharge of groundwater
Resilience	Evaluates the building's ability to adapt to changing environmental conditions and the ability to maintain functionality in the face of stress or disturbance.	• Assessment of potential risks • Improved physical integrity • Quantification of resilience demonstrated through calculations for passive performance and autonomy for critical functions • Improved operational continuity through a risk management and recovery plans
Affordability	Evaluates the building's financial costs for initial investment and ongoing operations. Teams must look at operations and maintenance costs that determine the total cost of ownership.	• Construction cost analysis for rightsizing, use of local or repurposed materials, and other strategies • Financing cost analysis for faster construction methods • Lifecycle cost analysis

Innovation	Evaluates the application of innovative techniques, technologies, or business models through creative approaches to enhance performance in other contest areas. It requires the team to identify specific problems in the region or the market and present their innovation as a solution to those problems and explore ongoing research and development activities within or disruptive technologies outside the buildings sector.	• Complete narrative based on the Innovation guidelines • Integration of innovation in the design
Health and wellbeing	Evaluates the building's capability to provide thermal comfort and good indoor environmental quality, which is essential for ensuring occupants' health and wellbeing. Teams are evaluated based on their solution to provide indoor thermal comfort for all occupied hours and desired indoor air quality and fresh air.	For thermal comfort • Provision of indoor thermal comfort based on a chosen standard • Annual simulations demonstrating thermal comfort • Strategies for reducing thermal stress in the outdoor environment and minimising thermal shock in transitional spaces. For ventilation and air quality
		• Provision of desired indoor air quality and adequate fresh air • Simulations or sizing calculations to achieve the above for natural and mechanical ventilation
Engineering and operations	Evaluates the effective integration of high-performance engineering systems and understanding of building operations. Teams are expected to provide an operation and maintenance plan for the building. The operation plan should include the key quantities that should be measured during the operation to ensure high performance.	• Engineering system design and right-sizing • Constructability at scale in terms of availability of material, technology, and labour For smart building operation: • Building operation narrative that lists the Do's and Dont's for the proposed building systems, along with a list of key parameters to measure the performance of the building • Building automation and control with control narratives and schematics
Architectural design	Evaluates the architectural design for its creativity, integration of systems, and ability to deliver functionality and aesthetic appeal desired by the market or client. Teams are encouraged to bring together aesthetics with sound building science, performance, comfort, affordability, and resilience.	• Use of an integrated, evidence-based, and creative process • Generation of an appropriate aesthetic and user experience for the end users at site, building, and interiors • Functionality and efficiency in terms of circulation, space allocation, servicing, adjacencies, densities for the site, building, and interiors • Integration of building systems and enabling their performance to respond to the other contests for the site, building, and interiors.
Embodied Carbon	Evaluates the design for the use of building materials and construction technologies that reduce embodied carbon emissions, which is essential for net-zero global emissions. Teams should demonstrate, through calculations, the reduction of carbon emissions in their design compared to a baseline.	• Narrative of the low embodied carbon materials and construction technologies • Reduction of embodied carbon • Construction details demonstrating the integration of low embodied carbon materials and construction technologies
Value Proposition	Evaluates the team's ability to convey the value proposition of the design and its performance to relevant audiences. Teams are encouraged to provide a succinct and compelling narrative with clear messaging and articulating the value proposition to relevant audiences.	• Completeness and clarity of the project • Compelling narrative for end users with clear messaging and articulation of the value proposition.

Table 4 is the contest requirements as of year 3. In the first 2 years, there were contest areas such as 'Presentation', 'Communication', and 'Market Potential and Scalability'. Based on the feedback that the organisers received from the faculty mentors and Jury experts in year 3, the 'Market Potential',

'Presentation' and 'Communication' contest areas were refined and added to the 'Value Proposition' contest area. Further, the 'Scalability' contest area was added to the 'Affordability' contest area. In year 3, a new contest area, 'Embodied Carbon,' was added for the participants to tackle construction methods and building materials.

Reviewing the score of the finalist projects in Year 1, on average, 56% of teams produced designs supported with evidence through Building Performance Simulation (BPS) and calculations. In Year 2, the number increased by 12% [13].

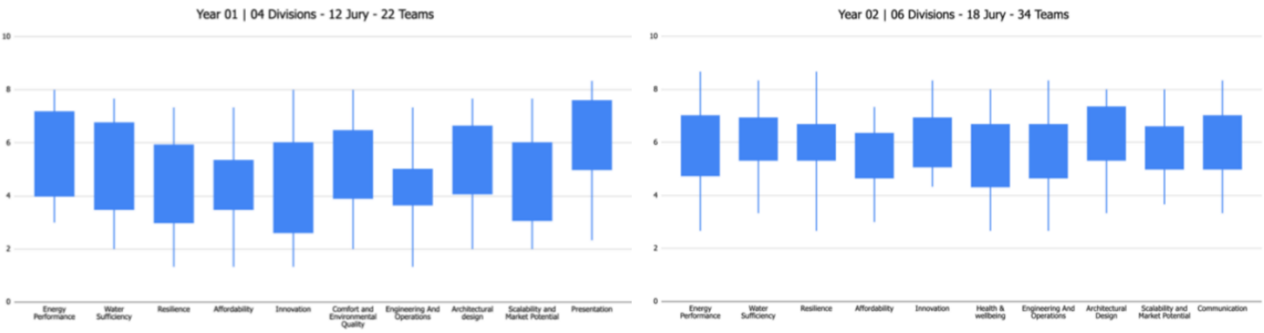

Figure 1: Based on feedback received by the Organisers, the presentation contest area was changed to 'Communication' in Year 2. In year 2, the competition guide was extensively refined to make it comprehensive for the participants

a. Review of Jury Scores

The authors of the paper analysed the scores given by the Jury members, who consisted of experts from the industry with deep expertise in designing and implementing net-zero buildings in the real world. Each contest area had a maximum score of 10. In the first year, the median score of the final competition entries (n=22) was in the range of 4 to 6 out of 10 for every contest area. The energy performance and presentation contest areas saw the highest scores by the Jury.

In Year 2, the median score for the final entries ranged between 5 and 6.5 out of 10 (n=34). In Year 3 (Figure 2), the median scores ranged between 5 and 6 out of 10 (n=36).

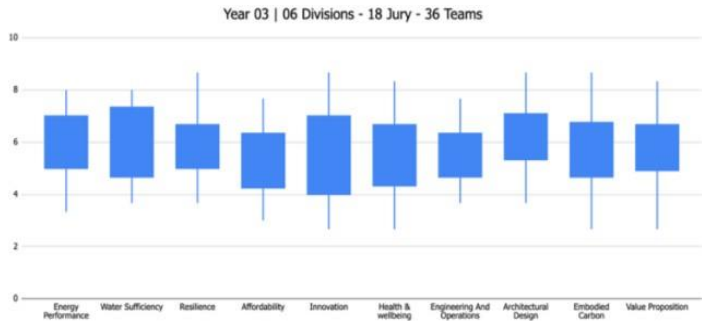

Figure 2: In year 3, the 'Market Potential' and 'Communications' were combined into 'Value Proposition'. 'Scalability' was merged with 'Affordability', and 'Embodied Carbon' was introduced as a new division.

The scoring rubric of SDI that is given to the Jury on a point scale of 1-10 [14] shows that scores between 5-6 are given when the student's work meets a minimum expectation of quality or is of very good quality.

b. Assessing Faculty expertise

In the SDI competition, each team is mentored by faculty members. At the beginning of year 3 of the challenge, the organisers conducted an FDP with the objective of training them to mentor the teams better. A self-assessment survey form was provided to the 40 faculty members at the program to document their expertise areas in the ten contest areas. While most faculty had expertise in Architectural design, their scores in other contest areas were lower. Another self-assessment survey was given to the faculty at the end of the challenge year after the finals. Figure 3 shows a comparison of their self-assessment scores at the beginning and the end of the challenge year. The data show a 10-30% increase in the scores of the faculty after they went through the SDI programme. The median scores of the faculty had improved by about 5% percent in contest areas like Energy performance, Engineering and Operations, and Architecture. The Embodied Carbon contest area saw the largest improvement in median scores, which was 15%.

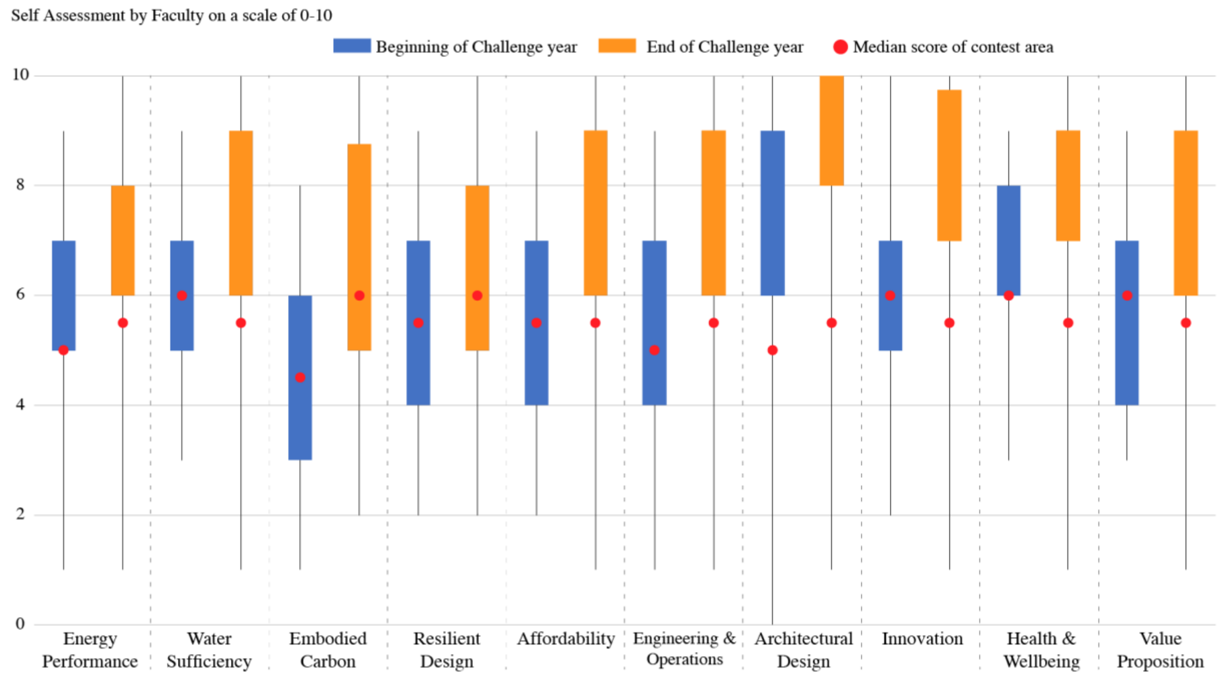

Figure 3: Self-assessment scores by faculty mentors in the SDI at the beginning and at the end of the SDI challenge.

From the scores given by the Jury members to the teams and from the self-assessment done at the beginning of the Challenge year by the faculty, it seemed like the teams did not do well in the subject areas in which their faculty did not have expertise. Contest areas such as Resilience, Affordability, Engineering, and operations, where the faculty lacked expertise (Figure 3), seemed to be the areas in which the teams also did not do well as per the Jury scores (Figure 2). This shows the importance of building capacity among faculty members as well as among students. Specific training sessions will be required in specific contest areas such as Resilience, Affordability Engineering, and operations.

Discussion

India's National Determined Contributions for the Paris Agreement entail a 45% reduction in carbon emissions intensity by 2030 and achieving net zero emissions by 2070. To attain these goals and mitigate emissions in the building sector, climate-resilient net-zero buildings are crucial. The building sector's long-term impact necessitates urgent enhancements in building performance due to its 150100-year lock-in effect.

This study asserts that interdisciplinary building sector education in architecture, civil, mechanical, and electrical engineering must cultivate competencies in the climate trifecta:

1. **Climate Literacy:** This encompasses comprehension of anthropogenic global warming, sectoral greenhouse gas contributions, climate change impacts on society and biodiversity, and relevant policies, including carbon credits and taxation.
2. **Climate Justice:** This entails recognizing regional and population vulnerabilities, equity issues, resilient infrastructure interconnectedness, and vulnerability assessment techniques.
3. **Climate Action:** This demands skills in crafting carbon-neutral buildings, zero waste strategies, disaster-resilient infrastructure, biodiversity enhancement, innovative product design, and evidence-based processes that align with regulations.

The faculty self-evaluation at the beginning of the SDI challenge indicates that the current higher education curriculum and the teachers are not ready to prepare for future building professionals for climate trifecta. The jury scores of the student teams and the faculty self-evaluation at the end of the SDI challenge provide evidence that large-scale improvement in abilities to address the climate trifecta is possible. The ten contests of the SDI challenge are broad enough to identify weaknesses or gaps in the curricula, and among the educational or training systems reviewed in the paper, these 10 contests seem to be comprehensive for the climate trifecta. SDI also appears to have a structured pedagogy with its combination of learning resources, faculty development program, and hands-on problem-solving for a real project. These elements can be included in coursework and curriculum, which also make the teaching more in alignment with the New Education Policy of 2020. Recently, the CoA of India has endorsed the SDI programme and has recommended that architecture schools across the country provide academic credit to participation in SDI. Stronger inclusion in the curriculum may result out of the work of the Climate Change Sub-Committee to the CoA. Meanwhile, another way to integrate the programme into the coursework is to include the 10 contest areas as learning objectives for courses that are taught in the curriculum. The self-learning modules and learning resources could be offered as learning resources or MOOCs to help the faculty to teach without having to create the learning materials themselves.

Conclusion

The current architectural undergraduate curriculum lacks focus on climate change and zero-energy buildings. Existing coursework, though not mandatory, lacks depth. National bodies AICTE and CoA recommend minimal energy-related courses. Some engineering programs address physical climate vulnerability. Climate literacy, action, and justice aspects are absent.

Certain international institutions are developing undergraduate architecture curricula incorporating climate change courses.

Continuing education in the building industry introduces learners to evidence-based design and climate literacy; however, NZEB design requires comprehensive, evidence-based design, and the SDI competition covers ten areas of expertise, enhances climate literacy, addresses climate justice, drives participants to practice climate action and provides the educational materials to achieve the trifecta. The SDI framework can help to revise technical higher-education and enhance faculty and student capacities for teaching and learning.

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Evaluation of Thermal Discomfort and Non-refrigerant-based Cooling Methods as Mitigation Measures in Indian School Buildings

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Highlights

- Thermal comfort of students has been assessed.
- Impact of evaporative coolers on improving thermal comfort has been investigated.
- Recommendations have been provided to shift policy focus towards designing school buildings considering thermal comfort.

Abstract

The atmospheric temperature of the Indian subcontinent is rising steadily, with maximum and minimum temperatures increasing by up to 0.9º C and 0.5º C, respectively. Heat waves are becoming more frequent, posing a threat to vulnerable communities, including students, leading to changes in school schedules or closures in northern India. Unfortunately, thermal comfort assessment in Indian schools has received limited attention to date. To address this, a study was conducted in Ajmer (Hot and Dry climate) to evaluate thermal discomfort caused by heat stress in schools. The study investigates the relationship between students' thermal comfort and indoor/outdoor thermal conditions and the effectiveness of low-energy cooling technology, such as ceiling fans and evaporative coolers, in mitigating thermal discomfort during heat stress conditions. Data collection and evaluation have been conducted before and after the deployment of evaporative coolers to gauge their effectiveness in improving the thermal comfort of the students. A Simulation-based approach is adopted post-deployment of coolers to quantify the improvement in thermal comfort. The study aimed to provide insights into the benefit of adopting effective cooling technologies for improving the indoor classroom environment for students and enabling policymakers to assess indoor thermal conditions and choose suitable technologies to help mitigate heat stress in schools.

The results show that low-energy cooling technology, like evaporative air coolers, helps in bringing down the indoor temperature to a thermally comfortable range for the students. In addition, this study established that there is a need to focus on thermal comfort while developing the school infrastructure, as it helps in improving the students' learning cognizance, attendance ratio and physical well-being.

Keywords: Thermal Comfort, Heat stress, Low-energy cooling techniques, Evaporative Air Coolers.

Introduction

India is one of the largest and most populated economies in the world, with its average temperature being projected to rise by ~4.4°C by the end of the 21st century—which would result in extreme heat stress, with devastating impacts on human health and energy security [1]. Incidentally, it has been estimated that an increase in surface temperature and humidity will intensify the heat stress across India, particularly over the Indo-Gangetic and Indus River basins [1]. Thus, wider access to cooling is necessary in order to bring benefits to human development, health, well-being, and economic productivity. With around 4 trillion-person cooling degree days [2], coupled with a lack of access to cooling and thermal comfort, rising temperature, rapid population growth, and urbanization will not only amplify heat stress but will also fuel the demand for space cooling. According to the India Cooling Action Plan (ICAP) 2019 [3], India has one of the lowest access to cooling, with per capita space cooling energy consumption at 69 kilowatt-hours (kWh) compared to the world average of 272 kWh [4]. Access to affordable and sustainable cooling for attaining thermal comfort is no longer considered a luxury but, rather, a necessity for meeting the larger environmental goals as well as enhancing the overall quality of life, productivity, and well-being [4]. Various studies have also indicated that India's rapidly changing climate will have a severe impact on the heat stress situation within the entire ecosystem. Particularly, children are identified as one of the vulnerable groups and are adversely impacted by rising heat stress in the absence of adequate thermal comfort infrastructure put in place in the schools [1].

Need for Thermal Comfort in India's Academic Institutions

As per the Unified District Information Systems for Education Plus (UDISE+) 2019-20 report by the Ministry of Education [5], India has more than 15,00,000 lakhs (1.5 million) schools, from which 11,16,932 lakhs schools are managed by the government, and 3,37,499 are managed by private entities. However, none of the reports (inclusive of the one mentioned above) or policies focusing on India's education sector encompasses thermal comfort as one of the key priorities for the school infrastructure, as shown in Figure 1. Thus, it can be said that thermal comfort in India's academic sector has never been prioritized, while it can provide multiple benefits. Moreover, India's policy and regulatory framework do not bestow information on the associated benefits of providing access to thermal comfort for children in academic institutions; this area has been least focused on. However, there have been persistent attempts in the literature to understand the existing thermal scenario in academic institutions and emphasize the need for ensuring thermal comfort in the former to address the heat-related challenges for this age group. In particular, the literature highlights the number of studies that have assessed thermal comfort through field surveys in educational buildings globally [6] [7]. A number of these are focused on assessing the thermal environment in classrooms compared to common thermal comfort standards. Also, most of the studies conclude that students' thermal preferences are distinct from the comfort range prescribed in the standards. This wide disparity in thermal neutralities underlines the need for micro-level thermal comfort studies. In the Indian context, for instance, a study by Jindal A [8] conducted in 2015-16 investigated thermal comfort in naturally ventilated classrooms of three government residential schools located in the composite climatic zone of India and also assessed students' thermal perceptions. The study concludes that the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) adaptive thermal comfort model is an adult-based standard and was developed for the pan-global thermal environment. The same cannot be applied to children and teenagers in the regional climatic context of India. Also, the study highlights the need to segregate the data of the middle and secondary-class students and determine the differences between their thermal comfort acceptability range. These findings can provide guidelines for architects to design thermally comfortable and energy-efficient schools without compromising occupant comfort.

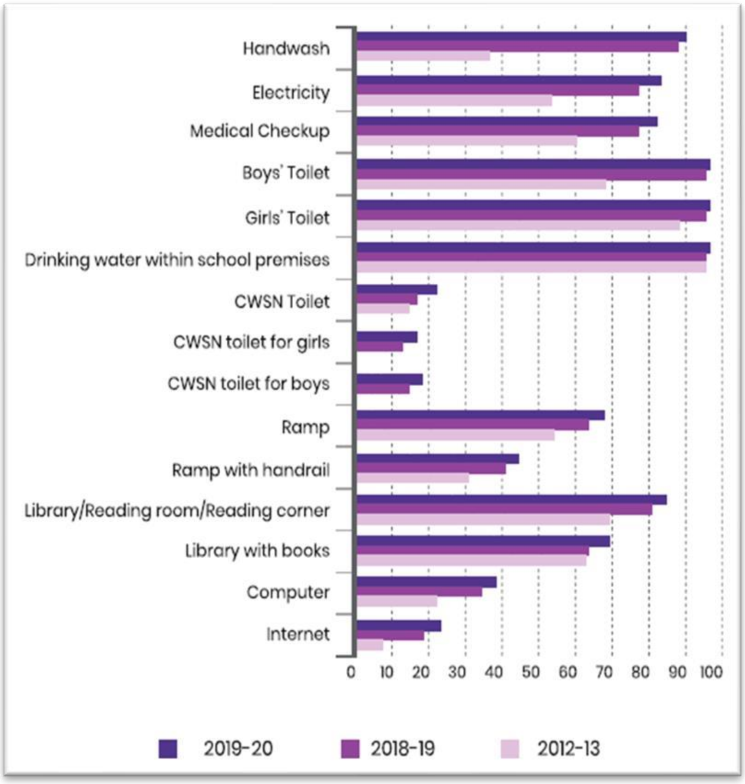

Figure 1: Percentage of Schools Having Specific Infrastructure Facility 2012-2020 [5]

Therefore, to substantiate the assessments on the subject of thermal comfort range in schools as well as the thermal comfort perception of students across different age groups, we have based our analysis on simulation-based exercises and field survey of selected schools in the districts of Rajasthan (Ajmer), to determine actual thermal conditions and thermal comfort perceptions.

Achieving thermal comfort in the academic sector is vital to bring about systemic changes on multiple fronts, ranging from increased attendance to enhanced quality of education and improved quality of life. In addition, it can also help in creating equal exposure opportunities and attending school for women as they are disproportionately impacted by heat stress, more so during the menstruation period. Furthermore, bringing the students closer to using evaporative air coolers (EAC), a Non-GWP refrigerant-based space cooling solution to achieve thermal comfort in the constantly warming world, can lead to wider adoption of energy-efficient space cooling appliances—leading to Thermal Comfort for a Billion Lives (TCBL).

Therefore, with the recommendations of the 'Decoding Evaporative Air Coolers (EAC)' report [4] being the foundation stone, the AEEE team has collaborated with Symphony Ltd. to take forward the Supporting Affordable Heat Action for Resilient Academic Institutions Programme (SAHARA)

Programme, a programme initiated to Supporting Affordable Heat Action for Resilient Academic Institutions. The project envisions providing access to thermal comfort for children in India's academic institutions, which is the most under-looked area.

Thermal Comfort Scenario in Indian Academic Institutions – A case study of Ajmer

In order to understand the on-ground reality of heat stress, a school located in the Ajmer district of Rajasthan has been selected (shown in Figure 2) to assess the thermal comfort of students during heat stress conditions and evaluate the effectiveness of EAC in improving the thermal comfort of students. Indoor and outdoor temperature and humidity of the classrooms were measured before the deployment of the evaporative coolers. The survey was conducted to gauge the thermal perception of the students in the classrooms. The indoor environment of the classrooms post-deployment of EAC has been evaluated through simulations. The climatic condition of the region is dry and hot, with dry bulb temperature typically varying between 23 to 41°C. The subsequent section details the methodology adopted while executing the analysis.

Characteristics of the classrooms

The school building considered for the study has three classrooms and a hall on each floor. The layout of the classrooms and the cross-section of the wall and roof assemblies are shown in Figure 2. The school has an ancient building at the time of British rule converted to a school and made of stone masonry.

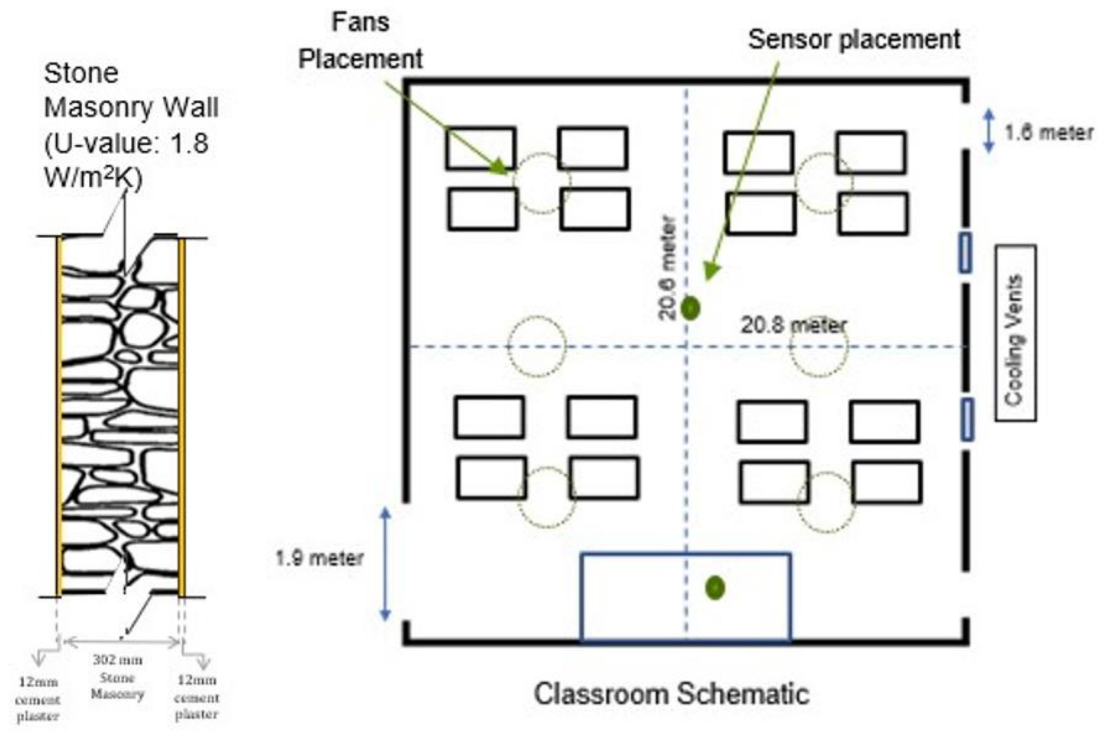

Figure 2: Classroom Schematic and Wall Construction

Table 1 shows the thermal properties of the construction materials used in the school building.

Table 1: Thermal Physical Properties of the Building Components

Building Components	Description	Thermo Physical Property
External Walls	The wall comprises stone masonry and cement plaster; the total thickness of the wall is 0.32m	U value – 1.80W/m^{2}K
Internal Walls	The wall comprises burned brick and cement plaster; the total thickness of the wall is 0.20m	U value – 1.62W/m^{2}K
Floor	The floor is made up of single-layer cast concrete with a thickness of 0.125m	U value – 4.31 W/m^{2}K
Roof	The roof is made up of single-layer cast concrete with a thickness of 0.125m	U value – 4.31 W/m^{2}K
Window	The window has been installed with clear glass 5 mm	U value – 1.960 W/m^{2}K

Results and Discussion

Thermal performance analysis of the classroom

Temperature and humidity of the classrooms were measured between 5th April 2023 to 28th April 2023 before deploying the EAC in the classrooms. Temperature and humidity data were recorded at intervals of 1 hour with HTC-1 digital thermometer (accuracy ± 1 ℃, mention accuracy for humidity). Figure 3 shows the placement of the sensors in the classrooms.

Figure 3: Placement of the sensor for collecting the real time data

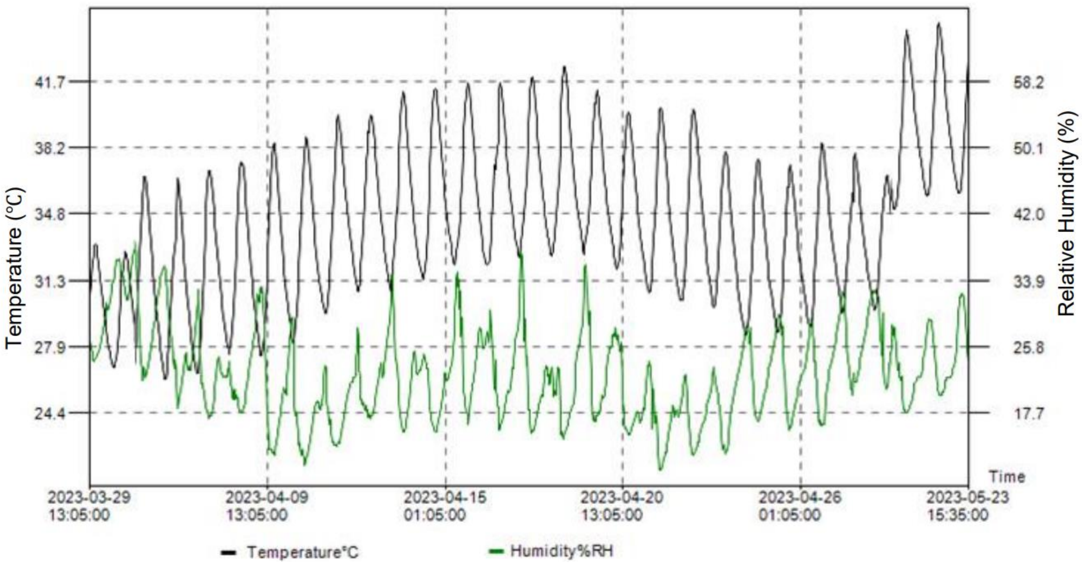

Figure 4: Indoor experimental temperature and relative humidity for the peak summer

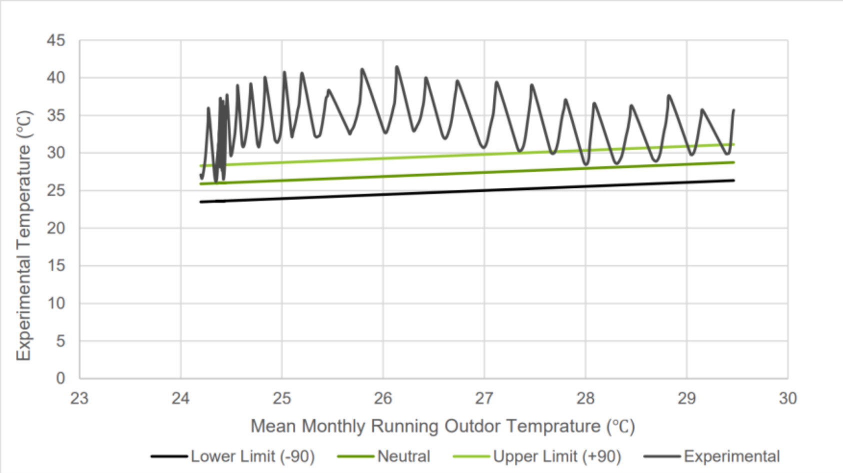

Figure 5: The outdoor running temperature with fans and natural ventilation

Figure 4 shows the temporal variation in the classroom's temperature and relative humidity in the month of April. It can be observed from the figure that relative humidity is low, which offers potential for evaporative cooling in the classrooms. Figure 5 shows the plot of the classroom's temperature with the IMAC thermal comfort band [9]. It can be observed from the figure that 188 hours are out of the thermal comfort band from the total occupied hours of 207, while school is typically running in two shifts from 7:00 am to 4:00 pm, according to the school principal.

Evaluation methodology of Post deployment of EAC

To analyze the thermal properties of classroom post deployment of EAC, the measured data of air temperature and humidity has been used in equation (1) to calculate the effective air temperature after deployment of EAC. In order to calculate the effects of evaporator air coolers on the thermal comfort of the classrooms within the schools, the team calculated the wet bulb temperature using the following equation [10].

Tw = T * arctan [0.152 * (Rh + 8.3136) ^(1/2)] + arctan(T + Rh%) - arcta.n(Rh - 1.6763) + 0.00391838* (Rh)^(3/2) * arctan(0.0231 * Rh) - 4.686 (1)

Where,

Tw = Wet Bulb Temperature

T= Experimental Indoor Temperature

Rh = Relative Humidity

The saturation efficiency was considered to be 70% to calculate the temperature reduction after operating the EACs. Some assumptions were also considered while executing the analysis to formulate the results.

Thermal performance analysis

Figure 6 shows the plot of air temperature with the IMAC thermal comfort band. It can be inferred from the figure that nearly none of the points were crossing the upper limits of the IMAC model out of the total occupied hours 207 falls. This showcases that in hot and dry climatic conditions, Evaporative Air Coolers (EACs) can play a major role in meeting the thermal comfort requirement of the school.

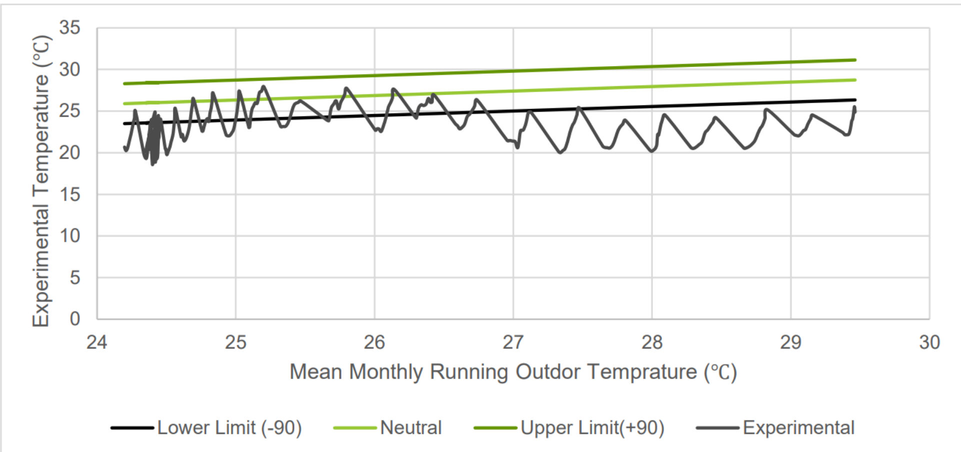

Figure 6: The outdoor running temperature with Evaporative Air Coolers

Figure 7 demonstrates a remarkable reduction in the number of discomfort hours experienced in classrooms, ultimately reaching zero. This compelling evidence solidifies the effectiveness of EACs as a viable technology for schools throughout Rajasthan. By highlighting this significant improvement, it becomes evident that EACs can play a pivotal role in facilitating a systemic shift toward adopting more efficient cooling solutions in the region. This is especially relevant in a place like Rajasthan, where traditional evaporative cooling is a suitable and viable solution due to various factors. Consequently, widespread adoption of EACs can unlock equitable access to cooling solutions for all, aligning with the broader objective of ensuring thermal comfort for billions of lives.

The findings emphasize the necessity for including a provision in the UDISE data to monitor the thermal comfort parameter in Indian schools. By doing so, we can address a crucial and often disregarded issue, granting much-needed access to cooling solutions for a vulnerable community, specifically students. This step is of utmost importance in ensuring that the well-being and comfort of students are prioritized, as thermal comfort significantly impacts their ability to learn and thrive. By incorporating the tracking of thermal comfort into the UDISE data, we can shed light on this critical aspect and pave the way for effective interventions and policy changes to improve the learning environment for students across the country.

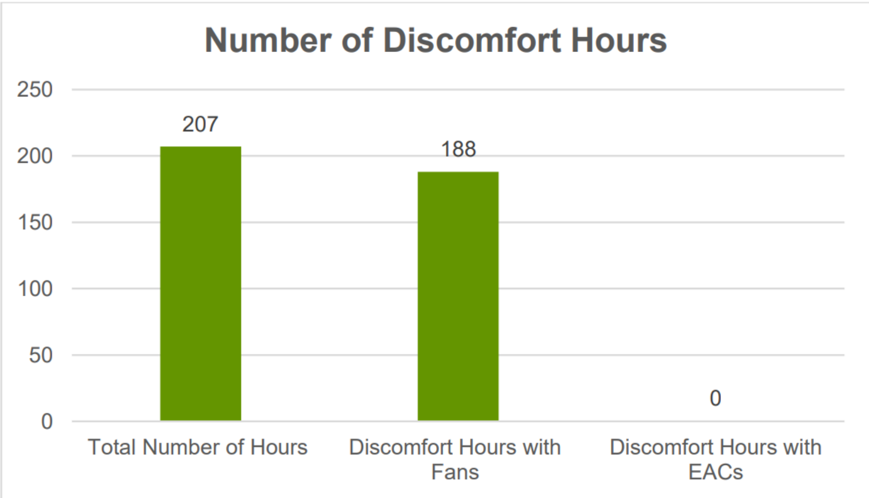

Figure 7: Reduction in Thermal Discomfort Hours Fans vs EACs

Thermal comfort perception of students

A descriptive cross-sectional survey research design was used to assess the students' comfort level pertaining to thermal cooling in schools and the impact of usage of energy appliances on electricity consumption. The sample comprises students from classes IX to XII and not from Primary classes because higher age group students are able to discuss school infrastructure and respond better about their comfort and concentration level during the summers.

A stratified random sampling technique was used to select the schools to collect responses from the students. The survey deals with the students who were initially asked about their profile, like gender, and then their comfort level with the cooling environment in schools and the impact on their comfort and concentration.

The survey findings are shown in Figure 8, where 261 respondents, including students, teachers, and administrative staff of the schools, have responded to the need for thermal comfort in the classrooms and awareness regarding the subject of energy efficiency. The students' response exhibited a bias towards their school, stemming from the deep sense of pride they harbour for their institution. However, it's essential to acknowledge and address the error in their responses. Thus, to negate the error, In addition to the students, it's important to consider the perspectives of the teachers and administrative staff, who also operate within the same premises and are subject to the same set of challenges and discomforts.

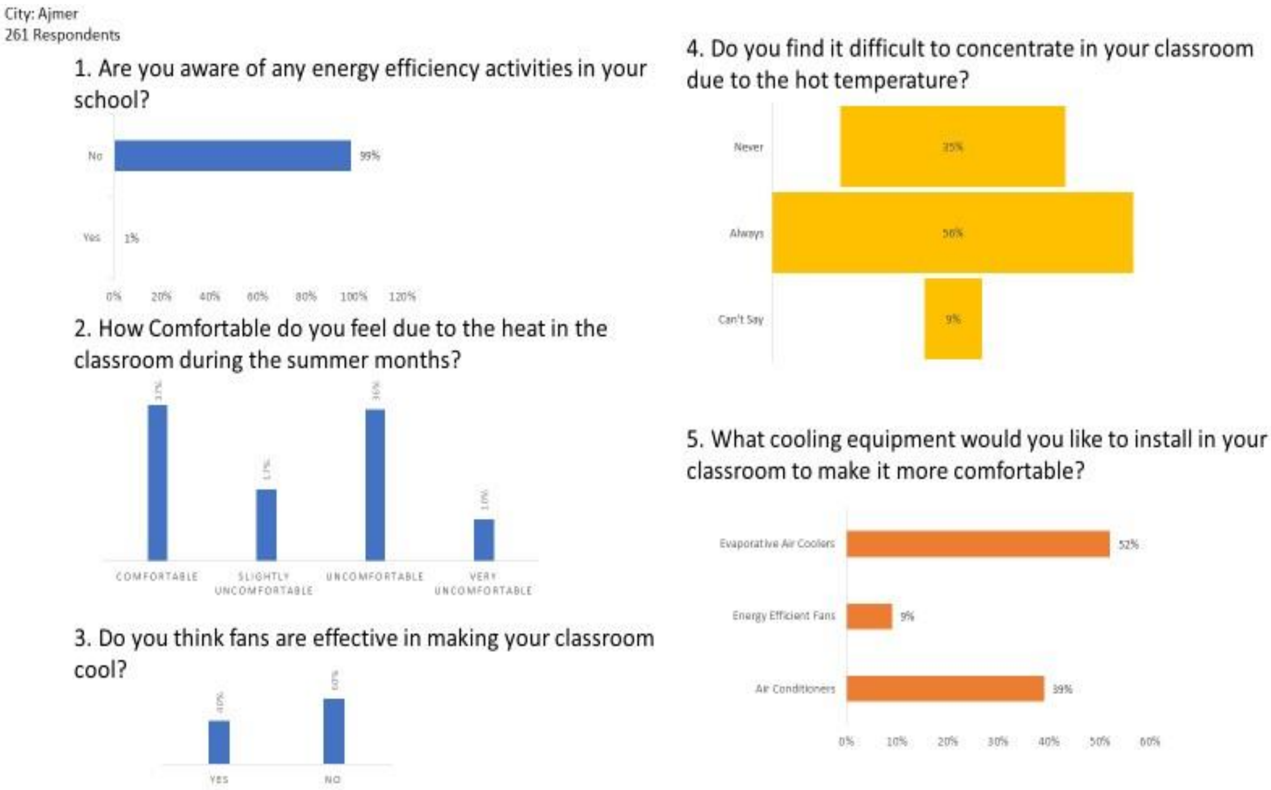

Figure 8: Survey Findings with Emphasis on Thermal Comfort and Energy Efficiency in Schools

The survey results indicate that a significant proportion, specifically 60% of the respondents, perceive fans as inadequate in meeting the requirements for thermal comfort. Additionally, an impressive 52% of respondents recognize evaporative air coolers as a viable and effective solution for addressing the thermal comfort needs in classrooms. These findings highlight the growing demand and recognition for such technology in educational settings. As a result, there is an ever-increasing need for the implementation of advanced cooling technologies like evaporative air coolers in classrooms. By embracing these solutions, educational institutions can ensure a conducive environment for optimal learning and enhance the overall well-being of students.

Recommendations

Institutionalizing thermal comfort in Indian academic institutions requires a collective effort of multiple organizations from different ministries and associations. Since the context of thermal comfort is multidimensional and traverses across wide sectoral stakeholders, therefore the institutional mapping has been done in three categories:

1. **Educational Infrastructure –** To achieve a wider goal of thermal comfort for all citizens, the Ministry of Education can create a thermal comfort scenario mapping across Indian classrooms, identifying areas that require cooling interventions and paving the path for the creation of green schools. Based on the data collected, the Ministry can thus prepare guidelines for the education sector and may include the same as recommendations under the Nation Education Policy (2020), which already recommends improving the infrastructure of India's academic institutions to boost the overall quality of education.
2. **Energy Security –** The increase in the demand for electricity is one of the priority concerns for the Ministry of Power (MoP). According to the India Cooling Action Plan (ICAP) [3], there will be an eight-fold increase in the overall cooling demand, which will result in a surge in electricity consumption in the future. It is not sustainable to meet this demand by relying solely on-air conditioning technologies. Therefore, it is essential to focus on deploying other non-refrigerant cooling technologies in various sectors, including schools. The Ministry of Power should work towards promoting the use of such technologies to meet the growing cooling demand while minimizing the environmental impact and reducing the strain on the electricity grid.
3. **Climate Mitigation & ICAP Recommendation –** According to recent projections [3], the demand for refrigerants is expected to increase by a staggering 6.5 times in the coming years. In light of this concerning trend, it is crucial for the Ministry of Environment and Forest Climate Change to take proactive measures, such as deploying energy-efficient cooling solutions in multiple schools. This initiative holds immense potential in providing the masses with access to cooling technologies that produce no greenhouse gas (GHG) emissions. Considering that schools in India serve various purposes, ranging from hosting elections to organizing boot camps in rural areas, the widespread

adoption of Evaporative Air Coolers (EACs) can drive a systematic change in meeting the thermal comfort needs of the masses.

Conclusion

This study establishes that Evaporative Air Coolers (EACs) have a pivotal role in meeting schools' thermal comfort requirements. The comprehensive data collection and evaluation conducted in a school in Ajmer, Rajasthan—a region characterized by hot and dry climatic conditions—clearly demonstrate a remarkable reduction in thermal discomfort hours upon deploying EACs in classrooms. The findings of this study provide compelling evidence of the effectiveness of EACs in creating a more comfortable learning environment for students. By adopting this technology, schools can effectively mitigate the challenges posed by harsh climatic conditions, ensuring that students can focus and thrive in a conducive setting.

The survey results indicate that a significant proportion, specifically 60% of the respondents, perceive fans as inadequate in meeting the requirements for thermal comfort. Additionally, an impressive 52% of respondents recognize evaporative air coolers as a viable and effective solution for addressing the thermal comfort needs in classrooms. These findings highlight the growing demand and recognition for such technology in educational settings. As a result, there is an ever-increasing need for the implementation of advanced cooling technologies like evaporative air coolers in classrooms.

Moreover, this paper places significant emphasis on providing recommendations to key stakeholders in the domains of Educational Infrastructure, Energy Security, and Climate Mitigation. The stakeholders to whom these recommendations are directed include the apex authorities of the Ministry of Education, the Ministry of Power, and the Ministry of Environment and Forest Climate Change. By addressing these stakeholders, the paper seeks to foster collaboration and encourage proactive measures in addressing the thermal comfort needs of educational institutions. It highlights the importance of integrating energy-efficient cooling solutions into educational infrastructure, ensuring the security of energy resources, and promoting climate mitigation efforts.

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Hospital Energy Consumption Survey: The Lived Experience

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Highlights

- The lived experience of the survey administrators of a nationwide hospital energy survey capturing on-ground realities and learnings often precluded from technical survey reports
- Transferrable learnings that can help make future commercial building energy consumption surveys quicker, less cumbersome, less costly, and more effective

Abstract

As part of the effort to foster a more systematic approach to commercial building energy data collection and reporting, this paper aims to bring out the "lived experience" of on-ground data collection from the recently concluded Hospital Energy Consumption Survey conceptualized and conducted by the National Centre for Disease Control (NCDC), Directorate General of Health Services, Ministry of Health & Family Welfare, Government of India, under the aegis of the National Program for Climate Change and Human Health. It was administered and overseen by the Alliance for Energy Efficient Economy (AEEE) and the Centre for Chronic Disease Control (CCDC). This paper captures the authors' on-ground survey experience and transferable learning, typically precluded from technical survey reports. The authors believe that given the challenges in collecting relevant energy data from the buildings sector, their experiences can offer a unique insight into the on-ground realities of collecting technical data and suggest transferrable learnings that can help make future commercial building energy consumption surveys quicker, less cumbersome, less costly, and more effective.

Keywords: Hospital, commercial building, energy efficiency, survey, data

Introduction

The imperative need for healthy, energy-efficient, and low-carbon buildings is growing alongside rising expectations of private and public sectors' environmental, social, and governance (ESG) performance. Per its updated Nationally Determined Contributions (NDCs), India will, inter alia, reduce the emissions intensity of its GDP by 45% by 2030 (over the 2005 baseline) and achieve 50% cumulative electric power installed capacity from non-fossil fuel-based energy resources by 2030, in the run-up to its long-term goal of reaching net-zero by 2070 [1]. India's Long-Term Low Emissions

Development Strategy (LT-LEDS) launched at COP27 highlights the potential to significantly reduce the national power demand by improving the building sector's energy efficiency in terms of design, construction, and operations [2]. Therefore, enhancing the energy efficiency of the commercial building stock should be an important aspect of India's national energy policy framework. Understanding how buildings use energy is critical to formulating any new policy that may impact energy use, underscoring the importance of credible data. Data enables informed decision-making, and good quality data is essential for policymakers to prioritize energy-saving strategies and track implementation.

A data-driven policy framework for systematically targeting energy efficiency in both new construction and existing buildings has largely been missing. There is currently no quantifiable mechanism to track the impact of code adoption through regular reporting or surveying of energy consumption in the commercial building stock – something essential for developing updates to the codes. Most importantly, benchmarking data can be utilized to formulate building performance standards with targets commensurate with a city/state/country's decarbonization goals – such data-driven building performance standards are currently unavailable in India. As part of the effort to foster a more systematic approach to commercial building energy data collection and reporting, this paper aims to bring out the "lived experience" of on-ground data collection from the recently concluded Hospital Energy Consumption Survey conceptualized and conducted by the National Centre for Disease Control (NCDC), Directorate General of Health Services, Ministry of Health & Family Welfare, Government of India, under the aegis of the National Program for Climate Change and Human Health. It was administered and overseen by the Alliance for Energy Efficient Economy (AEEE) and the Centre for Chronic Disease Control (CCDC).

Background

The survey was intended to be a starting point for, among other things, (i) identifying areas of energy efficiency and renewable energy interventions in hospitals, (ii) formulating data-driven policies and programmes, and (iii) identifying best practices and setting aspirational goals for hospitals towards climate-smart healthcare. It was intended to be administered in all 5 climate zones, 18 states/Union Territories (UTs), and across 10 hospital typologies of publicly and privately-owned "hospitals", i.e., centres of medical care with in-patient beds. The sample stratification was done in layers based on the ownership, climate zone, and hospital typology. The details of the sampling methodology can be found in this peer-reviewed paper: "Towards Climate-smart Hospitals: Methodology and Pilot of India's First Nationwide Hospital Energy Survey" [3]. The survey utilized the AEEE Hospital Energy Survey Questionnaire [4], which was created during this project. A total of 623 hospitals (357 public and 266 private) were surveyed, which is 3.6% of the estimated hospital population in India. For comparison, the US Commercial Building Energy Consumption Survey (CBECS) 2018 selected a sample size of 16,000 buildings, which was 0.27% of the estimated 5.9 million commercial buildings in the US [5]. The project was kicked off in January 2021 and took over 2.5 years to complete. The project timelines were extended due to challenges related to the COVID-19 pandemic. Full details about the survey methodology, the survey findings, recommendations, and future work can be found in the survey report [6]. This paper captures the authors' on-ground survey experience and transferable learning, typically precluded from technical survey reports. The authors believe that given the challenges in collecting relevant energy data from the buildings sector, their experiences can offer a unique insight into the on-ground realities of collecting technical data and suggest transferrable learnings that can help make future commercial building energy consumption surveys quicker, less cumbersome, less costly, and more effective.

The lived experience

Survey agency selection: The survey was conducted by a combination of two different survey partners with different levels of technical competence. Initially, a company primarily experienced in market research (not necessarily technical energy consumption surveys) was chosen to implement the entire survey. The personnel conducting on-ground surveys from this company were generalists with a bachelor's degree and 1-2 years of field experience. Parallelly, a validation group of around 60 public and private hospitals was surveyed by experts in building operations (energy engineers/auditors). These experts were chosen to ensure that the data collected was of high quality and reliable. Their data was used as a benchmark to validate the data collected by the generalist market research company. Though trained (see "surveyor training" below), the on-ground surveyors from the generalist surveyors found the survey too technical and could not provide consistently high-quality data like the experts. Therefore, based on this experience and a few expert consultations, the administrators decided to discontinue with the generalist market research company. The specialists were chosen to complete the rest of the surveys. Although the specialists were at least significantly more expensive than the generalist market research company, a smaller sample size was opted for to keep the costs manageable. The underlying logic for this decision was that while sampling error is likely to comprise only a small share of the total error (up to 10%), inaccurate data transfer between the surveyor and the respondent could lead to larger errors if the questions are not explained and understood well. Hence, it was decided to prioritize data quality over quantity.

Surveyor training: On-ground surveyors were given rigorous training before being deployed in the field for the pilot and the main survey. Surveyors received an overview of the study and specific instructions. A comprehensive survey toolkit and manual were provided to each surveyor. To ensure they were prepared, the surveyors carried out multiple rounds of supervised mock surveys. Thorough feedback was provided to each surveyor at the end of each mock survey. Also, during the first few real surveys, experienced team members were around to help the surveyors. Despite extensive training of surveyors and mock sessions, the survey was perceived to be too technical to be administered by the generalist market research agency. Although care was taken to make the data asks as clear as possible in the questionnaire with additional explanations such as "tool tips", the survey pilot and initial rounds of data collection revealed that sometimes the questions were not being correctly presented to the respondents. Additionally, the survey length sometimes led to respondent fatigue and poor data quality. This highlighted the need for energy specialists to conduct the surveys, which is when the validation group described above was constituted. The energy specialists ensured better data quality by minimizing errors creeping in because of misrepresenting some questions and data asks.

Onboarding of hospitals: Public and private hospitals were identified and onboarded for the survey as closely as possible per the sample stratification. A top-down approach was followed to onboard public hospitals, which NCDC facilitated under the aegis of the National Program for Climate Change and Human Health. NCDC convened a meeting of the State Nodal Officers for Climate Change (SNOCCs) to explain the nature and scope of the national survey and secure their support. This was followed by written communications to each state requesting to nominate public hospitals for the survey. The State and District Nodal Officers for Climate Change facilitated the selection of facilities in respective states where surveys could be administered. Over 500 leads were gathered for contacting public hospitals across 14 states. To identify private hospitals, an exhaustive list of about 7,353 private healthcare facilities was compiled by merging the private hospital network lists of health insurance providers, namely, ICICI Lombard, MD India Health Insurance TPA (P) Ltd., and the hospital list of Association of Healthcare Providers of India. The hospitals were then classified into single-specialty and super/multi-specialty based on the healthcare services provided by them. The list of private medical colleges was retrieved from the National Health Profile 2020 [7].

The following benefits were offered to hospitals in exchange for their participation in the survey:

- A high-level summary of their hospital energy performance, including their hospital's position on various energy performance indicators and how it compares to similar hospitals.
- A compilation of additional energy-saving/indoor air quality improvement measures practised by similar hospitals to help improve the energy/environmental performance of the hospital and the health and well-being of building occupants
- Anonymized raw data of all hospitals participating in the survey
- A training program on HVAC systems operations and maintenance at concessional fees

Clear data confidentiality terms eased the onboarding process. No personal data regarding individual patients, doctors, hospital staff, etc., was collected – only the primary survey respondent's contact information (i.e., name, email ID, and phone number) was asked. As mentioned in the survey insights report, the primary survey respondent agreed to the data confidentiality terms [6]. Once the management felt inclined to participate in the survey, the process of engagement with private hospitals was relatively linear and smooth. In contrast, engaging with the public healthcare systems was less linear since various government departments with varying authorities and roles were engaged to run the public healthcare system.

Survey lead times and questionnaire optimization: At the time of data collection, the survey team learned the opportunity cost involved in a lengthy questionnaire and the need to prioritize the quality of responses over the quantity of responses. Engagement with multiple layers of the system caused delays. Conflicting priorities for healthcare workers, some of which were associated with the pandemic, created bottlenecks for committing time to the survey. It was often found to be difficult to identify the right person to take the survey. In the case of larger hospitals, multiple departments needed to be involved, which also contributed to longer lead times. After the pilot survey, an effort was made to optimize the questionnaire and assess which data fields are most meaningful for meeting the project objectives, including assessing the baseline for hospital energy consumption, gaining insights into their energy intensities of area and bed, energy saving practices, and the energy efficiency of end-use technologies. The questionnaire underwent many revisions (including cutting down the number of questions to one-third from 65 data points to 20 data points).

Respondent profile and modes of data collection: The main survey was administered to chief engineers or other officials from the engineering/facility management department (and the administration department for questions related to business metrics). The biomedical department was approached (for questions related to medical refrigeration and imaging equipment) in the larger public medical colleges and all private hospitals. It was administered to presiding doctors and/or visiting service technicians in smaller typologies. The survey was administered in a combination of 2-3 in-person and virtual meetings per hospital using a digital version of the questionnaire and/or its hardcopy version in those areas where internet connectivity was not reliable. Many respondents showed a preference for hard copies over the digital version of the questionnaire. At the beginning of the survey, the respondents were informed of the data-sharing terms and presented a consent form to sign for the collection of data.

A mix of three methods of data collection was followed:

- **Web-based:** The online survey link was shared with the respondents/departments via email. The respondents then responded to the questionnaire and submitted the survey, which was uploaded to the server. Telephonic follow-ups were made to ensure a high level of participation.
- **Telephonic interviews:** A team of trained personnel conducted telephonic surveys with the concerned person/ department to get feedback. Prior appointments were fixed for conducting the interviews.
- **Face-to-face intervention:** The interviewers carried a tablet with the online version of the questionnaire or a hard copy of the questionnaire to conduct the face-to-face intervention.

A survey tracker to ensure the timely completion of facility onboarding and completion of surveys was established. In some cases, the lead times for interviews were very long due to the lack of availability of staff for the survey. Some of these lead times took as long as a few weeks per hospital. Identification and timely communication with the appropriate respondent was challenging in many hospitals.

Data collection: The on-ground experience of collecting some key data is detailed in Table 1.

Table 1: Experience, ease of collection and data quality

Data ask	On-ground experience	Level of effort	Data quality
Monthly and annual grid-connected electricity consumption (kWh)	Obtaining monthly electricity consumption was difficult. Hospitals would often be missing electricity bills and records for certain months, which would make arriving at annual sums tricky. Hospitals would more often just have the information of the expenditure on electricity than the absolute consumption. This was often found to be misreported as consumption numbers in back-checks. Additionally, back-calculating consumption from electricity bills is not always straightforward and can lead to misleading numbers. Many public hospitals did not have a record of electricity consumption since their bills were paid through the district electricity offices. The electricity consumption was not tracked at the end-use levels by most hospitals.	Medium	Medium
Total gross floor area(ft^2)	ANSI/ASHRAE Standard 105 (ASHRAE 2022, 2018, 2021) uses other definitions, including gross square footage, as included here. For the purposes of this study, the total gross floor area is the super built-up area between the outside surface of the exterior walls of the building. This includes all areas inside the building, including supporting areas. It includes lobbies, common areas, meeting rooms, break rooms, restrooms, elevator shafts, stairwells, mechanical equipment areas, basements, and storage rooms. It excludes exterior spaces, patios, exterior loading docks, driveways, covered walkways, outdoor play courts (tennis, basketball, etc.), all parking areas, the interstitial plenum space between floors that house pipes and ventilation), and crawl spaces. Although the total gross floor area was clearly defined in the questionnaire, the respondents still had trouble reporting the correct information. The accurate area of hospitals was often not available. To counter-check, the team used Google Maps to corroborate the reported gross-floor area of the facilities. There were some reporting issues regarding the units (ft_2 v. m^2). In many healthcare units, the staff were not aware of the actual floor area of the hospital as the healthcare units have undergone the addition of new buildings or floor plates over a period of time. The updated building drawings and floor area data were not readily available to the administration team. In the absence of this information, the surveyors either measured using measurement tape or counted the number of tiles with the help of hospital staff to roughly calculate the floor area, which is not practically feasible for bigger hospitals.	Medium	Low
Total number of beds considering male, female, OBG-related, post-op ward, emergency ward, daycare, and other general ward beds	Some healthcare units reported beds that were not operational at the time of the survey.	Low	Medium
Annual number of in-patients discharged	Capturing or estimating the average length of in-patient stay was found to be difficult. The product of the reported average length of in-patient stay and number of in-patients, which could be interpreted as a measure of	High	Low

Average length of in-patient stay	occupancy ("in-patient days"), would sometimes exceed the available bed capacity.	High	Low
Total air-conditioned area (ft^2)	Data on air-conditioned area (sq. ft.) was often not available for air-conditioned hospitals. Among the hospitals that did report air-conditioned area, there was limited data on the installed cooling capacity, i.e., DX and/or chiller. In some cases, the reported air-conditioned area was greater than the total area for hospitals. The reported data was often a guesstimate, which may not have been accurate.	Medium	Low
Total operational cooling capacity for each type of DX unit tonnes of refrigeration (TR)	In some cases, the refrigeration tonnage of individual units was misunderstood as the total installed tonnage of the given unit type.	Medium	Medium
Onsite solar PV to support hospital energy needs	Hospitals that had installed solar PV systems were not always using the power generated by the installation. Some hospitals that used onsite solar power were not capturing the amount consumed.	Low	High
Peak capacity in kilowatt peak (kWp)		Low	High
Annual energy consumed from onsite solar PV (kWh)		Medium	Medium
Share of LED lights as a percentage of overall hospital lighting	Most hospitals were not able to provide an accurate number across types of lighting used in the facility. The associated survey question was later revised to a multi-choice question about the share of LED lighting in the facility.	Medium	Medium

In the case of in-person data collection, the energy specialist surveyors were able to glean anecdotal or qualitative insights by observing and interacting with the survey respondents, who were not a part of the survey questionnaire. These insights helped create more rounded recommendations based on the survey findings. For example, it was observed that most of the solar PV systems in public and private hospitals were observed to be on-grid systems, barring a few public hospitals located in remote areas that had off-grid systems. Most of the hospitals did not deploy solar PV systems as a source for critical load backup; instead, they relied on diesel generators to provide critical services during the hours of power supply failure. In both public and private hospitals, the maintenance of solar PV plants was conducted through an annual maintenance contract issued to the solar PV plant service provider. It is observed that in public hospitals, the maintenance of the solar PV plant was not effectively conducted, with the energy survey team visibly confirming the presence of the broken component of solar panels and as informed by the hospital administrative staff. Some of the hospitals surveyed even indicated that the solar PV plants' components needed detailed repairing and replacement. Nonrenewal of annual maintenance contracts was common in public hospitals, which indicates that solar installations in public health systems have not happened following an institutional approach.

Data quality control: Data quality control systems were established through a rigorous check at frequent intervals of all data collected throughout the survey. The following measures were undertaken:

- Regular check-ins of participating teams to ensure that the standard data collection process was being followed.
- A subset of data was reviewed, and feedback was provided to survey teams where the data monitoring teams encountered additional inputs or missing data.
- Several data points were back-checked with hospitals through a combination of in-person visits and telephonic communications.
- Feedback on the survey experience was also collected from respondents to ensure the genuineness of the survey exercise.

Data screening: A multi-level filtering approach was used to eliminate dubious data points further. The first level of filtering was done based on the availability of consent forms provided by private hospitals for authentication and the availability of critical data points from hospitals, including the number of beds, total gross floor area, and annual electricity consumption for FY 2019-20. The second level of filtering eliminated outliers, which were identified based on ranges derived using a combination of literature and distribution of sample data. Only the hospitals that passed through both filtering levels were considered for the final analysis. Despite the data screening and quality checks, some data points that do not accurately represent the on-ground situation may have yet passed through due to the various factors elaborated above.

Conclusion: Transferrable learnings for future surveys

Building energy data gathering is almost always resource-intensive, time-consuming, and extremely susceptible to data quality problems. As a result, the scope and priorities for data gathering should be carefully evaluated and chosen based on a number of important factors. The authors' lived experience corroborates the suggestions presented in related literature, particularly "Establishing a Commercial Buildings Energy Data Framework for India: A Comprehensive Look at Data Collection Approaches, Use Cases and Institutions" [8].

- **Begin with the use case rather than the data:** To decide on the needs and priorities for data, always refer to the KPIs associated with the use cases or survey objectives. Every data field should be included in the survey for a specific reason, such as serving as an input for a KPI or a normalizing/clustering variable.
- **Keep in mind the level of effort:** The amount of work needed to obtain data varies greatly amongst data fields. Detailed end-use energy disaggregation is much more complex to collect than the total number of guest rooms in a hotel. When deciding which areas to prioritize for collection, it may be helpful to rate the level of work necessary to get the data for each field on a scale of 1 to 5. Consider using proxy fields instead of difficult-to-collect crucial fields whenever possible. For example, use the chiller's nameplate efficiency if determining its real operational efficiency is difficult.
- **Analyze the possibility of poor data quality:** While certain fields might appear simple to fill out, they could be particularly vulnerable to bad data. Experience shows, for instance, that even a seemingly basic data category like gross floor area can contain major errors. Alternative measurements of floor area may be more accurate for specific building types. For instance, it is probably more dependable because net leasable area serves a crucial business function in leased buildings.

The following are crucial factors for the survey design and data collection strategy after the data fields have been chosen and prioritized.

- **Data quality versus quantity:** Sampling error is likely to comprise only a small share of the total error, say up to 10%, while the majority of the error is likely to creep into technical energy consumption surveys on account of inaccurate data transfer between the surveyor and the respondent if the questions are not explained and understood well. Hence, it is important to prioritize data quality over quantity.
- **Onsite versus remote data collecting:** In general, collecting data remotely (e.g., over the phone, using web survey forms, or via email) is easier than gathering data physically. It might be challenging to forgo site visits for some data points totally. However, by gathering as much information remotely as feasible, the amount of time spent onsite could be reduced.
- **Reduce the number of points of contact used to collect the data:** In any particular facility, it's unlikely that any one person will have access to all the information needed. To make the process of gathering data easier, the number of touchpoints should be kept to a minimum. For large portfolio owners, for instance, a central repository might have information on all properties. While such central repositories may currently be scant, mandatory, and self-verified, data disclosure by a certain category of hospitals (large multi or super-speciality hospitals) could, in the future, ease energy data collection and more informed decision-making at the facility as well as policy level.

The methodology used in this survey can be applied to address energy data gaps in various energy-intensive building types, such as hospital and hotel chains, ICT companies, airports, and more. It offers a valuable framework for designing and implementing future efforts in closing energy data gaps for these building typologies. Further, the applications of on-ground learnings in data collection can inform future commercial building energy surveys to make them more effective, less prone to error, less cumbersome, and less expensive. Obtaining accurate and comprehensive information about the building's energy systems, equipment, and historical energy usage is challenging. The complexity inherent in commercial buildings and potential resource constraints underscores the importance of employing skilled energy surveyors and interdisciplinary collaboration. Leveraging the lessons learned from this survey, we advocate for a strategic approach that amalgamates expert energy assessment, multidisciplinary cooperation, and robust data analysis, culminating in more accurate and actionable survey outcomes.

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Futureproofing with Passive Buildings: Is It Cost Effective and Is It Thermally Adequate?

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Highlights

- The paper summarizes the calibration process used to analyze thermal comfort and LCC in different wall assemblies.
- The calibration process met the thresholds for Mean Bias Error (MBE) and Root Mean Squared Error (RMSE) outlined in ASHRAE Guideline 14.
- The calibrated model proved useful in identifying problems with the measured data.
- Preliminary results indicate that insulated walls are cost-effective in a 50-year lifecycle analysis when the entire building is air-conditioned.
- The study underscores the significance of including future weather files in Life Cycle Cost (LCC) analysis, enhancing accuracy, and facilitating informed decision-making in construction and energy efficiency.

Abstract

The paper aims to highlight the importance of employing a robust Life Cycle Cost (LCC) method that incorporates future weather files and a calibrated model. The study evaluates a 50-year LCC for wall insulation in an experimental building in Bangalore. It compares the LCC calculated using the future weather data with results obtained using the Typical Meteorological Year (TMY) file, providing a more accurate assessment of long-term cost-effectiveness.

The results show that insulated walls have a lower LCC when fully air-conditioned, while mixed-mode settings show higher LCC. A detailed thermal comfort analysis indicates that insulated walls offer adequate thermal comfort (11-13% discomfort hours) under full adaptation to thermal conditions. Without full adaptation, when the adaptive comfort equation of the National Building Code (NBC) does not work, discomfort could rise to 31%. However, with ceiling fans (6-7 ºC cooling power index), it would suffice to provide comfort in the experimental building. The study underscores that well-designed buildings in Bangalore with insulation, passive strategies, and natural ventilation can ensure prolonged comfort without mandatory air-conditioning.

Keywords: Calibrated model; LCC analysis; MBE and RSME; adaptive thermal comfort; future weather file

Introduction

Globally, the building sector generates 37% of energy-related CO_2 emissions, and about 24% of total energy and process-related CO_2 emissions are from India [1]. Further, India's CO_2 emissions are projected to rise by 50% in the next 20 years. Therefore, the building sector has a significant responsibility for reducing greenhouse gas emissions. Designers and builders have an opportunity to decarbonize the building sector with the use of innovative passive design techniques to meet the 1.5°C target. Apart from decreasing building energy consumption, improving thermal comfort through passive solutions has also been important due to global carbon emissions and the requirement for a good quality of life [2]. Therefore, evaluation of building passive design techniques and thermal comfort is necessary.

Figure 1: Experimental Building

This paper presents the analysis of an experimental building (see Figure 1) of 432 m^2 in Bangalore, India, which was constructed with different technologies and materials to test passive innovative technologies that could be implemented in buildings on a 55-acre campus. The wall insulation was considered a significant investment. The insulation cost for the larger campus was estimated at 50 million INR. If cladding of insulation was considered, that added another estimated 270 million INR. The cladding also had a high maintenance cost. This was the motivation behind the detailed cost-benefit analysis presented in this paper.

The wall systems in the experimental building were built with cement stabilised earth blocks (CSEB), rammed earth (RE), autoclaved aerated concrete (AAC) blocks, extruded polystyrene (XPS) insulation, granite stone cladding, china mosaic, and plaster. Three wall systems built from combinations of these materials are all insulated, and their performance has been monitored. Bangalore has a temperate climate, with an average daily high temperature of around 27°C with an annual maximum temperature of 35°C. To assess the cost and benefit of these wall assemblies, a detailed audit, longer-term monitoring, and model calibration were conducted for the experimental building.

Using a calibrated model, a life cycle cost benefit analysis was conducted for the three wall types built and an additional 5 types of wall types (total of eight) to understand the value of investment for the upcoming buildings in the 55-acre campus. These eight wall systems (Table 1) were identified by the design and construction team as viable alternatives for the campus. The calibrated model was also used to determine the value of the insulation in terms of the thermal comfort that it provided. The initial analysis was done with a TMY file and the current weather data.

However, running a simulation using the TMY file is not adequate. Many studies have concluded that the need for space cooling will increase in the future due to climate change [3]. Factors like rising temperatures and urban heat islands (UHIs) play a significant role in causing discomfort in buildings [4] [5]. Therefore, it is important to simulate buildings to test performance with future weather scenarios to identify the cost-effectiveness of energy conservation measures, achieve thermal comfort, and create buildings that can withstand future climate change.

Therefore, this paper uses future weather files to establish the difference in LCC and thermal comfort for insulated versus uninsulated walls. The significance of this research is the rigorous methodology used to establish the value of insulated walls and, in the process, demonstrate the difference in LCC between fully air-conditioned spaces and mixed-mode operation of those spaces, as well as the difference in thermal comfort achieved in unconditioned spaces between current and future weather scenarios.

Table 1: Eight wall systems and their civil cost

Alternate	Wall systems	Civil Cost (INR/m^2)
Alt 1	AAC+ Plaster+ China mosaic	2,485
Alt 2	Plaster + AAC + Insulation + CSEB+ China mosaic	3,337
Alt 3	230 CSEB	1,466
Alt 4	CSEB + Air gap (50mm) + CSEB	2,932
Alt 5	CSEB + Insulation + CSEB	3,784
Alt 6	CSEB + Insulation + Cladding	7,303
Alt 7	Rammed earth wall	1,983
Alt 8	Rammed Earth + Insulation + Cladding	7,819

Method

Calibrated energy models have shown utility for commissioning building systems, measuring and verifying building retrofit projects, and predicting savings from energy conservation measures [6]. The evaluation of the measured and simulated data for energy and thermal comfort has provided the opportunity to analyse the possibilities of improving the design, control strategies, and the choice of the most cost-effective measures [7][8]. Calibration of simulation models leads to a greater level of accuracy to enable more meaningful analysis [9]. Accuracy and the availability of measured energy and comfort data increase the model's accuracy [9][10]. Fabrizio & Monetti [11] note various levels of calibrating a building model. The most detailed level of calibration is where the short-term and long-term monitoring data and a detailed audit are used.

Model Data Input

The energy simulation model of the experimental building was created using DesignBuilder with its EnergyPlus simulation engine. It included information on building geometry, envelope characteristics, internal loads, HVAC system characteristics, and operation schedules. Weather data for the modeling was sourced from the weather station on the building, encompassing parameters like dry bulb temperature, relative humidity, global horizontal radiation, wind direction, and speed. Details concerning the building envelope and glazing types, including inputs for walls, windows, floors, ceilings, doors, and shading devices, were extracted from construction drawings and incorporated into the model. About 30% of buildings are conditioned with Split-Air Conditioning HVAC system with outdoor units on the roof, with a coefficient of performance (CoP) of 3.52 and a cooling set point temperature of 26°C. The rest of the building is naturally ventilated with no air-conditioning equipment. But even the spaces with the split ACs are operated in temporal mixed mode. Implementation of HVAC modulation was executed through the "Simple HVAC" option in DesignBuilder. The window and HVAC operation schedules were based on on-site surveys and interviews with the building occupants. Each space in the building was modeled as a separate thermal zone. Internal loads, including occupancy load, lighting load, and equipment load, were established through a detailed building audit.

Table 2: Building envelope characteristics

Envelope	U-Value (W/m^{2}K)
External walls	
CSEB wall with insulation and cladding (CSEB-I-C)	0.52
Rammed earth wall with insulation and cladding (RE-I-C)	0.54
AAC and CSEB wall with insulation and china mosaic (AAC-I-CSEB-CM)	0.35
Internal walls	
CSEB wall	1.95
Rammed earth wall	2.86
Roofs	
Precast RCC Joist (Clay Tile Flooring, 75 mm XPS Insulation, cement screed and Kota stone slab)	0.40
Filler slab (Clay Tile Flooring, 100mm Exfoliated vermiculite Insulation, cement screed and clay trough)	1.48
RCC flat slab (China mosaic tile, 50mm XPS insulation and RCC slab)	0.40
Ceilings	
Precast RCC Joist (Floor finish, cement screed and Kota stone slab)	2.37
Filler slab (Floor finish, cement screed and clay trough)	2.53
Jack Arch (Floor finish, cement screed and hollow clay block)	2.31
Ground	2.85
Window (6mm DGU with 12mm air cavity)	2.68
Doors (6mm DGU with 12mm air cavity)	2.68

Model Calibration

The simulation model underwent a four-step calibration process. Since hourly energy data was not available, hourly data for indoor temperature, inside wall surface temperature, and outside wall surface temperature were used to calibrate the model's thermal behavior. Simulations were compared with measured data for September 2021 to assess accuracy. The calibration process involved correcting the model's geometry, size, thermal properties, construction assemblies, and occupancy schedule.

Life Cycle Cost Analysis

When the model was calibrated, additional wall systems were modeled, and LCC analysis was conducted for a total of eight wall systems. The cost components of the LCC used material costs, installation costs, maintenance costs, and energy consumption data. Additional parameters, including utility tariffs, power factor, discount rate, and inflation rate, were identified and obtained from reliable sources. Table 3 below shows the parameters that were considered for the LCC.

Table 3: All the inputs that were used for the Life cycle cost calculation

Parameters	
Electricity consumption charge (INR/kWh)	21.4
Electricity demand charge (INR/kVA)	240
Power factor	0.75
Social cost of carbon (INR/kWh)	12.8
Cost of air-conditioning system INR Per TR	65000
Service factor (cooling)	1.15
Discount rate	8%

Inflation rate	7%
GST	1.18
Project management cost (Capex)	1.15
Energy consumption data	From the calibrated model
Civil Cost of all Wall systems (materials + labour)	**(INR/m^2)**
1. AAC+ Plaster+ China mosaic	2,485
2. Plaster + AAC + Insulation + CSEB+ China mosaic	3,337
3. 230 CSEB	1,466
4. CSEB + Air gap (50mm) + CSEB	2,932
5. CSEB + Insulation + CSEB	3,784
6. CSEB + Insulation + Cladding	7,303
7. Rammed earth wall	1,983
8. Rammed Earth + Insulation + Cladding	7,819

A comprehensive calculation framework was developed to account for all relevant cost components for the 50-year life of the wall systems. This framework included all the parameters that are listed in Table 3. Other parameters like maintenance costs, repair costs, and replacement costs are also considered based on the wall system type.

Using the collected data and the established calculation framework, the LCC analysis was conducted for each wall system. LCC was conducted for two reasons: (1) to understand the benefit of insulation in the wall system and (2) to understand the importance of using future weather files.

Future weather files

This step investigates the impact of future weather files on LCC by utilizing a weather file generator specifically developed for India. The generator, developed by Manapragada et al. [13], employs a geo-filtering-based spatial technique, temporal downscaling, and machine learning (ML) based bias correction proposed by Belcher et al. [14]. The generated future weather files encompass three representative concentration pathways (RCPs) - 2.6, 4.5, and 8.5 - for the years 2030, 2050, 2070, 2090, and 2100. Historical data from present-day weather files, specifically the typical meteorological year, are utilized for testing and training ML models to correct biases. Using this weather file generator, simulations were conducted for the years 2020, 2050, and 2080 for Bangalore to be used in the calibrated model. Simulations were run for a rammed earth wall, with and without insulation, for a mixed mode and fully air-conditioned operation to get the energy consumption and indoor operative temperature values.

Interpolation of the energy data

The LCC is calculated for 50 years of the life cycle. Future weather files were made for 2020, 2050, and 2080 for simulations for those years. The energy consumption for these years was plotted to get a quadratic equation that was then used to interpolate energy consumption data for the intermediate years. LCC analysis used this annual energy consumption data. The results were then compared with the LCC calculated using the TMY file.

Results

Calibration for MBE and RMSE

For hourly data, ASHRAE guideline 14-2014 [12] prescribes that the MBE should be less than 10% and the RMSE should be less than 30%. The MBE and RMSE were calculated in 4 steps for indoor air temperature and surface temperature. Both MBE and RMSE are around 20% for the first 3 steps, showing that correcting the design model for envelope and internal loads had minimal impact. However, the actual meteorological year (AMY) measured data reduced the MBE and RMSE to 13% and 17%, respectively, as shown in Figure 2.

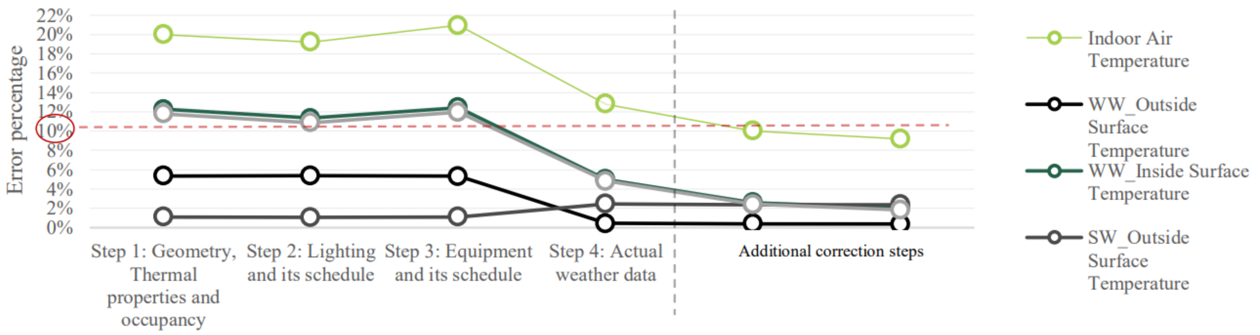

Figure 2: Mean bias error (MBE) of step six that was followed for calibration (WW is west wall, and SW is south wall)

Additional correction of the model

The MBE (13%) achieved at step 4 was not within the acceptable tolerance; therefore, further investigation was carried out for the indoor air temperature and surface temperature data. It was observed that the measured indoor air temperature for the unoccupied hours was higher than the simulated data. A thermal imaging survey of the interiors was undertaken to identify the source of the internal loads.

Thermal images of the interior of the IoT sensor led to the discovery of components inside the IoT sensor box that produced heat and affected the temperature sensor, causing the readings to be higher with a constant profile (see Figure 3 a and b). This constant temperature profile was disturbed for a short period when there were gusts of air, as with the window opening in the mornings. When compared with data from HOBO sensors, the air temperature read by the IoT box was 3°C higher. This led to a reconfiguration of the sensors and electronics for the IoT box.

No time lag was observed between the air temperature and the inside surface temperature, which implies a zero thermal mass of the wall. In the same data, when the outdoor air temperature drops, there is no drop in the indoor air or surface temperature, which implies extremely high thermal mass (as shown in Figure 3c). These two observations were contradictory. Upon further investigation, it was found that the surface temperature probes were cylindrical, with only tangential contact with the wall. The probes were also uninsulated. Therefore, more surface area of the probe was in contact with air and less with the wall. Hence, the surface temperature sensors were reading air temperature, and therefore, no time lag was observed in the data. This, too, was corrected in the building.

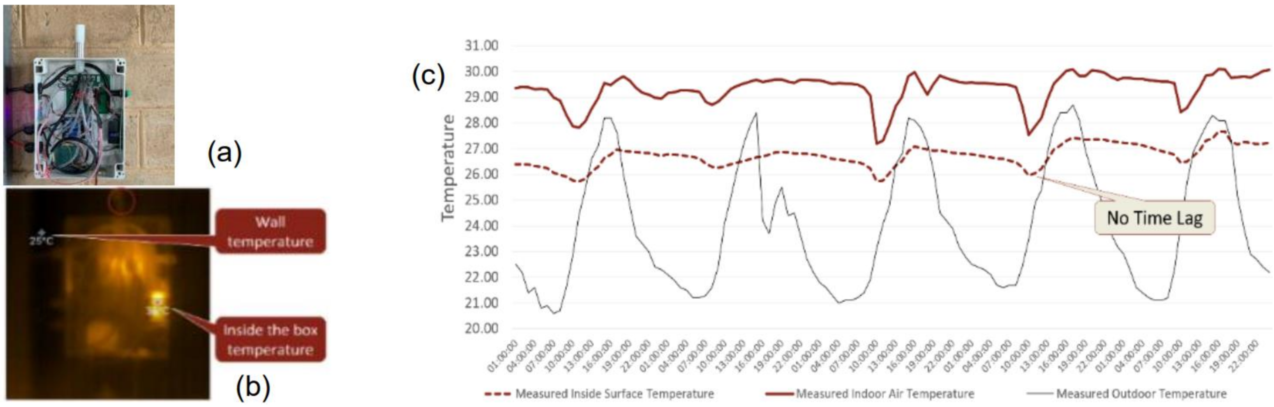

Figure 3: IoT box (a) and the thermal image of the box inside (b), Indoor air temperature, and inside surface temperature (c)

Meanwhile, the study continued using HOBO sensors and data loggers.

When the simulation results were compared with the HOBO readings, the MBE was at 1%, and the RMSE was at 17%. Therefore, both RMSE and MBE are within the acceptable tolerances of ASHRAE guideline 14-2014. The maximum temperature difference observed between the measured and simulated was 1°C (as shown in Figure 4).

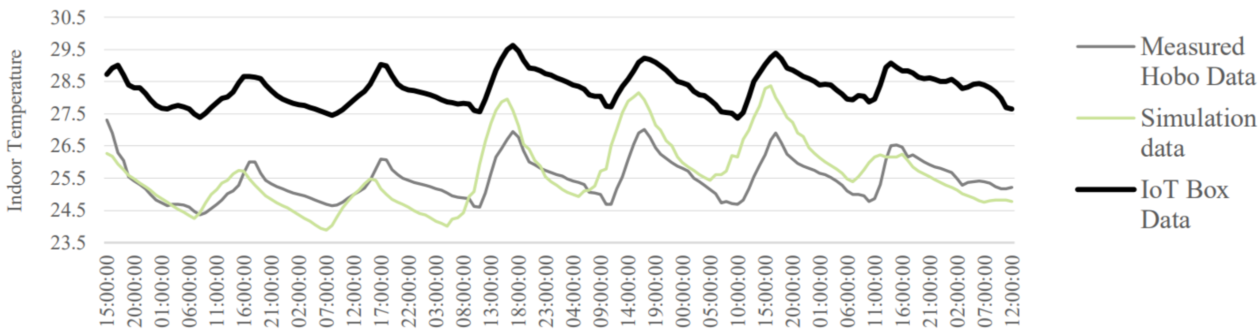

Figure 4: Measured and simulated indoor air temperature for the validation of the model result

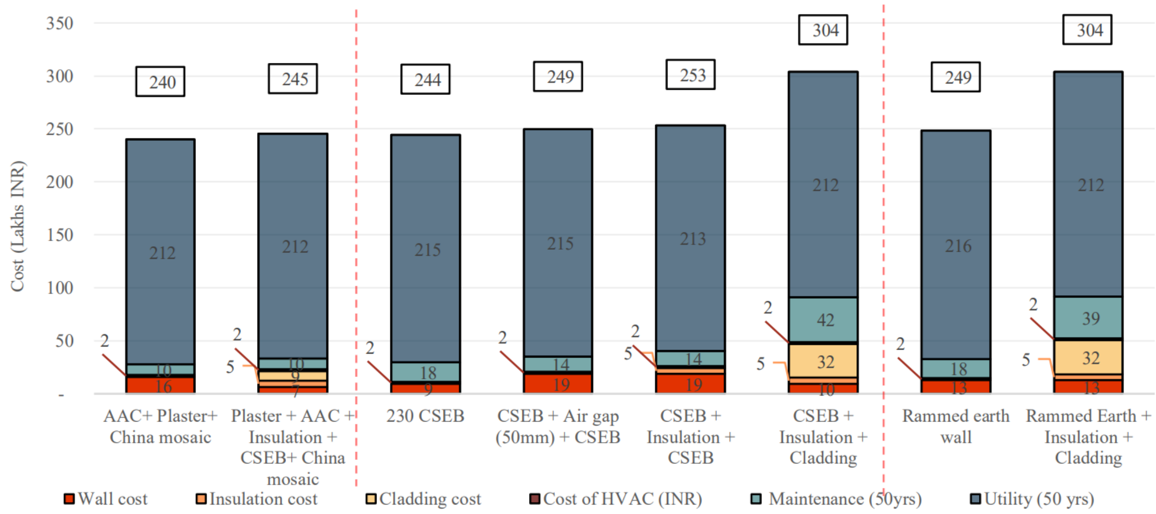

Figure 5: LCC summary for mixed mode

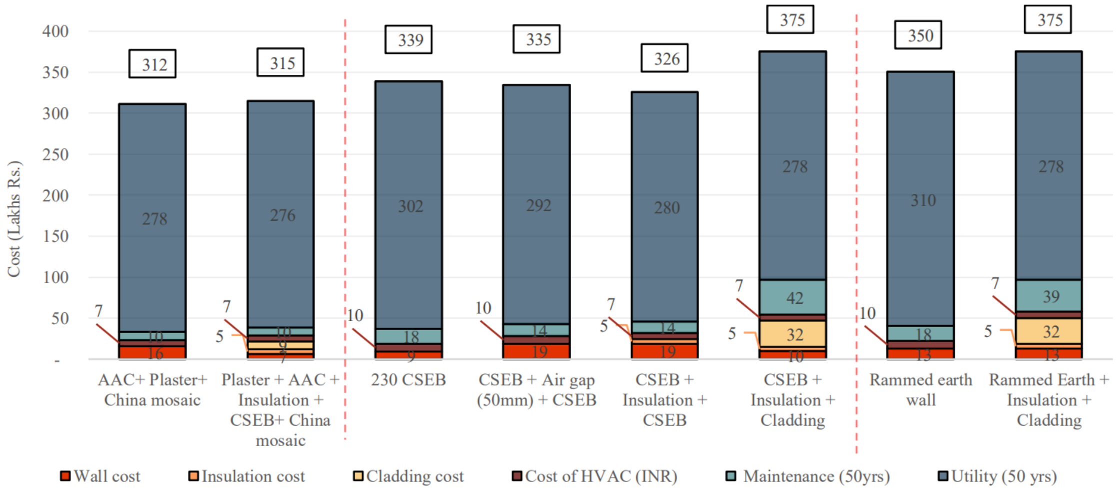

Figure 6: LCC summary for fully conditioned

LCC Analysis using the TMY weather file

The results from the mixed mode scenario showed that when the walls are insulated, the LCC increases by about 2-25% (see Figure 5). It is to be noted that the walls that include insulation, as well as cladding, have a significant increase in the LCC.

For the fully conditioned operation, LCC for the insulated walls increased by about 1-10% see Figure 6). However, when we look at the results of the four CSEB walls, we can see that LCC reduces as insulation is added, except in the case where cladding is also included. Looking at all the wall options, we can observe that even though utility (energy) costs are reduced significantly for all options that have insulation, it is the cost of cladding (capex as well as maintenance) that drives the LCC to make the insulated walls expensive.

LCC Analysis using the future weather files

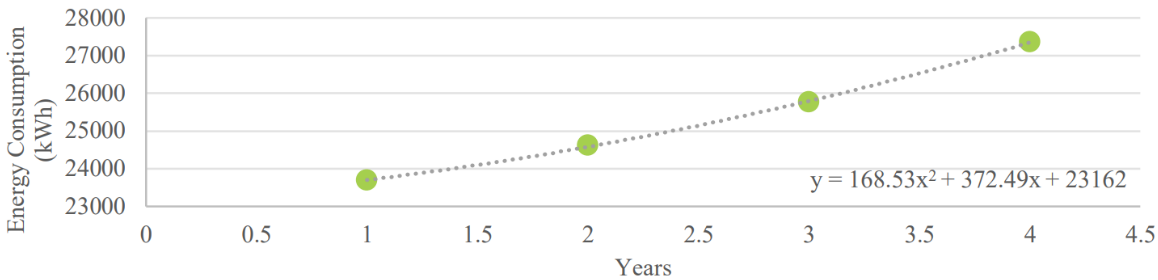

Figure 7: Energy data for 2020, 2050 and 2080 and the quadratic equation for Non-insulated (Rammed earth wall) in mixed mode scenario

Figure 7 shows a quadratic equation for a non-insulated rammed earth wall in a mixed-mode scenario. Similar equations for insulated rammed earth wall in mixed mode scenario, Non-insulated (Rammed earth wall), and insulated rammed earth wall in the fully air-conditioned scenario were also generated. These equations were then used to interpolate the energy consumption across the 50 years. LCC was then calculated using the interpolated energy data. This part of the analysis focuses on the rammed earth walls (with and without insulation) and mixed-mode and fully air-conditioned operations.

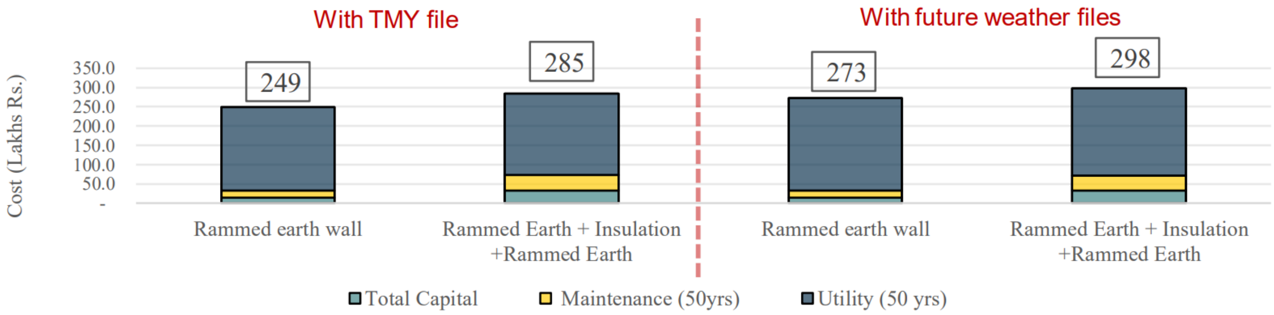

Figure 8: LCC comparison for mixed mode operation between TMY file and future weather file

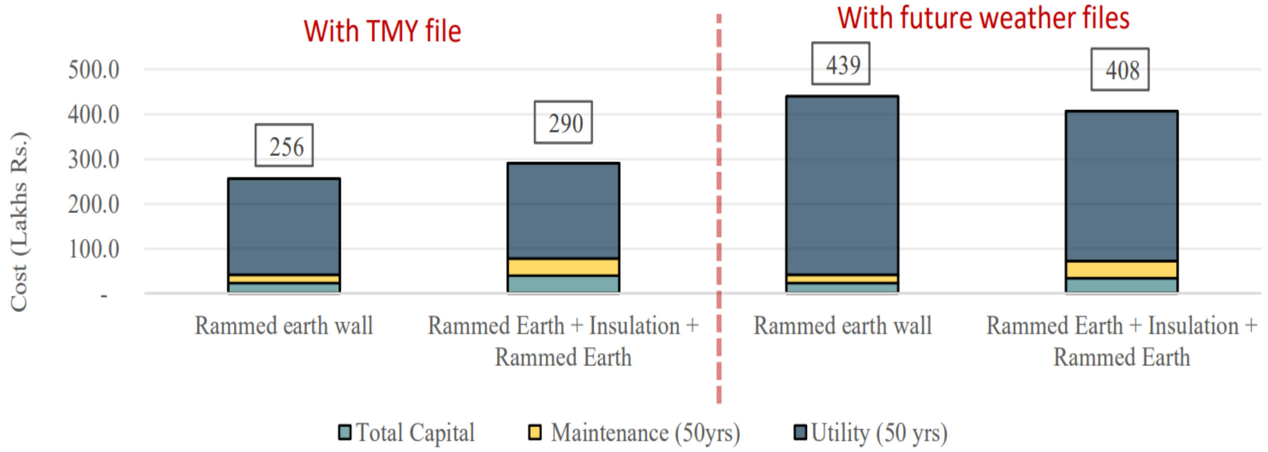

Figure 9: LCC comparison for fully air-conditioned operation between TMY file and future weather file

In Figure 8, which shows the results for the mixed mode operation, we can see that LCC increases for the insulated walls by 9% to 16% in both the TMY weather LCC and the future weather LCC. This is primarily the result of the large increase in Capex and maintenance resulting from the insulation and the fact that the insulated walls have 2 rammed earth layers.

In Figure 9, on the other hand, we see that with the fully air-conditioned operations, the TMY weather LCC has increased by about 13% for the insulated walls, but the future weather LCC shows a reduction in LCC by 10% for the insulated walls.

Thus, for mixed-mode operation buildings, where the utility cost is smaller, a TMY weather-based LCC may be adequate, but for fully air-conditioned operation buildings, where the utility cost is higher, a future weather-based LCC may provide a more realistic cost-benefit view.

Thermal comfort assessment using the TMY and future weather files

While we established that mixed-mode operation (with 70% naturally ventilated spaces) does not show an LCC benefit to convince investors, some questions about the value of insulation remain:

- Does the insulation provide adequate thermal comfort in current weather scenarios, based on a TMY weather-based comfort analysis, such that these spaces can indeed be operated without additional mechanical means for conditioning?
- Does the insulation provide adequate thermal comfort in current weather scenarios, say until 2080, such that these spaces can indeed be operated in the future without additional mechanical means for conditioning?
- If the answers to either of the above questions are a "no", then is the mixed mode operation LCC an appropriate analysis to be presented to investors?

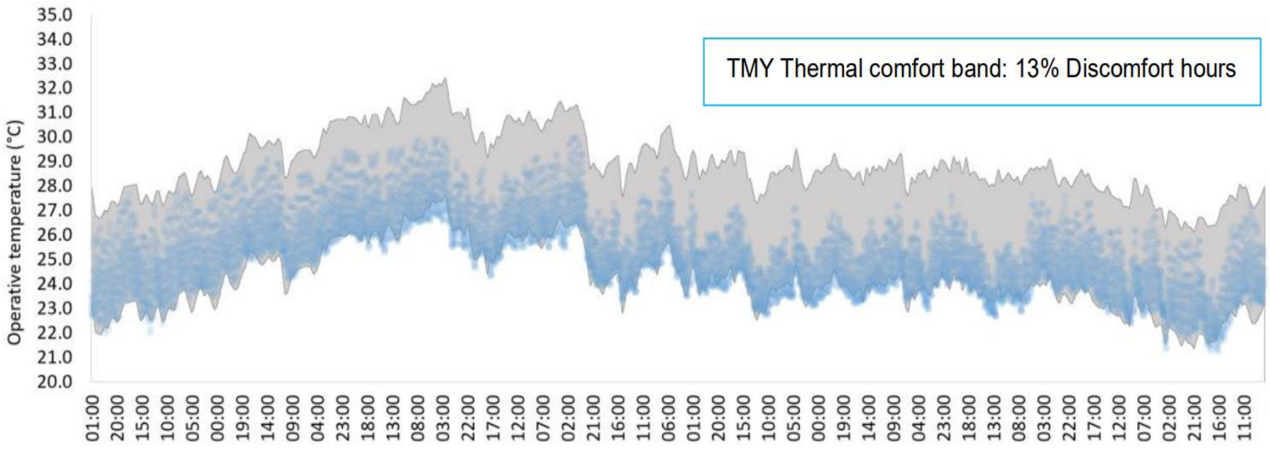

*Figure 10: OT with rammed earth wall (with insulation), the grey area shows the adaptive thermal comfort band (**TMY**) according to the National Building Code of India*

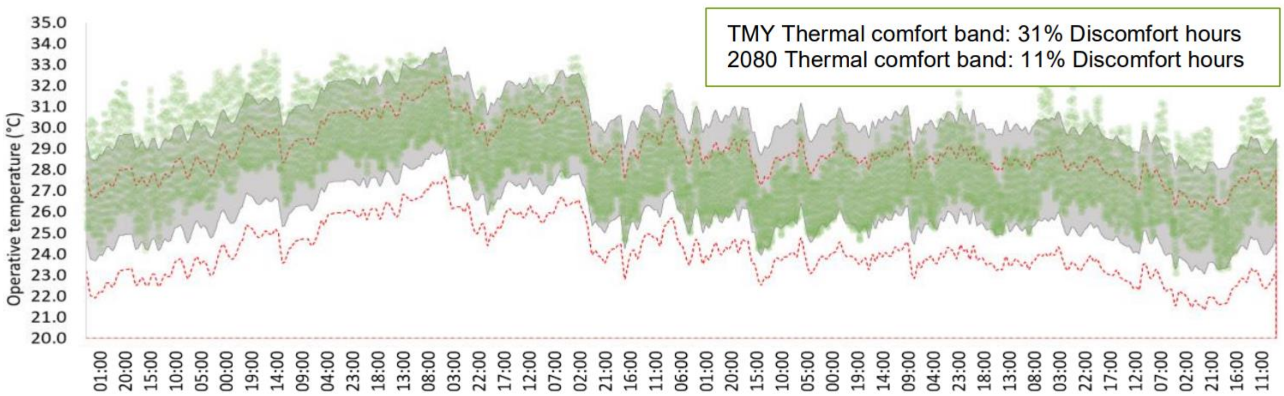

*Figure 11: OT of the workstation room with rammed earth wall (with insulation), the grey area shows the **future weather,** and the two red lines show the **TMY** adaptive thermal comfort band according to NBC*

Figure 10 shows the OT achieved with natural ventilation for the rammed earth wall with insulation using the recent historic weather data (TMY weather file). When compared with the NBC adaptive thermal comfort band for mixed mode operations, it shows that only 13% of the annual hours may be uncomfortable, where the discomfort hours are largely below the thermal comfort band. This is not a cooling problem and could easily be solved by aggressively closing the windows during times when the ambient temperatures are particularly low.

Figure 11 shows the OT achieved with natural ventilation for the rammed earth wall with insulation, using future (2080) weather files. The OT results are plotted against the NBC adaptive thermal comfort band for mixed mode operations. Here, there are 2 thermal comfort bands shown: one that uses the 2080 weather to calculate the 30-day running mean outdoor temperature (assuming we have adapted to much warmer conditions) and the other that uses the current (TMY based) weather (assuming we will not adapt so drastically to a set of warmer global and local temperatures). The 2080 building operation OT against the 2080 NBC band shows that the naturally ventilated building will have only 11% discomfort hours, with the OT going a maximum of 3ºC above the upper limit of the band. Literature shows that ceiling fans may have adequate cooling power index to compensate for this and provide comfort to the occupants [15]. The 2080 building operation OT against the TMY NBC band shows that 31% of the hours may be uncomfortable, with the OT going a maximum of 6ºC above the upper limit of the band. Literature shows that even under this less adapted scenario, ceiling fans may have an adequate cooling power index to compensate and provide comfort to the occupants [15].

Conclusion

This paper summarizes the lifecycle cost-benefit analysis of wall insulation for an experimental building in Bangalore, India. The method includes detailed audits of the building, long-term monitoring, and a calibrated energy model. The 50-year LCC was conducted with recent historical weather (TMY weather files), as well as with future weather files (2020, 2050, and 2080 synthetic weather). The overall results of the LCC analysis show that insulated walls have a lower LCC if the building is fully air-conditioned, whereas mixed-mode operations (70% naturally ventilated and 30% airconditioned) show a higher LCC for the insulated walls. This is true for both the TMY weather-based analysis and the future weather-based analysis.

A Detailed thermal comfort analysis for TMY weather and 2080 weather showed that the insulated building is able to provide adequate thermal comfort with 11-13% discomfort hours over the year (3ºC outside the thermal comfort band) under a fully adapted scenario. If the 2080 case does not include the full adaptation of thermal conditions consistent with the adaptive comfort equation of the NBC, the worst case would be 31% discomfort hours (5ºC outside the thermal comfort band). Cooling power index of ceiling fans is shown to be 6-7ºC, and therefore, ceiling fans would suffice to provide comfort in the experimental building in Bangalore.

The large question that this study is able to answer is whether a building such as the one studied, with adequate good passive design, thermal insulation, and natural ventilation, can provide comfort without the use of air-conditioning in Bangalore well into the future. Air conditioning in such a building may only be needed if ceiling fans are reported to be noisy or excessive air movement is reported to be problematic by the occupants. If an LCC cost-benefit analysis for insulation were to be conducted, the authors recommend that the insulated building be costed without any air-conditioning and the non-insulated building be costed with air-conditioning.

Acknowledgement

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'Fit for Purpose' Urban Heat Island Effect Study Methodology for Indian Cities

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Highlights

- A systematic review of the Urban Heat Island Effect (UHIE) assessment literature and practices.
- Derivations and defining the Level of Detail (LoD) classification.
- Identifying the purposes of the UHIE study and categorizing the LoD for a 'Fit for Purpose'.
- Developing a commonly agreed methodology for Indian Cities.

Abstract

The paper recognizes that the Urban Heat Island Effect (UHIE) occurs primarily due to urbanization impacting land surface characteristics, where the blue-green cover is replaced with complex-built fabric and increased anthropogenic heat emissions within urban areas. Without a common agreed-upon methodology with specific objectives that cities wish to accomplish, Indian cities are adopting varied methods to assess UHIE that do not help them attain the predefined objectives and are often found to be less scientific. This paper proposes a standardized methodology and underpins its argument on two frameworks, 'Fit for the Purpose' and 'Level of Details,' making it easier to adopt. Such efforts are expected to help cities account for the UHIE assessment with specific objectives that cities can optimize with available data and human and economic resources. The paper relies on a systematic literature review and considers the ground realities to develop the methodology. The proposed framework could be one of a kind to be adopted in India, helping cities evaluate their context and navigate them to solutions. It also aims to balance the suitable trade-off between data fidelity and decision-making efficiency, tailored to specific needs and constraints.

Keywords: urban heat island effect, level of details, fit for purpose, heat action plan, outdoor thermal comfort.

Introduction

The paper is structured into four sections: Introduction, Methodology, Discussions, and Recommendation. The introduction provides an overview of UHIE, its consequences, and the existing research gaps. It also introduces two terminologies: 'Fit for the Purpose' (FFP) and 'Level of Detail' (LoD). The methodology section relies on the systematic literature review to develop a scientific rationale by identifying the critical objectives, methods for mapping and assessing UHI variability, critical study parameters, and their datasets. The methodology also highlights the critical reasoning for how this standardized methodology is expected to aid the gaps before illustrating the proposed FFP framework for UHIE assessment with its LoD characterization. The discussion section elaborates on the methodology for one sample purpose, with key datasets and their associated LoDs required to meet the objectives and to conclude the proposed framework. It also summarizes the methodology for mapping and assessment for each purpose and their best possible LoDs against their objectives. The recommendation section highlights the level of resources necessary for each purpose and their LoDs.

With emerging urbanization, UHIE became one of the most frequently examined themes by urban experts since it accelerates environmental hazards and human mortality. The ongoing research on the UHIE has integrated urban planning, sprawl, and climate change phenomena, three of the most significant environmental concerns of the 20th century. UHIE is also crucial in energy consumption as it is associated with the urban microclimate, neighbourhood morphology, etc. Between 1990 and 2012, greenhouse gas emissions in India and Pakistan nearly doubled, and the urban areas accounted for more than 60% of that [1]. The countries with lower-middle and lower-income groups will be most adversely affected and reportedly lose 4% and 1.5% of their GDP by 2030, which is also projected to increase by up to 9% by the end of 2100 [2]. Therefore, state governments, municipalities, and urban planning authorities must develop the appropriate policies, pilot programs, necessary toolkits, and capacity-building to reduce heat stress, greenhouse gas emissions, energy conservation, and to improve thermal comfort conditions [3].

A recently published study from the Indian Meteorological Department (IMD) mentioned that heatwaves have significantly increased by about 24% during 2010-19 compared to 2000-2009, while they also highlighted a spike in mortality rates of 27 % during that period [4]. A recent study mapped the UHI intensity across the major Indian cities, and the results ranged between 1.76 to 4.6 °C [5]. Authorities in India are stepping up their efforts, drawing inspiration from Ahmedabad's landmark Heat Action Plan (HAP) [6]. Indian Meteorological Department (IMD) and National Disaster Management Authority (NDMA) have already designated 23 states (such as Delhi, Rajasthan, Maharashtra, etc.) to implement the HAP as a comprehensive extreme heat alert system and preparedness strategy [7]. In 2019, NDMA laid the guidelines [8] as a roadmap for the Indian states and cities to develop the context-specific HAP integrating urban planning, meteorology, and public health infrastructure. Besides heat hazard analysis, IMD also works on three-tier impact-based forecasts and risk-based warning systems [9]. As per the recent publication [10], they are planning to roll out a heat index by mapping the critical meteorological parameters (relative humidity, max., and min. air temperature, duration of heat spell, wind) to provide a real feel of temperature along with a color-based warning system [11]. With the recent urbanization trend, mapping of UHI hotspots by focusing on hyperspectral aerial imagery from remote sensing [12], increasing networks of metadata collection stations with low-cost sensors, and assessing the dual threats (considering heat waves) on microclimate and thermal discomfort is imperative for effective policy making and preparation of climate resilient action plan [3]. The National Institute of Urban Affairs (NIUA) is working on an assessment framework focusing on UHIE, urban planning, energy use, and blue-green networks for climate-smart cities and holistic revision in the existing planning guidelines [13].

From the existing UHI studies, critical issues such as (i) inconsistent data mapping due to the unavailability of datasets, (ii) absence of ground truthing to validate the satellite imageries, (iii) optimum spatio-temporal resolution, and (iv) determining the spatial grid for station point distribution, identified during the data collection and mapping [14]. Moreover, the concurrent gaps with numerical modelling and canopy level simulation studies can be concluded as (i) idealized parameter settings used for the model-boundary conditions; (ii) the actual context and target parameters do not get reflected due to the simplification of 3D land use land cover modelling techniques; (iii) the unsatisfactory accuracy of the numerical simulations [15]. Determining and assessing the urban energy budget and its effects on UHI intensity is crucial in the UHIE study. A recent study [16] has also indicated the need for standardized metrics to determine a city's energy budget model. Presently, to manage the heat waves, UHI, and developing an integrated policy to mitigate the UHIE and thermal discomfort, (i) cities cannot evaluate the required datasets, appropriate boundary conditions, and optimized assessment metrics, (ii) multiple approaches without scientific evidence lead to an outcome that may not be appropriate to the context, (iii) the absence of a commonly agreed methodology does not help in coordination at the national level to access the risk and mitigation measures on the similar platform eliminating the possibility of cross-learning at the same time. The proposed LoD-based FFP framework will allow decision-makers to develop common strategies and help share their success and failure stories.

Level of details (LoDs)

The Level of Detail (LoD) refers to a technique that involves representing objects or data at different levels of complexity or detail, depending on the specific requirements or constraints of the application.

Such concepts are used in several fields, including computer graphics, data visualization, and medical sciences. The LoD concept allows for the efficient representation of larger datasets. Considering every available single data point can be overwhelming to process. Therefore, lower levels of detail can be used to present an overview of the data. The higher LoD can be progressively revealed as decision-makers zoom in or interact with the dataset, providing more specific information or granular views.

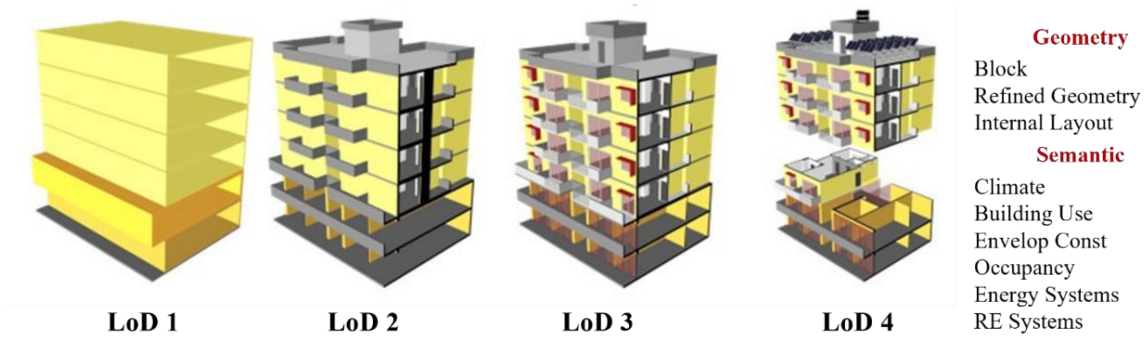

Figure 1: An example of LoD characterization adopted for Urban Building Energy Modelling (UBEM) [17]

As illustrated in Figure 1, suitable LoD characterization has been developed for an FFP framework for urban building energy modelling (UBEM) to aid in the persistent gaps (e.g., accuracy, classification, and complexity of modelling inputs, standardized metrics, reliability of calibration methods) in modelling, simulation and enable highly targeted data collection approach. In the context of the UHIE mapping and assessment, if the objective is to determine the hotspots across the city, one needs only a snapshot or single point in time data at peak hours with values of only four or five data points. But suppose the objective is to assess urban microclimate and to determine the outdoor thermal comfort by integrating the universal thermal climate index (UTCI). One will need consistent data over a few days at an hourly interval and for about 15 to 16 data sets across multiple stations. The LoD approach aims to strike a suitable trade-off between data fidelity and decision-making efficiency tailored to the specific needs and constraints of the system or application.

Fit for purpose

The underlying principle of developing the standardized UHIE methodology is to recognize the objective of the exercise at the very first instance. Any activity that needs to be carried out to understand the impact of UHIE needs to identify the target on which UHIE may have an effect. This paper has adopted 'Fit-For-Purpose' (FFP) as a terminology based on earlier work by the same authors to identify the objective of the exercise. The methodology to understand the impact of the UHIE will depend upon FFP.

The FFP refers to a framework that helps define the suitable or appropriate aim that needs to be achieved. It also helps customize the methodology to attain the specific solution. The FFP often involves accessing and ensuring that the methodology's qualities, features, functionality, performance, and reliability lead the process to the expected outcomes. The LoD characterization for the required datasets is evaluated in this paper against four critical purposes for comprehensive UHIE mapping and assessment to develop the FFP framework. The purposes are primarily concluded as an integrated measure for multiple interlinked objectives from the key findings of the literature.

Aims and objectives of the study

The study aimed to develop a LoD-based FFP framework for Indian cities as a standardized method for mapping and assessment of UHIE without compromising the accuracy of the results. This proposed framework will aim to address all the critical objectives regarding UHIE assessment and the required data sets with their suitable LoDs, which will be context-specific and adaptable based on the complexity of the study objective (e.g., spatio-temporal resolution, accuracy), projected outcome and available resources (e.g., manpower/expertise, cost, instrumentation, and time).

Methodology

Literature review

The paper adopted a systematic review of the extensive work carried out internationally and nationally for a comprehensive literature review. The existing studies regarding urban climate, built morphology, and their impact on UHIE were reviewed to comprehend the dynamics and mechanism of an urban environment with the changing urban characteristics before mapping the spatio-temporal variability of UHI. At the same time, the urban spatial scales and datasets have been evaluated for mapping and assessment of canopy layer urban heat island (CLUHI) and surface layer urban heat island (SUHI), with their critical technical parameters. Studies adopted rigorous measurement protocols and field surveys to validate the empirical/numerical models developed for a specific urban region. Ground truthing was also integrated into the studies to enhance the accuracy of the hyperspectral satellite data boundary conditions of simulation models and improve the overall reliability of the study outcome. The existing research gap and limitations were also reviewed to strengthen the evidence-based rationale for the study. The overall structure adopted for the literature review is illustrated in Figure 2.

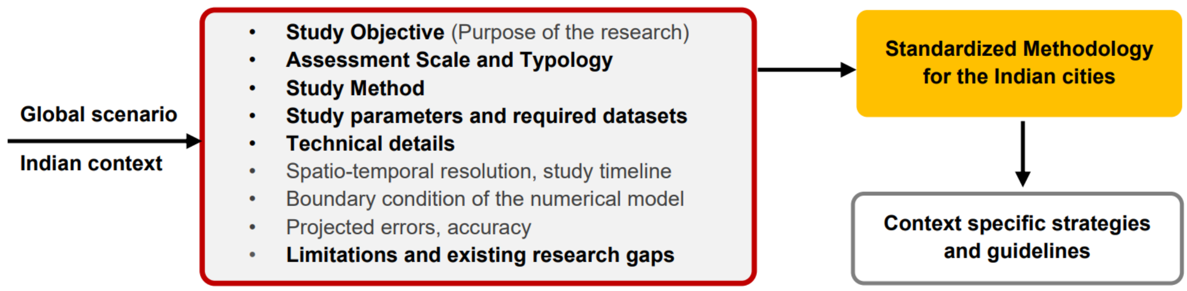

Figure 2: Structure of literature review adopted for the study

The outcome of the literature review

It is crucial to determine the key purposes/objectives adopted in the empirical studies for developing an appropriate rationale before concluding them in the proposed standardized framework. The key findings are summarized in Table 1. The studies mostly adhered to determine the hotspots and assess the projected impact of LULC/urban sprawl, surface characteristics, urban geometry on land surface temperature (LST), and urban microclimate.

Surface layer UHI (SUHI) studies mostly concentrated on investigating the spatiotemporal variability of LST and assessing their co-relationship with the changing LULC pattern. They have been associated with the land surface layer and conducted mostly at the meso scale. However, The Canopy layer UHI (CLUHI) studies are mostly conducted at the local or micro-scale and conclude the urban canopy layer (UCL) or building canopy layer (BCL), as illustrated in Table 2.

Table 1: Major study purposes/objectives concluded from the literature

Study objective/purposes	References
Mapping and assessment of hotspots, UHI intensity	[18], [19], [20-27], [28-30]
Assessing the impact of land use land cover (LULC) changes/ urban sprawl/ urbanization	[20], [23], [31-36]
Determining the impact of surface characteristics on UHI intensity	[37-40]
Assessing the built environment on microclimate/ improving the outdoor thermal comfort	[41-50]
Reducing building energy consumption/ cooling load/ GHG emission	[51-54]

Table 2: The scale of UHI assessments concluded from the literature

UHI Type	Horizontal scale		Vertical scale		References
SUHI	Meso scale (city/regional level) ~ upto10’s km		Land surface layer		[20-23], [55]
CLUHI	Local-scale (neighbourhood level) ~ 1 to <10 km	Micro-scale (street/block level) ~ 1 to 100's m	Urban canopy layer (UCL)	Building canopy layer (BCL)	[18], [37], [56-59]

Studies on UHI variations have concentrated on either temporal [21], [23], [60], [61] or spatial anomalies [62], [63] and, in some studies, both [60], [64], [65]. The ratio between the SUHI-based studies considering land surface temperature (LST) acquired by remote sensing technique [22], [23], [26-29] with Landsat, MODIS, etc., and others that examined the intensity of CLUHI using meteorological data (air temperature, relative humidity, and solar radiation) acquired from either fixed weather stations [66], [67] or mobile traverse [18], [68], [69] was high among those that were reviewed. Moreover, some of the CLUHI-based studies integrated automatic weather stations [32], [70], WRF modelling [71-72], artificial neural network-based algorithms, and field campaigns for a comprehensive study outcome.

For the CLUHI-based assessment, the Weather Research and Forecasting (WRF) model coupled with Urban/Regional Climate Model (UCM/RCM) as meso-scale [16], [73] and experimental CFD simulation using the appropriate turbulent model [18], [74] [75] as microscale modelling was identified as the commonly adopted tools to assess the UHIE magnitude and critical hotspots. Urban microclimate simulation with ENVI Met and ANSYS Fluent aided with various turbulence models have been conducted at the block level [76-78], focusing on the HVAC field and indoor thermal comfort and at the neighbourhood level [79-83] investigating the influence of vegetation, water bodies, building morphology, ventilation corridors, and anthropogenic heat on the urban thermal environment considering the thermal comfort indices, e.g., Universal Thermal Climate Index (UTCI), Physiological Equivalent Temperature (PET), Predicted Mean Vote (PMV), etc.

Moreover, multivariate statistical models were applied to determine the impact of urban sprawl, urban morphology, and meteorological indices on UHI intensity with their spatiotemporal variation. They also validated the simulation results and hypothetical assumptions with the real-time scenario. For CLUHI assessment, Multiple linear regression (MLR)-based models were extensively used. They frequently obtained high degrees of accuracy, as evidenced by the previous studies [84-86], and sometimes coupled with random forest (RF) models [87]. However, in SUHI-based studies, limited research has been performed to establish simplified numerical tools to investigate the spatiotemporal changes of LST from satellite imagery datasets for a more extended period [31], [88], [89]. Multiple studies that acquired the primary data from Remote Sensing, GIS or LiDAR, have adopted statistical analysis such as- canonical correlation analysis (a multivariate analysis) [23], spatial autocorrelation, lag model (SLM) and the spatial error model (SEM) [90], Fractal analysis [91], Spearman correlation analysis, Automatic linear modelling algorithm [21], Ordinary least squares (OLS), Support vector machine (SVM), Random forest [92], Ordinary least squares (OLS) regressions [26], Spearman correlation analysis [93] to validate, error fix and assess the acquired thermal image by further processing to investigate the SUHI.

Table 3: Study parameters and required datasets for UHIE study- as concluded from the literature study

Parameter	Data sets	Reference
Meteorology	Air temperature, Relative humidity, wind dynamics- speed and direction, solar radiation, cloud cover, Surface temperature	[36], [39], [55], [94-97]
Urban Infrastructure	Land use land cover classification.	[20], [23], [31], [32]
	Neighbourhood configuration (layout, setbacks, street geometry)	[46-50]
	Building geometry (form and height/no of floors)	[21], [23], [90], [92], [93], [98]
	Tree vegetation properties	[33-35]
Semantic data	Surface characteristics (albedo, emissivity, etc.)	[37-40]
	Building information (age, class of the property)	[45], [50]
Energy consumption	Cooling energy load	[51-54]
Thermal comfort	MRT, PET, UTCI, PMV, PPD	[41-45]

Benefits of determining LoDs and FFPs

The critical evaluation of the literature was carried out to overcome the gaps with probable integrated measures such as (i) developing a standardized research framework/methodology for UHIE, (ii) focusing on accurate boundary conditions for numerical modelling and specific metrics that allow the urban morphology and meteorological datasets to reflect their respective characteristics in the UHI assessment, and (iii) establish a composite scale based on the first two recommendation that can effectively quantify the degree of the UHI variability.

The LoD-based FFP framework will help to standardize the UHI assessment studies, enabling the city planners and managers to employ appropriate assessment techniques and metrics for data collection and analysis and to forecast future scenarios specific to the context. The method will also help to investigate the critical hotspots and other contributing factors to UHIE. The outcome will also aid decision-makers in developing coordinated strategies for comprehensive master planning and the policy-level guidelines in the public-private domain substantiated by setting future goals.

Development of a fit-for-purpose methodology with LoD characterization

This document has concluded four purposes from the literature review (refer to Table 1). These four purposes can be further synthesized with their usefulness, probable outcome or targets (as illustrated in Table 4), methodology to conduct the assessment (e.g., data collection, mapping, analysis, and validation), required data sets with their LoD characterization, and a plan of action for a successful implementation, as a way forward from this proposed methodology.

Table 4: Key purposes of the FFP framework of the UHIE study and their projected outcomes

Purposes		Probable outcomes/targets
P1	Development of a Heat Action Plan (HAP)	Mapping the present and future hotspots
		Development of a composite heat vulnerability index
		Developing a UHI mitigation performance index with a real-time monitoring system
P2	Assessing the spatiotemporal dynamics of urban planning on UHI intensity	Reduction in anthropogenic heat from the building and transportation sector
		Revision of policies (spatial planning, transportation, energy), building By-laws, energy codes
		Integrated measures for local area plan / Transit orient development to limit urban sprawl and emphasize the nature-based solution (NBS)
P3	Improving outdoor thermal comfort	Improving present and future microclimate scenarios and enhancing indoor thermal comfort at the building or unit level
		Minimizing the cooling energy demand
		Developing a support-based decision-making tool for low-carbon and climate adaptation
P4	Reduction in the GHG emission	Developing and testing Urban energy modelling tools and alternate methodologies
		Developing energy-space syntax and identifying trends in energy consumption
		Energy forecasting of the present and future scenario

Based on the increasing complexity, each study parameter with its datasets is assigned a suitable LoD from one to four, with one being the simplest and four being the most complex. The required datasets are categorized into seven critical parameters for assessing the four purposes related to the UHIE study, as illustrated in Table 5. They are adaptable, considering the resources and limitations of each study.

Table 5: Proposed LoD characterization for a fit-for-purpose UHIE assessment framework

Level of Detail	Study Parameters						
	Meteorology	**Urban Infrastructure**	**Semantic**	**Operational profile**	**Energy consumption**	**Spatial resolution**	**Temporal resolution**
LoD 1	Air Temp.	LULC	Surface Characteristics	Deterministic-Single	Connected Loads	1000 m.	Decadal
LoD 2	LoD 1 + Surface Temp.	LoD 1+ Plot boundaries	LoD 1 + Building use	LoD 1 + Deterministic-Multiple	LoD 1 + Load profiles	100 m	Annual
LoD 3	LoD 2 + Relative Humidity + Solar Radiation	LoD 2+ Building footprint	LoD 2 + Age of property	LoD 2 + StochasticSpace based	LoD 2 + Metered data	30 m	Monthly
LoD 4	LoD 3 + Cloud cover + Wet bulb globe temp.	LoD 3 + Building height + Tree properties	LoD 3 + Building archetype	LoD 3 + Agent-based	LoD 3 + Submeter end-use data	10 m	Daily/hourly

Note: Each parameter is assigned a colour palate to differentiate from the table, and the hues of the colour become darker as the LoD increases for the datasets concluded in each parameter to map and assess the UHIE.

Discussion

To conclude the proposed FFP framework, a sample purpose of developing the heat action plan has been discussed in detail with the recommended UHIE assessment framework and their suitable LoD characterization for the required datasets. However, the proposed LoDs can be seen as the optimum range and can be modified as per the study context.

Methodology for mapping and assessment of UHIE- to develop the heat action plan

Urban heat island0 is a complex environmental phenomenon. Therefore, to investigate the UHIE and draw a correlation among the major contributors requires a multi-level and systematic approach considering the meso, local, micro level, and even some time at the plot or building level attributes to develop a comprehensive heat action plan or guidelines for extreme heat adaptation for the cities to adapt. Assessing the surface and the canopy level UHI intensity is also recommended to achieve more nuanced inferences for the studied urban region. A sample framework to map and assess UHIE has been detailed in Table 6.

Table 6: Recommended framework for UHIE assessment- to develop the Heat Action Plan

UHI types	Spatial Scale of Assessment		Key Objective	Key study variable
SUHI	Meso scale (region/city) ~ upto10's km		1. Mapping and assessment of present and future hotspots	Land surface temperature
CLUHI	Local-scale (neighbourhood) 1 to <10 km	Micro-scale (block/street) 1 to 100's m	2. Mapping of isopleth	Meteorological (Air temperature, Relative humidity)
			3. Assessment of Outdoor thermal comfort	Thermal comfort indices (MRT, UTCI, PET, PMV)

Required datasets and level of details (LoDs)

To facilitate the purpose of developing the heat action plan, the required data sets for the UHIE assessment according to their LODs are selected as per the three specific objectives mentioned in Figure 3 to conduct the surface (SUHI) and canopy layer UHI (CLUHI) assessment. These LoDs will allow a suitable trade-off to match the application case attributes of the project. The most suitable LoDs for each purpose will enable us to scale up the modelling and assessment exercise with more granular data to achieve higher accuracy with minimal effort.

Extending the fit-for-purpose methodology, we have summarized the most suitable LoDs for each purpose (illustrated in Figure 4). It is aimed to enable the practitioners and decision-makers to further synthesize them by the ideal combinations of any of these datasets across all the recommended LoDs according to their available resources and desired outcomes. It will also help scale the study with all the constraints in each context for respective Indian cities. Moreover, in Table 7, we have also summarized the UHIE assessment methodology (e.g., data collection and mapping, analysis, and validation) along with their recommended spatial assessment scale against each purpose and their respective objectives, as concluded in the proposed FFP framework.

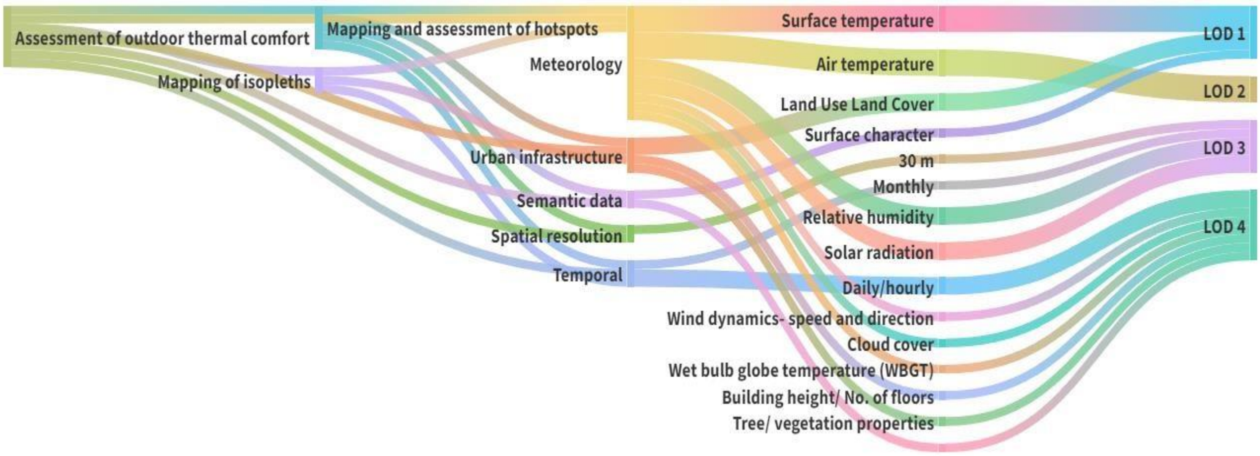

Figure 3: Sankey diagram showing the critical datasets and their most suitable LOD for developing the HAP

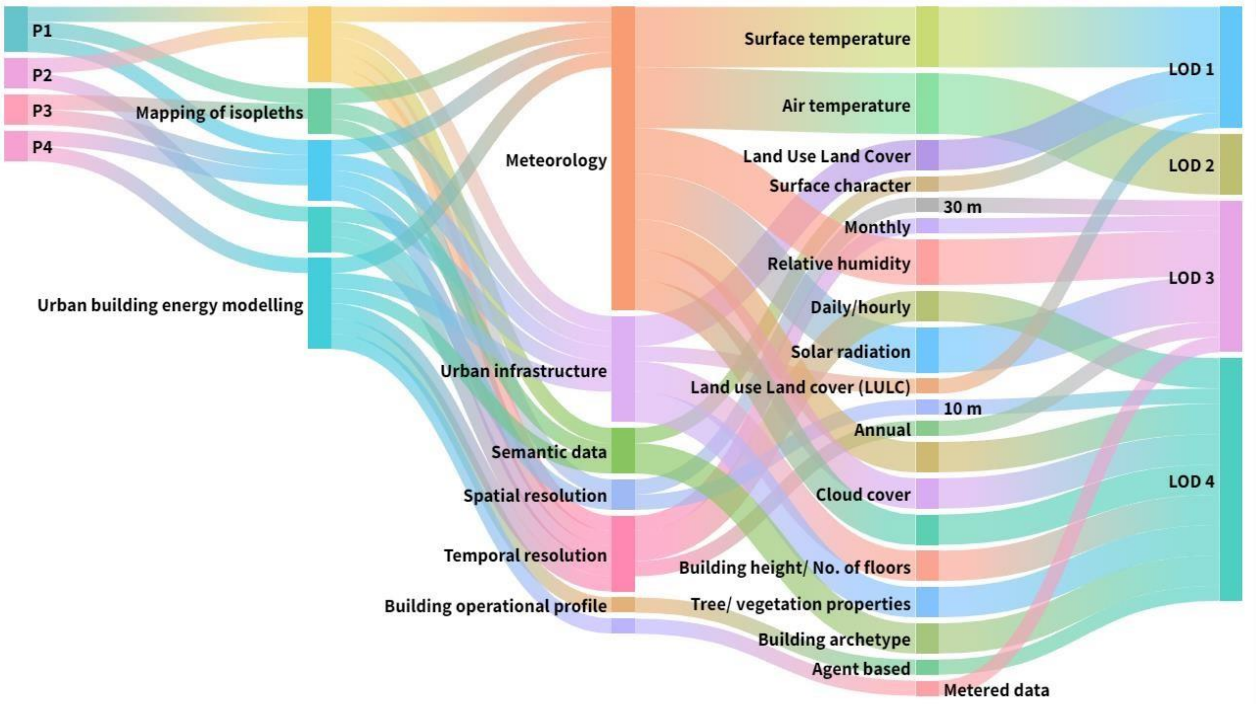

Figure 4: Sankey diagram summarizing the four key purposes adopted in the proposed FFP framework

[Note: P1- Development of Heat Action Plan, P2- Assessing the impact due to urban planning, P3- Improving the outdoor thermal comfort, P4- Reducing the GHG emission]

Table 7: Summary of UHIE assessment for the four purposes adopted in the proposed FFP framework

Purpose	Objective	UHI type	Spatial scale of assessment	Methodology		
				Data collection and mapping	**Analysis**	**Validation**
SP1	a. Mapping of Hotspots	SUHI	Meso	Remote sensing	Statistical models	
	b. Mapping of Isopleth	CLUHI	Local and/ Micro	Field survey, ArcGIS (interpolation)	----	----
	c. Determining Outdoor thermal comfort			---	Urban Microclimate modelling	Statistical models
P2	a. Mapping of LULC	-----	Meso	Remote sensing	Statistical models	
	b. Mapping of Hotspots	SUHI				

P3	Refer to the details of CLUHI assessments of P1 (Development of Heat Action Plan)			
P4	a. Refer to the details of CLUHI assessments of P1 (Development of Heat Action Plan)			
	b. Estimate and forecast urban energy use and GHG emission	------	Meso and/ Local	Urban Building Energy Modelling (UBEM)

Recommendation

As a way forward with the proposed FFP framework, the level of resources against each purpose (e.g., instrumentation/ data, manpower- expertise, and timeline) have been further mapped in this LoD-based FFP framework could be one of a kind to be adopted in India, helping cities evaluate their context and provide evidence-based solutions on the same platform considering the pressing threat due to heat waves and UHIE at the national level.

Table 8 shows the level of resources matrix according to the level of detail. This matrix will help us select the most suitable LoD and customize the overall methodology for UHIE study in any Indian city. Considering the complexity of each purpose, the data acquisition or instrumentation techniques are very critical as they involve the in-situ measurements of metadata along with other datasets (e.g., semantic, urban infrastructure, energy use, etc.) which require a high level of accuracy, high-end tools/instruments, periodic calibration to maintain the consistency, finer resolution of spatial grids across the studied region and continuous monitoring at the hourly interval at times. Mapping and analysis of the data also need precise granularity to model the appropriate boundary condition, which is time-consuming, costly, and requires higher expertise to perform and obtain the desired results with enhanced reliability.

For example, considering the purpose of the 'Development of Heat Action Plan' (P1) and 'Reduction in GHG emissions' (P4), in the case of instrumentation/data, LoD3 requires a medium level for P1 while a very high level of resources are needed for P4. Moreover, if we look at the timeline, considering LoD2, it needs a shorter timeframe for P1 and a longer period for P4 to conclude the study. This matrix will enable the decision-makers to efficiently manage and optimize the resources for a desired outcome.

This LoD-based FFP framework could be one of a kind to be adopted in India, helping cities evaluate their context and provide evidence-based solutions on the same platform considering the pressing threat due to heat waves and UHIE at the national level.

Table 8: Level of resources matrix- a tool to customize the FFP for efficient decision-making

Level of Resources	**Instrumentation / Data**				**Manpower - Expertise**				**Timeline**			
Level of Details	LoD1	LoD2	LoD3	LoD4	LoD1	LoD2	LoD3	LoD4	LoD1	LoD2	LoD3	LoD4
Development of Heat Action Plan	Low	Medium	Medium	High	Low	Low	Low	Medium	Low	Low	Medium	Medium
Impact due to Urban Planning	Low	Medium	High	High	Low	Medium	High	Very High	Low	Medium	Medium	High
Improving Outdoor thermal comfort	Low	Medium	Very High	Mandatory	Low	High	Very High	Mandatory	Medium	High	Very High	Mandatory
Reduction in GHG emissions	Low	High	Very High	Mandatory	Low	Very High	Mandatory	Mandatory	Medium	High	High	Mandatory

(yellow)	Low	(orange)	Medium	(red)	High	(dark red)	Very High	(black)	Mandatory

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Optimizing Urban Morphology to Mitigate Urban Heat Islands: A Case of Hyderabad

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Highlights

- Delineates a methodology to study urban residential neighborhoods to understand the effect of urban morphology on microclimate.
- Enumerates morphology parameters that can be modified to reduce the UHI phenomenon.
- A numerical model, ENVI-met, simulates microclimate and various statistical models to evaluate the extent of the inter-relationship between critical morphology parameters and climate variables.

Abstract

Urbanization, changing urban geometries and surfaces, forms hotspots called urban heat islands (UHI). Several studies have been conducted to understand its cause, intensity, and impact on urban microclimate. The current study attempts to assess the impact of the urban morphology of multiple residential urban blocks in Hyderabad on urban heat island intensity. The study explores the possibility of UHI mitigation by modifying morphology constructed on policy measures like zoning regulations. Six urban residential blocks under the city's peri-urban belt are studied for their morphology and microclimate. Field study, 2D building database, and satellite imagery are used to develop urban built geometry of the blocks. The microclimate, i.e., air temperature and wind speed, is determined using a numerical model, ENVI-met. The simulated microclimate data is used to compute UHI intensity based on reference climate data of an urban block at the time of the investigation. The urban morphology is then modified to reduce UHI intensity. The modified urban geometry with a significant reduction in UHI intensity is used to suggest planning/design recommendations through zoning regulations. Further, the paper reinforces the significance of the correlation between UHI and urban morphology, which can be regulated through zoning.

Keywords: Microclimate, Urban heat island, Urban morphology, UHI mitigation, Zoning regulations

Introduction

Indian metro cities are undergoing rapid urbanization with a growing economy and population. The natural population growth or migration has resulted in densification and spatial expansion of cities, with a surge in infrastructure and natural resources demand. This led to the saturation of land and other resources in cities, permanently modifying the surface and material properties, resulting in heat accumulation and an imbalance in urban energy flow. To accommodate and cater to the demands of the growing population, suburbs of metro cities become prospective for planned development. This allows the newer developments to follow a top-down approach of planning sustainable neighborhoods and siting green buildings within them to reap maximum benefits of their efficiencies against the conventional bottom-top approach of designing green buildings in an overbearing climate context. Following are the concepts dealt with in different sections of the paper.

Urban Morphology: The unprecedented growth of cities led to the rapid modification of urban morphology or changes in the tangible elements that create a city's urban form. These tangible or physical elements that are continuously evolving include the natural setting, street, street block, plots, buildings, etc. Urban morphology can be discussed by its morphology parameters or the various physical characteristics of urban form, which include measurable aspects like size, density, building height, pattern, etc. [1].

Urban Microclimate: Morphology varies across an urban area, and its interaction with atmospheric climate creates a unique microclimate. This divergence of urban climate conditions from the atmospheric conditions due to changes in urban surfaces and forms is called urban microclimate [2].

Urban Heat Island: Oke [3] defines an urban heat island as a measure of near-surface air temperature contrast between urbanized and adjoining rural areas or urban centers with different forms. This model works in units of degrees Celsius and uses an empirical formula.

Urban Block: It is a neighborhood with homogeneity in design, demography, and socioeconomic status. Urban blocks are considered minimum planning units where planning tools can be implemented to regulate development [4]. They hold 500 to 5000 people on 15 to 500 acres of land with shared retail and community facilities (elementary school, park).

UHI studies in India were initiated in the early 20th century [5]. These studies are carried out in metro cities to examine the presence of UHI, its intensity, and influencing factors. Hyderabad is a rapidly urbanizing city, witnessing an urban sprawl of planned residential developments along the outer ring road [6]. These developments are controlled by zoning regulations, which must be climate-informed to achieve a better quality of life and human comfort in the face of climate change. Hence, the current paper focuses on this requirement to study the upcoming residential neighborhoods for magnitude and factors responsible for UHI. Modification of responsible factors, the urban morphology, regulated by policy framework is attempted as a mitigation measure of Urban Heat Islands [7]. Following are the research questions explored in the paper.

1) How do urban morphology and its parameters impact microclimate?
    a) What morphology parameters shape an urban form?
    b) What is the extent of the impact of morphology parameters, individually and collectively, on the climate of an urban block in terms of an urban heat island?
2) How does zoning regulation define urban form or morphology?
    a) How can its modification through zoning regulations alleviate an urban heat island created by an urban morphology?

Methods

The methodology developed in this study can be applied to other studies and is not typical of the study area demonstrated in this paper. The study methodology is developed by an extensive literature review, which inquiries about the data collection models, computation tools and techniques. The five segments of study are (1) Urban morphology and parameters- Data and computation, (2) Climate variables- Data collection and methods, (3) Relationship between morphology parameters and climate variables- Analysis and results, (4) Urban heat island- Computation and results (5) UHI mitigation- Measures and approaches. The methodology used in this is shown in Figure 1.

The study synthesis led to the identification of urban morphology parameters and zoning regulation parameters. The mentioned empirical formulae and software tools calculate the parameter data. This is followed by analyzing their relationships with various microclimate variables using statistical tools like correlation and regression analysis, where simulated climate data from the numerical ENVI-met model is used [2]. The inputs of the numerical model include the site's physical properties and nearest weather station data. The results from the analysis are used to identify the study block experiencing higher air temperatures compared to the rest, called the critical urban block. Based on the relationship results, interventions to the urban form are tested on the critical urban block to reduce the effect of Urban heat islands.

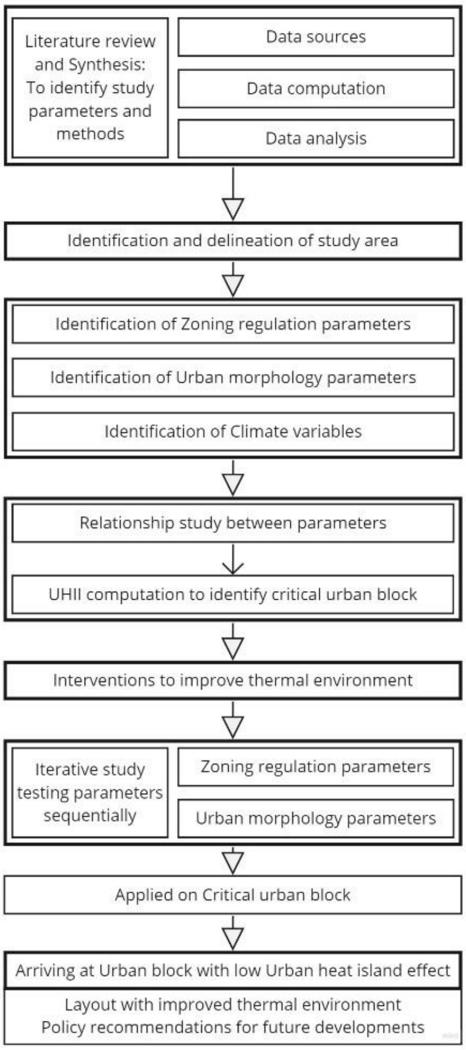

Figure 1: Illustrative methodology chart

Need for UHI study in Hyderabad

Hyderabad ranks as the third-largest metropolitan city in terms of area and the fourth-largest in terms of population in the country. The development plan for 2031 by the planning body HMDA 2008 projects a growth rate of 428.8% in the Peri-urban belt, out of which 30% is a gross residential area [6], compared to the growth rate of 1.02% in the city centre, 37.8% in the urban belt. Hence, an understanding of the microclimate of planned residential urban blocks in the Peri-urban belt gives an insight into the mitigation measures and their scale of implementation. The approach to studying UHI using atmospheric temperature data helps understand the effect of urban geometry on microclimate, unlike the multiple existing studies [6] [8] [9], which use land surface temperatures that only account for the influence of surface material and green cover. The scope of the current study is to investigate mitigation measures at the scale of modifying urban form and not just through surface properties or green covers.

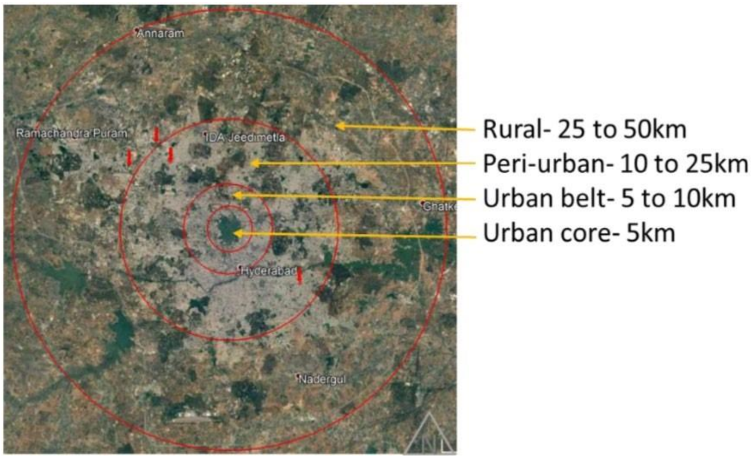

Figure 2: Urban belts of city development with the location of six study sites

The six study blocks (MN, PN1, PN2, VN1, VN2, and AL) selected have similar properties with variations in physical parameters, which provides a scope to study their influence on block microclimate. The following are the criteria taken into consideration during site selection:

Table 1: Study Urban blocks NS-EW oriented (left), NESW-NWSE oriented (right)

Criterion	Pragathi Nagar1 (PN1)	Pragathi Nagar2 (PN2)	Matrusree Nagar (MN)
Block area & dimension	35,200sqm & 220x160m	35,200sqm & 220x160m	59,925sqm & 225x235m
Deviation from North	0°	0°	3.5° NE
Face blocks	5	4	7
Building blocks	65	63	71
Building height	G to G+5	G to G+5	G to G+6
Road width	18 | 12 | 9 | 7.5m	18 | 12 | 9 | 7.5m	9 | 7.5m
Open space type	Vacant plots	Play ground	Play ground
Green space type	Street vegetation	Street vegetation	Park | Jogging track
Building coverage ratio	34.4%	33.3%	26.2%
Building volume density	4	3.5	4.2
Green coverage ratio	26.5%	20.7%	29.5%
Nearest weather station	AWS 10995- Kukatpally Balanagar	AWS 10995- Kukatpally Balanagar	AWS 10995- Kukatpally Balanagar

Criterion	Vivekananda Nagar1 (VN1)	Vivekananda Nagar2 (VN2)	Alkapuri (AL)
Block area & dimension	46,000sqm & 230x230m	46,000sqm & 230x230m	40,000sqm & 200x200m
Deviation from North	45.6° NE	45.6° NE	42° NW
Face blocks	6	6	3
Building blocks	84	75	74
Building height	G to G+4	G to G+4	G to G+4
Road width	15 | 9 | 7.5m	15 | 9 | 7.5m	12 | 9 | 7.5m
Open space type	Vacant plots | School ground	-	Vacant plot
Green space type	Street vegetation	Public park | street vegetation	Street vegetation
Building coverage ratio	35.7%	32.11%	35.3%
Building volume density	2.95	2.45	3.12
Green coverage ratio	47.8%	54.5%	26%
Nearest weather station	AWS 10995- Kukatpally Balanagar	AWS 10995- Kukatpally Balanagar	AWS 11204- LB Nagar GHMC

Planned residential neighborhoods in the Peri-urban belt are identified. The blocks comply with GO 168 (zoning regulations followed in Hyderabad).

- The block length dimension ranges from 150-250m with a peripheral road as a physical boundary marker.
- The building typology in the block includes Residential and essential commercial/retail along roads.
- Building heights vary from low rise (up to G+3) to mid-rise (up to G+5) with ground coverage according to plot size.
- Variations in road width, ranging from 6m to 12m ROW.
- Variations in street orientations; NS-EW orientation and NESW-NWSE orientation.
- The number of open spaces in a block is responsible for variations in building volume density; FAR.
- Open spaces and green space coverage in the study blocks vary. They include Vacant plots, open playgrounds, incidental open spaces, neighborhood parks, and street vegetation.

Study parameters

Urban morphology parameters

The parameters used for the study are selected based on their recurrence in the existing literature and are termed critical morphology parameters. The scale at which the five identified parameters are studied is categorized into intra-block and Inter-block comparisons. In intra-block, street aspect ratio and its orientation and sky view factor are studied for their influence on microclimate within the block. In inter-block comparison, building coverage ratio, building volume density, and green coverage ratio are studied for their influence on microclimate across the six blocks. This comparative study gives an insight into the scale of interventions in urban form that can be implemented. The urban morphology data from ground surveys, 2D maps, and Google Earth images are used to compute the parameter data using established empirical formulae.

Table 2: Urban morphology parameters

Comparison	Morphology parameters	Definition	Empirical formula
Intra block	**Street aspect ratio and orientation**	The aspect ratio is the ratio of the **mean height** of the buildings to the **width of the street**. One metric of studying **urban street canyon**; a space above the street and between the buildings.	*Symmetrical= H/W* *Asymmetrical= (H1+H2/2)/W*
Inter block	**Building coverage ratio**	BCR- The ratio of the **lot area** that is covered by **building area**, which includes the total horizontal area when viewed in plan.	*ΣBuilding footprint/Block area*
Inter block	**Building volume density**	Or **urban land density**- is the ratio of the **built-up area** to the buildable area in a block. Refers to FAR at building level	*ΣBuilding footprint x height / Block area*
Inter block	**Green coverage ratio** (open space ratio)	Used as an **index of an amount of plants**. A ratio of the areas of plants to the total area of investigation	*ΣVegetation cover/Block area (Block area Building+ green/Block area)*
Intra block	**Sky view factor** (indirect parameter)	The ratio at a point in space, between the **visible sky** and a hemisphere centered over the analyzed location (Oke 1981). 0<SVF<1. Second metric of studying **urban street canyon.**	*Skyhelios & RayMan*

Zoning regulation parameters

A review of the zoning regulations followed in Hyderabad gives an insight into the various parameters covered. According to the previously identified urban morphology parameters and their empirical formulae, zoning regulation parameters are associated. The basis of zoning regulations in Hyderabad is the road width ROW and the plot size, which decides the allowable building height and marginal open space MOS.

Table 3: Zoning regulation parameters

Morphology parameter	Zoning regulation parameters		
Aspect ratio	ROW	Height	MOS
Sky view factor	ROW	Height	MOS
Building coverage ratio	Plot size	MOS	
Building volume density	Plot size	MOS	Height

ROW= Right of Way
H= Building height
MOS= Marginal open space

Climate variables

The study focuses on the urban heat island effect, which measures higher air temperature in urban areas. It also deals with urban form, which involves the aerodynamics due to street aspect ratio, its channelizing effect and street vegetation, their wind-blocking effect. For these contextual reasons, air temperature and wind speed are studied and analyzed for their modification caused by morphology parameters, creating a microclimate. The microclimate is studied for diurnal variation using results of six hours of investigation (10hr, 14hr, 18hr, 22hr, 2hr, 6hr) at a four-hour frequency, covering a 24-hour cycle.

Results

Relationship between zoning regulation parameters and urban morphology parameters

The correlation and regression analysis is carried out with 93-125 observations, where zoning regulation parameters are the X 'independent' variable and urban morphology parameters are the Y 'dependent' variable. The outcome of each analysis is in terms of the percentage variability of the Y variable that can be predicted by the X variable, both collectively and individually.

Their R^2 and P- values consolidate the analysis results to a set of zoning regulation parameters that can be attributed to modifying morphology parameters. Building height (R^2=62.49%) and marginal open spaces (R^2= 26.28%) have a higher degree of influence on the Aspect ratio and Sky view factor, plot size (R^2=3.46%) on the building coverage ratio and building height (R^2=1.81%) on the building volume density. The terms of these parameters are used to bring variations in urban morphology parameters and, in turn, on the microclimate.

Critical urban block

Mean air temperature at each hour of investigation (10hr, 14hr, 18hr, 22hr, 2hr, 6hr) is collected from the microclimate simulation of the six urban blocks. This data is used to compute urban heat island intensity using the following formula,

$$\Delta T = \text{Max. } T_{X,\ mean} - \text{Min. } T_{Y,\ mean}$$

Where $T_{X,\ mean}$ - Mean air temperature of Urban block of investigation and $T_{Y,\ mean}$- Mean air temperature of reference Urban block at the time of the investigation. The reference urban block is the one with the minimum mean temperature at the time.

Table 4: Computation of UHII for a critical urban block

Canopy layer air temperature

	10hrs	UHI	14hrs	UHI	18hrs	UHI	22hrs	UHI	2hrs	UHI	6hrs	UHI
MN	30.750	5.175	33.490	4.86	29.235	0.785	25.800	0.855	**24.750**		26.110	2.960
PN1	30.195	4.620	32.585	3.955	**28.450**		**24.945**		24.860	0.110	25.925	2.775
PN2	31.085	**5.510**	33.675	**5.045**	29.260	**0.810**	25.240	**0.295**	25.165	**0.415**	26.460	**3.310**
VN1	30.605	5.030	33.220	4.590	28.890	0.440	25.110	0.165	25.045	0.295	26.285	3.315
VN2	30.675	5.100	33.235	4.605	28.795	0.345	25.085	0.140	25.040	0.290	26.420	3.270
AL	**25.575**		**28.630**		31.830	**3.380**	30.585	**5.640**	27.910	**3.160**	**23.150**	

The urban block PN2 experiences the highest temperatures during the day (after sunrise), 3.3°C to 5.5°C higher than the reference block AL. AL experiences higher temperatures at night, 3.1°C to 5.6°C higher than the reference blocks MN and PN1. Though the occurrence of high-temperature shifts from day to night, PN2 is continuously exposed. This reason for prolonged exposure to high temperatures during both day and night is the criterion that makes PN2 the critical urban block where the thermal environment needs improvement through the mitigation of Urban heat islands.

Relationship between urban morphology parameters and climate variables

This is to study the diurnal variation of microclimate in terms of air temperature and how the urban morphology parameters affect this variation. The analysis is carried out where urban morphology parameters are the X 'independent' variable and climate variables are the Y 'dependent' variable. The outcome of each analysis is in terms of the percentage variability of the Y variable that can be predicted by the X variable, both collectively and individually. The relationships are studied at six hours of investigation, at a four-hour frequency, covering a 24-hour cycle. The analysis takes daytime and nighttime hours separately to understand this effect in the identified critical urban block.

Observations at the intra-block level show that during the day, around 4% of the variation in air temperature can be accurately predicted by the two urban morphology parameters collectively and peaks at 18 hours with 9.7% predictability. Out of the two urban morphology parameters, street aspect ratio ($R^2$10hrs=3.6%, $R^2$14hrs=1.6%, $R^2$18hrs=7%) has a higher degree of influence, followed by sky view factor planar ($R^2$10hrs=0.38%, $R^2$14hrs=2.27%, $R^2$18hrs=3.21%), on the variation of air temperature. During the peak hour of influence, i.e., at 18hrs, a unit increase in the H/W ratio causes a 0.693-unit decrease in air temperature (-ve correlation). A unit increase in SVF planar results in a 0.0054-unit increase in air temperature (+ve correlation). Around 3-4% of the variation in air temperature during the night can be accurately predicted by the two urban morphology parameters collectively and peaks at 22 hours with 7% predictability. Out of the two urban morphology parameters, street aspect ratio ($R^2$22hrs=5.6%, $R^2$2hrs=1.32%, $R^2$6hrs=0.4%) has a higher degree of influence followed by sky view factor planar ($R^2$22hrs=0.06%, $R^2$2hrs=1.32%, $R^2$6hrs=2.8%), on the variation of air temperature. During the peak hour of influence, i.e., at 22hrs, a unit increase in the H/W ratio causes a 1.513-unit decrease in air temperature (-ve correlation). A unit increase in SVF planar results in a 2.754-unit decrease in air temperature (-ve correlation).

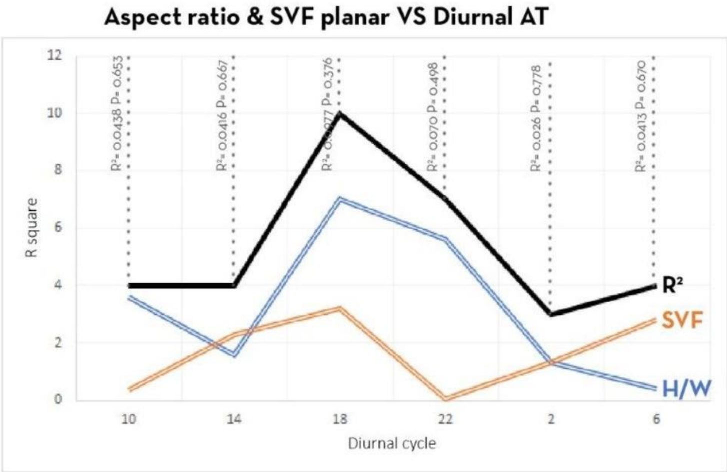

Figure 3: Diurnal variation of regression results- Aspect ratio and SVF vs. Air temperature

Observations at the inter-block level show that during the day, around 80-99% of the variation in air temperature can be accurately predicted by the two urban morphology parameters collectively and peaks at 14hrs with 98.94% predictability. Out of the three urban morphology parameters, GCR ($R^2$10hrs=58.33%, $R^2$14hrs=55.96%, $R^2$18hrs=58.46%) has a higher degree of influence, followed by BCR ($R^2$10hrs=32.67%, $R^2$14hrs=36.59%, $R^2$18hrs=12.31%), then by BVD ($R^2$10hrs=7%, $R^2$14hrs=6.46%, $R^2$18hrs=6.15%) on the variation of air temperature. During the peak hour of influence, i.e., at 14hrs, a unit increase in GCR ratio causes a 0.25°C increase in air temperature (+ve correlation). A unit increase in BCR results in a 0.036°C decrease in air temperature (-ve correlation). A unit increase in BVD results in a 4.022°C increase in air temperature (+ve correlation). During the night, around 9096% of the variation in air temperature can be accurately predicted by the three urban morphology parameters collectively and peaks at 6 hours with 96.9% predictability. Out of the three urban morphology parameters, GCR ($R^2$22hrs=71.09%, $R^2$2hrs=35.38%, $R^2$6hrs=74.44%) has a higher degree of influence, followed by BCR ($R^2$22hrs=14.22%, $R^2$2hrs=40.1%, $R^2$6hrs=22.56%), then by BVD ($R^2$22hrs=2.84%, $R^2$2hrs=16.51%, $R^2$6hrs=2.26%), on the variation of air temperature. During the peak hour of influence, i.e., at 6hrs, a unit increase in GCR ratio causes a 0.171°C increase in air temperature (+ve correlation). A unit increase in BCR results in a 0.053°C decrease in air temperature (-ve correlation). A unit increase in BVD results in a 2.644°C increase in air temperature (+ve correlation).

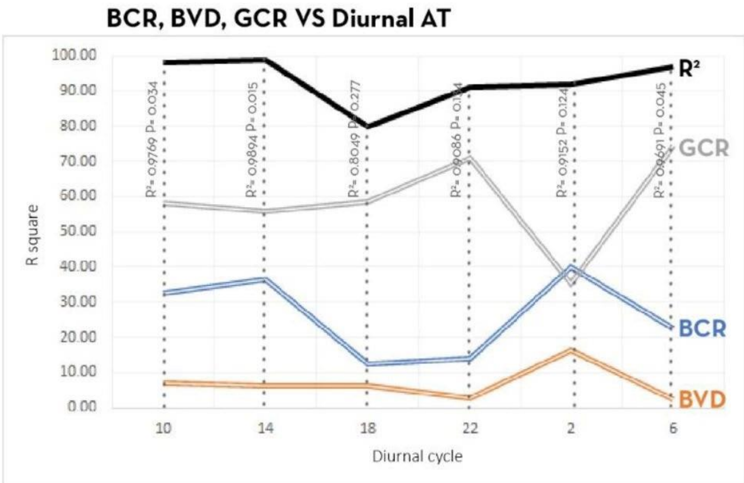

Figure 4: Diurnal variation of regression results- BCR, BVD, and GCR vs. Air temperature

Their R^2 and P- values consolidate the correlation and regression results to a set of urban morphology parameters that can be attributed to modifying the air temperature of the microclimate. These urban morphology parameters are prioritized while formulating the design intervention options.

Table 5: Prioritized urban morphology parameters

INTRA BLOCK	PN2	Remark
Orientation & Aspect ratio	***High priority***	+ve correlation with AT for 2/3 of diurnal cycle As H/W increases --> AT increases (peak influence at 18 followed by night)
SVF	Low priority	Changes with H/W
INTER BLOCK		**Remark**
BCR	***Mid priority***	High coverage by urban surfaces --> Cool spots due to absorption during day & Hot spots due to release and trapping of heat at night
BVD	Low priority	Trapping of heat in canyons
GCR	***High priority***	Night time cooling by presense of trees Trap heat during day

Discussion

The sequence of iterations to improve critical blocks and results

Based on the priority of urban morphology parameters' influence on climate variables, different street orientation and aspect ratio variations, building coverage and green coverage ratios are tested for their microclimate performance compared to the existing base case. Each case is a set of variations of one morphology parameter. The iteration of a case with a lower temperature is carried forward to introduce the next set of variations of the succeeding case. The result is the best-suited urban form that improves the thermal environment of the identified critical urban block PN2.

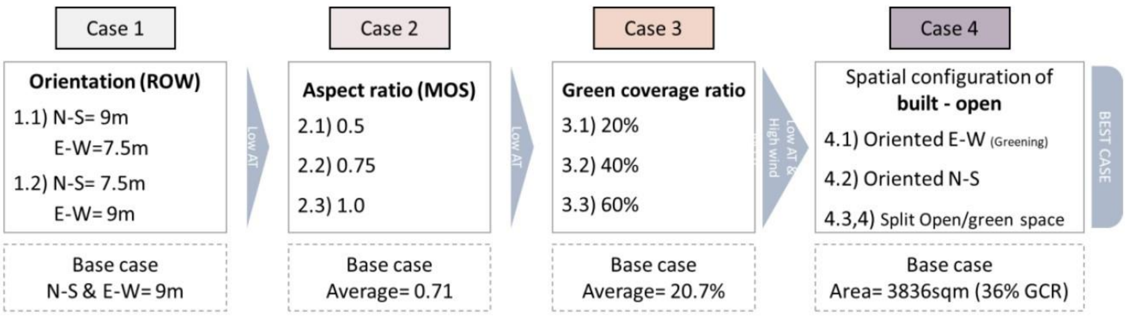

Figure 5: Sequence of iterations and details of each case

Results of Case 1 - Orientation (ROW)

Hourly air temperature difference between the two iterations of varying ROW widths according to their orientation is examined. The base case has no consistency in the ROW, with the width of the internal streets ranging from 6m to 9m. Case 1.1, with N-S streets of 9m and E-W streets of 7.5m, experiences a temperature reduction of 0 to 0.44°C. This reduction varies with the time of the day, as visible in the results of the six hours of investigation.

Results of Case 2 - Aspect ratio (MOS)

Hourly air temperature difference between the three iterations of varying aspect ratio, corresponding front MOS and the base case of H/W ratio of 0.71 are examined. Case 1.1 is used to introduce the new variations of aspect ratio. Case 2.3, with a H/W ratio of 1.0, experienced a temperature reduction of 0.52 to 1°C. SVF being an indirect parameter dependent on aspect ratio, Case 2.3 gives access to the night sky with an SVF of an average of 0.76, ranging from 0.63 to 0.85.

Results of Case 3 - Green coverage ratio

Hourly air temperature and wind speed difference between the three iterations of varying green coverage ratio and the base case of GCR of 20.7% are examined. Case 2.3 introduces the new variations of the green coverage ratio. Case 3.2, with a GCR of 40%, experienced a temperature reduction by -3.17 to 5.075°C from 25 to 34°C of the base case. Mean wind speed is in the range of 0.75 to 0.785m/s compared to the base case of 0.7 to 0.75m/s. The effect of vegetation along the streets and in the open space is visible modulation of diurnal temperature fluctuations and channelization of wind in street canyons of different orientations.

Figure 6: Final layout of Urban block PN2

Results of Case 4 - Spatial Configuration

Hourly air temperature and wind speed variation achieved by the four iterations of varying built-open space configurations is examined. Case 3.2 is used to reconfigure the open-green space into lots further. Case 4.2, with open-green space oriented north-south, experiences a temperature reduction of 3.3 to 5.3°C from the base case. The mean wind speed ranges from 0.75 to 0.785m/s compared to the base case.

Conclusion

The thermal environment in the urban block is improved by a reduction in maximum temperature by 0.43 to 0.54 °C from the base case, occurring at 14hrs. The minimum air temperature is reduced by 0.53 to 10.05°C, occurring 6hrs. On average, air temperature reduction ranges from 0.63 to 5.3°C. The maximum wind speed is increased by 0.07 to 0.13 m/s; on average, there is an increase of 0. 04 to 0.065 m/s.

Table 6: Improvements in the thermal environment from the base case

Air temperature °C		10	14	18	22	2	6
PN2	Max	32.12	35.25	29.85	26.37	25.76	26.99
	Min	30.05	32.1	28.67	24.11	24.57	25.93
	Avg	31.085	33.675	29.26	25.24	25.165	26.46
Improved PN2	Max	31.69	34.71	33.35	31.89	29.76	26.46
	Min	20.28	22.05	23.81	24.47	24.04	19.85
	Avg	25.985	28.38	28.58	28.18	26.9	23.155
Reduction	Max	**0.43**	0.54	*-3.5*	*-5.52*	*-4*	**0.53**
	Min	9.77	**10.05**	4.86	*-0.36*	**0.53**	6.08
	Avg	5.1	**5.295**	**0.68**	*-2.94*	*-1.735*	3.305

Wind speed m/s		10	14	18	22	2	6
PN2	Max	1.45	1.41	1.37	1.38	1.39	1.49
	Min	0	0	0	0	0	0
	Avg	0.725	0.705	0.685	0.69	0.695	0.745
Improved PN2	Max	1.53	1.51	1.49	1.51	1.52	1.56
	Min	0	0	0	0	0	0
	Avg	0.765	0.755	0.745	0.755	0.76	0.78
Increment	Max	0.08	0.1	0.12	**0.13**	**0.13**	**0.07**
	Min	0	0	0	0	0	0
	Avg	0.04	0.05	0.06	**0.065**	**0.065**	**0.035**

Design recommendations

The street's orientation and width, defined by ROW in zoning regulations, play a significant role in exposure to solar radiation. The N-S streets are less exposed to intense late afternoon southwest radiation and long hours of morning radiation from the southeast due to overshadowing by buildings abutting the street. However, they experience brief exposure to intense high-altitude radiation from the south during mid-day. Hence, the lesser temperature at a width of 9m. The E-W streets have prolonged exposure to the southwest and southeast radiation and exposure to intense, high-altitude radiation in the case of broader ROW. Hence, a 7.5m wide ROW facilitates over-shading by buildings.

1. Internal streets- N-S streets with a ROW of 9m and E-W streets with 7.5m.

A macro-level investigation of the zoning regulation parameter, front MOS, and the corresponding aspect ratio reveals that a compactly built morphology that allows mutual shading and shading of the open street results in air temperature reduction.

2. Achieve an aspect ratio of 1.0 by modifying front, rear, and side marginal open spaces according to the setbacks prescribed as per plot size, abutting ROW, and permissible building height.

Adding street vegetation proved beneficial by shading streets and modulating air temperature. Wider canopy trees, heart-shaped or spherical, can shade the E-W streets prone to prolonged exposure to radiation. The cylindrical avenue variety of street trees channelizes wind and sometimes increases the wind velocity. This is evident in the N-S streets. Though not oriented along the prevailing wind direction, the cylindrical tree canopies channel and accelerate the wind. The amount of green coverage must be mandated in the zoning regulations regarding the green coverage ratio of the planned development. Specifications regarding the type of plants, their canopy style, and their location along streets can be suggested.

3. A 40% green coverage ratio is introduced by vegetation along the street and in open areas, along with the prescriptions of onsite green strips.

4. Trees of the wider canopy shade E-W streets.

5. N-S streets' wind channelization by cylindrical canopy trees.

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Evaluation of Embodied Energy for Building Construction under Urban Renewal Schemes in Core City Area - A Case of Rasta Peth, Pune

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Highlights

- Urban Building Energy Modelling (UBEM) is used to study embodied energy in urban redevelopment scenarios.
- In comparison with existing and conventional 2030 scenarios, the low-carbon 2030 scenario had lower embodied energy (EE) and Embodied carbon (EC).
- Choosing low-carbon materials and optimizing massing layouts play a crucial role in reducing total embodied carbon in the building stock.

Abstract

Building construction accounted for more than 40% of global energy consumption and 30% of greenhouse gas emissions. It is essential to understand embodied carbon in buildings at the neighbourhood level, as after construction, it will be locked there for several years. This study aims to analyze the embodied energy (EE) of the neighbourhood for redevelopment scenarios using (UBEM). The study area chosen was Rasta Peth, Pune. The primary sources of embodied energy were discovered by analyzing existing dense neighbourhoods. Massing cases for redevelopment scenarios were created according to UDCPR guidelines. A comparative analysis of EE between the redeveloped 2030 scenarios was conducted. The research results show that the low carbon 2030 scenario has 27.9% lower EE than the conventional scenario. The findings emphasized the importance of embodied energy in sustainability strategies for urban planners and policymakers. This research contributed valuable insights for reducing embodied energy in urban areas.

Keywords: Embodied energy, Neighbourhood, Redevelopment, Urban Building Energy Modelling (UBEM)

Introduction

The built environment significantly consumes energy resources and has a lasting environmental impact. Rather than embodied energy, operational energy is the primary energy consumer throughout a building's lifespan. Embodied energy refers to the energy used in extracting, producing, and transporting construction materials. Embodied carbon emissions constitute about 10% of global CO_2 emissions [1]. The whole life cycle energy of a building encompasses both operational and embodied energy. Measured in CO_2, global warming potential reflects the associated embodied emissions. Embodied carbon emissions are primarily released during the construction, renovation, and deconstruction phases, making them challenging to monitor and control [2]. Urban centers have the potential to both contribute to and mitigate climate change [3]. Over 100 cities have committed to achieving net-zero carbon emissions by 2050, and India is targeting carbon neutrality by 2070. To ensure carbon emissions from the global building stock stay below 300 $GtCO_2$ by 2050 [4].

The embodied energy of a building includes the energy consumed during the extraction, manufacturing, transportation, and assembly of construction materials. Through building renovation or new construction, urban renewal initiatives seek to revitalize urban areas. However, these activities have an impact on the environment because they use resources and energy. This study aims to evaluate the embodied energy related to building construction in urban renewal initiatives within core cities. This research helps promote sustainable building methods in the context of urban revitalization by looking at the environmental effects of urban renewal. The research objectives are to study the embodied energy of materials in the redeveloped scenario by constructing a new material inventory, to examine trends in building materials for redevelopment, and to predict future embodied emissions, to design multiple building massing layouts for the redevelopment scenario, calculate their embodied emissions, and to propose strategies to minimize embodied energy. With an emphasis on urban renewal initiatives, the research is intended to provide insightful contributions to understanding and reducing embodied energy in building construction.

Embodied energy refers to the energy that is required to produce, transport, and construct building materials and systems [5]. The built environment accounts for a significant proportion of global energy consumption, and the embodied energy of buildings - that is, the energy used in their construction, operation, and disposal - is an essential factor to consider in achieving sustainable development [6]. The energy usage of a building can primarily be categorized into operational and embodied energy; depending on the composition of a building, embodied energy can range up to 60% of the total energy spent, as there is a need to consider Embodied energy emissions [7]. However, embodied energy has received significantly less consideration than operational energy, both in practice and within academia [8].

About 36% of final energy use and 39% of energy-related carbon dioxide emissions are attributed to the building sector [9][10]. In recent years, researchers have developed methods to assess and reduce embodied energy in building materials, such as using the Universal Building Energy Model (UBEM) and Rhino + UMI software. Urban building energy modelling (UBEM) is a physics-based bottom-up method for simulating the thermal performance of multiple buildings that has been created to act as the analytical foundation for the above-described decision-making procedures [11].

There is a need for accurate and up-to-date data on building stocks, particularly in light of climate change and the increasing importance of sustainable urban development [12]. Urban Building Energy Modelling is an efficient, low-cost, and scalable workflow that can be used to model the energy performance of buildings in urban areas [13]. UMI is a "multi-scale, multi-physics platform that allows users to simulate and visualize the performance of buildings and urban areas at various scales [14].

Rapid urbanization is taking place in developing countries at an unprecedented rate, with the majority of the world's population projected to live in urban areas by 2050 [15]. The redevelopment approach aimed to revitalize deteriorating inner-city neighbourhoods through the demolition of substandard housing, commercial buildings, and other structures [16]. Dense neighbourhood redevelopment has become a popular strategy for addressing urban sprawl and improving urban liveability [17].

Using energy-efficient building materials such as low-emissivity glass, insulation, and reflective roofing can significantly reduce the energy consumption of buildings. Using energy-efficient building materials in high-rise residential buildings reduced the cooling load by 15%, reducing energy consumption and carbon emissions [18]. Sources such as IPCC, India's construction material database for embodied energy data that is used in the construction industry for analysis. The Global Warming Potential (GWP) of construction materials can depend on several factors, including material composition, extraction and production, transportation and maintenance, and end-of-life disposal [19].

Methodology

According to the figure below, the methodological framework for this research study is organized into four steps. A broad area of interest was identified before beginning the main research, and related literature was reviewed to find areas for improvement.

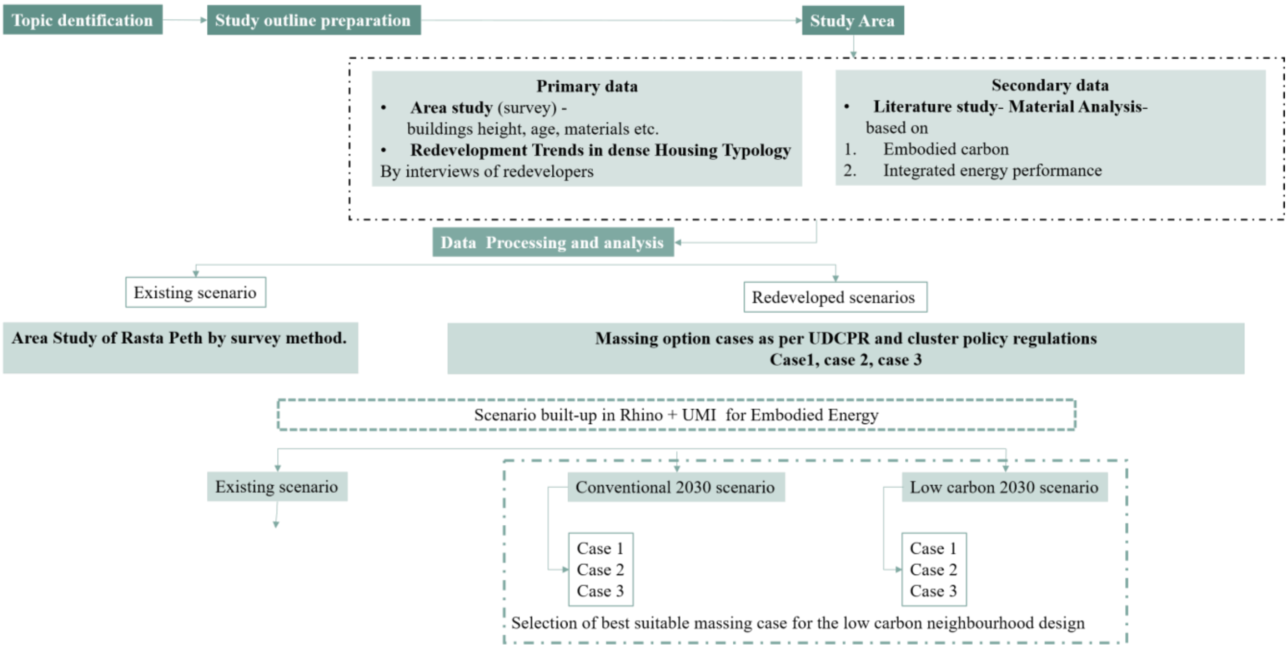

Figure 1: A methodological framework for the research study.

The following steps can formulate this research:

Step 1: Topic identification and generate the study's basic outline

The first step was to define the purpose of the study, as well as its expected outcomes, goals, and objectives.

Step 2: Finalizing study area and data collection

Data gathering focused on embodied energy. Primary data was gathered using QGIS with the Kobo tool application for mapping and field surveys. To understand how construction material trends have changed, information on redevelopment was collected in addition to secondary data for embodied emissions from the India Construction Materials Database. In this study, only structural systems with envelopes with floor finishes were considered. Considering scenarios for 2030 when analyzing EE is essential as it will help to anticipate and assess potential changes in technology, materials, and practices within construction and manufacturing industries.

Step 3: Data processing and analysis

The data collected in Step 2 was processed by developing scenarios and then simulated in UMI (Urban Modelling Interface) using a Rhino plug-in. Rationalized densities and house types were taken into account to simulate a redevelopment scenario in Rasta Peth. Based on UDCPR guidelines, simulations of the Rasta Peth redevelopment scenarios were performed. The service life of buildings is considered to be **60 years**. To finalize the massing layout for low-carbon redevelopment and comply with UDCPR regulations, many massing cases were generated and evaluated. The built-up area for all redeveloped cases is constant. Products used were manufactured within a radius of 200-800 km, and the transportation distances from distribution from distributor to site were in the range of 25-130 km were considered.

Step 4: Recommendations and results

The simulation results were thoroughly examined and visually presented, resulting in significant findings and recommendations. By comparing conventional and low-carbon 2030 scenarios, it will be possible to understand the potential impact of shifting towards more sustainable practices.

Study area

The proposed study area is Rasta Peth in Pune, Maharashtra. It has mixed-use typology buildings with a distinct planning character of grid-iron road networks segregating access and service road networks. For the proposal of Urban Renewal Schemes, the study area is divided into 12 blocks named Block A-L, as shown in Figure 2.

The existing scenario of neighbourhood type is Low Rise- High Density.

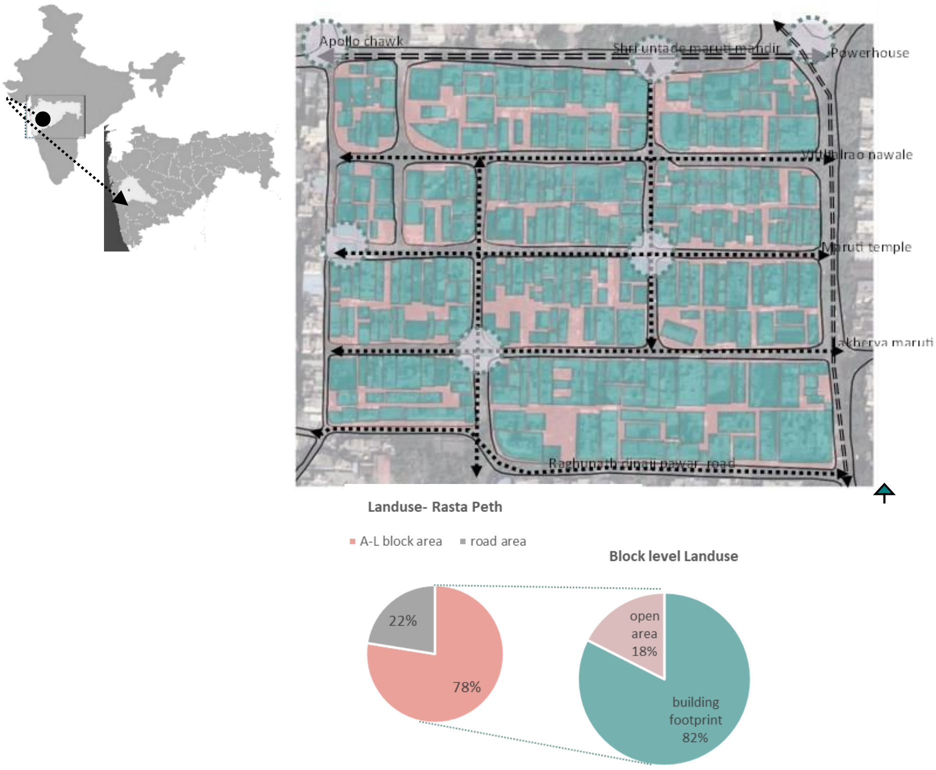

Figure 2: Site plan- Rasta Peth, Pune- An existing scenario with area distribution

• Total site Area- 105303 m^2 Total No. Of existing structures- 326   Total no. of blocks- 12

Primary data collection by gathering data related to existing site development was field study and survey and building level mapping with the help of software like QGIS. The mapping attributes were Building footprint, building typology, no. of floors, age range of buildings, building envelope materials, and structural type.

Data processing

Existing scenario generation

The existing scenario for embodied energy analysis is modelled and simulated based on the existing material assembly of Rasta Peth. The study scope was limited to structural systems, envelopes, and floor finishes.

- Site Area- 105303 m^2
- No. of Households-2187 Nos.
- Max. Building Height- 18 m

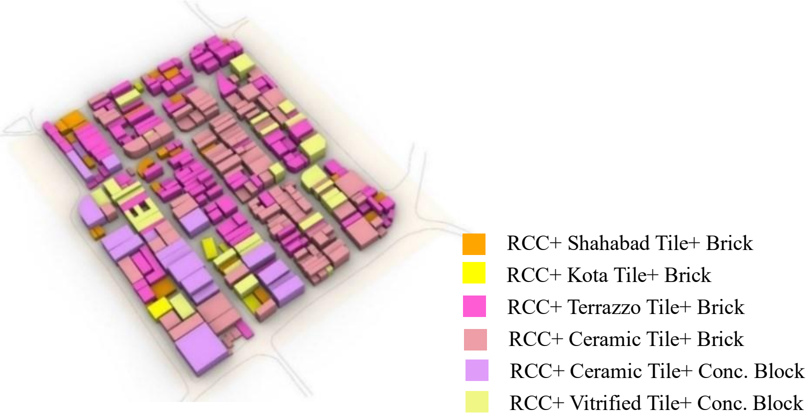

Figure 3: Embodied energy and embodied carbon for the existing scenario

Table 1 presents the material template for the existing scenario.

Table 1: Existing material inventory *source- India construction material database*

Elements	Materials	Embodied energy (MJ)	Embodied carbon (kg CO_2 eq.)
Wall	Bricks (common/facing)	4.40	0.39
	Concrete block- AAC	3.70	0.50
Floor Slab/ Roofing	RCC	2.12	0.24
	Reinforcement	30	2.60
Flooring	Terrazzo Tile	4.60	0.51
	Shahabad Tile	0.44	0.056
	Kota tile	0.79	0.056
	Ceramic Tile	7.80	0.67
	Vitrified tile	8.20	0.68
Windows	Aluminium Frame	280	26
	MS frame	51	3.50
Glass	Single glazed opaque glass	191.80	10.10
	Single glazed clear glass	191.80	10.1 0

Redevelopment scenario generation- Calculations as per UDCPR and Cluster policy regulations.

The proposed redevelopment project aims to revitalize the core area of the city by replacing outdated buildings with high-rise, high-density structures that maximize the available floor space. The project site is located in a strategic location, surrounded by key commercial and public amenities, making it an ideal location for a mixed-use development that caters to the diverse needs of the community.

Overall, for the redevelopment area calculations considering various factors and variables, developers and local governments can work together to determine the appropriate size, shape, and scope of the redevelopment project, ensuring that it meets the needs of the community while complying with relevant regulations and building standards.

The proposal was developed block-wise. The massing cases were based on the UDCPR and cluster policy guidelines. The intent of sustainable development was mainly based on embodied carbon as the built structure will exist there for the next 60 years, and embodied energy will be locked for a long time. Along with this, the environmental quality parameters were considered for the user's health and well-being.

Redevelopment scenario- Massing cases for site development, Rasta Peth

For redeveloped scenarios, massing cases were referred from the Handbook of Replicable Designs for Energy Efficient Residential Buildings published by BEE. However, slight modifications may be necessary during the detailed design

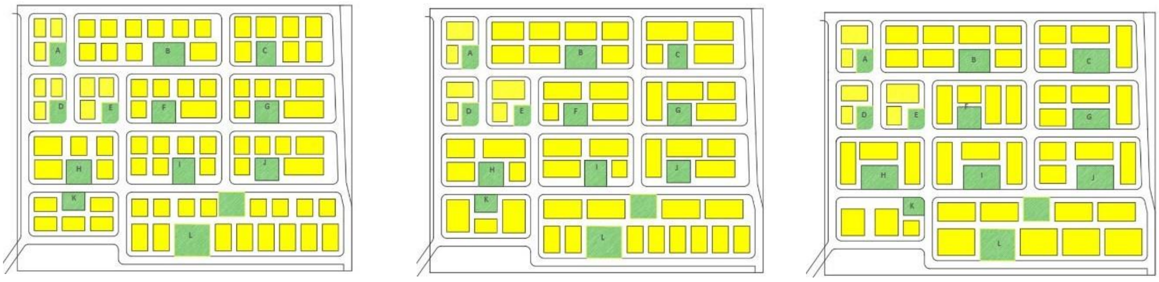

Figure 4: Massing cases 1, 2, and 3 for the Redeveloped scenario

stage. Here, the total built-up area for all 3 cases is considered the same, i.e., 4,30,960.15 m^2 by altering the massing modules.

Case 1: The first scenario features a mixed-use development with a mid-rise high-density block. The percentage of ground coverage area is 43% of the net plot area. The building footprints of blocks are comparatively smaller, have a height ranging from 8-13 stories, and consist of a combination of residential and commercial units. (Considered commercial floor height is 4.5 m and residential floor height is 3m). The lower levels are dedicated to retail and commercial space, while the upper levels are for residential apartments.

Case 2: The second scenario features a mixed-use development with a mid-rise high-density block. The percentage of ground coverage area is 49% of the net plot area. The building footprints of blocks are comparatively wider and rectangular by amalgamating 2 blocks from option 1, have a height ranging from 7-12 stories, and consist of a combination of residential and commercial units.

Case 3: The third case also features a mixed-use development with a mid-rise high-density block. The percentage of ground coverage area is 45% of a net plot area. The building footprints of blocks are comparatively wider and rectangular by amalgamating 2 blocks from option 1, have a height ranging from 8-11 stories, and consist of a combination of residential and commercial units.

Conventional EE 2030 scenario generation

Table 2: Material inventory for Conventional 2030 scenario *source- India construction material database*

Elements	Material	Embodied energy (MJ)	GWP (kg CO_2 eq)
Walls	AAC blocks	3.7	0.50
Slab/ Roofing	200 mm RCC slab	12.2	1
	Steel reinforcement	30	2.6
	Cement plaster	4.8	0.44
Flooring	Vitrified tile flooring	8.2	0.68
	Ceramic tile flooring	7.8	0.67
	RCC	2.12	0.24
Windows	Single glazed clear glass	191.80	10.1
	Al. Frames	280	26

A conventional embodied scenario is to evaluate the environmental impact of a building's materials and construction processes. This scenario is based on current material trends after conducting informal interviews with developers in Pune, which includes a comprehensive assessment of the materials used in buildings, such as their extraction, transportation, manufacturing, installation, and end-of-life disposal. This material palette is identified from the materials used for the current redevelopment building construction in Rasta Peth.

With the help of this knowledge, it will be possible to spot opportunities for a building's environmental impact to be reduced by choosing more green building materials and enhancing construction procedures, as well as to make educated decisions for a building's overall carbon footprint reduction. The above is the material template for the conventional 2030 scenario.

Low carbon EE 2030 scenario generation

In this scenario, as per the research, it was realized that the use of low-carbon materials helps to reduce EE. Hence, for this scenario, regionally available materials with recycled contents were preferred. These materials will be produced using renewable energy sources, which will reduce the carbon footprint of the manufacturing process. By using electric vehicles and improving supply chain logistics, there will also be an emphasis on lowering the amount of energy needed for transportation. The following is the material template for the low carbon 2030 scenario. Total item-wise material quantities were calculated and used as input for the EE calculations.

Table 3: Material inventory for Conventional 2030 scenario *source- India construction material database*

Elements	Material	Embodied energy (MJ)	GWP (kg CO_2 eq)
Walls	FaLG blocks with fly ash content 30% (200 mm)	0.83	0.20
	AAC blocks with fly ash content 30% (100 mm)	0.97	0.34
Slab/ Roofing	Prefabricated 200 mm RCC Filler slab	0.87	0.45
	Reinforcement 50% recyclable content	14.8	1.05
	Cement 30% Flyash content	1.87	0.11
Flooring	Ceramic tile flooring	7.80	0.65
	Cement mortar with 30% fly ash content	1.87	0.11
Windows	Single glazed low E glass	96	5.06
	UPVC Frames	61	3.70

Results

Embodied energy for the existing scenario

Site Area- 105303 m^2

Gross Floor Area- 225101 m^2

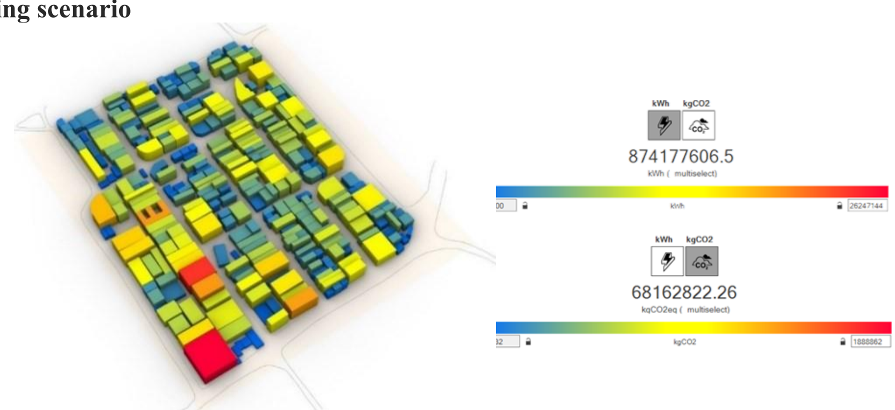

Figure 5: Embodied energy and embodied carbon for the existing scenario

The results of UMI simulations are carried out for the existing scenario of the low-rise, high-density area of Rasta Peth, Pune.

The existing scenario was run by inputting the existing material inventory given in Table 1; embodied energy and embodied carbon values for 3 massing cases were generated, as shown in Figure 5.

The total embodied energy for the existing scenario is 874177606.50 kWh. i.e., 874 GWh, and total embodied carbon is 68162822.26 kg CO_2eq.

As shown in the following results, the building assemblies with bigger footprints have higher EE.

Conventional building wall material assemblies like red brick have relatively higher EE than concrete blocks.

The conventional terrazzo tile flooring with RCC construction has relatively lower EE than ceramic tile flooring with a similar building footprint area.

Block L has relatively newer constructions with mostly more than G+4 height structures; hence, the EE for the L block is higher.

Embodied energy (EE) for redeveloped conventional 2030 scenario

All massing cases were run by inputting the conventional 2030 material inventory given in Table 2; embodied energy and embodied carbon values for 3 massing cases were generated, as shown in Figure 6. Gross floor area- 4,30,960.15 m^2.

The total embodied energy for the conventional 2030 scenario for case 1 is 1249 GWh, and the total embodied carbon for the conventional 2030 scenario is 91961217.89 kg CO_2 eq. For case 2, EE is 1100 GWh, and total embodied carbon is 81198000.65 kg CO_2 eq. For case 3, EE is 998 GWh, and the total embodied carbon for the conventional 2030 scenario is 73529667.14 kg CO_2 eq.

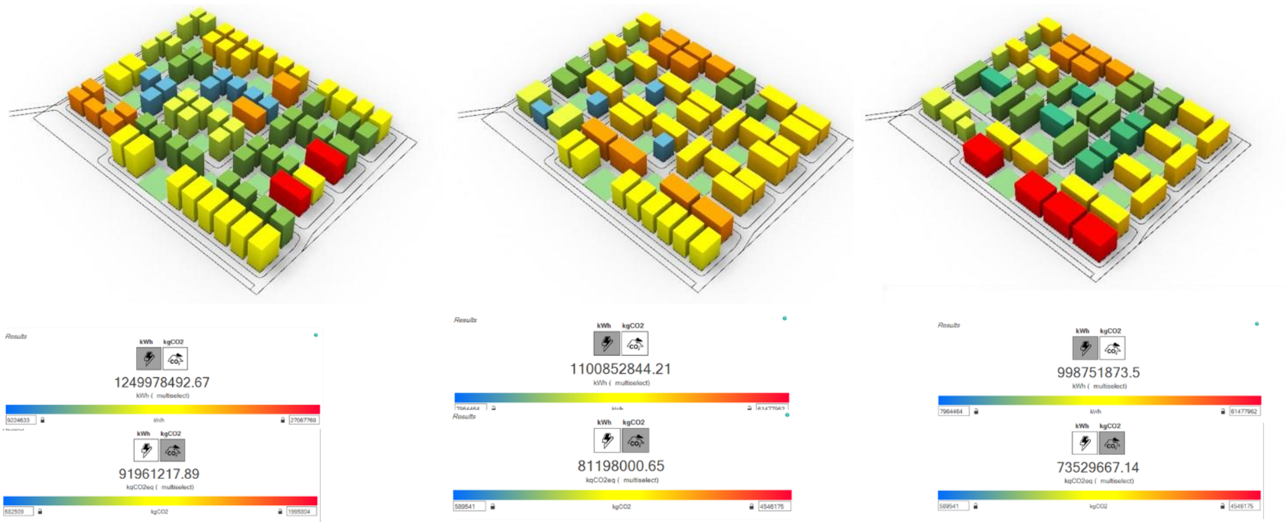

Figure 6: EE and EC of cases 1, 2, and 3 for conventional 2030 scenario

The comparative analysis is done for all cases for the total embodied energy for the conventional 2030 scenario and is shown in Figure 7.

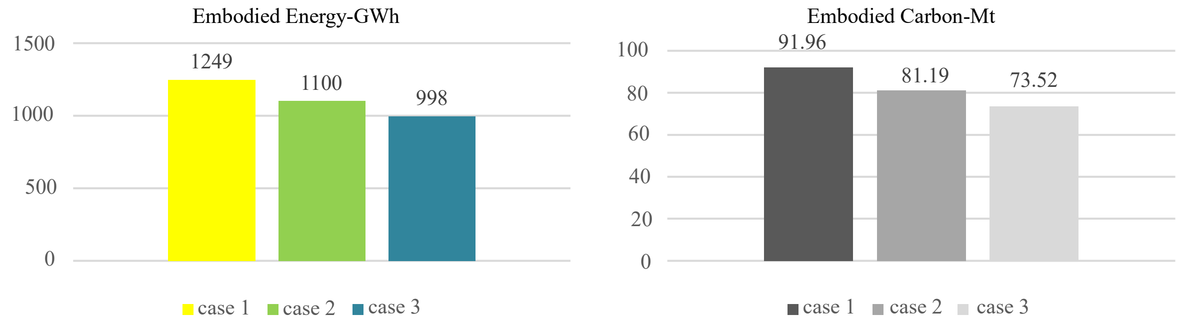

Figure 7: Comparative analysis for EE and EC of all 3 cases for conventional 2030 scenario

From the comparative analysis (Figure 7), it is seen that there is a 20% reduction in the embodied energy of case 3 from case 1 and a 21% reduction in embodied carbon of case 3 from case 1.

Embodied energy (EE) for redeveloped low carbon 2030 scenario

All massing cases were run by inputting the low carbon 2030 material inventory given in Table 3; embodied energy and embodied carbon values for 3 massing cases were generated, as shown in Figure 8.

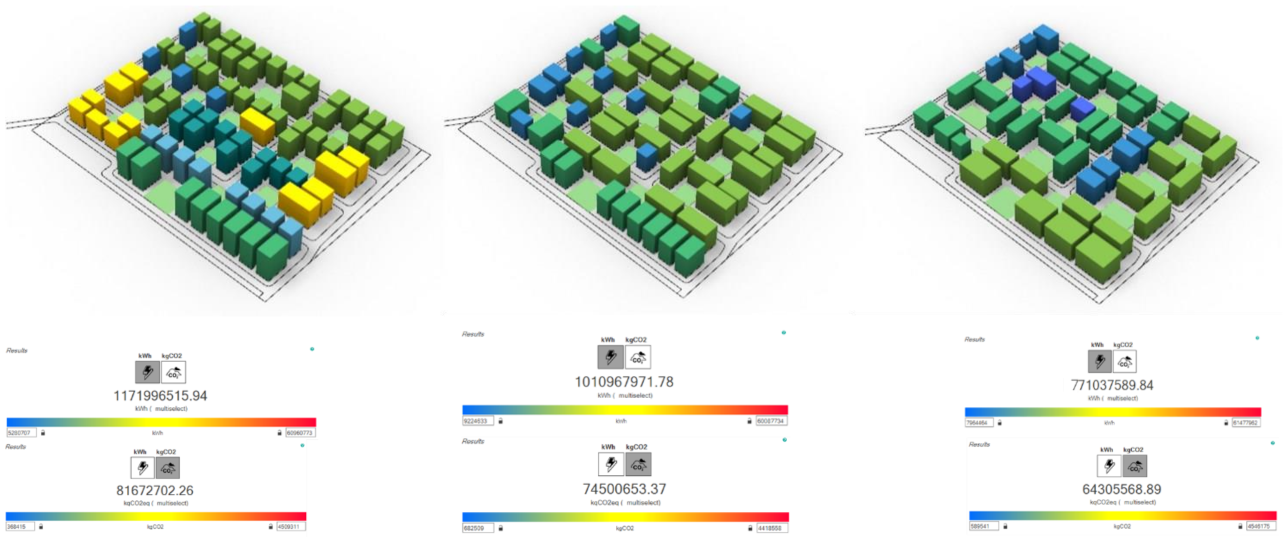

Figure 8: EE and EC of cases 1, 2, and 3 for the conventional 2030 scenario

The total embodied energy for the low-carbon 2030 scenario for case 1 is 1171 GWh, and the total embodied carbon for the low-carbon 2030 scenario is 81672702.26 kg CO_2 eq. For case 2, EE is 1010 GWh, and the total embodied carbon is

74500653.37 kg CO_2 eq. For case 3, EE is 771 GWh, and the total embodied carbon for the conventional 2030 scenario is 64305568.89 kg CO_2 eq.

The comparative analysis is done for all cases for the total embodied energy for the low carbon 2030 scenario, as shown in Figure 9.

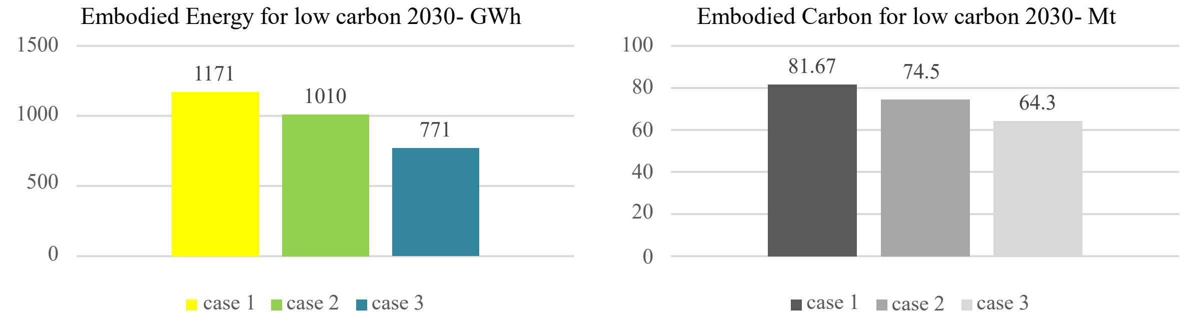

Figure 9: Comparative analysis for EE and EC of all 3 cases for the low carbon 2030 scenario

From the comparative analysis (Figure 9), it is seen that there is a 34.1 % reduction in embodied energy of case 3 from case 1 and a 21% reduction in embodied carbon of case 3 from case 1.

Data Analysis

For redeveloped scenarios- conventional 2030 and low carbon 2030, 3 massing cases were designed according to UDCPR and cluster policy rules. The simulation results showed that case 3 had the lowest embodied energy and embodied carbon among the three cases in both scenarios.

This is because case 3 requires comparatively less building materials quantity compared to massing cases 1 and 2. Additionally, the wider shape design of the building allows for more efficient use of space, with the reduction in areas of circulation spaces, further reducing the amount of building materials required.

Comparative analysis of existing vs. conventional 2030 vs. low carbon 2030 scenarios for total EE and EC

Existing systems refer to products and systems as they are available today in the given context. In contrast, conventional 2030 refers to a scenario where products and systems still use conventional techniques and technologies for redevelopment.

The low carbon 2030 scenario has the least amount of average embodied energy as well as embodied carbon, respectively. It has 22.7% less Embodied Energy and 13% less Embodied carbon than the conventional 2030 scenario.

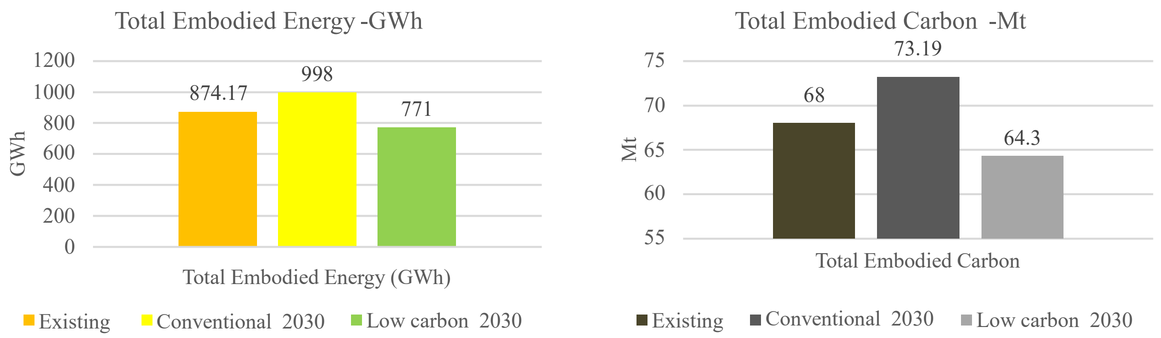

Figure 10: A comparative analysis of existing vs. conventional 2030 vs. low carbon 2030 scenarios for total EE and EC

- The total embodied carbon values are not rising exponentially in the low carbon scenarios despite the predicted densification of the building stock in the future scenarios.
- Variations in the total amounts of embodied carbon can be observed with changes in the materials selected.

Overall, the findings imply that, compared to the conventional 2030 scenario, switching to a low-carbon 2030 scenario would significantly reduce the embodied energy and embodied carbon per unit area.

Discussions

This paper addressed the UBEM tool and strategies that can encourage the construction industry to effectively incorporate embodied carbon considerations and thus reduce its contribution to global greenhouse gas emissions. The success of these reduction strategies depends on the understanding and proper execution of all stakeholders involved in a project. Rising awareness among manufacturers and industry professionals will result from more research and information sharing, such as carbon labeling, eventually reducing the instances of missing data.

Scenarios like materials with a higher percentage of construction and demolition waste and recycled content can be built to analyze further reduction from conventional scenarios. Exploring a range of low-carbon alternatives that can contribute to sustainable urban development is imperative. One such consideration involves refurbishing existing buildings. While the low-carbon benefits of refurbishment are evident, it's essential to acknowledge certain challenges like structural limitations, meeting modern building codes, and addressing potential hazardous materials. A thorough lifecycle assessment is crucial to quantify the environmental impact of both options.

Conclusions

This study conducted a comprehensive evaluation of the design and construction sector to assess the industry's current status and scope regarding its impact on embodied emissions.

A comparative analysis of embodied energy in redeveloped scenarios was performed to provide insights into the potential environmental impacts of various building designs and materials. According to the study, a conventional 2030 scenario would result in higher embodied energy than a low-carbon 2030 scenario. This suggests that to achieve carbon neutrality by 2070, efforts to lower embodied energy in building materials and construction methods will be required.

By selecting materials with a low carbon footprint, initiating recycled content products, and using renewable energy sources for manufacturing can reduce embodied emissions. For the low carbon 2030 scenario, low-carbon materials like AAC Blocks with fly ash contents significantly reduce embodied energy by 22% and embodied carbon by 13%.

The densification of the building stock and the material inventory are both factors that affect total embodied carbon. Hence, changes in total embodied energy are based on massing layouts.

As different layouts may require different amounts of materials and energy for construction, factors like massing layouts can have a significant impact on embodied energy. The kind of materials used, the location of the construction site, and the modes of transportation employed to move materials and goods are additional elements that can impact embodied energy.

For the proposed scenario, regionally available materials were preferred. Considering the lifespan of construction materials is in the range of 30-60 years, the end of the lifecycle of a product and preventing it from going to landfills will reduce the embodied energy of the material.

These results demonstrate the importance of considering Embodied energy in building design and how careful planning and consideration can result in more sustainable neighbourhoods.

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Identifying the High Urban Heat Vulnerability Zones of a City for Prioritizing Mitigation Measures

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Highlights

- Construction of a composite heat vulnerability index (HVI) using the unweighted additive overlay method
- The framework is applicable for obtaining the HVI for any city
- Policymakers and urban planners can utilize the framework to mitigate heat hazards and provide relief

Abstract

Climate warming is raising global temperatures by 0.2°C every decade, generating severe heat waves and health risks. In India, urbanization has increased heat and humidity. The Urban Heat Island effect in Delhi puts many people at risk for heat-related health issues. This research identifies Delhi's high-vulnerability zones based on people's environmental, demographic, and socioeconomic conditions. The study analyzed vulnerability variables such as land surface temperature, land use, land cover, population density, and income level to identify high-risk zones in Delhi using the "unweighted additive overlay" approach. It is found that heat stress is most prevalent in 40 wards in Delhi's central-western and eastern regions. These findings underline the necessity for adaption methods and specialized urban design strategies and policies for heat reduction for those with weak adaptive ability. The study would assist officials in providing heat relief to high-vulnerability wards and include heat mitigation methods in Delhi's new master plan.

Keywords: urban heat island effect, heat vulnerability index (HVI), mitigation, temperature

Introduction

Delhi, located in the north of India and consisting of 289 wards and 11 districts, is one of the largest and fastest-growing metropolitan agglomerations in the country [1]. It also ranks second globally for having the highest number of 'person-days' per year [2]. As per the National Building Code (NBC) of India [3], the region exhibits a composite climate characterized by elevated maximum temperatures during the summer season. Additionally, owing to its geographical location, the area falls within the west-central Indo-Gangetic plain airshed, which renders it susceptible to higher temperatures due to high air pollution [4]. The inhabitants of the region are susceptible to a potentially grave concern, namely, exposure to high temperatures, particularly during the summer season, wherein the diurnal temperatures surpassed 45°C six times in May 2020 [5]. The phenomenon of near-surface urban heat island effect (UHIE) in the city contributes to the exacerbation of extreme heat. Numerous research endeavors in Delhi, spanning a significant duration, have demonstrated the interrelationship between diverse physical parameters, namely the built-up area's growth, vegetation alteration, and land surface temperature [6,7]. These parameters are, in turn, associated with the phenomenon of the urban heat island effect (UHIE). From these studies, it can be inferred that the development of urban heat islands in Delhi is primarily driven by the normalized difference vegetation index (NDVI), normalized difference built-up index (NDBI), and land use/land cover changes.

There are two broad ways to curb the UHIE and promote urban cooling - by diminishing the heat accumulation and by applying cooling techniques, such as the introduction of greenery in the form of tree-covered walkways and cool pockets [8], shaded places like pedestrian arcades and covered parking [9], and conscious selection of surface finishing materials [10], painting roof surfaces with high albedo materials and green roofs [2][4], and control the energy consumption by buildings [12], are a few of them. The effect of these mitigation strategies in the domains of the building envelope, urban landscaping, pavement, and street geometry have been analyzed by the researchers using software for 3D numerical simulations such as FLUENT-ANSYS, BES with CFD simulations, and MITRAS [13] [14]. Though a lot of studies on mitigation strategies were found, there was a lack of studies that considered the direct involvement and role of people in the mitigation of urban heat islands (UHI) [15][16]. In a recent case study of Singapore in 2020, the researcher conducted a survey to determine the willingness of the UHIE-affected population to participate in heat mitigation [17]. It was found that the willingness to pay (WTP) was directly proportional to the income and education of the population, that is, the socioeconomic factors. This study suggests that apart from evaluating the mitigation strategies, it is crucial to involve human perspective and vulnerability to estimate the social benefits of the solutions. Nordin. A. N. et al., in 2020, reviewed the studies that focused on the factors that influence people's WTP [18]. This research suggests that the UHI mitigation strategies, such as urban green spaces (UGS), fail due to insufficient funds by the government for its maintenance as well as a lack of sense of belongingness in people regarding the UGS. The accessibility, quality, and size of UGS also affect its relationship with people belonging to different socioeconomic backgrounds. Hence, there is a need to involve people in suggesting mitigation strategies according to their requirements and behaviour by conducting qualitative as well as quantitative surveys.

It can be said that UHIE is an urban-scale phenomenon that varies by the area's microclimate and can be mitigated through area-specific interventions that affect different populations based on their vulnerability level [19]. Even with the implementation of heat mitigation measures, some populations, such as children, migrants, and people in the low-income group, are more vulnerable to heat-stress-related health risks. Hence, in the absence of epidemiological data, the areas that are at a higher vulnerability risk within a UHI need to be identified using heat vulnerability indices [20]. The utilization of a composite index is a viable approach to evaluating the susceptibility of populations to health hazards associated with high temperatures, commonly referred to as the "Heat vulnerability index" (HVI). This method can effectively identify areas that require prompt intervention to ensure optimal outcomes that are both efficient and equitable [21]. The composite index generally integrates diverse environmental, social, and demographic variables, encompassing air temperature, availability of air conditioning, poverty level, age, and health condition, to generate a holistic representation of a community's vulnerability to heat strain. The computation of the HVI for a particular region enables decision-makers to optimize interventions and allocate resources precisely and efficiently. This is because the HVI offers insights into the communities that are most vulnerable and the specific factors that contribute to their vulnerability. The aforementioned data holds significant importance in strategizing and executing public health measures, such as establishing heat warning systems, disseminating heat-health education initiatives, implementing tree-plantation programs, and facilitating cooling centers to mitigate the detrimental health effects of heat waves [22].

The notion of susceptibility to thermal strain is frequently depicted as the aggregate of three interrelated components: exposure, sensitivity, and adaptive capacity [22].

- **Exposure** pertains to the magnitude of heat stress and how high it can get. The components of exposure can be broadly classified into two categories: *Direct measures* and *Indirect measures*. The former includes heatwave days, consecutive hot days, min/mean/max air temperatures, and land surface temperature, while the latter comprises impervious surfaces, vegetation, urban density, land cover, land use, homes without A.C., and population density.
- **Sensitivity** refers to the degree to which an individual can be impacted. The categories of sensitivity are older adults, infants, young age, sex, diabetes, cardiopulmonary, renal, respiratory, and obesity.
- **Adaptive capacity** refers to the resources available to an individual or group to help them cope with heightened exposure to heat. The categories of adaptive capacity are air-conditioning access, living alone, income, homeownership, unhoused, education, ethnicity, language, foreign-born, cognitive impairment, and mobility/transportation.

In a study carried out between 1990 and 2000 in the City of Phoenix, which has higher average temperatures, near-surface air temperature, and NDVI were taken into account as the indicators for exposure, age over 65 as the indicator of sensitivity, and household income, ethnicity, and length of stay as the indicators for adaptive capacity. The study developed a composite vulnerability index using various indicators. Results indicated that social indicators, such as ethnicity and age, are more significant in determining vulnerability as compared to physical indicators [23]. A comprehensive study was conducted in various cities in the United States, utilizing ten vulnerability variables to determine the extent of vulnerability variation from local to national levels [24]. A vulnerability study was conducted in Seoul, Korea, in 2018. The study utilized the principle component analysis method to analyze sensitivity indicators, such as age and diabetes, and adaptive capacity indicators, such as income level and education, to calculate the HVI district-wise [25]. A study was conducted in Delhi to investigate the relationship between greenspace and social vulnerability to the urban heat island effect in urban areas. The study concluded that there was a significant correlation between higher vegetation and increased adaptive capacity of the population [26].

Though many studies have identified a correlation between vulnerability indicators, there is a limited number of research offering a streamlined approach to classify a city's wards based on their heat vulnerability. In the past few years, and with growing casualties due to heat waves, many nations have declared high temperatures a "national emergency" and a disaster [27, 28]. Facing any disaster requires a framework that can identify the people most affected by it and formulate mitigation techniques to decrease its impact. So, by considering high-temperature and heat waves as natural disasters, this study aims to categorize wards based on heat vulnerability. This will aid policymakers and urban planners in identifying priority wards for detailed surveys to determine appropriate mitigation strategies, implementation of those strategies, and summer heat relief measures.

During the period spanning from 2000 to 2020, Delhi underwent a swift expansion in anthropogenic activity and land use practices, which resulted in a persistent reduction in vegetation cover. This phenomenon led to an elevation in land surface temperature [6]. Significant alterations were noted in the minimum and maximum temperatures of the urban area. Specifically, the minimum temperature for May in the year 2000 was recorded at 23.20°C, while the maximum temperature was 34.85°C. These values escalated to 26.31°C and 39.92°C, respectively, in 2010.

Furthermore, in 2020, the minimum temperature was 31.70°C, and the maximum was 46°C. The NDVI has exhibited a decline from 82% to 62%, while the non-vegetated region has undergone a reduction from 82% to 62% over the past two decades, owing to rapid urbanization and land conversion. The swift urbanization process has resulted in significant alterations in surface conditions, leading to a substantial transformation in the region's demography, landscape, and ecosystem. These changes can potentially impact the vulnerability, as evidenced by the rise in reported health issues related to heat waves [27]. Therefore, we have selected Delhi as the city for our case study.

The main objectives of our study are –

i. To identify and map the physical and social indicators that are important and accessible for assessing the vulnerability of a ward.
ii. Design a simplified framework for identifying the heat-vulnerable wards of Delhi.
iii. Defining a heat vulnerability index (HVI) and identifying the vulnerable wards of Delhi.

To achieve our objectives, we formulated a metric to assess the susceptibility of individuals to heat stress in Delhi, India, by considering physical exposure factors such as population density, land surface temperature, land use, and land cover, as well as the adaptive capacity of the human population as indicated by income level. We proceeded to analyze the spatial distribution of this metric for a representative summer day and identified the wards of Delhi with the highest vulnerability to heat waves. According to the Indian Meteorological Department, India is at its peak of heat vulnerability when it experiences heat waves between May to June and sometimes in July [29]. Hence, May was selected as the time period for this study.

Methodology

The present investigation focused on the urbanized region of Delhi, as delineated by the 2011 Census. To derive a composite HVI, these five measures representing physical exposure and adaptive capacity were identified, as shown in Table 1.

Table 1: Measures for heat vulnerability index, their sources, and implications

Measure	Source	Indicator of/relationship to total vulnerability
Physical exposure		
1. Land surface temperature (LST)	Landsat 8 & 9	Ground-level heat stress in the region / positive
2. Land cover (built area)	Landcover map of Delhi	Low albedo and high imperviousness have high heating potential / positive
3. Land use	ESRI living atlas	Residential zones are more vulnerable/ positive
4. Population density	Census India	Higher population vulnerable to heat stress/ positive
Adaptive capacity		
5. Income level	NCAIR report	Lack of wealth/ positive

After identifying these measures, a framework for constructing HVI was derived, as shown in Figure 1.

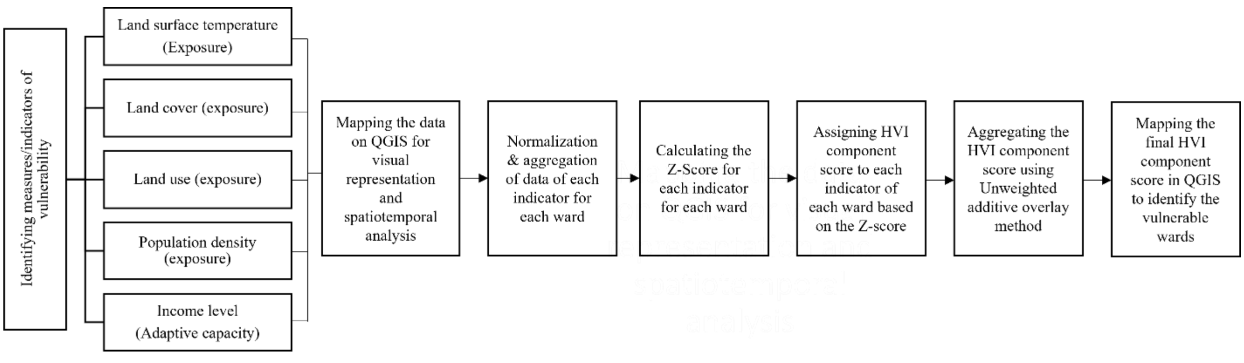


Figure 1: Framework for construction of HVI using unweighted additive overlay method.

The month of May, in which Delhi experiences the highest temperatures and heatwaves, was chosen for obtaining the data for vulnerability measures/indicators. Once, the data was gathered, it was mapped using a geographic information system software called QGIS for spatiotemporal analysis. Previous research in this field shows that regions exhibiting the most significant biophysical susceptibility do not coincide with those demonstrating the highest social vulnerability, and it is challenging to ascertain the relative significance of any particular measure. Therefore, an assumption was made that all measures carry equivalent weightage in evaluating susceptibility to extreme heat. Hence, upon completion of the georeferencing and conversion of all raw data to shapefiles, an “unweighted additive overlay” method was applied. The approach involved assigning a Z-score to each vulnerability indicator in every ward, with values ranging from below -2 to above 2. The z-score is obtained by applying equation 1 for each value of each vulnerability indicator. Equation 1 is as follows:

$$Z\text{ - }score = \frac{Observed\ value\ of\ the\ vulnerability\ indicator - mean\ of\ the\ vulnerability\ indicator}{Standard\ deviation\ of\ the\ vulnerability\ indicator} \quad (1)$$

The HVI component score was derived by assigning a value between 1 and 6 based on the corresponding Z-score, with a score of 1 being assigned to Z-scores of -2 or lower and a score of 6 being given to Z-scores of 2 or higher as shown in Table 2. The HVI of each indicator was mapped ward-wise. The final value of the unweighted HVI (HVI_{UnW}) is determined by aggregating the HVI component scores of each individual indicator, and the ward that obtains the highest score is deemed the most vulnerable. The unweighted HVI (HVI_{UnW}) was calculated using equation 2:

$$HVI_{UnW} = \text{HVI component score of [LST + \% percentage of built area + percentage of residential area + population density + income level]} \quad (2)$$

The values from Equation 2 were then used to construct the composite HVI map for Delhi. Table 3 shows the calculation of unweighted HVI (HVI_{UnW}) for four of such wards (183, 184, 185, & 187) of Delhi. In Table 3,

- P_D 2020 = Population density of ward in 2020
- I_L = Income level, where the high-income group is 1, the medium is 2, and the low is 3
- LC = Landcover percentage considering the built-up area percentage of each ward
- LST = Mean land surface temperature (LST) of each ward
- LU = Landuse, considering the residential area percentage of each ward

Table 2: A scoring mechanism for HVI construction

Range of Z-Score	HVI component score
-2 or lower	1
-2 to -1	2
-1 to 0	3
0 to 1	4
1 to 2	5
2 or higher	6

Table 3: Calculation of unweighted HVI for wards 183, 184, 185 & 187

Ward no.	Parameters					Z-score					HVI score					HVI_{Unw}
	P_D	I_L	LC	LST	LU	P_D	I_L	LC	LST	LU	P_D	I_L	LC	LST	LU	
183	1182.6	3	100	40.1	100	1.3	1.4	0.6	0.56	1.32	5	5	4	4	5	23
184	284.6	1	99.6	39.6	81.6	-0.3	-1.3	0.6	0.25	0.86	3	2	4	4	4	17
185	239.4	3	73.6	40.3	15.4	-0.4	1.4	-0.7	0.68	-0.83	3	5	3	4	3	18
187	372.8	2	45.3	41.9	0	-0.1	0.1	-2.1	1.64	-1.22	3	4	1	5	2	15
	Continued…															

Results and discussion

Land surface temperature (LST) was employed as a physical exposure indicator on a sunny day in May 2020. The thermal image was acquired from the United States Geological Survey (USGS) via Landsat 8 satellite. LST was calculated from thermal data (band 6) utilizing the mono-window algorithm based on the thermal transference equation. May and June in Delhi experienced high temperatures conducive to the UHIE. Our weather station data indicate that these months had frequent hot, clear, and calm days and nights. Early summer heat waves in May may increase the risk of heat-related injuries as residents are not yet acclimatized to the sudden rise in temperature (EPA, 2006). In May 2020, the recorded values for maximum land surface temperature (T_{max}) and minimum land surface temperature (T_{min}) were 56°C and 28°C, respectively, in May. Higher Tmax and Tmin magnitudes indicate greater heat vulnerability. The land surface temperature data was analyzed in QGIS to identify wards with higher heat vulnerability based on the highest and lowest temperatures, as shown in Figure 2 (a). From the temperature data obtained from the LST map, an HVI map was also created to understand the wards with high vulnerability due to high LST, as shown in Figure 2(b).

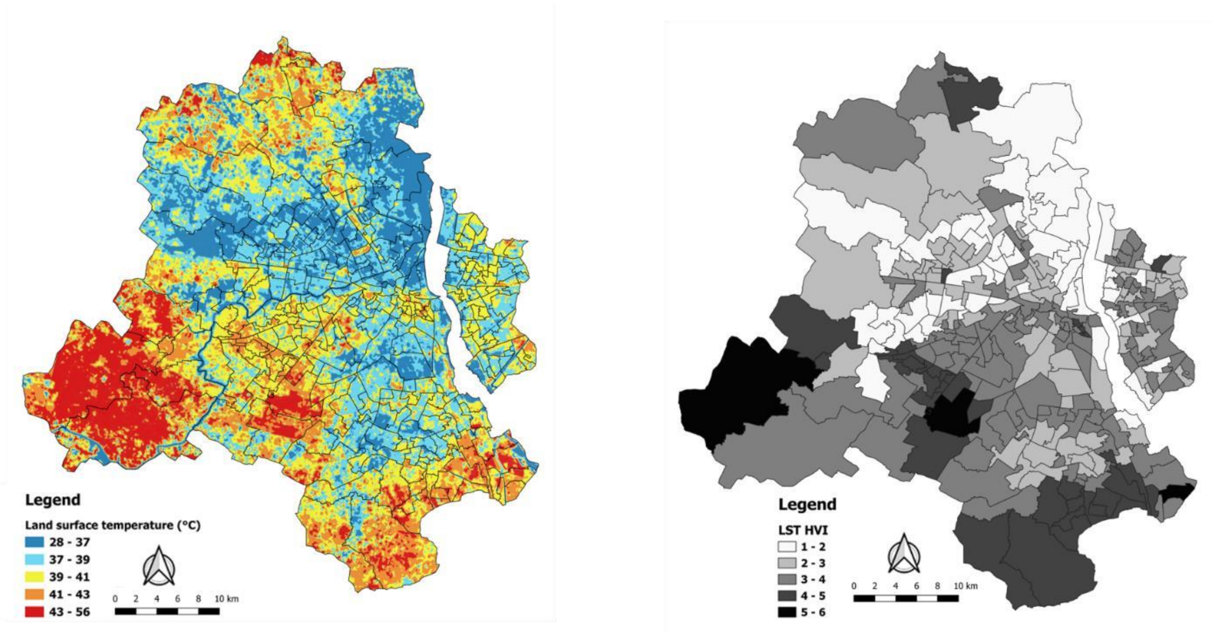


Figure 2: (a) LST map of Delhi on 16th May 2020 (b) HVI map for LST

The land cover map of Delhi is the second exposure indicator obtained from the Delhi Municipal Corporation (DMC), as shown in Figure 3(a). It comprises seven categories: water, trees, flooded vegetation, crops, built area, bare ground, and range land. Only the built area feature was considered significant in contributing to higher heating effects due to its high imperviousness, low albedo, and potential for increased anthropogenic heat generation. Wards with a built area exceeding 60% were classified as highly vulnerable (HVI 3-4), those with a built area ranging from 40% to 60% were classified as moderately vulnerable (HVI 2-3), and wards with a built area less than 40% were classified as the least vulnerable (HVI 1-2) as shown in Figure 3(b).

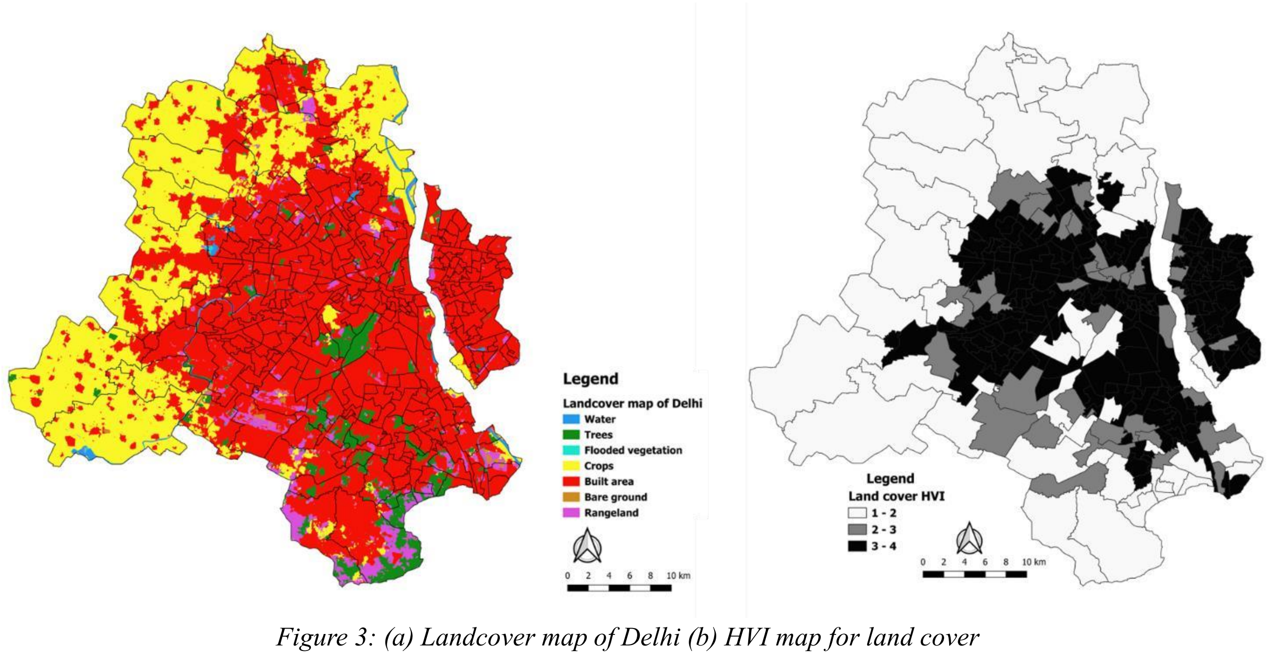
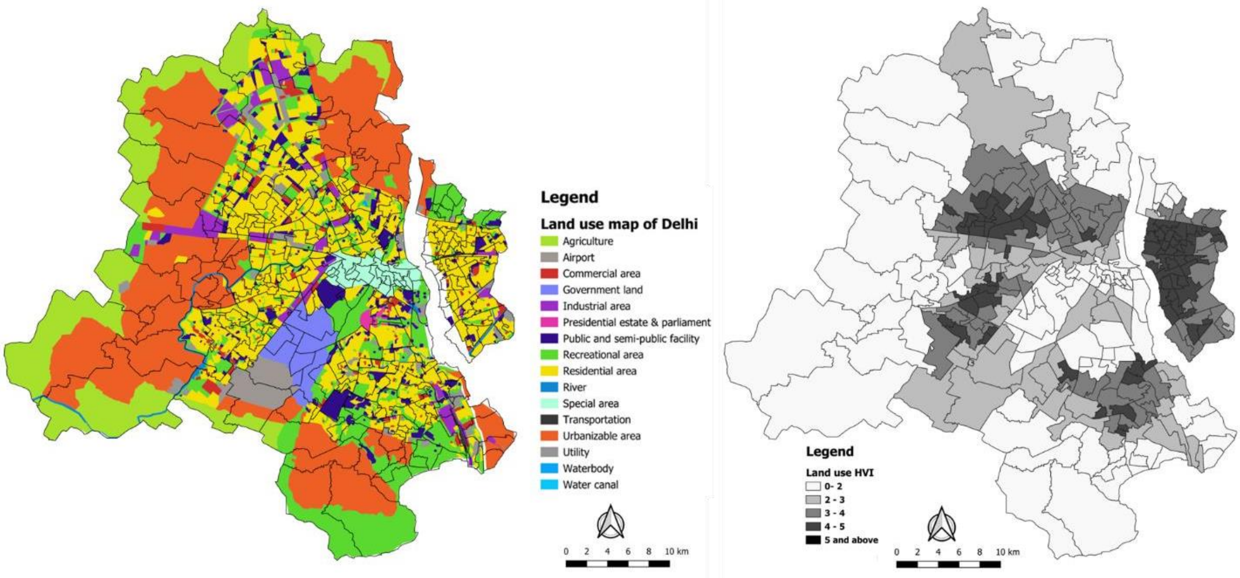


Figure 3: (a) Landcover map of Delhi (b) HVI map for land cover

Figure 3 shows that wards with more built-up area and impervious surfaces have a higher degree of vulnerability and is concentrated in the central and eastern part of Delhi.

The land use plan of Delhi was acquired from the ESRI living atlas through ArcGIS software as the third exposure indicator. The land use plan is classified into 17 categories, including agriculture, commercial, residential, industrial, recreational, and government land, as shown in Figure 4(a). Residential areas have been identified as more vulnerable



than other land use categories. Wards were categorized based on the percentage of the residential regions they contained. Those with residential areas of more than 60% were deemed highly vulnerable (HVI 4 and above), those with 40% to 60% were moderately vulnerable (HVI 3-4), and those with less than 40% were considered the least vulnerable (HVI 3 and below) as shown in Figure 4. The spatial analysis was visualized through Figure 3 utilizing the QGIS mapping software.

Figure 4: (a) Land use plan of Delhi (b) HVI map for land use

Figure 4 indicates that the wards with higher residential areas at the higher end of vulnerability are concentrated on the eastern side, with a few small concentrations in the central and southeastern parts of Delhi.

One of the purposes of this study is to identify the highest number of people who are most vulnerable to heat stress. Therefore, population density represents the fourth indicator of exposure. The census data pertaining to the population of each ward was obtained from the DMC database for the year 2020. It is believed that wards characterized by bigger population density are likely to harbor a more significant proportion of individuals susceptible to higher temperatures, rendering them more susceptible to adverse effects of heat. The population densities of the wards were categorized into five groups based on their magnitude, ranging from the highest to the lowest, as shown in Figure 5(a). The wards were classified into three degrees of vulnerability- high vulnerability for higher population density (HVI 5-6), moderate vulnerability for medium density (HVI 4-5), and low vulnerability for low density (HVI 3-4). The graphical representation of this phenomenon is illustrated in Figure 5(b).

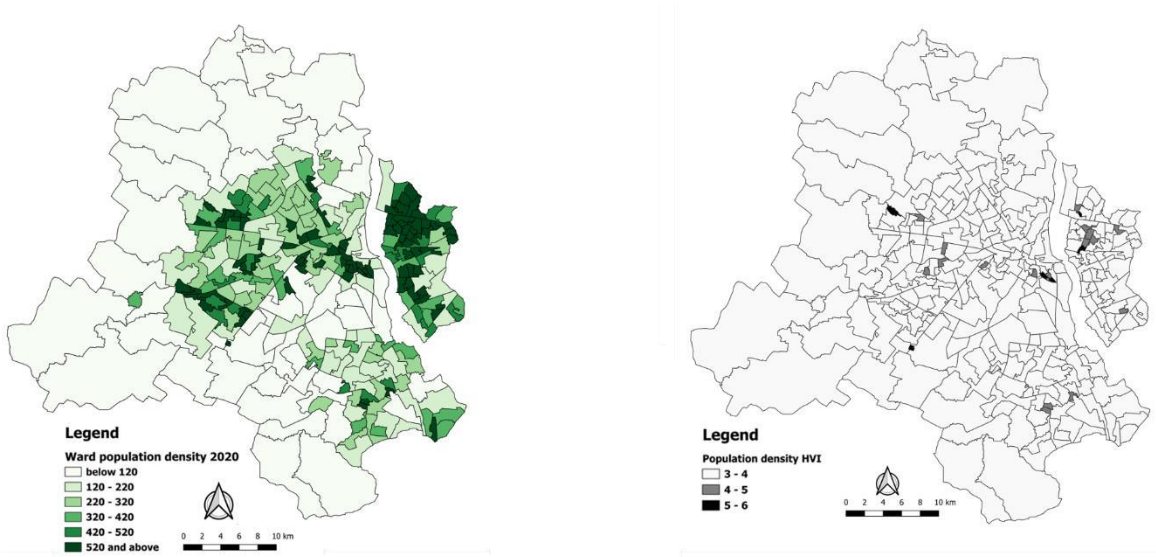


Figure 5: (a) Delhi ward population density for the year 2020 (b) HVI for population density

There are only six wards that have high vulnerability according to the population density of Delhi, as shown in Figure 5.

The adaptive capacity of various wards was assessed based on the income levels of their respective residents. As per the 2022 report by the World Bank [30], a significant proportion of India's populace, approximately two-thirds, subsists on a daily income of less than 2 USD. The acquisition of an air-conditioning unit in India can result in an average expenditure ranging from 260 USD to 500 USD, rendering it a luxury that only 8 percent of Indian households can afford. Therefore, it can be inferred that individuals with lower income levels are likely to be the most susceptible to heat waves. Figure 6(a) displays the income distribution across various wards [31]. So, to keep the indicator unidirectional, we assigned one vulnerability point to the high-income group, two to the middle-income group, and three to the low-income group and created an HVI map based on that, as shown in Figure 6(b). Figure 6 shows that the low-income, high-vulnerability population is concentrated in the western and southeastern parts of Delhi.

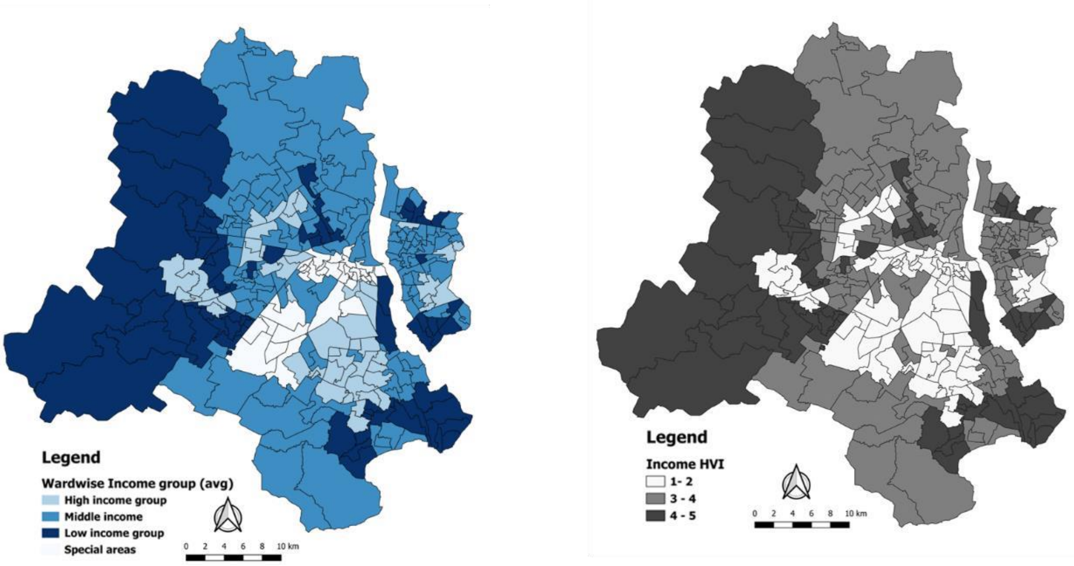


Figure 6: (a) Ward-wise income level of Delhi (b) HVI for income level

The composite heat vulnerability map with HVI_{UnW} is created from the data obtained from equation 1 and is illustrated in Figure 7.

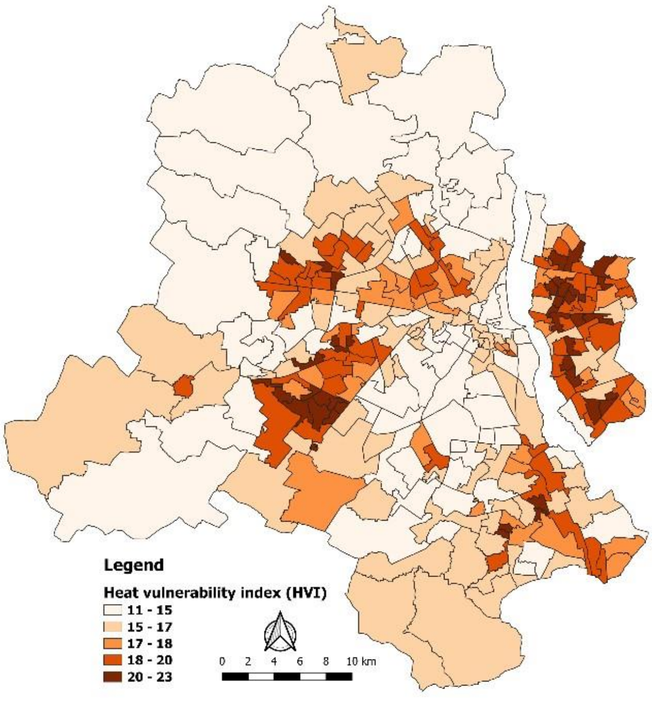
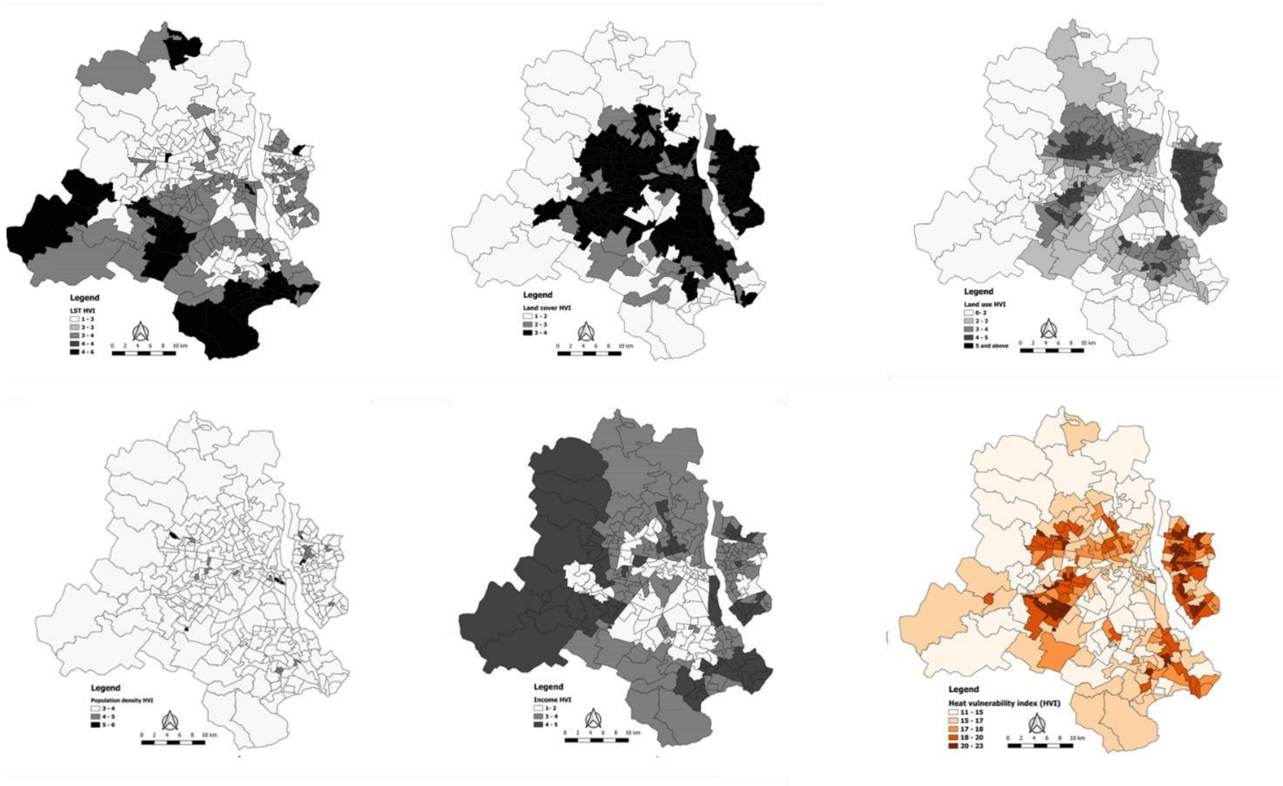


Figure 7: HVI of wards of Delhi using unweighted additive overlay.

Forty wards exhibit the highest degree of vulnerability, as depicted in Figure 7. Wards with HVI 20-23 are primarily located in eastern and central-western Delhi. Meanwhile, the wards exhibiting low vulnerability, categorized as HVI 11-15, are predominantly situated in Delhi's northern and central-southern regions. Figure 8 displays the HVI maps for each indicator and a composite HVI map containing all indicators. The high vulnerability zones on the individual map exhibit



partial overlap. Thus, it can be inferred that a single indicator is insufficient in accurately predicting the vulnerability of a group.

Figure 8: A comparison between HVI maps created using each indicator (top left to right) LST, land cover, land use (Bottom left to right) population density, income level, and composite HVI map of all five indicators

Conclusion

The study has documented how the heat vulnerability index varies with the input of different indicators individually as well as compositely. It also shows that better accuracy in finding the HVI can be achieved if five indicators are used instead of one. The vulnerable wards identified through this study can be prepared for the next heatwave to reduce casualties caused by high temperatures during summer. With Delhi on the way to becoming the most populous city in the world by 2030, it is very likely that more land cover will be urbanized, and the population density will also increase, ultimately resulting in a large population susceptible to heat hazards. This may result in a heightened susceptibility to heat hazards. The study's framework is helpful for policymakers and urban planners to create heat mitigation and relief plans. However, a more detailed analysis utilizing a complex HVI construction method and multiple vulnerability indicators can improve the accuracy of HVI prediction.

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Analysis of Hydrogen Delivery Costs: PEM Electrolysis as a Case Study for India

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Highlights

- This study showcases the significance of publicly available US Department of Energy Models for hydrogen production and analysis for India.
- H2A (Hydrogen Analysis Model) shows that the production cost of hydrogen by PEM Electrolysis is INR 439.44 ($5.31) per kg.
- HDSAM (Hydrogen Delivery Scenario Analysis Model) for New Delhi, India, as an example, is valuable for analyzing delivery costs by pipeline and tube trailers
- HDSAM Models give a perspective on delivery costs ranging from $ 5-10 per kg at higher market penetration and higher dispensing rate of hydrogen, which merits an understanding in the Indian context

Abstract

In its aspirations to achieve net zero goals by 2070, India is considering multiple renewable energy options. With the expectation of replacing fossil fuel-based feedstocks, hydrogen is being seen as a potential option for the transportation industry [1]. Replacing a fuel distribution infrastructure based on fossil fuel-based feedstocks to address a futuristic emerging option like hydrogen will receive an impetus if challenges on its introduction in an urban setting are duly identified through a combination of first principles engineering optimization base analyses and techno-economic analysis. Our work utilizes the H2A (Hydrogen Analysis Model) and HDSAM (Hydrogen Delivery Scenario Analysis Model) Model developed by the US Department of Energy (US-DOE) for modeling the cost of delivering hydrogen from a central production facility into a vehicle. The delivery infrastructure deploys all transport, storage, and conditioning activities from the outlet of the hydrogen production plant to the fueling station.

Keywords: Hydrogen, Renewable Energy, Urban Planning, Techno-economic analysis, Optimization

Introduction

Global warming and climate change require and demand scientists and engineers to devise solutions for their immediate addressal. The 6th Intergovernmental Panel on Climate Change Report (IPCC) highlights the rapid switch to renewables as the need of the hour and warns society against the dire consequences of inaction [1]. In the recently concluded COP 27, the UN Secretary-General declared, "We are on a highway to climate hell with our foot still on the accelerator." The Sharm el-Sheikh Implementation Plan is an advance over Glasgow in its more emphatic commitment to limiting global temperatures to 1.5 degrees Celsius. Such a commitment will require sustained reductions in greenhouse gas (GHG) emissions.

Hydrogen fuel is an efficient, clean, secure, affordable, and versatile form of energy. According to the International Energy Agency (IEA), the demand for hydrogen will rise fivefold to 500-680 million metric tonnes (MT) by 2050 globally. Currently, nearly 90% of the hydrogen consumed in India comes from fossil fuels and is categorized as black and gray hydrogen. Supplementary to this, hydrogen produced from renewable sources is called "green hydrogen." The Energy and Resource Institute (TERI) predicts that by 2050, around 80% of the hydrogen produced will be from renewable sources, which will be labeled as "Green Hydrogen" [2]. The momentum of hydrogen technologies is accelerating, with different production pathways focused prominently on renewable sources like water electrolysis, wind energy, and solar energy.

In the race to develop clean energy systems, hydrogen production pathways are enjoying unprecedented momentum with full support from the government. India is the 4th largest consumer of energy in the world after the USA, China, and Russia. However, India is not endowed with abundant energy resources. One of the major challenges faced by India is meeting its energy needs while achieving 8% economic growth and also meeting the energy requirements of its population (which is the world's second-largest, at affordable prices). It requires a sustained effort to increase energy efficiency while increasing domestic production, especially in clean energy systems. According to the recent report "Getting India to Net Zero" released by Rudd, the investment required for a net zero transition will be $13.5 trillion if the target is to be met by 2050. In India, the National Hydrogen Mission was announced in the Union Budget 2021-22 with the aim of transforming the transportation sector.

Hydrogen is considered the most promising energy carrier and is reckoned to be a supplement for natural gas in the future. Hence, it is imperative to study the economic production of hydrogen, delivery infrastructure, and storage options from a country-specific point of view. In its efforts to develop a sustainable economy, India is looking at a variety of renewable energy sources, with hydrogen standing out as a promising fuel for the transportation industry [3]. However, using hydrogen as a fuel in an urban environment presents a number of difficulties that must be recognized and resolved. Through a combination of first principles engineering optimization and techno-economic analysis, this study seeks to comprehend the integration of hydrogen into the current energy infrastructure.

The H2A and HDSAM models created by the US Department of Energy are one of the primary tools presented in this research for analyzing the cost of transferring hydrogen from a central production site to a fueling station [4]. The study's preliminary findings show that the cost of green hydrogen is in the $5- $6 range, highlighting the need for additional effort to reduce the cost. The study aims to highlight the difficulties in implementing hydrogen as a fuel for transportation in an Indian city. It also provides knowledge that could help urban planners and building scientists work toward a sustainable future.

Methods

One of the promising processes being explored for the production of green hydrogen is the polymer electrolyte membrane (PEM) electrolysis process, the results of which are presented here. A detailed analysis of the significant options has been conducted by Sharma et al. [5].

Hydrogen production by polymer electrolyte membrane (PEM) electrolysis process description:

According to the US Department of Energy's description of the H2A model, water is electrochemically split into oxygen and hydrogen in this process. Hydrogen is produced at the cathode, and oxygen is produced at the anode. In the presence of a catalyst, water at the anode splits into protons (H^+), electrons (e^-), and oxygen. This process operates at a high pressure and low-temperature range between 20-1000^{0}C [4].

The protons are carried to the cathode by the proton-conducting membrane. At the cathode (negative terminal), the electrons combine with hydrogen protons (H+) to produce H_2. On the other hand, the electrons travel from the anode via an external power circuit, providing the cell voltage (driving force) for the reaction. The major cell components of this process include membrane electrode assemblies (MEAs), which are separated into cathode and anode, gas diffusion layers (current collectors), and separator plates.

The reactions taking place inside the cell are:

At cathode $$2\,H^+ + 2\,e^- \rightarrow H_2 \quad (1)$$

At anode $$H_2O \rightarrow 2H^+ + 1/2O_2 + 2e^- \quad (2)$$

Overall reaction $$H_2O \rightarrow H_2 + 1/2O_2 \quad (3)$$

Input parameters for cost analysis:

The capital cost for the PEM production pathway includes the cost of the membrane stack, and the mechanical and electrical balance of the plant (BoP) is summarized in Table 1. The production capacity of hydrogen is 50,000 kg/day, and the amount of heat liberated by the complete combustion of 1 kg of hydrogen is around 150,000 KJ/kg.

Table 1: Capital investment costs (50,000 kg/day)

Major pieces/systems of equipment	**Baseline Installed Costs (US$)**
Stack Capital Cost	INR 403.1 cr ($ 48,776,376)
Mechanical BoP	INR 38.05 cr ($ 4,604,677)
Electrical BoP	INR 96.5 cr ($ 11,685,216)

The indirect depreciable costs incurred using combined plant scaling and escalation factors are summarized in Table 2.

Table 2: Indirect depreciable costs (50,000 kg/day)

Indirect Depreciable Capital Costs	**Reference Year (2021) Dollars**
Site Preparation ($) (may change to construction costs)	INR 10.7 cr ($1,301,325)
Engineering & design ($)	INR 53.7 cr ($6,506,627)
Project contingency ($)	INR 80.6 cr ($9,759,940)
Up-Front Permitting Costs ($) (legal and contractors fees included here)	INR 80.6 cr ($9,759,940)

The fixed operating costs for the PEM production pathway are summarized in Table 3. The H2A default values are used to calculate fixed operating costs in generating the scenario.

Table 3: Fixed operating costs (50,000 kg/day)

Fixed operating Costs	Reference Year (2021) Dollars
Burdened labor cost, including overhead ($/man-hr.)	INR 4332 ($52.42)
Labor cost, $/year	INR 9.01 cr ($10,90,244)
G&A ($/year)	INR 1.802 cr ($2,18,049)
Property taxes and insurance ($/year)	INR 15.5 cr ($ 18,85,414)
Material costs for maintenance and repairs ($/year)	INR 16.1 cr ($19,51,988)

Economic assumptions for H2A model

To calculate the levelized cost of hydrogen from various production routes, different scenarios can be developed using the H2A model. The general economic assumptions for developing an Indian scenario to calculate hydrogen cost are akin to all the production routes so as to develop a comparative analysis between the resultant costs of hydrogen.

General economic assumptions:

- Analysis methodology: Discounted cash flow analysis with an internal rate of return
- Financial structure - 40%
- Equity financing with an 11% after-tax real internal rate of return model allows debt financing also.
- Inflation rate - 1.9%
- Interest rate on debt - 3.70% at constant debt
- Reference year - All the result costs are in 2021
- Basis year - Cost input in 2018
- Length of construction period -3 years
- Working capital -15% of the yearly change in operating cost
- Analysis period - 25 years
- Plant life - 40 years
- Depreciation type and schedule for initial depreciable capital cost - Straight line - 20 years

- Salvage value - 10% of the total capital investment for the plant.
- Percentage of capital Spent in 1st Year of Construction - 50%
- Percentage of capital Spent in 2nd Year of Construction - 30%
- Percentage of capital Spent in 3rd Year of Construction - 20%
- Decommissioning cost - 10% of the depreciable capital investment
- Federal tax: 21%
- State tax: 16.0%
- G&A Rate - 20% of the staff labor costs above
- Property tax and insurance rate - 2% of the total capital investment per annum
- Unplanned replacement capital cost factor - 2% of the total direct depreciable cost per annum
- Capacity factor - 90%

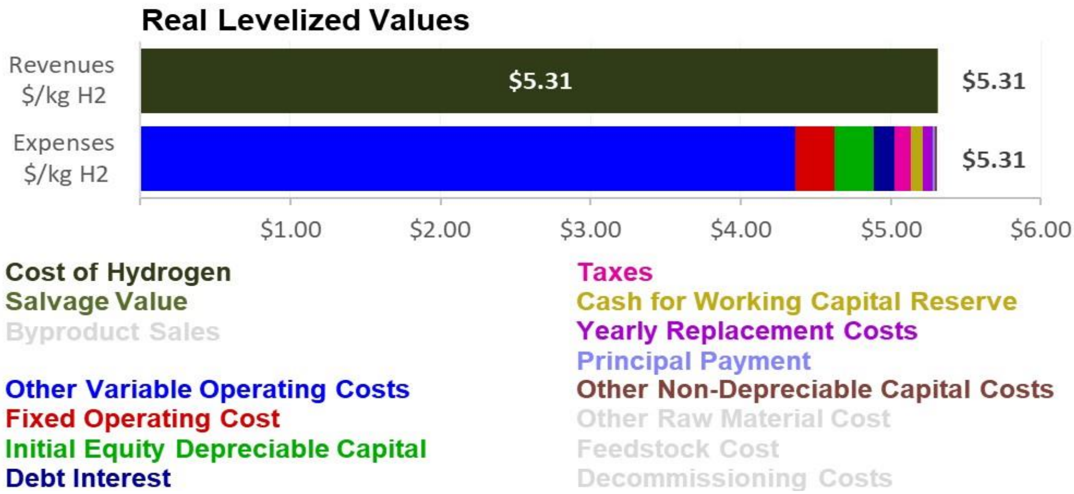

Figure 1: Cost breakdown of PEM electrolysis

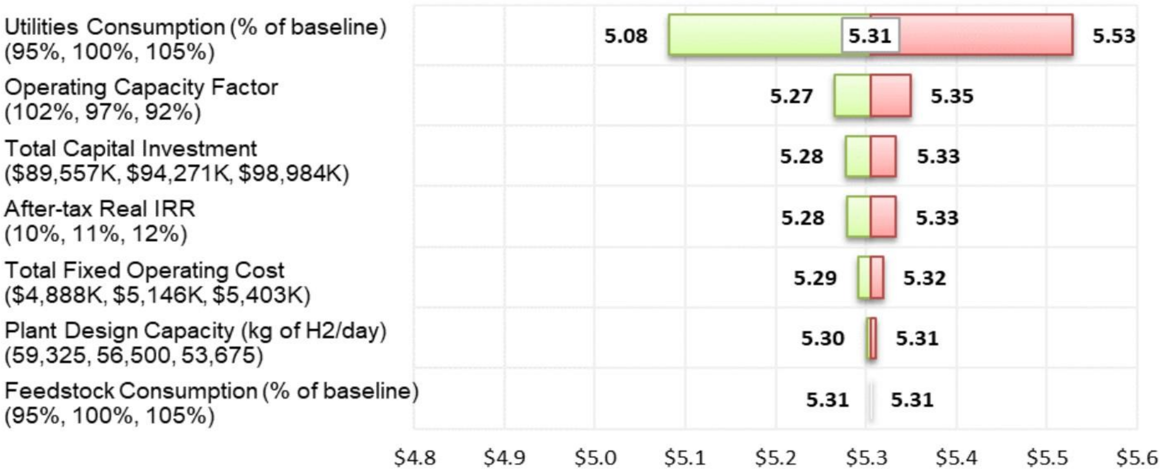

Figure 2: Tornado plot for PEM electrolysis

Hydrogen delivery scenario analysis model

In our study, we have also utilized the Hydrogen Delivery Scenario Analysis Model (HDSAM). The hydrogen delivery scenario analysis model is a tool that enables the examination and comparison of various approaches to the transportation and distribution of hydrogen while taking into account a number of different aspects, including cost, effectiveness, safety, and environmental impact.

A variety of input data are used by the model, including the location and accessibility of hydrogen sources, the infrastructure already in place for transportation and distribution, the future demand for hydrogen, and any regulatory or policy issues that might have an impact on the market.

After that, it creates a number of scenarios, each of which represents a particular combination of inputs, and assesses them using a variety of quantitative and qualitative criteria. HDSAM enables comparison of many scenarios and identifies the most effective tactics according to the data's clear and understandable presentation [6].

The model's key attributes include the capacity to simulate present-day and future-day scenarios, the inclusion of multiple stakeholder viewpoints, the use of cutting-edge optimization techniques to find the best answers, and the incorporation of uncertainty and sensitivity analyses to assess the robustness of the findings.

Results

Cost breakdown for PEM electrolysis

The results obtained for the levelized cost of hydrogen and sensitivity analysis from the production route of PEM electrolysis are shown in Figures 1 and 2, respectively. The analysis shows that the production cost of hydrogen by PEM electrolysis is INR 439.44 per kg ($5.31).

In the production of hydrogen by the PEM electrolysis method using industrial electricity as a feedstock, the variable operating cost, which includes the energy utility and material cost, is the major contributor to the cost of hydrogen.

Hydrogen delivery cost analysis

The results below are based on the assumptions for the low-carbon scenario analysis for road transportation in New Delhi. The analysis is concentrated around the National Capital Territory (NCT Delhi). The city area is 573 square miles. The hydrogen market is urban and the population data is taken from the census of India. Figure 3 shows the delivery cost of hydrogen in New Delhi at the present year at 10% market penetration. The cost parameters are determined for 3 scenarios, viz., cost of gaseous hydrogen with pipelines as the transmission and distribution medium, cost of gaseous hydrogen with tube trailers as the transmission and distribution medium, and cost of liquid hydrogen from delivery and transmission by trucks. The cost is highest when the refueling station capacity and the desired dispensing rate is 100 kg/day and it goes on decreasing when the demand is increased to 2000 kg/day. Figure 4 and Figure 5 show the cost of hydrogen when the market penetration is increased to 50% and 75%, respectively. The delivery cost of both liquid and gaseous hydrogen is estimated to be between $2-5 per kg when the dispensing rate is highest and market penetration is the highest. From the analysis of New Delhi, it can be concluded that market penetration does not play a significant role in determining the delivery cost of hydrogen, but it is the desired dispensing rate that plays a major role in determining the delivery cost.

Figure 6 shows the difference between the cost of gaseous hydrogen and the cost of liquid hydrogen for New Delhi. It can be concluded that for the low refueling station capacity of 100 kg/day, there is a significant difference between the cost of gaseous and liquid hydrogen. However, when the capacity is increased, the cost comes down between $2 and $4 per kg. With a high market penetration rate and high refueling station capacity, the cost of hydrogen is at par with the cost of conventional fuels like natural gas.

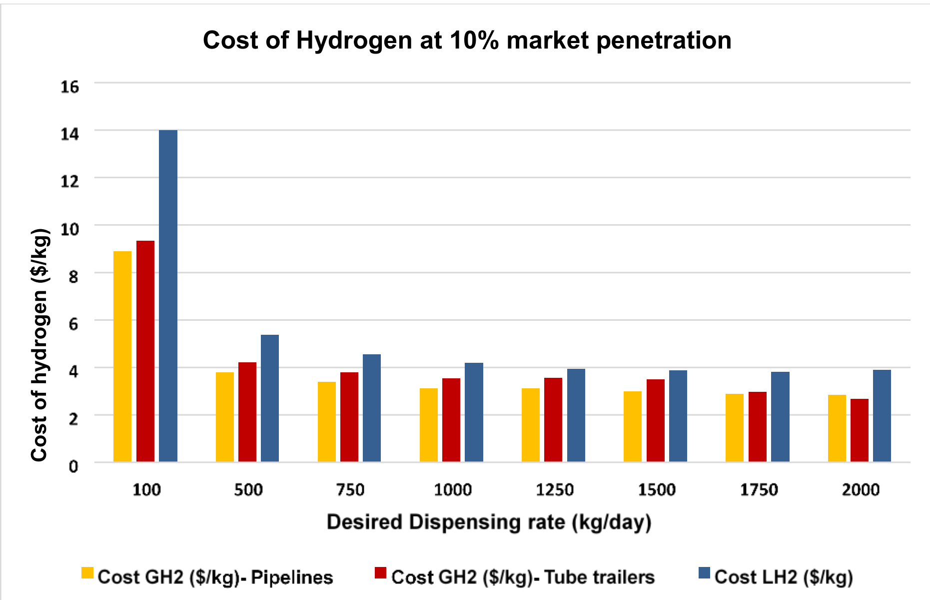

Figure 3: Delivery cost of hydrogen at 10% market penetration

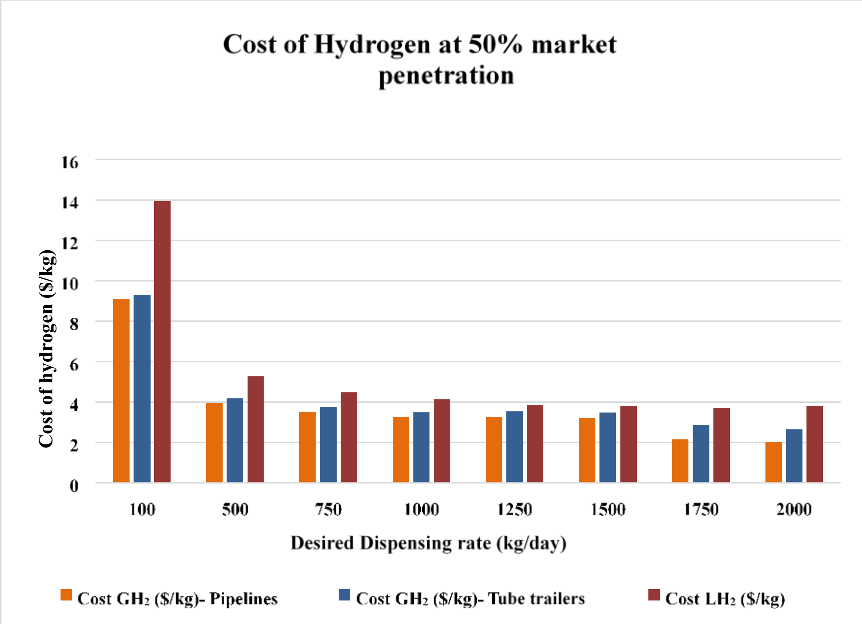

Figure 4: Delivery cost of hydrogen at 50% market penetration

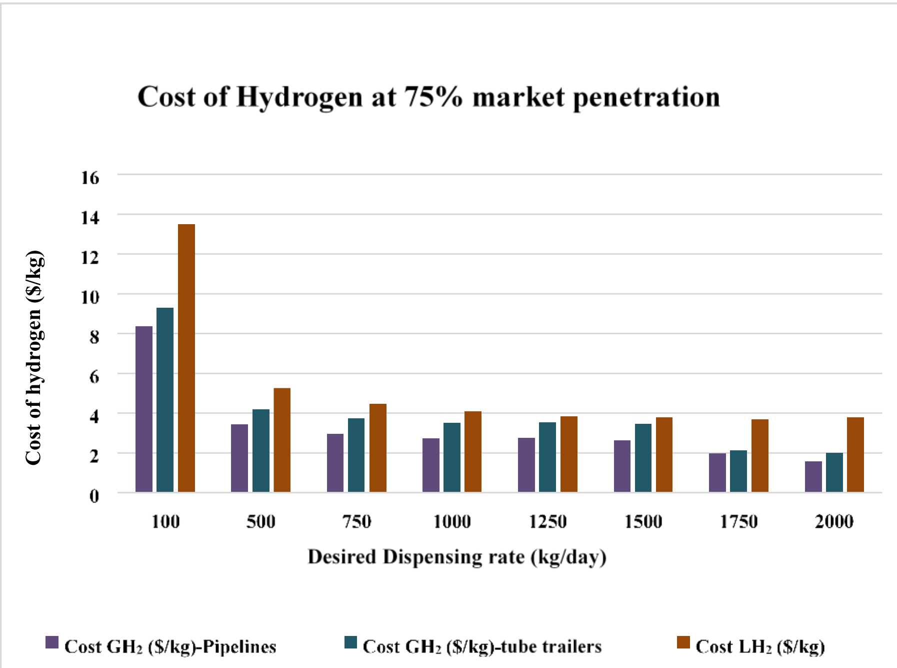

Figure 5: Delivery cost of hydrogen at 75% market penetration

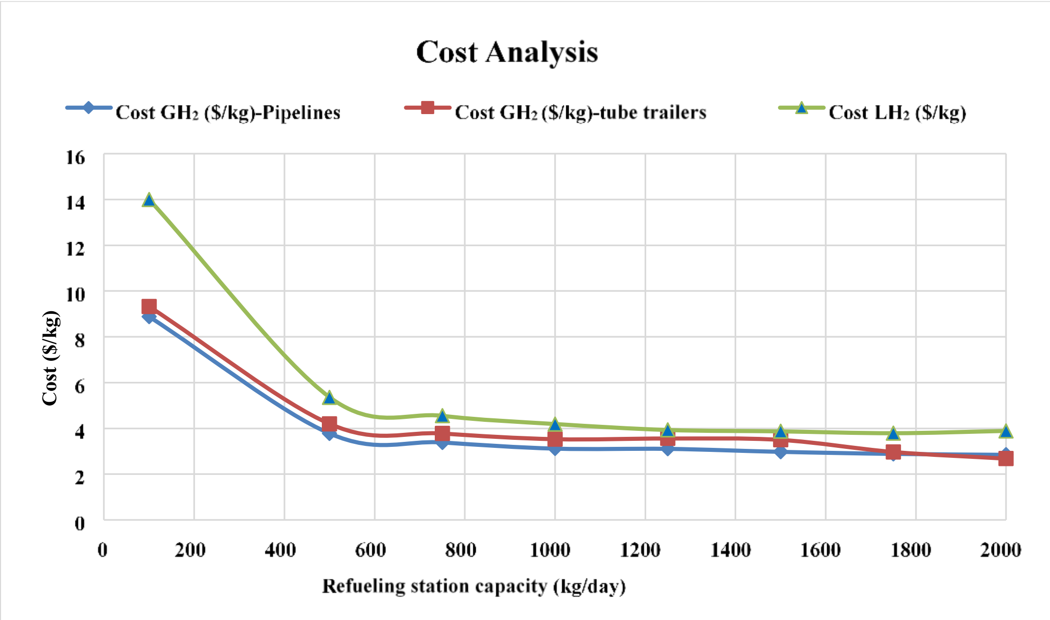

Figure 6: Delivery cost of liquid and gaseous hydrogen

Conclusion

This study showcases the importance and utility of the US Department of Energy Models for the analysis of hydrogen production and delivery options, namely, the H2A (Hydrogen Analysis Model) and Hydrogen Delivery Scenario Analysis Model (HDSAM). The analysis by the H2A model shows that the production cost of hydrogen by PEM Electrolysis is INR 439.44 per kg ($5.31).

For HDSAM, the combinations used for transmission and distribution modes analyzed are pipeline and tube trailer. Through analysis for New Delhi, India, it has been determined that the dispensing rate and refueling station capacity play a major role as a delivery cost parameter. For the highest dispensing rate of 2000 kg/day, the cost is estimated at $2-$4 per kg. This is because as the capacity of the refueling station increases, the lesser refueling stations are required to process the same amount of hydrogen fuels. The cost comparison between liquid and gaseous hydrogen has also been drawn. It can be concluded that for a low dispensing rate, the cost of liquid hydrogen is higher than that of gaseous hydrogen. This might be due to higher liquefaction costs. However, at different market penetration rates of 10%, 50%, and 75%, the delivery cost of hydrogen decreases with more penetration of hydrogen vehicles in the market.

In the context of urbanization and its planning, this analysis is a first step in planning leveraging the gas distribution network for hydrogen. A few challenges emerge - the cost of production of green hydrogen is at least 2.5 times higher [5] than conventional grey hydrogen, and the use of natural gas pipelines for transporting hydrogen is being explored. An early adoption of these models in planning the urban infrastructure for hydrogen fuel distribution shall be of immense value in the Indian context.

Disclaimer

The views and opinions of the authors expressed herein do not necessarily state or reflect those of the Government of India or any agency thereof, and the results are based on publicly available open source models. This material is based upon work supported by the Ministry of Education, GoI.

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Nomenclature

BOP- Balance of Plant

COP- Conference of Parties

G&A rate- General and Administrative rate

GHG-Greenhouse gas

GH_2- Gaseous Hydrogen

GOI- Government of India

H2A- Hydrogen Analysis

HDSAM - Hydrogen Delivery Scenario Analysis Model

IAEE- International Association of Energy Economics

IEA- International Energy Agency

IPCC-Intergovernmental Panel on Climate Change

LH_2- Liquid Hydrogen

MEA- Membrane electrode assemblies

MT- Metric tonnes

NCT- National Capital Territory

PEM-Polymer Electrolyte Membrane

TERI- The Energy and Resource Institute

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Choice of Cooking and Lighting Energy Sources in Households: Empirical Evidence from Urban India

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Highlights

- This research highlights the effect of the household economy on the fuel choice for cooking and lighting fuels in urban India.
- The population working as casual labour tends to use the most polluting fuels like kerosene, coal or charcoal due to the lack of disposable income and, thus, the inability to pay for the initial cost of using cleaner fuels.
- The low-income households have a higher monthly expenditure on fuels than others, as they are using less efficient fuels, which are also the more polluting ones.
- Electric cooking is energy and cost-efficient; it must be promoted among middle and lower-income households through policy measures.

Abstract

Household energy consumption constitutes approximately 30% of India's total energy usage. Since the fuel choice for cooking and lighting includes unclean fuels like kerosene, coal, dung cakes and firewood, studying it becomes imperative. This study examines the fuel choice for cooking and lighting in urban Indian households through Multinomial Logistic Regression Analysis. The analysis incorporates variables depicting household economy, such as land ownership, expenditure, employment type, housing ownership, meals served, and access to the public distribution system. It is assumed that households make choices based on their specific household characteristics to maximise fuel utility. This study utilises data from the Household Consumer Expenditure Survey (2011-12) conducted by the National Sample Survey Office (NSSO) of India. Results show that employment type, amount of food cooked, fuel availability, and household expenditure capacity significantly influence fuel choices. Additionally, households using cleaner fuels experience lower expenses for cooking and lighting due to improved fuel efficiency.

Keywords: Energy Mix, Household Energy, Cooking Energy, Lighting Energy

Introduction

India is the third-largest contributor to anthropogenic carbon emissions [1]. Out of the net energy consumption in India, more than 80% of the total demand is still being met by coal, oil and solid biomass [2]. If the conveyance is excluded, approximately 30% of the total energy consumption in India is in households [3], [4]. In households, cooking is the highest energy-consuming service, accounting for a share of 66% in urban and 78% in rural of the net energy consumed. With increasing urbanisation, the transition to clean and energy-efficient fuels for cooking and lighting services is observed [5].

In India, approximately 68.7% of the urban population uses Liquified Petroleum Gas (LPG) for cooking, and 95.6% uses electricity for lighting, which accounts for approximately 115 million still using polluting fuels for cooking and 16 million for lighting [6]. India's urban population is supposed to increase up to 35% in 2020 [7]. With the high rate of urbanisation and changing lifestyles, the urban energy demand can increase multi-fold in the next few decades. However, few research works focus on urban fuel consumption patterns in India. In this study, we have focused on the factors affecting the choice of cooking and lighting fuels in urban India. For the analysis, the data from the survey done by the National Sample Survey Office, Ministry of Statistics & Programme Implementation (MOSPI), Government of India has been used [6].

This research also aligns with national and global policy developments. During the UNFCCC's 26th Conference of Parties (COP26) in Glasgow, the Prime Minister of India announced that the country aims to reduce one billion-tonne emission from now until 2030. India aims to develop its renewable energy capacity by 2030 from 450GW to 500GW while ensuring that 50% of the total energy is generated through renewable sources. In the speech on India's 75th Independence Day, the Prime Minister also announced the country's plan to become a net-zero carbon emitter by 2050. The 2030 Agenda for Sustainable Development [8], adopted by all United Nations Member States in 2015, talks about the 17 Sustainable Development Goals. A few of these goals discuss energy efficiency, sustainability and climate action.

Literature Review

According to Stoner et al. [9], almost 53% of the global population was using polluting cooking fuels in 1990, which dropped to 36% in 2020. They suggest that 31% of people will still mainly use polluting fuels in 2030, "the global community is far off track from reaching universal access to clean cooking by 2030", and the business-as-usual scenario will lead to approximately 2.7 billion people using polluting fuel by then. Thus, it becomes necessary to study the household characteristics that influence household fuel choices.

The most commonly studied cooking fuels are biomass, charcoal, coal, kerosene, gas, and electricity [9]. These fuels have been classified and studied in numerous ways. Katutsi et al. [10] define fuels as traditional fuels (firewood), transitional fuels (charcoal), and modern fuels (LPG & electricity). Earlier, the classification was based on whether the fuels were solid fuels or other fuels, but now they are most often also classified as polluting fuels consisting of unprocessed biomass (wood, crop residues, and dung), charcoal, coal, and kerosene, and clean fuels consisting of gaseous fuels (liquified petroleum gas or LPG, natural gas, biogas), electricity, alcohol, and solar energy [9]. "Besides cooking, lighting is one of the most vital household energy needs", highlights Danlami et al. [11]. In the case of lighting fuels, electricity and solar energy are studied as clean fuels, while kerosene, candles, and solid fuels are considered polluting fuels.

In India, disparities exist in energy consumption by urban and rural regions and among various socio-economic groups [3]. Stoner et al. [9] mention that the urban population is mostly using gaseous fuels, and they are gradually moving towards using electricity, whereas the rural population is still highly dependent on biomass-based fuels. The clean break with the more probable use of traditional fuels in rural areas than their urban counterparts has also been observed by Kuo and Azam [12]. However, given the population size of the country, and the economic disparity in the urban regions, a study on urban areas is also required.

Other phenomena observed with the use of cooking fuels are fuel stacking behaviour and the energy ladder concept. The use of more than one fuel is known as fuel stacking behaviour [13], whereas the energy ladder [14] concept hypothesises that fuel types follow an order. Kuo and Azam [12] observe that the household characteristics which promote the use of clean fuels might also promote fuel stacking in rural households, but it is not the same in urban households. Kapsalyamova et al. [15] observe that the availability of a fuel such as electricity does not necessarily lead to a complete transition, but it might lead to fuel stacking. Cheng and Urpelainen [16] used the NSS (National Sample Survey) data of India from 1987 to 2010 and observed that in the case of lighting, the fuel stacking is decreasing as households are becoming completely dependent on electricity, while in the case of cooking fuels, LPG is being used in addition to biomass-based fuels. They highlight their most important finding that high household income reduces fuel stacking for lighting but not for cooking.

Various variables have been used to study the choice of fuels in households. Demographic variables are one of the widely used set of variables [17], which contain household size, age of household/head [10], [18], [19], gender of household head [10], marital status [10], and level of education [10], [20].

The next widely studied factor is the household economy [21]. The economic variables which have been observed to influence fuel choice are employment status, income [10], [12], [22], expenditure, land ownership, number employed, type of employment [23], credit access [20], ownership of ICT [24]. The factors which can be considered as proxy variables of economic status such as housing characteristics, namely: ownership of housing [24], [25], housing type [18], [25], housing area, and number of rooms in the housing, have also been used widely.

Critical factors like the price of fuel [21] and its availability [15], [24] directly influence fuel choice; these have been significantly studied in the case of rural areas but not in their urban counterparts. Additionally, road connectivity to housing [12], location of household [10], and neighbourhood properties [26], type of food cooked [23], [25], energy saving awareness [18], technological advancements [26], and in-home time-use [27] have also been used for the study of cooking fuel choice.

In the case of lighting fuels, household demography and economic status have been observed to affect fuel choice in the same way as in the case of cooking fuels. The factors are household size [28], [29], age of household/head [11], [30], [31], gender of household head [28], [29], [30], marital status [29], and level of education [28], [29], [31], household income [11], [28], [29], [30], [31], ownership of housing, housing type [31], and housing area [11], [31], location of household [11], [28], [29], [31], [32], neighbourhood properties [28], and availability of fuel [11], [16], [29].

It is observed that researchers have extensively focused on household demography, while the critical factors related to the household economy, such as employment characteristics, have been overlooked. Research shows that after controlling the economic factors, the demographic factors might not show a significant influence on fuel choice [23]. This creates a need to specifically study the economic variables. In the case of India, PDS, which ensures the availability of fuels like kerosene, is vital to understanding the fuel choice in the case of polluting fuels. Additionally, the amount of food being cooked, specifically in agricultural or industrial households, are important in defining fuel choice. In this study, these factors have been the focal point of analysis.

Methodology

Researchers have studied the choice of cooking and lighting fuels in households using methods like Multinomial Logistic Regression [10], [11], [15], [20], [29], [31], Ordered Probit Model [30], and Multiple Discrete-Continuous Extreme Value [24], [26], [27]. According to Liao et al. [23], some clean fuel types might not have advantages over others, the fuels can be ordered on the basis of their properties, and households might use two or more fuels. Hence ordered logit and binary logit cannot be used for such analysis. There is a clear predominance of Multinomial Logistic Regression for such analyses; hence, this study uses Multinomial Logistic Regression to analyse the household fuel choice for lighting and cooking in urban India. Since multinomial logistic regression is effective when the dependent variables are polychotomous categorical [15], and there is a dominant choice, which in our case is LPG for cooking and electricity for lighting. Since we have considered multiple independent variables, the multinomial logistic regression supports our analysis.

The available choices for cooking fuels are LPG (base category), coke/coal/charcoal, firewood/ chips, cow dung, kerosene and electricity. The available choices for lighting fuels are electricity (base category), kerosene, gas and candle. The independent variables were selected on the basis of a literature review and are detailed in Appendix 1. A few new variables were chosen, namely: (a) Accessibility to the Public Distribution System (PDS), as it leads to the accessibility of fuels like kerosene in India, and (b) 'Meals served to non-household members' as the amount of food to be cooked also influences the fuel choice. It must be noted that the households which have performed ceremonies have been removed from the study to avoid errors occurring from out-of-routine activities.

This research studies the data from the survey of Household Consumption of Various Goods and Services in India, conducted in 2011-12 (National sample Survey 68th Round, Schedule-1, Type-2), which is representative of the whole country[6]. For the survey, 7,469 villages and 5,268 urban blocks were surveyed, comprising 119,378 households in rural areas and 83,935 in urban areas of India. However, after removing households which organised ceremonies and extreme values, 40739 datasets were selected. The survey was conducted by the National Statistical Office (NSO) under the Ministry of Statistics and Program Implementation (MoSPI), Government of India. The survey contains information about household characteristics like household size, land holdings, type of income, housing characteristics and type of main fuel used for cooking and lighting. The data description for the selected variables is shown in Appendix 1.

Results and Discussion

Analysis of Choice of Cooking Fuels

For analysing cooking fuels, LPG was taken as a base category, as 68.7% of the Urban Population uses LPG for cooking. The results are shown in Table 1.

Table 1 Results of Multinomial Logistic Regression Analysis for Cooking Fuels with LPG as Base Fuel

Variables		**Cooking Fuels (LPG as base)**				
		Coke, Coal, Charcoal	Firewood, Chips	Cow dung	Kerosene	Electricity
Household Size		-0.069** (0.022)	-0.109*** (0.010)	0.017 (0.025)	-0.285*** (0.022)	0.298*** (0.041)
Land Owned (in Ha)		-0.258* (0.102)	0.186*** (0.017)	0.157*** (0.034)	-0.752*** (0.162)	-0.669* (0.320)
Monthly Expenditure on Fuel (in Rs)		-2.509*** (0.212)	-2.634*** (0.097)	-1.047*** (0.251)	-1.505*** (0.148)	-4.074*** (0.400)
Total Monthly Expenditure (in Rs)		-0.520*** (0.071)	-0.455*** (0.030)	-0.618*** (0.116)	-0.268*** (0.032)	0.034 (0.039)
Fraction of Total Expenditure on Fuel Expenditure		2.849*** (0.224)	3.065*** (0.118)	1.931*** (0.308)	1.787*** (0.210)	-0.342 (0.545)
Employment Type	**Salaried**	-0.005 (0.131)	-0.196** (0.067)	0.212 (0.251)	-0.490*** (0.088)	0.202 (0.211)
	Self-Employed	0.221 (0.152)	-0.366*** (0.060)	-0.348 (0.234)	0.350*** (0.101)	0.062 (0.227)

	Casual Labour	0.534*** (0.148)	0.134* (0.058)	0.421 (0.216)	0.400*** (0.105)	-0.190 (0.245)
Housing Ownership	**Owned**	1.058*** (0.157)	1.243*** (0.062)	1.516*** (0.223)	1.335*** (0.108)	-0.038 (0.293)
	Hired	-0.477** (0.174)	-0.386*** (0.088)	0.719 (0.419)	-0.726*** (0.131)	-0.211 (0.381)
Number of Meals Served to Non-household members in One Month	**0**	-0.576*** (0.156)	-1.074*** (0.080)	-0.109 (0.412)	-0.010 (0.109)	0.102 (0.353)
	1-5	-0.103 (0.366)	-0.830*** (0.129)	-1.072** (0.355)	-0.009 (0.249)	-0.570 (0.466)
	6-10	-0.562 (0.374)	-0.757*** (0.132)	-0.882* (0.365)	-0.266 (0.256)	-0.561 (0.484)
	11-30	-0.920* (0.385)	-0.637*** (0.133)	-0.712 (0.365)	-0.297 (0.259)	-0.771 (0.497)
Availability of PDS		-0.730 (0.403)	-0.514*** (0.138)	-0.560 (0.379)	-0.231 (0.269)	-1.014 (0.546)
Intercept		-0.910* (0.434)	1.550*** (0.169)	-3.114*** (0.600)	-0.163 (0.296)	-2.434*** (0.625)
Log Likelihood		-55053.2				
Pseudo R-square		0.190				
Observations		40739				
Note: LPG is base category; ***p < 0.01, **p < 0.05, *p < 0.1						

Firewood/Chips and Kerosene have a negative coefficient for household size, while other fuels are not. This might indicate that the population with small household sizes prefers these fuels. Firewood/Chips and Cow Dung have a positive coefficient for with land owned, while other fuels are not. Firewood and cow dung are generally used by households involved in agricultural practices, giving them accessibility to cow dung through cattle reared and firewood through the plantation. The prevalence of such data in urban households is there because the 'urban areas' here refer to administrative classification, and urban fringes are thus included in the dataset. The coefficient of monthly expenditure on fuel is extremely low in the case of electricity, which indicates that people using electricity are spending considerably less on cooking fuel, whereas the coefficient of total monthly expenditure is negative for electricity. This indicates that the households spending more are using electricity as fuel.

The population working as casual labour is most likely to use polluting fuels as all of its coefficients are positive and significant. In case the casual labours are migrants, they might not possess a local permanent address, and the absence of a certificate of residence would mean that they will not have access to PDS. As mentioned by Gangopadhyay et al. [33], the migrants might get access to kerosene through illegal diversions in case of unavailability to PDS. However, all the coefficients for accessibility to PDS are negative, indicating that people with accessibility to PDS are more likely to use LPG. With the increase in the number of meals served to non-household members in one month, households prefer LPG over other fuels.

Analysis of Choice of Lighting Fuels

For analysing lighting fuels, Electricity was taken as a base category, as 95.6% of the Urban Population uses electricity for lighting. The results are shown in Table 2.

Table 2 Results of Multinomial Logistic Regression Analysis for Lighting Fuels with Electricity as Base Fuel

Variables		**Lighting Fuels (Electricity as base)**		
		Kerosene	Gas	Candle
Household Size		0.019 (0.018)	-0.254* (0.129)	-0.128 (0.071)
Monthly Expenditure on Fuel (in Rs)		-5.004*** (0.212)	0.408 (0.256)	-0.689 (0.391)
Total Monthly Expenditure (in Rs)		-0.441*** (0.054)	-0.036 (0.118)	-0.017 (0.078)
Fraction of Total Expenditure on Fuel Expenditure		2.296*** (0.174)	1.448 (0.841)	1.856*** (0.490)
Employment type	**Salaried**	-0.033 (0.118)	0.357 (0.648)	-1.121** (0.345)
	Self-Employed	0.541*** (0.110)	0.240 (0.681)	-0.001 (0.309)
	Casual Labour	0.882***	0.271	0.237

		(0.109)	(0.786)	(0.333)
Housing Ownership	**Owned Housing**	-0.145	-1.050	-1.132***
		(0.103)	(0.657)	(0.319)
	Hired Housing	-0.919***	-0.396	-0.780*
		(0.119)	(0.651)	(0.318)
Availability of PDS		0.043	-0.267	-1.170***
		(0.069)	(0.392)	(0.219)
Intercept		-1.062***	-6.213***	-3.824***
		(0.148)	(0.874)	(0.386)
Log Likelihood		-12204.4		
Pseudo R-square		0.181		
Observations		40739		
Note: Electricity is base category; ***p < 0.01, **p < 0.05, *p < 0.1				

Most of the coefficients are highly negative or insignificant, depicting that all the households are highly likely to use electricity for lighting. The only different case is with casual labour because its coefficient is highly significant and highly positive, indicating they might use illegally diverted kerosene as fuel [33].

Discussion

In this study, the respectively cheaper fuels, such as Firewood/Chips and Kerosene for cooking, and gas or candle for lighting, are found to have a negative coefficient for household size, which signifies that an increase in household size will lead to a decrease in the use of these fuels. At the same time, households that have better employment status do not seem to use these fuels. This result might indicate that economically weaker social groups, who are not living with families, such as casual labours, might frequently use polluting fuels for both cooking and lighting. Cooking a larger amount of food and lighting a bigger housing might be difficult with these fuels, and hence, people might shift to better alternatives in case the household size increases. Research points out that household size might positively influence the energy-saving potential, which aligns with previous studies [22].

The frequency of using kerosene is higher in casual labours. But, it is lower in the population which has access to Ration Card (Public Distribution System). Gupta and Ravindranath mention that the "subsidised kerosene option is cheaper than wood in the traditional stove" in India. After the Government of India eliminated subsidies on kerosene [34] in 2021, the population using kerosene is bound to decrease.

In the case of expenditure patterns, the observation is the population which is using polluting fuels has higher monthly expenditure on fuels than the ones that are using LPG or Electricity for cooking and Electricity for lighting. Moreover, the households using cleaner fuels are spending lower fraction of their expenditure on the fuel. The households with higher net monthly expenditure tend to use electricity for cooking, which is one of the most efficient forms of fuel for cooking. Since the initial investment cost for cleaner fuel is higher, the population having lower expenditure power is using fuel forms with lower energy efficiency of utilisation [3], [4]. This pattern emphasises the limited access to cleaner fuels to economically weaker households. The initial investment cost such as price of buying LPG or electric cookstoves and LPG cylinders might be too high for them. Along with the initial investment costs, lack of distribution networks [3], the habit of using polluting fuels like dung cake or firewood [35], availability of solid biomass fuel in neighbourhoods [35], and the taste of cooked food [35] are a few hindrances in the population moving towards cleaner fuel alternatives.

Our results show that an increase in the economic status of the household, through steady income and better ownership of assets, tends to shift them towards using cleaner fuels. This pattern has also been observed in other research works [3], [4], which signify that increase in income causes the population to shift from cheaper and less convenient fuels to more expensive and more convenient ones.

We also observe that households with higher land ownership are tended to use Solid Biomass Fuels (SBF) like firewood and dung. Previous research [4], [35] suggests that in regions with the availability of solid biomass fuel through home production or collection, LPG usage is low, and this usage remains unaffected by income as opportunity cost comes into effect [36]. The SBFs are present at no inherent costs to such households, and this also leads to fuel stacking in households [37]. Given the huge availability of SBF in India and the efficiency of biogas being six times that of SBF [38], policies supporting initial investment costs for the setup of biogas plants can be proposed. Biogas is a cleaner fuel and also promotes efficient utilisation of SBFs [4].

Our results show that with the increase in the number of guests eating at the household, they prefer LPG over other fuels, including electricity. This aligns with previous research works showing that approximately 69.2% of households prefer to use LPG for cooking if guests are present [35].

LPG turns out to be the most popular choice of fuel in Indian urban households. Previous research also suggests that LPG is used mainly by the middle and high-income groups in India, and given its high initial cost, it remains inaccessible to the poor [4]. LPG is convenient, clean and efficient, and hence the government has been pushing towards increasing its use through various policies such as Pradhan Mantri Ujjwala Yojana (PMUY), which ensures its better distribution and higher subsidies. However, some studies suggest that PMUY needs policy review as a significant amount of its beneficiaries purchased no refills during the first year of implementation [39], [40]. Several households which were previously using SBF have shifted back to it, and even though LPG could have been a preferred choice of the households, they are not being able to use it because of habitual and economic constraints, and higher fuel stacking can be expected.

The samples representing the population using electricity were low. However, we can observe that stability in employment status has a positive coefficient for the use of electricity for cooking, which signifies that stable employment leads to more use of electricity for cooking. Researchers mention that electric cooking advantages like cleanliness, ease to use, high standard of living, no drudgery, and high conversion efficiency [4]. But, the use of electric cooking appliances is limited to high-income groups due to high initial costs of equipment [4].

However, the recent increase in LPG prices has made electric cooking the cheaper option, and electric cooking is more efficient than LPG [41]. About 17% of the households in a few cities have switched to electric cooking, and a greater percentage of people who have switched believe that it is cheaper, faster and can meet all kinds of cooking demands [42]. Consequently, electric cooking has entered the households of middle-income groups, and push-through policy measures can further increase its frequency in lower-income groups as well.

In the case of lighting, almost all households show a tendency to use electricity except those working as casual labours. This can be attributed to the fact that their housing might not even have an electricity supply. However, recent studies show that more than 97 per cent of households are electrified in India [43], and hence we can see the improvements in future studies.

Conclusions

This study reinforces the well-known fact that the economy plays a key role in the fuel choice of households. The research emphasises that the type of employment is critical in determining fuel choice, with casual labours tending to use the most polluting fuels, like coal or charcoal, due to the lack of disposable income and inability to pay for the initial cost of using cleaner fuels. The concerning part here is that low-income households have a higher net expenditure on fuels than others as they are using less efficient fuels.

Another finding suggests that the availability of any fuel, polluting or not, highly influences fuel choice. The access to kerosene has been controlled through de-subsidising it. However, households that have free access to SBF still prefer it over cleaner fuels. Fuels like biogas have much higher efficiency than SBF, and financial support, combined with awareness among SBF-using households, might lead them to shift their fuel choices. Although government policies have managed to increase access to LPG, careful planning and policy implementation can help in penetrating lower-income households. Popularising electric cooking in middle and lower-income households should be the future target, and policies should be framed accordingly. Given the fact that electric cooking is energy and cost-efficient, it is much easier to shift to it once the households are acquainted with it.

The way to ensure that 100% of the households in the country use electricity for lighting is to ensure uninterrupted power supply to them. Un-notified residential areas in cities mostly face this problem, and hence the policies should focus on housing supplies first.

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Appendix 1: Data Description and Statistics

Variable	Description	Mean	Standard Deviation	Frequencies
Household Demography				
Household Size	Number of members in Household	4.27	2.19	-
Household Economy				
Land Owned (in Ha)	Total land possessed as on the date of survey (in hectares) (owned + leased-in + otherwise possessed + leased-out)	0.17	0.89	-
Monthly Expenditure on Fuel (in Thousands of Rs)	Total value (in Rs) spent on fuels in last 30 days	0.73	0.49	-
Total Monthly Expenditure (in Thousands of Rs)	Total Monthly Expenditure in the last 30 days (in Rs)	2.49	2.15	-
Employment Type	Categorised as: self-employed; salaried; casual labour; others	-	-	self-employed =15258; salaried =15874; casual labour =5263; others =4344
Housing Ownership	Categorised as: owned; hired; no housing; others	-	-	owned =27592; hired =11371; no housing =37; others =1739
New variables				
Number of Meals Served to Non-household Members in One Month	Number of meals served to non-household members during the last 30 days. Categorised as (in numbers): 0; 1 to 5; 6 to 10; 11 to 30; more than 30	-	-	0 =24020; 1to5 =6870; 6to10 =5819; 11to30 =3362; more than 30 =668
Accessibility to PDS	Possession of ration card (yes; no)	-	-	yes =29259; no =11480
Dependent Variables				
Main Cooking Fuel	Categorised as: coke, coal and charcoal; firewood and chips; LPG; cow dung; kerosene; electricity; others	-	-	coke, coal and charcoal =997; firewood and chips =7394; LPG =27989; cow dung =493; kerosene =1788; electricity =228; others =345
Main Lighting Fuel	Categorised as: kerosene; gas; candle; electricity; others	-	-	kerosene =1515; gas =33; candle =104; electricity =38950; others =53

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Exploring the Potential of Neighbourhood Approach to Low Carbon Development in India

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Highlights

- A top-down approach for sectors and a bottom-up approach to integrating local knowledge and indigenous measures are vital for sustainable low-carbon development.
- Among 128 Indian cities analyzed, only 10 have comprehensive sectoral approaches for city climate action.
- Adopt performance-based codes for local area plans, replacing conventional zoning and form-based codes for climate action.
- Low-carbon design strategies are identified from urban design concepts, which can be used in design for achieving low-carbon development at the neighborhood scale.

Abstract

India has committed to addressing climate change through its Nationally Determined Contributions (NDC) and has set a target of achieving net-zero emissions by 2070. The National Action Plan on Climate Change (NAPCC) Low carbon strategies for Long-Term Low Emission Development Strategy (LT-LEDS) and State Action Plans on Climate Change (SAPCCs) provide a framework for addressing climate change. However, there is a lack of emphasis on climate change action in the development plans of urban local bodies. This research aims to extend the findings from government documents at the city scale that are aligned with SAPCCs in promoting low-carbon development and explore how urban design can be utilized by local governments to integrate climate action plans into local area development plans. The study analyses city climate-related documents from 128 cities in India and proposes various urban design interventions to achieve low-carbon development goals.

Keywords: Low carbon development, Urban Design, City climate action plans, Local area plan', Performance-based code.

Introduction

Cities contribute significantly to global warming. While they constitute less than 2% of the planet's surface area, they are responsible for approximately 60% of global greenhouse gas emissions and consume 78% of global energy [1]. India's growing economy and large population will result in a significant increase in the number of cities with over 1 million residents, expanding from 42 to 68 [2]. Therefore, India's growth trajectory is crucial for the accomplishment of the world's sustainable development goals. As stated in the United Nations Framework Convention on Climate Change (UNFCCC), India is committed to tackling the issue with strict adherence to multilateralism based on equality and the principle of common but differentiated responsibilities and respective capabilities (CBDR-RC). India has pledged to address climate change through Nationally Determined Contributions (NDC) to ensure long-term growth and development towards net zero by 2070 [3].

Based on NDC, India's National Action Plan on Climate Change (NAPCC) aims to mitigate and adapt to climate change. One of the eight missions of India's National Climate Action Plan is to deploy appropriate technologies for the adaptation and mitigation of greenhouse gas emissions [4]. In alignment with NAPCCs, 28 States and 6 Union Territories have prepared their State Action Plan on Climate Change (SAPCCs) as shown in Table 1. The SAPCCs provide a mapping of regional climate vulnerability, examine future projections, arrive at sectoral implications, and frame actionable strategies for combating climate change. Hence, each city can have a climate action plan drawn out per the SAPCCSm [5].

A major part of India's emissions is from cities, with buildings within cities accounting for more than 40% of India's total energy consumption. As mentioned in India's Long-term low carbon development strategy (LT-LEDS) [6], this presents a unique chance to advance the ambitious climate policy by empowering the local governments. This is especially significant in the case of India, where there are five distinct climatic zones and climate types across the country [7]. The Urban Local bodies are poised to possess valuable contextual knowledge regarding the environment, infrastructure, and social issues unique to their respective localities. As per the 74th amendment of the Constitution of India in 1992, urban local bodies are recognized as institutions of self-governance at the local level; however, these bodies have little mandate to combat climate change [8]. Moreover, a study undertaken by Khosla and Bhardwaj revealed that climate change rarely features in the development plans of these bodies [9].

The purpose of this research is to study the government's various climate change-related documents issued in alignment with SAPCC and assess their efficacy in advocating for low-carbon development. The paper also looks at how urban design can be used as a means for local governments to institutionalize a framework for implementing climate action plans into Local Area Development Plans (LAD).

Literature review

The literature review offers a concise overview of different actors involved in climate governance, spanning from the international level to local bodies, and highlights India's endeavors towards achieving low carbon development.

The Kyoto Protocol, implemented in 2005, serves as an initial measure to tackle climate change by setting targets for industrialized nations and transitioning economies to limit and decrease greenhouse gas (GHG) emissions based on agreed-upon individual objectives under the United Nations Framework Convention on Climate Change [10]. Later, the 2015 Paris Agreement became the first global agreement on climate change that includes policy commitments for all nations. It is a combination of bottom-up and top-down approaches to global climate governance [11], [12]. Additionally, a legally enforceable climate change accord that seeks to keep global warming below 2°C, preferably 1.5°C. However, due to the severe climate impact consequences associated with exceeding the 1.5°C threshold, greenhouse gas emissions will peak by 2025 and decrease by 43 percent within 2030 to accomplish this goal.

NDCs are the specific national climate action plans that each government has been submitting since 2020. Countries describe their proposed efforts to reduce greenhouse gas emissions to accomplish the goals of the Paris Agreement in these plans. Additionally, they communicate strategies to enhance adaptability and resilience to climate change impacts. To establish a more comprehensive context for efforts focused on NDCs, countries are instructed to develop and submit long-term low greenhouse gas emission development strategies (LT-LEDS). It contains a country's long-term planning and development priorities, providing a vision and direction for future development [13].

To implement the commitments made through NDC, countries use an array of governance mechanisms to design and implement climate policies and establish time-bound targets for carbon or climate neutrality. According to Huovila et al., there is limited research that defines a "carbon-neutral city." However, as the scope of city emissions is within geographical, temporal, activity, or life cycle system boundaries, terms such as zero carbon, low-carbon, or carbon-neutral city are addressed through a proposal of three hierarchical emissions categories. These categories are internal emissions based on the geographical boundary, external emissions directly caused by core municipal activities, and internal or external emissions due to non-core activities [14], [15]. Each hierarchical category denotes a distinct carbon management approach. This approach of the categories can be broadly stated as - zero carbon aims at elimination, low-carbon aims at minimizing, and carbon-neutral city aims at balancing the carbon emissions [14]. In this context, low-carbon development emerges as a novel approach that strives to minimize carbon dioxide emissions without compromising economic growth and well-being [16].

Neighbourhoods are building blocks of our cities [17]. It extends beyond a single building by including open spaces and urban networks giving a demonstration of urban reality. It can be considered as a target for testing concrete interventions within a reasonable time frame [18],[19]. It is in neighbourhoods that climate action becomes tangible and can engage community participation involving individuals who are environmentally responsible through their actions [20], [21].

A neighbourhood, being the basic arena to create a sustainable environment, becomes the beginning point for the use of low-carbon strategies and technologies to address climate change, promoting the development of a low-carbon city. The underlying concept of a low-carbon neighbourhood forms when viewed from a perspective of low emission. A balance between carbon source control and carbon sink expansion [22]. According to wang et al. 2016, the five most important aspects of low-carbon neighbourhood assessment are layout planning, traffic planning, architecture planning and design, environment planning, municipal engineering planning, and construction management. These can be broadly linked with the parameters of the climate-smart city action framework for finding the best available urban design concepts, policies, design strategies, and smart goals/benchmarks that can cater to a low-carbon neighbourhood.

Clause 2.3 of the LT-LEDS document emphasizes the promotion of adaptation in urban design, energy and material efficiency in buildings, and sustainable urbanization. Within this clause, sub-clause 2.3.2.1 focuses on mainstreaming adaptation measures in urban planning and enhancing energy and resource efficiency through guidelines, policies, and bylaws. Sub-clause 2.3.2.2 highlights the importance of promoting climate-responsive and resilient building design, construction, and operation. Lastly, subclause 2.3.2.3 emphasizes the need to promote low-carbon municipal service delivery by efficiently managing water, solid waste, and liquid waste.

India's long-term low-carbon strategy development plan suggests a framework for cities known as the City Climate Action Plan (CCAP) [23]. The CCAP framework is designed to help cities develop a climate action plan based on their current emissions profile, identify potential mitigation measures, and develop strategies to transition to a low-carbon pathway. The framework includes key components such as conducting a greenhouse gas inventory, assessing vulnerability to climate change impacts, setting emission reduction targets, and implementing a range of measures in sectors such as energy, transportation, waste management, and urban planning. The CCAP aims to provide a systematic approach for cities to address climate change and promote sustainable development at the local level.

The Ministry of Housing and Urban Affairs has introduced the Climate Smart Cities Assessment Framework (CSCAF) [24] to facilitate a comprehensive evaluation and benchmarking of urban development in terms of climate change considerations. This framework is designed to align with the National Mission on Sustainable Habitat, NDC, Sustainable Development Goals, and Sendai Framework for disaster management. It serves as a valuable resource for cities to guide their investments, demonstrate tangible climate actions, and monitor outcomes. The CSCAF encompasses five key thematic areas: urban planning, green cover, and biodiversity; energy and green buildings; mobility and air quality; water management; and waste management. By utilizing this framework, cities can gain insights into their current climate performance, identify areas for improvement, and develop a roadmap for integrating climate change considerations into urban planning. The CSCAF empowers cities to make informed decisions, enhance their resilience to climate impacts, and contribute to the overall goal of low-carbon development.

In India, local area planning is conducted through a multi-tiered system involving the central government, state governments, and local bodies. The process encompasses several stages and stakeholders, although the approach may vary slightly across different states and regions. Here is a concise overview of how local area planning is typically carried out in India.

Through the 73rd and 74th Amendments, the constitutional framework grants authority to local self-government bodies, namely Urban Local Bodies (ULBs) and Panchayats, to plan and manage development activities within their jurisdictions. Urban planning in cities is primarily guided by development plans such as master plans, city action Plans, and local area plans, which establish the groundwork for land use, infrastructure development, environmental conservation, and social amenities [25]. Therefore, local Climate action plans need to be contextual and tailored to the specific region, climate, geography, and local conditions. The impacts of climate change can vary significantly across different areas, and therefore, the strategies and measures included in climate action plans should be designed to address the unique challenges and opportunities of each location.

Methodology

This study looks at the issue of low-carbon development in two sections. To begin with, the study analyses the action plan undertaken by 126 cities that participated in the CCAP assessment. Mumbai and Hyderabad tier-1 cities are also considered as part of this study, adding up to 128 city samples in total. Subsequently, the study presents various techniques that may be adopted by the city to achieve its target through urban design interventions. Since the goal of the country is to reduce GHG emissions, the adoption of various urban design interventions is expected to help cities reduce carbon emissions through a bottom-up approach. The Climate Action Plans considered for this study provide a detailed framework for measuring, tracking, and reducing existing and potential greenhouse gas emissions and other climate-related events. The city corporations or municipalities consider these action plans as a guide to address the impact of climate change on their environment and communities.

About the analysis of action plans undertaken by cities, it is important to note that a city climate action plan is generally prepared with differences in purpose, methodology, structure, and scope. Investigating the various city climate action plans revealed such differences. For example, the content of these plans varies, with some plans encompassing comprehensive climate action strategies that encompass greenhouse gas (GHG) assessments and low-carbon development strategies. On the other hand, certain plans focus specifically on low-carbon development roadmaps, outlining pathways for reducing emissions in energy-intensive sectors. Additionally, some climate action plans are integrated within broader documents that address climate resilience, including elements like GHG emission inventories and vulnerability assessments. Furthermore, sectoral plans also exist that target specific aspects of climate change, such as clean air action plans, district environment plans for waste management, and emergency response plans for events like heatwaves and flooding, referred to as disaster management plans and heatwave action plans.

The study sample consists of 52 metropolitan cities (tier 1), 34 large cities (tier 2), 33 medium cities, and 9 small towns. The focus of this study is on tier-1 metropolitan cities and tier-2 large cities and towns within the selected city sample.

The study took advantage of online climate action plans updated by the city and contacted the respective city representatives in cases where additional information or clarification was needed. The study assumes that cities have an online presence of their climate action plan and considers only those cities where a plan or policy was available. These action plans may be officially adopted by the municipal government or simply acknowledged; they may be legally binding or non-binding to the city administration. The study reveals that there are five types of climate action plans. The study develops the typology of climate action plans that serve as a framework for analysis, as presented in Table 1. The action plans are categorized based on approaches used by climate action plans, such as covering major energy-intensive sectors, the pattern followed by different organizations while preparing the plan, and the assessment of GHG emissions across sectors to minimize emission inventory.

Type A: In this category, the study includes city climate action plans relevant for the entire city for a 'climate change action plan' or 'climate change and environment action plan.' It includes mitigation and adaptation actions across sectoral themes, such as Energy and Buildings, Sustainable Mobility, Sustainable Waste Management, Air Quality, and Waste Resource Management. These plans include climate change impact on a multi-sectoral level, GHG emissions inventory assessment, assessment of existing policies on climate change developed by the urban/municipal authority, adaptation and mitigation actions for all sectors, and framework for monitoring and evaluation with an institutional setup, e.g., Ahmedabad Climate Change and Environment Action Plan and Mumbai Climate Action Plan.

Table 1: Typology of city scale climate action plans

Comprehensive (A)	Partial climate strategy approach (B)	Mainstreamed and inclusive (C)	Partial GHG emissions inventory, stand-alone (D)	Sectoral (E)
City Climate Action Plan of the urban authority that comprehensively (multiple sectors) addresses strategies, including both mitigation adaptation actions to achieve or adapt to low carbon emission development. The CCAP shall include baseline vulnerability assessment, GHG emissions inventory assessment, and climate action plan to mitigate GHG emissions and adapt to climate-prone disasters.	Climate Resilient Plans of the urban authority that addresses (multiple sectors) in terms of adaptation actions only. The climate resilient plan shall include climate risk and impact assessment, connecting climate profile to city development plans and strategies to adapt to identified climate risks. These plans do not include GHG inventory and reduction targets to mitigate the effects of climate change.	Low Carbon Development Plans cover aspects of disaster management plans, strategic low carbon development pathways across buildings, energy, mobility, water, and waste across all sectors. This typology also focuses on ward level or neighbourhood level institutional framework to achieve low carbon development	Plans covering aspects of partial GHG emissions inventory assessment for 3 or fewer sectors and impacts such as heat waves	Climate plan for parts of the municipal climate change mitigation operations, such as waste management, air pollution, and heat wave adaptation action plans
Example: City Climate Action Plan, District Climate Action Plan, Climate Change and Environment Action Plan	Example: Climate Resilient Plan	Example: Low carbon development plan	Example: Low Carbon Mobility Plan	Example: Heat Action Plan, Action Plan for Clean Air, District Environment Plan

Type B: In this category, the study includes climate resilient plans on 'city climate resilience plan' or 'climate resilient strategy', and includes adaptation measures majorly to cope up with the emerging climate change scenarios. These plans assess climate risks, vulnerability, and capacity of cities on the basis of dynamic factors that could affect the city, such as urbanization, impacts on physical, economic, and social infrastructures, creating awareness about climate risk from the ward level, and proposes strategies to adapt to the effect of climate change. In this case, strategies in terms of energy efficiency, solid waste management, wastewater treatment, natural disaster management, capacity building to stakeholders, and health monitoring systems are proposed as strategies in all the plans. These plans do not exclusively include GHG inventory and reduction targets to mitigate climate change effects, e.g., Climate Resilient Climate Action Plan - Udaipur and District Climate Resilience Plan - Jhansi.

Type C: This category includes low-carbon development plans. They are structured to identify, plan, and implement measures for achieving low GHG emissions across multiple sectors such as buildings and built environment, mobility, waste management, land use, and energy. These plans also integrate resilient measures to adapt to climate change impacts. They follow a bottom-up approach, starting from ward-level action plans to mobilize and implement low-carbon development strategies, e.g., Low Carbon Development Scenario Bhopal 2035

Type D: The focus in this type is partially on one sector, such as mobility, to curb GHG emissions. The plans focus on public bicycle sharing programs, amendments to building regulations such as e-vehicle charging facilities, e-mobility plans, and intelligent transportation systems to provide safe, universal, and easy mobility solutions for all. These plans help mitigate climate change actions by reducing the need for fuel-based motorized vehicles and increasing awareness of non-motorized transportation, e.g., Low Carbon Mobility Plan - Visakhapatnam and E-mobility Plan - Bhubaneswar.

Type E: Aspects of climate change mitigation strategies are observed in the District Environment Plan and Action Plan for air pollution control. These plans focus on waste management strategies and air pollution control. This compiled database of the cities is presented in Table 2. This gathered information includes climate action plans, climate resilience plans, low carbon development plans, low carbon mobility plans, and district environment plans. The study provides a systematic and objective approach to analyze and compare city climate plans, to identify commonalities, assess trends, and evaluate the effectiveness of these plans in addressing climate change, e.g., District Environment Plan - Raipur, Action Plan for Clean Air - Guntur, Heat Action Plan – Bhubaneswar.

In the above-mentioned five typologies, the components in types B, C, and D can be found in the type A plan. Type A provides a detailed and comprehensive understanding of mitigation and adaptation strategies across all sectors and also includes vulnerability assessment and low-carbon development pathways to reduce GHG emissions. For example, the Mumbai City Climate Action Plan includes city-wide mitigation targets, GHG scenarios, sectoral strategies as found in type D and C, and assessment of climate risk and vulnerabilities as seen in type B, sectoral plans, and institutional structures.

Table 2: Number of climate action plans across 128 cities.

States	**Cities**	**Type A**	**Type B**	**Type C**	**Type D**	**Type E**	**Action plan unavailable**
	N	N	N	N	N	N	N
Andhra Pradesh	6		1		1	4	0
Arunachal Pradesh	2						2
Assam	1		1				0
Bihar	4			1		2	1
Chattisgarh	3					1	2
Goa*	1		1		1		0*
Gujarat	7	2	3			1	1
Haryana	3			1		1	1
Himachal Pradesh	6		1	1		2	2
Jharkhand	2					2	0
Karnataka	9			1		5	3
Kerala	2					2	0
Madhya Pradesh*	7	2	1	1		4	0*
Maharashtra	14	3	3	1		4	3
Manipur	1						1
Meghalaya	1						1
Mizoram	1				1		0
Nagaland	1						1
Odisha*	3				1	3	0*
Punjab	4					3	1
Rajasthan	5		1		1	3	0
Sikkim	2						2
Tamil Nadu	11	1	3	1		2	4
Telangana	3					3	0
Tripura	1		1				0
Uttarakhand	1					1	0

Uttar Pradesh	14		1			6	7
West Bengal	3		1	1		1	0
Andaman and Nicobar Islands	1						1
Chandigarh	1			1			0
Dadra and Nagar Haveli and Diu and Daman**	2					1	1
NCT of Delhi	1	1					0
Jammu and Kashmir	2						2
Ladakh**	2					1	1
Lakshadweep	1						1
Puducherry	1	1					0
Total	128	10 (7.81%)	18 (14.06%)	9 (7.03%)	5 (3.91%)	52 (40.63%)	38 (29.68%)

Note: **Panaji has two types of plans: (1) Panaji-Low Carbon Action Plan for Urban Freight and (2) PanajiClimate Resilient Infrastructure Services*

**Bhopal has two types of plans: (1) Low Carbon Development Scenario Bhopal 2035 and (2) Climate Change and Environment Action Plan of Bhopal District*

**Bhubaneswar has two types of plans: (1) Bhubaneshwar E-mobility Plan and (2) Heat Action Plan*

***Ladakh, Dadra & Nagar Haveli, and Diu & Daman don't have a SAPCC.*

The sectors mentioned in the tables above, i.e., the Type A, B, C, D, and E plans, were then compared with the City Climate Action Plan (CCAP) framework to identify the plans that can be recommended for local area planning. The findings from these comparisons revealed that only Type A and C, which refers to the city/district climate action plan or low carbon development plan, presents a comprehensive approach to achieving low carbon development.

To implement the approach at neighbourhood scale, a plan that can lower carbon emissions as the core concept is required. This paper presents the urban design concepts across five CCAP sectors that can be incorporated for low-carbon development. The sectors are (i) Urban Planning, Green Cover and Biodiversity, (ii) Energy and Green Buildings, (iii) Mobility and Air Quality, (iv) Water Management and (v) Waste Management. Existing urban design concepts that can contribute to reducing carbon emissions were identified from global case studies. Supporting design strategies to implement the concepts are also mentioned. These can serve as effective tools across the given sectors mentioned in the Climate Change Action Plan (CCAP) to reduce greenhouse gas (GHG) emissions at a neighbourhood scale.

Urban planning, green cover, and biodiversity

A neighbourhood in an Indian setting could be a ward or a sector, as it is the smallest administrated unit [26]. Every neighbourhood is unique, with its own microclimate, topography, and natural resources. Therefore, urban design concepts that focus on sustainability, walkability, and proximity, such as the 15-minute neighbourhood concept, are appropriate for promoting low-carbon development [27].

Beginning with a two- dimensional designed layout, special zones for low emission can be the nodes of transition for future expansion of net zero buildings. For three-dimensional extrusion, solar envelope limits can be used to decide the maximum and minimum height of buildings depending on the street orientation and location [28]. Green cover consisting of roof gardens and green canopy on streets of neighbourhood for carbon sequestration helps in balancing out the carbon emission [29]. Setting a carbon target ward/sector-wise, allocating a carbon budget based on emission sector-wise, and nature-based solutions for controlling carbon sources and carbon sinks can help in measuring the performance of each neighbourhood.

Energy and building

Buildings and construction sectors emit around 40% of total GHG emissions on a global scale. Currently, buildings are responsible for around one-fifth of all CO_2 emissions and for roughly one-third of the nation's overall energy consumption. It is anticipated that the construction industry will increase CO_2 emissions by seven folds by 2050, as compared to 2005, if mandatory energy efficiency improvements and regulatory codes are not implemented [30]. To figure out the most carbon-emissive buildings in the neighbourhood, ' Vulnerability Mapping' needs to be undertaken [31]. This can reveal the highest carbon-emitting buildings based on their age. Such buildings can be prioritized for retrofitting or replacement. For newer buildings, superblocks would be the way forward compared to individual units in dense neighbourhoods. A superblock is a rectangular urban area bounded by arterials and main streets [32]. In the case of Barcelona, each superblock consists of 3×3 blocks (approx. 400m x 400m). Outer streets are separating them from each other. The internal street network of a superblock can take different forms. Superblocks can incorporate mixed use and rely on renewable energy sources to increase efficiency and help decarbonize cities. These blocks are designed with the aim of incorporating a higher percentage of green spaces, reducing road networks, and promoting human and social biodiversity to ensure social cohesion whilst ensuring efficient material flow of water and energy. The Superblock project in Barcelona is a prime example of how sustainable urban planning can help reduce energy consumption [33].

Mobility and air

In a 15-minute neighbourhood layout, reducing vehicle usage and promoting walkability or cycling are key factors in reducing carbon emissions and improving air quality. Streets allocated for vehicular traffic take up more space compared to walkable streets. By freeing up public space from motorized vehicles, these areas can be repurposed as green spaces, which further aids in carbon sequestration and mitigates the urban heat island effect [29]. The concept of Green Transit-Oriented Development (TOD) prioritizes pedestrian, cycling, and transit infrastructure, mixed land uses, and sustainable building practices to achieve liveable streets, reduced emissions, minimal waste, and energy self-sufficiency. It fosters vibrant street life and closer destinations. When considering street morphology, factors such as street connectivity, width, and length are important. Studies on street centrality indicate that a 50% increase in the number of junctions per kilometre of street reduces vehicle kilometres traveled (VKT) by 15% [27]. Higher connectivity enhances permeability, making the urban fabric more vibrant and safer. Research conducted on British cities reveals a super-linear correlation between the total length of streets and CO_2 emissions, showing that longer streets tend to have higher CO_2 emissions. Narrow streets, which receive less solar exposure, tend to be cooler [28]. Street width can be managed through landscaping and street furniture rather than solely relying on building edge. Cooler streets enhance walkability. Streets also serve as ventilation corridors, facilitating air movement and the dispersal of urban heat islands.

Water Management

India's freshwater ecosystems, including lakes, reservoirs, and wetlands, contribute 4% of global GHG emissions, mainly from municipal wastewater pollution and agricultural surface runoff [34]. Water-sensitive urban design is to integrate stormwater as well as wastewater into the existing urban fabric for efficient use of all the potential water resources. It consists of a sustainable urban drainage system and decentralized wastewater management for Pollution abatement in waterbodies (source). Espino et al. conducted a comprehensive lifecycle analysis to evaluate and compare the economic, environmental, and social performance of two drainage systems: sustainable urban drainage systems (SuDS) and traditional drainage systems. The case study of the Rancho Bellavista housing development in Querétaro, Mexico, revealed that SuDS outperformed traditional drainage systems in terms of environmental and social factors. Notably, SuDS demonstrated significant advantages in reducing carbon emissions and promoting sustainability [35].

Waste Management

In developing nations, over 50% of collected municipal solid waste is not properly managed, leading to open burning or landfill disposal. This contributes to 5% of total GHG emissions [36]. In Indian cities, the average per capita waste generation is 670 grams per day, with landfills being the most common method of waste disposal. Landfill waste emits methane, which has a global warming potential 21 times that of CO_2, implying that every tonne of waste saved from landfill saves 21 equivalent tonnes of CO_2 emitted (CO_2 e). A major challenge faced in Indian neighbourhoods is the lack of a sorted waste collection system from the source [37]. The conventional techniques of door-to-door collection, truck collection, etc, have lower environmental impact in fossil fuel-based scenarios. However, in a life cycle analysis study conducted by Chafer et al. on an Automated Waste Collection System (AWCS) in Barcelona, comparing different waste collection methods and energy sources, the pneumatic waste collection system showed superior performance [38], [39]. It can be inferred that AWCS is the most efficient in terms of convenience and GHG emission, considering the source of energy is renewable energy for a neighbourhood. Further, the collected waste can be a resource through circular urban metabolism (CUM). In a CUM framework, even pollution and waste products can be reintegrated into the circular system as secondary raw materials. Table 3 showcases various urban design concepts and their implementation approaches, highlighting a few cities that have already adopted these measures [40], [41],[42].

Table 3: Low carbon urban design concepts, principles, and strategies

Sr. No.	Sector and Urban Design concept	Low carbon design principles	Low carbon design strategies	Case study
1	Urban Planning, Green Cover and Bio diversity 15-minute neighbourhood	Grid pattern	For efficient land use, it supports active transportation, facilitates energy-efficient infrastructure, and integrates green networks for urban cooling.	Barcelona
		Solar envelope	Calculation for minimum and maximum height of buildings for integrating passive design features.	Vancouver
		Open spaces (Green Infrastructure)	Infrastructure consisting of parks, green roofs, and Urban Agriculture helps in carbon sequestration and storing	Singapore
		Zoning	Low emission zones can create pollution free spots within neighbourhood	London, Berlin
		Tree Canopy	For pollution capture, temperature reduction, carbon sequestration, and storage	Bristol
2	Energy and Buildings Superblock	Adaptive reuse	Vulnerable buildings with architectural and historical value can undergo retrofitting to incorporate energy-efficient measures, allowing them to be repurposed for new uses that align with sustainability goals.	New York
		Mixed built use	Stable energy profile as the peak hours of residences is during morning and evening and commercial during the day.	Sydney
		Material selection	Incorporating low-emitting, low-carbon materials like recycled or renewable materials, energy-efficient insulation, and sustainable wood products can greatly reduce building carbon emissions.	Stuggart
		Net zero building with solar access	Ensure solar access to all buildings, facilitating the optimal utilization of solar energy.	Vancouver
3	Mobility and Air Transit Oriented Development	Street length	Main streets are linear, and arterial streets are shorter in length, lowering vehicular carbon emissions.	Barcelona
		Street width	Reallocation of road space for landscaping makes walking paths narrow & cooler.	Oslo
		Centrality	The maximum centrality of a road ensures improved permeability and shorter travel distances, enhancing accessibility and connectivity within the urban environment.	Barcelona
		Walkability and cycle paths	Walking and cycling are emission-free modes of transportation that provide well-connected paths, contributing to compact and sustainable economic development.	Copenhagen
		Ventilation corridors	It creates pathways for cool air to sweep in and reduce the higher urban temperatures.	Stuggart
4	Water Management Water Sensitive Design	Water bodies	Designed to be natural carbon sinks	Zhejiang
		Sustainable drainage system	Use indigenous vegetation, rainwater harvesting, bioretention basins and swales, and permeable surfaces for water management.	Helsinki
		Blue Infrastructure	Restoration of coastal habitats, mangroves, and seagrasses contributes to carbon sequestration in marine and coastal ecosystems.	Tokyo
5	Waste Management Circular urban Metabolism	R principle	Recycling centre as a physical infrastructure	Amsterdam,
		Disassembly and adaptability in Design	Design for disassembly and adaptability criteria of buildings through Carbon reduction or salvaging requirements for demolishing	Vancouver, Portland,
		Solid waste Network	Pneumatic waste conveyance system	Barcelona

While the paper presents principles spanning five sectors, certain limitations require consideration. This optimal solution may not align with the nuanced Indian context. Instead, a potential improvement lies in adapting selected concepts from the case study to be explored while preserving the essence of India's urban landscape.

Discussion

This study explores the current status of climate action plans of various cities in India. The paper investigates and reveals that all 128 cities have some type of climate action plan in some capacity. However, in 52 cities (40.63%) the plans are environmental plans required for improved liveability, such as clean air plans or heat action plans. The study also finds that the comprehensive climate action plan is present in 10 cities (7.81%).

It is also important to mention that the study considers only those cities that have documentation for such plans. Another notable fact is that most states have some level of State Action Plan. However, such action plans are rarely translated to city action plans, which are then to be translated into a local area plan. Hence, this study focuses on identifying cities with such action plans that can be translated into a local action plan. Additionally, in almost all States, some level of budget is allocated, and action plans have been developed. However, there is no comprehensive outlook with cities and neighbourhoods as the basic building blocks.

The paper also finds that climate action plans can be used as a reliable source for local area planning; however, one notable gap identified is the absence of carbon emission targets in the climate action plans. The carbon emission targets will help allocate carbon budgets for each sector.

As mentioned in Lifestyle for Environment (LIFE) by the Government of India, low-carbon development is a choice that India has adopted. The United Nations Environment Programme (UNEP) Emissions Gap Report 2020 has dedicated its last chapter to low-carbon lifestyles [3], [43]. Hence, a sector-wise approach from top to bottom does not suffice, but an individual's decision on lifestyle choices plays a huge role in adapting to climate change.

Every neighbourhood in India is unique, with its own history, characteristics, context, and microclimate. Therefore, a sector-based approach may miss out on many of the neighbourhood's potentials and natural resources that can be well utilized if explored. The above-given examples from each sector, as mentioned in Table 3, could be adopted based on the Indian context in such a way that it uses local resources and contributes to economic growth. A low carbon economy, therefore, would bring a major alteration in the structure of economic flow and can provide resilience to any kind of disaster by displacing the geopolitics [44]. Considering India's net zero goal for 2070, a two-way approach can bring a rapid and steady transition in switching from a high consumption pattern of energy to a self-providing situation, as mentioned in Atmanirbhar Bharath.

The conventional approach of zoning-based codes, which includes use-based and rule-based regulations that resulted in incongruent margins and street fronts, unmatched spikes in built forms, inefficient use of urban land, and loss of the neighbourhood's unique character. The shift to performance-based codes (PBCs) in urban design signifies a departure from traditional codes. PBCs prioritize achieving specific performance outcomes like energy efficiency and carbon reduction over dictating land uses and physical forms. This approach enables flexibility in implementing innovative design solutions aligned with sustainability and walkability, integrating green infrastructure.

Cities around the world are embracing performance-based codes (PBCs) in urban design. For instance, Portland mandates net-zero energy buildings, San Francisco requires LEED Gold standards, and Austin encourages mixed-use neighbourhoods. It can empower cities to address climate change and resource depletion through low-emission zones and nature-based solutions. PBCs foster sustainable communities by promoting mixed-use development and compact urban forms, reducing reliance on private vehicles, and improving air quality. Green infrastructure integration is facilitated by PBCs, leveraging urban forests, green roofs, and permeable surfaces to manage stormwater, enhance biodiversity, and improve city resilience. Collaboration among stakeholders, including planners, architects, policymakers, and communities, is crucial for successful PBC implementation. Digital tools like Building Information Modelling (BIM) and digital twin technologies further support PBC integration by assessing, monitoring, and optimizing urban designs. In summary, PBCs revolutionize urban design by prioritizing performance outcomes, leading to sustainable and resilient cities.

Conclusion

In conclusion, this paper investigates climate change-related reports aligned with respective state action plans to assess their potential integration into Local Area Plans for achieving low-carbon development. The findings reveal that, out of the 128 cities examined, only 7.81 % have comprehensive climate action plans. It is clear that cities must urgently develop such plans to combat climate change effectively. The analysis of sectoral approaches mentioned in climate action plans uncovers a promising avenue for neighbourhood development, highlighting the significant opportunity for urban design techniques and strategies to contribute to climate action goals. The urban design concepts presented in this paper can serve as a foundation for cities to establish a framework for formulating low-carbon emissions plans. Thus, it is essential for cities to explore these concepts and adopt various existing design standards and techniques to achieve their overarching goal of reducing carbon emissions.

Further scope involves delineating the implementation strategies for the recommendations put forth in the paper. Clarifying which recommendations necessitate policy-level interventions, which can be integrated into Development Control Regulations, and which could benefit from incentive-based approaches would enhance the feasibility of the proposed urban design strategies. Additionally, an area of exploration could involve assessing the effectiveness of these strategies post-implementation, considering how their impact on promoting low-carbon development can be measured and evaluated. This would contribute to a more comprehensive understanding of the practical implications and outcomes of the suggested urban design interventions.

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An Evaluation Framework for Deploying Energy-efficient, Climate-friendly Cold Rooms for Agriculture Cold-Chain in India

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Highlights

- Evaluation framework for energy-efficient agriculture cold rooms.
- Enabling sustainable cold-chain for agri-business.
- Inclusion of energy efficiency in government subsidies.

Abstract

Post-harvest losses in India are estimated to be 6-15%, with an annual value of about Rs 1 lakh crore. Produce loss impacts farmers' incomes. Further, every wasted ton of fruit and vegetable decomposes into ~1.5 tons of greenhouse gases. Effective post-harvest protocols and integrated cold-chain infrastructure are essential to reduce post-harvest losses. However, there is a 97% gap in integrated pack-houses. Integrating sustainable technologies in the upcoming cold-chain infrastructure could contribute to a sustainable agri value chain, potentially reducing energy and refrigerant demand compared to business-as-usual scenarios. Currently, there are insufficient guidelines for assessing energy-efficient, climate-friendly technologies for cold-chain. This paper presents an evaluation framework to assess energy efficiency, energy supply, and refrigerants in cold-chain product offerings. The framework was used to evaluate cold room solutions from nine vendors. The framework can be integrated into government schemes for cold-chain and enable agri-businesses to assess and deploy energy-efficient, climate-friendly cold rooms.

Keywords: cold-chain, energy-efficient, pre-cooling, staging cold room

Introduction

Post-harvest losses in India are estimated to be 6% in cereals, 8% in pulses, 10% in oilseeds, and 15% in fruits and vegetables, with an annual value of about Rs 1 lakh crore [1]. Produce loss impacts farmers' incomes and livelihoods. Further, every wasted ton of fruit and vegetable decomposes into ~1.5 tons of greenhouse gases (GHG) [2]. Effective post-harvest protocols and integrated cold-chain infrastructure are essential to reduce post-harvest losses and to enable value-addition for produce. Per the India Cooling Action Plan (ICAP) 2019, there is a 97% gap in integrated pack-houses with processes for sorting, grading, washing, packing, pre-cooling, and staging cold rooms [3]. Integrating energy-efficient and climate-friendly technologies in the upcoming cold-chain infrastructure could ensure a sustainable built trajectory, potentially reducing energy and refrigerant demand compared to business-as-usual scenarios. While the central and state governments have schemes to support the development of cold-chain, there are no published standards for the energy performance of cold-chain equipment and insufficient guidelines for assessing and deploying energy-efficient, climate-friendly technologies.

The Bureau of Energy Efficiency's (BEE) Standards and Labeling (S&L) program was instrumental in increasing consumer awareness and acceptance of energy-efficient appliances, leading to increased penetration of energy-efficient appliances in the market. Likewise, demonstrating energy-efficient, climate-friendly cold-chain technology, supported with technology evaluation guidelines and standards, is critical to building the credibility of energy-efficient, climate-friendly cold-chain solutions. Further, technology evaluation guidelines and standards will advance consumer awareness and acceptance of energy-efficient, climate-friendly cold-chain solutions, benefiting farmers and agribusinesses while helping to meet India's climate action goals.

The objective of this project is to demonstrate sustainable cold chain solutions to improve farmers' incomes and reduce post-harvest losses. The authors surveyed forty-eight Farmer Producer Companies (FPCs) and completed field visits to nine FPCs to identify use cases where cold-chain solutions would benefit farmers in reducing losses, preserving produce quality, and increasing produce value. The team identified four use cases for a technology demonstration of energy-efficient, climate-friendly cold rooms, of which one use case was selected. The team met with manufacturers of cold-chain equipment to learn about their products and consulted agriculture experts on the requirements for cold-chain in post-harvest management. The methods for evaluating cold-chain product offerings from vendors, selecting an optimal solution for pre-cooling and staging cold rooms, and the way forward are described in the following sections of the paper.

Methodology

In accordance with standard government procurement procedures, the selection process for sustainable cold-chain solutions can be divided into two primary stages: the Request for Proposal (RfP) preparation stage and the proposal evaluation stage.

The RfP preparation stage further comprises four steps:

1. Defining the necessary cold-chain solutions, such as pre-cooling and staging cold rooms, and the details of produce throughput.
2. Establishing weightage for technical and financial evaluation scores.
3. Setting the technical and financial evaluation criteria, as detailed in the Evaluation Framework section.
4. Defining additional terms and conditions, like payment terms and other requirements, which may include annual reports, audited balance sheets, or turnover statements.

The proposal evaluation stage also involves four steps:

1. Allocating weightage for technical and financial evaluation within the necessary specifications (criteria).
2. Defining the scoring criteria for the technical and financial evaluations.
3. Scoring based on the data provided in the techno-commercial proposals submitted by interested vendors.
4. Conducting reference checks on shortlisted vendors to obtain feedback from their existing customers.

The RfP, which could be dispatched to chosen vendors or opened for bidding, encompasses the items specified in the Evaluation Framework. Certain technical or financial evaluation criteria may be made obligatory, potentially disqualifying vendors for non-compliance. The final vendor is selected based on the combined technical and financial evaluation score and satisfactory reference checks. This evaluation framework provides a systematic method for choosing sustainable cold-chain solutions that support rural livelihoods and mitigate food losses.

Evaluation Framework

The framework for evaluating a cold room encompasses both technical and financial aspects. The suggested weightages for the technical and financial criteria in the cold room evaluation framework have been carefully determined to ensure a balanced assessment of the project's overall performance and sustainability. In government tenders and other similar evaluations, it is expected to allocate a higher weightage to technical aspects, as they directly impact the cold room's efficiency, reliability, and functionality. The weightage for technical and financial evaluation could be 70:30, adhering to the standard practice observed in government tenders. With a 70% weightage on technical criteria, the focus remains on the quality of design and implementation, which are crucial for achieving optimal performance and meeting the desired objectives.

In distributing the evaluation weightages within the technical criteria, the framework aims to comprehensively assess the cold room's design and functionality, aligning with the overall 70% technical weightage. Each aspect's suggested weightage aims to emphasize its significance: 20% dedicated to refrigeration system design to ensure energy efficiency and sustainability in the active cooling system, 12% for design intent to guarantee alignment with project goals, 10% for envelope design to maintain thermal integrity, and 7% each for renewable energy integration, monitoring and control, supply and installation, and operations & maintenance, all collectively contributing to the cold room's efficiency and longevity. This balanced distribution reflects the comprehensive evaluation needed to attain a successful cold room project.

In terms of financial criteria, the framework examines the upfront capital expenditures (CAPEX) (15% weightage) and operational expenditures (OPEX). The OPEX includes energy costs, i.e., either electricity or other fuels such as biomass (5% weightage) and O&M expenditures (10% weightage) associated with the cold room. The rationale behind the allocation of evaluation weightages for the financial criteria underscores the economic viability and sustainable operation of the cold room project.

While the two financial criteria are self-explanatory, below is a comprehensive description of the seven technical criteria and their respective sub-criteria, along with suggested evaluation weights:

1. Design Intent (12% weightage)

Produce incoming temperature (2% weightage): This sub-criterion refers to the temperature at which the produce enters the cold room or pre-cooling room. It depends on the source of procurement of the produce, i.e., either from the field or collection centre, or wholesale market. The handling and transportation practices also affect the incoming temperature of the produce. This information is used in the heat load calculation analysis for refrigeration system design and sizing.

Design temperature (produce outgoing) (4% weightage): This sub-criterion refers to the desired temperature condition for the produce to be maintained in the cold room or cooled down to in the pre-cooling room. The temperature range depends on the type of produce being stored and is specified in technical standards like NHB-CS-Type 02-2010 [4], which further refers WFLO Manual [5]. Maintaining the recommended temperature range helps to extend the storage life of the produce.

Design relative humidity (produce outgoing) (4% weightage): This sub-criterion refers to the desired relative humidity (RH) condition for the produce to be maintained or achieved in the cold room or pre-cooling room. The RH level required depends on the specific storage needs of the produce being stored and is specified in the NHB standard [4]. Maintaining the recommended RH level helps to prevent moisture loss or spoilage of the produce.

Lighting condition (2% weightage): This sub-criterion refers to the need to maintain dark storage conditions for perishable fruits and vegetables that are sensitive to light. Exposure to light can affect the visual appeal of the produce and make it less desirable to consumers. NHB standard [4] recommends dark storage conditions for such produce.

2. Envelope Design (10% weightage)

Layout of Pre-cooling and Staging Cold Rooms (1% weightage): This sub-criterion requires detailed drawings that show the plan, elevation, and sectional views of the pre-cooling and staging cold rooms with measurements. These drawings are important for designing the overall infrastructure and ensuring alignment with other facilities, such as distribution centres.

Internal Stacking Layout of Crates and Pallets (1% weightage): The internal stacking layout of crates and pallets inside the cold room or pack-house must be shown in plan and sectional views, along with measurements. This sub-criterion ensures that the cold room or pack-house dimensions are optimised for the handling capacity of the produce and that there is sufficient space for air movement around the crates to ensure effective and uniform cooling. As per NHB standard [4], crates, boxes, and bins should be well-ventilated, and the pallets should be stacked with four to six-inch-wide air channels to ensure adequate cooling. Improper stacking can cause poor air distribution and a decreased cooling rate leading to uneven cooling of all the stored produce. To optimise storage, multi-commodity cold storage chambers/facilities should use polyvinyl chloride (PVC) crates, bins, and ventilated cardboard boxes stacked in pallet frames, while jute/nylon net bags in pallet frames can be used for commodities not requiring rapid cooling.

Internal Floor Area (ft^2) (1% weightage): This sub-criterion involves the calculation of the interior floor area of the cold room from the measurements on the layout.

Internal Volume per MT (ft^3/MT) (1% weightage): The internal volume of the cold room should be calculated from the measurements on the layout. NCCD guidelines [6] state that 1 MT (metric tonne) of storage capacity requires 3.4 m^3 (cubic meter) or 120 ft3 (cubic feet) of temperature-controlled storage space and 11 m^3 (cubic meter) per 1 MT of storage capacity for ripening chambers. However, the internal volume required per MT of produce in the pre-cooling room is not specified in the referred NCCD guidelines.

Type, Thickness, and Density of Thermal Insulation for Walls, Roof, and Floor (2% weightage): This sub-criterion specifies the type, thickness, and density of thermal insulation materials used for walls, roof, and floor of the cold room. The insulation materials must have low thermal conductivity to reduce the amount of heat that can pass through the walls, ceiling, and floor of the cold room. The selection of insulation material is based on the desired temperature range and given ambient conditions. The NHB standard [4] outlines the minimum insulation thickness for different insulation materials to achieve the recommended U-values for cold storage, maintaining temperatures between -4 and +2°C.

Blowing agent used in PUF panel manufacturing (1% weightage): This sub-criterion focuses on the blowing agents used to manufacture PUF panels. It is important to ensure that the blowing agents used do not have high ozone-depleting potential (ODP) or global warming potential (GWP). The criteria for selecting appropriate blowing agents must be met to ensure that the manufacturing process is environmentally friendly.

Vapour barrier in wall and roof panels (1% weightage): This sub-criterion pertains to the importance of vapour barriers in wall and roof panels made of polyurethane foam (PUF). The PUF panels are sandwiched between pre-painted galvanized iron (PPGI) sheets that act as a moisture barrier. The appropriate thickness and level of galvanization of the PPGI sheets must be selected to provide the necessary moisture barrier and structural support to the PUF panels. The vapour barrier must be designed to prevent the ingress of moisture from both sides to avoid derating the thermal performance of the PUF panels over their life.

Air-tight doors (with stainless steel handles and hinges) and pressure relief valves (1% weightage): This sub-criterion emphasizes the importance of air-tight doors in cold rooms or pre-cooling rooms. Air-tight doors are critical to maintaining the thermal integrity of the cold room and preventing any leakage that may increase heat loads on the refrigeration system. Stainless steel (SS) handles and hinges are recommended for the durability of the door fittings. Pressure relief valves are also critical safety features that prevent damage to the door and injury to individuals in case of excess pressure. Proper construction and installation of the door frame, gasket, and hinges must be ensured to maintain a tight seal when the door is not in use.

Strip curtain or air curtain (1% weightage): This sub-criterion deals with energy-efficient barriers used in cold rooms or pre-cooling rooms to reduce air transfer and consequently minimize heat transfer and energy loss and maintain a consistent temperature. Two types of energy-efficient barriers are commonly used: strip curtains and air curtains. Strip curtains are made of PVC material and hang from a header mounted above the doorway. The strips overlap and create a barrier that allows people and equipment to move through while minimising the transfer of air. On the other hand, air curtains use a high-velocity stream of air to create a barrier between the inside and outside of the cold room. They are mounted above the doorway and blow a stream of air downward, preventing warm air from entering the cold room while allowing people and equipment to move through the doorway. Both strip curtains and air curtains effectively maintain temperature control, reduce energy costs, and protect against insects, dust, and other contaminants. The NHB standard [4] recommends strip curtains for cold rooms and air curtains for external outlets/inlets.

3. Refrigeration System Design (20% weightage)

Heat load calculations (3% weightage): This sub-criterion involves calculating the amount of heat that must be removed from the cold room or pre-cooling room to maintain the desired temperature and humidity levels. The heat load calculation considers ambient conditions, room size, insulation properties, produce load, door usage, and lighting. This calculation helps determine the appropriate refrigeration system, including the capacity and size of the outdoor refrigeration unit and the type and quantity of indoor evaporators. NHB standard [4] suggests using ASHRAE handbooks [7], [8] for heat load calculations and 0.4% annual design conditions of the location for ambient conditions to size the refrigeration system appropriately. Refrigeration capacities must be calculated at different operating conditions and should include arrangements for capacity control.

Refrigeration system details (2% weightage): This sub-criterion deals with selecting the type and number of compressors, condensers, and evaporators based on the application. For cold rooms, ceiling-suspended or wall-mounted evaporators are typically used, while for pre-cooling rooms, a floor-mounted evaporator unit with a recirculating water sprinkler is generally recommended. According to the NHB standard [4], vapour compression systems are commonly used for cold storage, but absorption systems can also be utilized where heat is readily available. The air handling units for pre-cooling should be specially designed for faster cooling with high RH.

Humidification system (1% weightage): This sub-criterion involves maintaining a specific humidity level to preserve the freshness and quality of perishable produce in pre-cooling or staging cold rooms. Humidification systems prevent moisture loss and ensure that the produce remains fresh. The NHB standard [4] recommends maintaining a low delta temperature in the cooling coil to achieve higher humidity levels of 85-90%, but during loading periods or if the humidity level exceeds 90%, a separate humidification system is strongly recommended.

Cooling capacity (1% weightage): This sub-criterion on the capacity of the refrigeration system for the cold room or pre-cooling room is determined by the heat load calculations.

Refrigeration system efficiency at different operating conditions (3% weightage): This sub-criterion involves specifying the coefficient of performance (COP) of the refrigeration system for different operating conditions, not just the design conditions. The efficiency of a vapour compression refrigeration system is heavily influenced by the type and efficiency of the compressor and the size and design of heat exchangers used. The COP is the ratio of cooling capacity and power input and should be specified for different combinations of evaporating and condensing temperatures.

Variable speed operation principle (2% weightage): This sub-criterion emphasizes the importance of variable frequency drives (VFDs) in efficiently operating refrigeration systems, especially under varying load conditions and ambient temperatures. By regulating the speed of compressors and fans, VFDs can match the actual cooling requirements and prevent damage from sudden power surges, leading to significant energy savings and noise reduction. The NHB standard [4] recommends using VFDs on fans to realize energy savings, but it does not mention their application on the refrigeration system compressor.

Refrigerant type (4% weightage): This sub-criterion highlights the impact of refrigerant choice on the environmental performance of refrigeration systems. The recommended approach is selecting refrigerants with zero ozone depletion potential (ODP), low global warming potential (GWP), and good heat transfer characteristics. While natural refrigerants such as ammonia have zero ODP and GWP, their safe use must comply with national and international safety regulations due to toxicity concerns. The NHB standard [4] recommends ammonia as the best refrigerant in terms of environmental and energy performance. Still, it also provides guidance for using alternatives such as R-134a and R-404a if there are restrictions on using ammonia at certain locations. However, the standard does not offer specific guidance on selecting refrigerants based on their overall energy and environmental performance.

Air circulation (1% weightage): This sub-criterion pertains to adequate air circulation in a cold room or pre-cooling room. Proper air circulation helps maintain uniform temperature and humidity levels throughout the room, prevents the formation of hot spots, and distributes cold air evenly. Strategically placed evaporator units that circulate cold air throughout the room can achieve this. The velocity and direction of the airflow can be adjusted to meet the specific requirements of the room and the horticultural produce being stored. This sub-criterion is expressed in available air volume (cubic meter per hour (CMH)) per metric tonne (MT) of produce. As per NHB standard [4], multi-commodity storage facilities must provide 170 CMH per MT of produce for quick cooling based on chamber capacity. After reaching the desired storage temperature, the airflow should be reduced to 34-68 CMH per MT with a VFD and control system to maintain a temperature variation of less than ±1°C throughout storage. For pre-cooled produce, the airflow can range from 67-100 CMH.

Pre-cooling (pull-down) time per batch (1% weightage): This sub-criterion pertains to the time required to pre-cool or pull down a batch of produce before storing it in a cold room or pre-cooling room. The pre-cooling time per batch can vary depending on several factors, such as the size of the batch, the produced incoming temperature, the desired storage temperature, and the efficiency of the pre-cooling system. Pre-cooling time can vary from a few hours to overnight, depending on the specific situation. The pre-cooling time per batch also sets the limit for the maximum number of batches that can be pre-cooled daily, thus determining the overall pre-cooler handling capacity. According to the NHB standard [4], most fresh fruits and vegetables (except apples and carrots) require a pre-cooling time of 4-6 hours to achieve 7/8th cooling.

Thermal energy storage (1% weightage): This sub-criterion pertains to the process of storing excess refrigeration capacity during off-peak periods and using it during on-peak periods to reduce energy consumption and costs. Thermal energy storage (TES) in cold rooms is achieved by using thermal storage systems such as ice banks, chilled water storage tanks, or phase change materials (PCMs). TES helps reduce the overall size of the refrigeration system, thereby reducing first cost, the peak energy demand of cold storage facilities, decreasing energy costs, and leading to more efficient operations. In the case of off-grid solar power systems, TES could be charged during the daytime and released during the nighttime.

Total overall connected load (1% weightage): This sub-criterion pertains to the overall connected load for the facility, which will affect the fixed demand charges that the local distribution company will levy on the facility. This is important to consider when designing the refrigeration system for a cold storage facility to avoid incurring financial penalties for overshooting the contract demand with the electricity distribution company.

4. Renewable Energy Integration (7% weightage)

Solar photovoltaic integration (4% weightage): This sub-criterion pertains to the integration of solar photovoltaic (PV) systems into the cold storage facility to generate electricity using solar energy. The size and type of PV system depend on the intended use and can be categorized as off-grid or grid-interactive. Off-grid PV systems typically incorporate battery energy storage, while grid-interactive systems can be classified as gross-metered or net-metered. The gross-metered system exports all the generated power to the grid, while the net-metered system uses the power generated by the PV system to offset the facility's electricity consumption and export the excess power to the grid.

Biomass (3% weightage): This sub-criterion pertains to the use of biomass as a renewable energy source for powering absorption technology-based cooling systems in cold storage facilities. Biomass refers to organic matter, such as wood, crop residues, or animal waste, that can be burned to produce heat or electricity. Biomass is a sustainable and cost-effective approach, as it is a renewable energy source that can often be locally sourced. However, the quality and type of biomass fuel, as well as the efficiency and emissions of the combustion or gasification process, must be carefully considered before deciding to use it as a primary source of energy.

5. Monitoring and Controls (7% weightage)

Remote monitoring and energy/environmental management controls (7% weightage): This subcriterion focuses on the remote monitoring system and the data it should store to track and monitor the performance of the system effectively. The data should be timestamped every one or two minutes and may include indoor and ambient temperatures and RH, power and energy parameters of each machine, TES charge level, solar PV power parameters and energy parameters, battery bank power parameters, compressor low-pressure and high-pressure monitoring, and ethylene levels in each room. The parameters should be customized based on the specific requirements of the project. The NHB standard [4] recommends using sensors, controllers, indicators, temperature scanners, centralised indicators, and PLC systems for regulating various parameters, depending on the cold storage capacity. However, the standard does not provide clear guidelines for smaller capacity pre-cooling and staging cold rooms.

6. Supply, Installation, Testing, and Commissioning (SITC) (7% weightage)

SITC timeline (3% weightage): This sub-criterion covers the timeline for the supply, installation, testing, and commissioning of the cold storage system, including the supply of necessary materials, equipment installation, system testing, and commissioning. The timeline must be well-planned and include milestones and deadlines to ensure timely project completion. The NHB standard [4], pertaining to SITC in general and not the SITC timeline specifically, recommends that the plant shall be installed, tested, and commissioned as per IS 660 [9] or ASHRAE Std. 15 [10].

Commissioning checklist (4% weightage): This sub-criterion covers the development of a commissioning checklist tailored to the project's specific needs. The checklist should include activities such as fine-tuning the system to optimize performance, training end-users on safe and effective operation, conducting final acceptance testing to ensure project requirements are met, and documenting the commissioning process in detail. The purpose of the commissioning checklist is to ensure that all the necessary steps are taken to ensure the proper operation of the equipment and system to meet the project requirements.

7. Operations and Maintenance (O&M) (7% weightage)

Warranty (manufacturing defects and workmanship) (2% weightage): This sub-criterion pertains to the warranty provided by the manufacturer or seller of the equipment or system being procured. The warranty may cover manufacturing defects, workmanship issues, or both and may be limited to certain product components. The warranty terms may also require the user to follow specific maintenance and usage instructions to qualify for the warranty.

Training of the local operations team and O&M manual (2% weightage): This sub-criterion pertains to the training of the local operations team and the creation of an O&M manual. The local team must be trained on how to operate and maintain the system or equipment efficiently. The O&M manual should include detailed instructions and guidelines on maintenance schedules, troubleshooting procedures, and safety guidelines. With proper training and a comprehensive O&M manual, the local team can ensure smooth operation, reduce downtime, and avoid equipment failure or maintenance issues.

After-sales services (3% weightage): This sub-criterion pertains to the after-sales services provided by the manufacturer or vendor to customers after the sale of a product or service. These services may include technical support, maintenance, repairs, and warranty support. The quality and availability of after-sales services can significantly impact the ongoing operation and maintenance of the equipment or system.

The suggested evaluation framework is applicable to the selection of cold rooms and pre-cooling facilities designed to manage perishable fruits and vegetables of varying storage/handling capacities, ranging from a few MT to thousands of MT. However, when considering Controlled Atmosphere (CA) storage, which is commonly used for the long-term storage of perishables like apples, pears, kiwis, cabbage, etc., an additional layer of O_2 and/or CO_2 regulation becomes necessary in conjunction with the specifications outlined in this assessment framework [11]. In terms of temperature and RH storage conditions, the evaluation framework can cover a range of 0°C to 21°C and 65% to 100% RH for various fruits and vegetables as specified in the NHB standard [4]. The applicable storage duration can also vary from short-term (7 to 10 days) to medium or long-term storage, extending up to 10 months.

Results and Discussion

The authors applied the framework to assess vendors of cold-chain equipment for pre-cooling and staging cold rooms, focusing on a specific use case selected through a comprehensive process. Surveys were conducted on forty-eight Farmer Producer Companies (FPCs), and field visits were made to nine of them to identify potential use cases that could assist farmers in reducing losses, maintaining produce quality, and increasing the value of their produce through cold-chain solutions. The research team evaluated four potential use cases to showcase energy-efficient and eco-friendly cold rooms. After careful consideration of the sufficiency principles, they selected one use case that would best suit the farmers' needs by defining the optimum requirements that were neither too large nor too cold.

The team then met with cold-chain equipment manufacturers to learn about their offerings. Subsequently, a Request for Proposal (RfP) was created that outlined the technical specifications required for the selected use case and the evaluation framework. The RfP was sent to fifteen vendors, out of which nine submitted their proposals. Each product was evaluated against the framework's criteria, which included technical and financial considerations. Two rounds of evaluation were performed as the RfP process aimed to solicit vendors' best available technology, with no detailed specifications in the first round. After the first round of evaluation, six vendors were shortlisted out of nine for final vendor presentations with project partners. The final round of evaluation for the six shortlisted vendors was conducted with additional information on design conditions and minimum performance specifications. During the detailed specification collection process, it was observed that there is a lack of emphasis on energy efficiency and sustainability in the business-as-usual scenario, indicating an awareness gap on both the demand (users) and the supply (vendors) sides. Through the entire evaluation process, vendors were better informed about energy efficiency and sustainability criteria for designing and developing cold-chain solutions. Three vendors were chosen based on the final technical evaluation, and their selection was supported by customer testimonials, further enhancing the technical and financial assessment. Based on the overall evaluations, one vendor was selected to deploy a pre-cooling cold room and two staging cold rooms. The vendor used innovative thermal energy storage, solar energy, low-GWP refrigerant, and energy-efficient cold room envelopes, all of which are environmentally friendly.

The authors contend that energy-efficient and renewable-powered cold-chain solutions with low operational expenditures will be more viable and sustainable for farmer groups, which the evaluation framework duly acknowledges. Further, the evaluation framework's focus on sufficiency and efficiency will contribute towards building energy-efficient, climate-friendly cold-chain infrastructure with a lower carbon footprint than business-as-usual (BAU) systems. The effectiveness of the cold rooms in reducing produce loss, increasing produce value, and the cold rooms' energy performance will be monitored for 3-6 months post-installation.

Integrating the evaluation framework in government schemes

The central government provides financial support for the development of cold rooms and other cold-chain infrastructure through schemes under the Mission for Integrated Development of Horticulture (MIDH) [12] and the Agricultural and Processed Food Products Export Development Authority (APEDA) [13]. The MIDH and APEDA schemes mandate adherence to NCCD protocols and standards [6]. Additionally, the MIDH scheme states that assistance will be provided for cold rooms that are energy efficient. While the NCCD protocols and standards provide a reference data sheet on technical criteria to consider while selecting a cold room, there are no criteria for energy efficiency.

The evaluation framework presented in this paper includes cold room specification criteria over and above those provided by NCCD, particularly criteria to assess energy efficiency and clean energy supply, such as refrigeration system efficiency at different operating conditions, variable speed operation principle, thermal energy storage, and renewable energy integration, among others. The authors suggest that this evaluation framework may be considered for inclusion in NCCD guidelines for cold rooms to enable applicants for MIDH, APEDA, or other government schemes to assess the energy efficiency of solutions from different vendors.

Further, the administrators for MIDH, APEDA, and other government schemes can mandate such a comparison between vendor solutions and disburse funds for the most energy-efficient, climate-friendly cold room. As more data on the energy performance of cold rooms is made available, and standards and labelling for cold rooms come into effect, scheme administrators can also mandate minimum performance standards for each criterion in the evaluation framework presented in this paper and disburse funds only for solutions that meet the mandated minimum performance standards. Government schemes for cold-chain can draw lessons from existing agriculture schemes for irrigation, such as PM-KUSUM [14] and state-level Agriculture Demand Side Management (AgDSM) [15] programs that mandate the use of energy-efficient and renewable energy technologies such as solar pumps and 5-star-rated energy-efficient pumps.

Conclusion

This paper's proposed evaluation framework can be vital for FPCs, wholesale and retail businesses dealing with horticultural produce, food processing industries, and state agriculture marketing boards. It can assist in analyzing various vendors' cold room solutions and making informed decisions about procuring and deploying energy-efficient, environmentally friendly cold rooms. Moreover, integrating this framework into government subsidy programs for cold rooms could encourage the growth of sustainable cold-chain infrastructure, as opposed to traditional business-as-usual technologies.

Along with the evaluation framework, the authors have also developed a monitoring system to track the efficiency and energy performance of assessed and subsequently deployed cold rooms. This gathered data will serve as an essential resource for establishing energy performance benchmarks for cold rooms.

Further, to enhance energy efficiency and sustainability in cold-chain equipment, a standards and labelling (S&L) program for cooling and refrigeration equipment, particularly for pre-cooling and staging cold rooms, could be instituted. The evaluation framework in this study and the energy performance data from field-deployed cold rooms could be instrumental in formulating this S&L program. The program should focus on reducing both direct and indirect emissions from cooling equipment, stressing energy efficiency and the appropriate choice of refrigerants [16].

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Introduction to State-wide Rebate based Incentive Program for Utility Companies for Promoting Energy Efficiency in India

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Highlights

- Rebate based Incentive Program will provide benefits to the end-users to incorporate energy efficiency practices.
- These programs will be beneficial to all Residential, Commercial, and Industrial end-users.
- The incentive programs will be implemented by the State Electricity Regulatory Commissions, Distribution Companies, and State Designated Agencies.
- A case study has been presented that highlights the benefits of rebate-based incentive programs for Maharashtra, Gujarat, and Tamil Nadu.

Abstract

Energy efficiency penetration in the Indian market is driven by the policies and schemes implemented by the Bureau of Energy Efficiency (BEE), Energy Efficiency Services Ltd. (EESL), and various state governments. This paper aims to introduce a rebate-based incentive program for achieving energy efficiency in India. This paper also delves into the current demand-side management activities in India. The different steps involved in the evaluation of rebate-based energy efficiency programs have been presented in this paper. A case study has been provided to estimate the amount of energy savings and the avoided CO_2 emissions that could be achieved by the implementation of rebate-based energy efficiency programs for the states of Maharashtra, Gujrat, and Tamil Nadu. It is estimated that the proposed energy efficiency programs could achieve 5,346 million units of electric savings and 3.8 million tons of avoided CO_2 emissions across the three states.

Keywords: Energy efficiency program, rebate-based incentive, utilities, demand side management, decarbonization

Introduction

India has been experiencing a significant increase in electricity demand, with an annual growth rate of around 5% over the last five years. However, power generation has not kept pace with this demand, leading to a consistent energy deficit of 4-8% during this period. The imminent connection of the remaining Indian households without electricity access to the grid will further exacerbate the demand-supply gap. Additionally, it is projected that the market for electric vehicles (EVs) in the domestic sector will experience a compound annual growth rate (CAGR) of 49% until 2030 [1]. While increasing electricity generation is one solution to this problem, limited resources are a hindrance, which makes it imperative for India to adopt energy efficiency measures to reduce its demand for electricity.

At the state level, various actors such as the State Electricity Regulatory Commissions (SERC), Distribution Companies (DISCOMs), and State Designated Agencies (SDAs) established under the Energy Conservation Act can play a crucial role in improving India's energy efficiency. Given the diversity of factors such as consumer mix, power purchase profile, and load curve, it is essential for each state to develop its action plan for energy efficiency with the active involvement of all stakeholders. DISCOMs, which often struggle to meet their peak demands and incur financial losses, can benefit significantly from energy efficiency (EE) and demand-side management (DSM) activities. The following clarification is provided regarding the use of the term demand side management in this paper. DISCOMs conduct DSM activities to flatten the load curve, reduce peak demand, and improve system reliability and quality. In this paper, we have adopted an expanded definition of DSM to include EE and EC activities. Unless explicitly stated otherwise, any reference to DSM activities should be understood to include Energy Efficiency and Energy Conservation activities. Through their extensive reach with consumers, DISCOMs can facilitate improvements in end-use efficiency and influence consumer behavior to reduce and manage their consumption.

In the past few years, there has been a surge in EE/DSM endeavors undertaken by DISCOMs, SDAs, and SERCs following the introduction of DSM regulations by several states. DISCOMs have been setting up DSM cells, devising action plans, and conducting pilot programs. Similarly, state governments have been introducing various orders on energy efficiency while also establishing energy conservation missions.

This paper presents an overview of the energy efficiency, energy conservation, and demand-side management activities carried out by SERCs, DISCOMs, and SDAs in three states of India, namely Maharashtra (MH), Gujarat (GJ), and Tamil Nadu (TN). The states were selected based on their high electricity consumption. This paper also presents an overview of incentive programs in different countries used for supporting energy efficiency projects. Based on this, a rebate-based incentive program is presented in order to develop a coordinated and coherent strategy for scaling up energy efficiency, energy conservation, and demand-side management activities at the state level in India.

A case study is conducted in this paper to calculate the approximate amount of electricity savings that can be achieved with a rebate-based incentive program for the states of Maharashtra, Gujarat, and Tamil Nadu.

An overview: DSM activities in India

Various DSM Programs are being carried out in India. The different Programs by EESL and SERCs, DISCOMs, and SDAs in Maharashtra, Gujarat, and Tamil Nadu are summarized in Table 1.

Table 1: Summary of DSM programs

Organization	Program Name	Description
Bureau of Energy Efficiency	Municipal Demand Side Management (MuDSM) [2]	Reduction of energy in utility services like street lighting, water pumping, sewage treatment, and in various public buildings.
	Perform, Achieve and Trade (PAT) cycles [3]	Designated consumers are given targets to reduce their energy consumption and trade energy savings certificates.
Energy Efficiency Services Ltd. (EESL)	UJALA [4]	Distributing LED bulbs, LED tube lights, and energy-efficient fans to households to replace conventional and inefficient models.
	Solar Induction Cooktop [5]	Proposing a solar-based induction cooking solution for Indian cooking applications through carbon financing.
	National Motor Replacement Program (NMRP) [6]	Establishing an infrastructure for the supply of high-efficiency motors in compliance with the IE-3 standard.
	Street Lighting National Program (SLNP) [7]	Replacing traditional streetlights with energy-efficient LED streetlights and recovering costs through energy savings.
	Agriculture Demand Side Management (AgDSM) [8]	Distributing energy-efficient agricultural pumps and smart control panels for remote operation, reducing energy consumption.
	Super-Efficient AC Program (ESEAP) [9]	Offering super-efficient air conditioners at rates equivalent to the most energy-efficient models, reducing cooling costs.
	Atal Jyoti Yojana (AJAY) [10]	Installing solar LED lights in areas with inadequate power coverage.
Maharashtra Electricity Regulatory Commission	Time of Day (ToD) tariff	Introduced ToD tariff for industrial consumers, incentivizing load shifting and offering rebates based on consumption, contracted demand, and load shedding hours.
Tata Power Company – Distribution (Maharashtra) [11]	Appliance Exchange Program	Implements appliance exchange program for replacing inefficient appliances like fans, tubelights, refrigerators, and AC.
	Thermal Energy Storage Program	Implements Thermal Energy Storage (TES) Program for energy storage.
	Manual Demand Response Program	Offers a manual Demand Response (DR) Program to curtail load.
	Energy Audit Program	Provides Energy Audit Program for industrial/commercial sectors.

	Heat Pump Program	Implements Heat Pump Program for industrial/commercial sectors.
Brihan-Mumbai Electric Supply (BEST) [12]	Pilot DSM Initiatives	Conducted pilot DSM initiatives, including replacements of fluorescent tubes, ceiling fans, & bulbs with energy-efficient options.
	LED Tubelights Program	Implemented a program for replacing conventional FTLs, conventional bulbs and CFLs with LED tubelights.
	Star-labelled Fans Program	Implemented a Program for replacing conventional ceiling fans with star-labelled fans.
Maharashtra State Electricity Distribution Company Limited (MSEDCL) [12]	Ceiling Fans Replacement Program	Replaced inefficient ceiling fans at sub-stations and section offices.
	Agricultural Pump-set Replacement Program	Conducted a pilot project for replacing inefficient agricultural pump-sets.
	CFL Distribution Program	Facilitated the distribution of CFLs in Nashik.
	Agricultural DSM through ESCO-based Program (Pilot)	Partnered with BEE for agricultural DSM through ESCO-based Program in a pilot project.
Maharashtra Energy Development Agency (MEDA) [12]	Street Lighting and Water Pumping Scheme	Achieving energy savings in street lighting and water pumping systems using automatic light sensors, voltage dimmers, SCADA, and web-based monitoring.
	Save Energy Program	Provides financial assistance for energy audits in various sectors.
	Waste Heat Recovery	Encourages industrial units to generate power and utilize waste heat.
	Energy Conservation Pilot Project	Replacement of inefficient appliances, installation of renewable energy systems, and implementation of building energy management systems in government/semi-government/urban local body buildings.
Gujarat Electricity Regulatory Commission (GERC) [12]	Time of Use Charges and Time of Day DSM Tools	GERC approved time of use charges and time of day as DSM tools for DISCOMs, offering rebates for maintaining a power factor above 0.90 and imposing penalties for power factors below 0.90.
Madhya Gujarat Vij Company Limited (MGVCL) [12]	Feasibility Study for Agricultural DSM Pilot	Conducted a feasibility study for an agricultural DSM pilot in Anand, covering pump-sets connected to four feeders.
	Tube Light Replacement Program	Implemented Program to replace conventional tube lights with T5 tube lights in MGVCL offices.
	Co-incidental Peak Reduction Program	Implemented measures to reduce co-incidental peak in MGVCL.
	Power Factor Correction Measures	Implemented power factor correction measures in MGVCL.
Uttar Gujarat Vij Company Limited (UGVCL) [12]	CFL and Electronic Ballast Program	Purchased CFLs and electronic ballasts for energy conservation in UGVCL offices.
	Pilot Program for Pump-set Replacement	Conducted a pilot Program in nine talukas to replace old pump-sets with energy-efficient ones, resulting in energy savings.
	Load Forecasting and Load Management	Implementing load forecasting and load management in DGVCL.
Torrent Power Ltd. – Gujarat [13]	Appliance Replacement Program	Proposed Program to replace inefficient appliances with energy-efficient ones in government premises, health centres, and anganwadis.
	Reactive Power Management Program	Proposed Program for better reactive power management in diamond and textile industries by installing a current sensing automated switch with consumer-owned fixed-type capacitors.
Tamil Nadu Electricity Regulatory Commission (TNERC)	Peak Hour Charges and Low Power Factor Surcharge	Implemented peak hour charges or Time of Day (ToD) tariff in Tamil Nadu since 2002.
Tamil Nadu Generation and	Efficient Lighting Program	This includes replacement of conventional lights with efficient LED.

Distribution Corporation (TANGEDCO) [12]	Efficient Pumping Program	Low-efficiency pumps were replaced with higher-efficiency pumps.
	Pilot Studies on REbased DSM & Demand Response	Initiated pilot studies to assess the feasibility of implementing RE-based DSM and demand response strategy.
	Promotion of EnergyEfficient Appliances	Initiated Programs to promote energy-efficient appliances in the domestic and commercial sectors in Chennai.
Tamil Nadu Electrical Inspectorate (TNEI) [12]	LED Village Campaign	Conducted an LED village campaign to promote efficient lighting.
	Demonstration Project in SME Clusters	Conducted a demonstration project in SME clusters.
	Investment-Grade Audits and Energy-Efficient Replacements in Buildings	Conducted investment-grade audits in government buildings and replaced pumps, air-conditioners, and lights with energy-efficient alternatives.

An overview: Incentive programs for energy efficiency

This section presents an overview of the two main types of incentive instruments that are implemented worldwide, along with their respective funding sources.

Government funded programs

Incentive instruments

Incentive instruments play a crucial role in promoting energy efficiency, and they can be categorized based on their type and the intended recipients. Governments employ a range of incentives, including fiscal incentives, cash incentives, and low-interest financing, to drive energy efficiency initiatives. These incentives can be directed towards different actors in the supply chain, with downstream programs targeting consumers and upstream programs targeting manufacturers. Downstream programs, such as fiscal instruments like tax credits or deductions, are visible and appealing to consumers, but they may impose upfront costs and exclude low-income households. VAT reductions and consumer reward programs offer upfront discounts and rewards for purchasing energy-efficient products. Early retirement and direct installment programs replace inefficient appliances, leading to energy savings and environmentally friendly disposal. On the other hand, upstream programs focus on manufacturers by reducing transaction costs and encouraging the production of energy-efficient equipment. Tax credits are effective upstream incentives, while production subsidies may or may not impact equipment prices. However, upstream programs lack the engagement of consumers to raise awareness of energy efficiency opportunities and impacts. Overall, a combination of downstream and upstream incentives can be employed to maximize the impact of energy efficiency programs [14][28][29].

Funding sources

Government programs are often funded through central budgets or exceptional stimulus funds, while some may be financed by bonds, which are low-interest rate debt instruments. International financial institutions like the World Bank, the Clean Technology Fund, and the Global Environmental Facility can provide financial support to governments in developing countries. As budgets shrink during financial crises, policymakers seek alternative funding sources, such as revolving funds or earmarked taxes. Taxes raised specifically for energy-efficiency programs are even more powerful. Government funding from general budgets is subject to political forces, making it vulnerable to instability, and funding can be reallocated to higher-priority areas during times of financial crisis [14][28].

Ratepayer-funded programs

Incentive instruments

Increasingly, governments are mandating energy providers to deliver energy savings as part of their operations. This has led to the implementation of various incentive programs targeting different stages of the energy supply chain. These programs help lower production costs, improve product availability, and enhance the market penetration of energy-efficient products. Midstream programs, on the other hand, incentivize retailers through rebates to promote and sell high-efficiency appliances, thereby increasing their stock and sales. Downstream programs directly influence customer purchasing decisions by offering consumer rebates, on-bill financing, and direct installation programs. Consumer rebates reduce the upfront cost of energy-efficient appliances, while on-bill financing allows consumers to pay in installments through their electricity bills. Direct installation programs involve home visits, equipment installation, and financial assistance. These various incentive programs collectively aim to drive energy savings and promote the adoption of energy-efficient technologies [14][28].

Funding sources

Ratepayer-funded mechanisms can be either explicitly or implicitly paid for by ratepayers. Explicit mechanisms involve charging a defined amount as part of the consumer electricity rate, whereas implicit mechanisms require utilities to meet target savings by spending a share of profits on energy efficiency.

The explicit mechanism provides a price signal that encourages investment in energy efficiency and generates revenue that is earmarked to fund energy savings. Efficiency investments result in lower rates because they prevent or delay capital investments in generation capacity. While such an approach raises rates initially, customers recover the extra costs through electricity savings.

In market-based programs, the costs of energy-efficiency measures undertaken to meet regulatory targets are generally passed through in energy prices, which is done explicitly when a regulated distribution charge is implemented on energy prices. Additionally, utilities can offer energy-efficiency services as part of their business plans, providing to pay a portion of customers' up-front costs for efficient equipment via a loan whose cost will be entirely borne by the customer. The utility earns a profit by sharing a portion of the customer's energy savings [14][28].

Program evaluation

Program evaluations are rigorous and unbiased assessments carried out at regular intervals or as needed to evaluate the effectiveness of a program in achieving its intended objectives in a cost-effective manner. These evaluations are crucial tools for management to obtain a broader perspective on program performance and accountability beyond routine performance monitoring and reporting. Program evaluations are categorized into impact evaluation, which measures the program's effect, and process evaluation, which assesses the effectiveness of the program's design and implementation.

Impact evaluations provide evidence that outcomes have occurred and estimate the proportion of outcomes attributable to the program. Cost-benefit and cost-effectiveness evaluations, a form of impact evaluation, quantify economic benefits from energy savings and compare them to program costs, providing monetary or non-monetary values of program outcomes. Together, these evaluations help managers improve program operations, justify past investments, and decide on future investments.

This paper focuses on the impact evaluation of a downstream program because the main advantage of downstream incentive programs is that end-users directly receive the rebate amount as compared to upstream and midstream, where the cost of energy-efficient equipment is reduced through the rebate. In the context of an energy efficiency program, impact evaluation seeks to determine the extent to which the program has contributed to energy savings and other related benefits, such as greenhouse gas emissions, between a group of program participants and a control group that did not participate in the program, etc. This paper focuses on determining the energy savings and its Non-Energy Benefits (NEB), such as reductions in greenhouse gas emissions, market penetration of energy efficiency, equipment cost reduction, jobs creation, and increase in Gross Domestic Product (GDP) of any country.

Steps of an energy efficiency program for downstream customers

The flowchart indicating the different steps of the program evaluation is shown in Figure 1. The steps are explained in detail in the following section.

Phase 1: Program planning

Step 1. Funds collection for the program

Funds for a program can be sourced from either the government or rate-paying customers. This paper focuses on the ratepayer-funded program wherein a small additional amount for every kWh consumption is levied on the customers by the utilities. The amount percentage varies for every country and every state in some countries. A fixed percentage of electricity tariffs can be considered for fund collection. The additional charges for energy efficiency programs range from 0.003 cents/kWh to 0.3 cents/kWh with a median value of 0.11 cents/kWh in 22 USA states. However, some Utilities charge more than the median value. In Denmark, the funding for the Danish Energy Trust is derived from a dedicated energy savings charge of 0.006 Danish krone per kilowatt-hour (equivalent to 0.0011 USD/kWh) that is levied on households and the public sector [14]. The fixed percentage or energy efficiency charge can be decided after various discussions with different stakeholders.

Step 2. Identify the program areas for downstream customers

In energy efficiency programs, customer sectors include Industrial, Commercial, and Residential, and the selection of these areas should be based on historical data related to energy consumption patterns. The prioritization of areas for energy efficiency improvements should consider factors such as the potential for energy savings, costs, and environmental benefits.

Step 3. Decide the evaluation objectives

In an energy efficiency program, the primary evaluation objective is to achieve energy savings, which is quantified in terms of kilowatt-hours (kWh). Other objectives include identifying the coincident peak demand savings in kilowatts (kW) and non-energy benefits (NEBs). These objectives provide the basis for assessing the effectiveness and impact of the program.

Step 4. Budgeting

Budgeting for energy efficiency programs involves different cost parameters, including rebates for customers, third-party evaluations to measure program impact and process effectiveness, management expenses, and other costs. Rebates are used to incentivize customers to participate in energy efficiency programs, while third-party evaluations are necessary to measure program effectiveness and ensure transparency. For residential and commercial equipment, rebates can be provided based on the capacity of the energy-efficient equipment like HP of motor, ton of air conditioning, volume of refrigerator, etc. For custom industrial applications, it is beneficial to provide rebates based on kWh of energy saved as energy efficiency projects involve complex equipment and processes.

The rebate amount is determined by calculating the incremental cost of acquiring energy-efficient equipment or implementing energy-efficient processes compared to the cost of baseline equipment or operating processes at baseline conditions. The incremental cost represents the additional expenses incurred to achieve higher energy efficiency. The determination of incremental cost in energy efficiency programs often involves conducting case studies on various equipment and processes.

In rate-funded energy-efficiency programs in the United States, a budget of 3-6% is allocated for independent third-party evaluators, which includes evaluation, measurement, and verification (EM&V). The 2012 CEE report stated that, on average, EM&V constituted 3.6% of the total budget [15]. In California, CPUC approved a budget of 4% (US$125 Million) of the overall portfolio budget for EM&V from 2010 to 2012 [16]. On the other hand, National Grid allocated an average of 2% (US$3.2 Million) of the portfolio budget for EM&V [17]. Management expenses are necessary for program administration and oversight, while other costs can include marketing and outreach efforts to promote program participation. Accurately budgeting for these costs is critical to the success of energy efficiency programs.

Step 5. Determine a timeline for completing the evaluation

The timeline should include clear milestones and deadlines for completing each stage of the evaluation, such as data collection, analysis, and reporting. The timeline should also consider any external factors that may affect the evaluation process, such as changes in program objectives, funding, or policies.

Step 6. Organizing program background data and records for use in the evaluation

This involves collecting and managing relevant information about the program's design, implementation, and outcomes. This data may include program plans, participant records, and energy consumption data. Organizing this data in a systematic and accessible way enables evaluators to use it effectively in the evaluation process.

Step 7. Develop and update Technical Reference Manuals (TRM)

A Technical Reference Manual (TRM) is a document that outlines the methodology for evaluating and measuring energy savings achieved through energy efficiency programs. It serves as a guide for implementing standardized energy savings calculation methods and measurement protocols. TRMs typically include a list of deemed measures, which are pre-approved energy efficiency measures and their corresponding energy savings values. TRMs provide a consistent and transparent approach to evaluating program performance and are used to establish baselines and verify energy savings achieved through various energy efficiency measures. This document must be updated every program year to incorporate new changes related to energy efficiency standards.

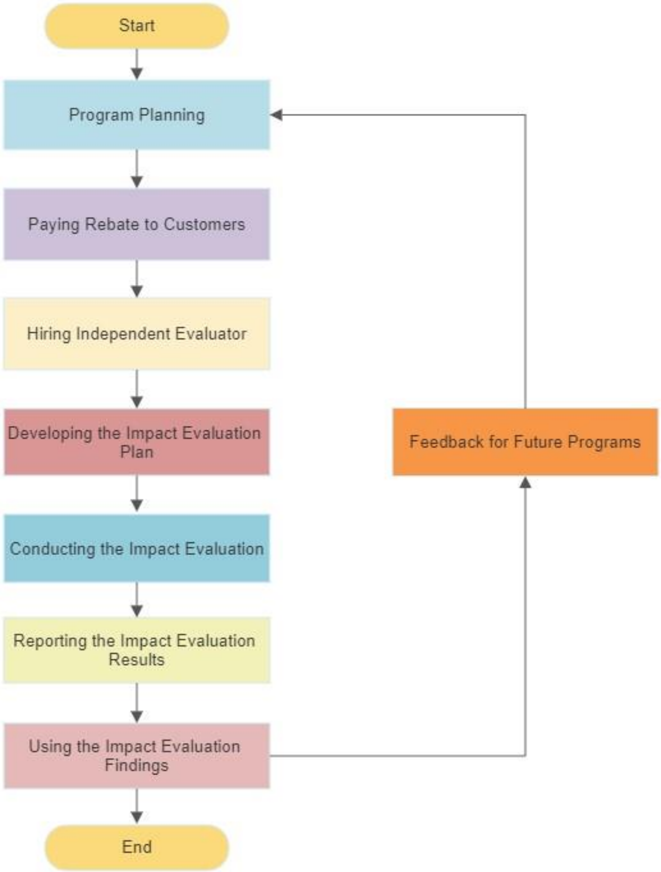

Figure 1: Flowchart for the evaluation program [18] [19]

Phase 2: Paying rebate to customers

Step 8. Collecting customer applications-

This step involves collecting data from customers who participate in the program, such as their contact information, details about the energy-saving measures they have implemented, and necessary documentation like equipment specification sheet and calculation methodology used for determining savings. This data is used to assess the effectiveness of the program and to identify opportunities for improvement.

Step 9. Sorting and approving the customer applications based on projected energy savings

Sorting customer applications based on projected energy savings is a crucial step in an energy efficiency program evaluation. This helps to identify high-performing measures and prioritize them for implementation, ensuring maximum energy savings. The sorting process involves reviewing and verifying the accuracy of the information provided by the customer in their application.

Sorting is only applicable when the rebate number of applicants is greater than the program-approved rebate amount. Different sorting conditions can be applied to provide equal opportunity to every customer to avail themselves of a rebate.

Step 10. Paying the rebate to the customers

After the applications are sorted and approved, the rebate amount is paid to the customer based on the application. The rebate amount can be paid in any form applicable. Direct Bank Transfer is an effective and faster way of rebate payment. It also leads to transparency between the end-users and the utility.

Phase 3: Hiring independent evaluators

Step 11. Put out tender to hire independent evaluator

This involves preparing the tender document, which would include the scope of work, evaluation criteria, qualifications, and experience required. After the tender document is ready, it will be advertised through the relevant channels. The scope of the project will need to be clearly defined in the Tender document. This will include the evaluation criteria and familiarity with relevant M&V protocols.

Step 12. Hire an independent M&V evaluator

After reviewing the received proposals and evaluating them against the selection criteria, the evaluator will be selected.

Phase 4: Developing the impact evaluation plan

Step 13. Define the evaluation outcome and the impact metrics

Defining the evaluation outcome and the impact metrics involves identifying the specific goals and objectives of the evaluation, as well as the metrics that will be used to measure the success and impact of the project. This may include measuring energy savings, greenhouse gas emissions reductions, cost savings, and other environmental or social benefits. Defining these outcomes and metrics provides a clear framework for the evaluation process and helps ensure that the project is being evaluated against its intended outcomes.

Step 14. Setting the time frame for the evaluation and reporting expectations

This involves establishing a clear timeline for when the evaluation process will take place, including data collection, analysis, and reporting. Reporting expectations outline what information needs to be included and how it will be presented.

Step 15. Preparing a technical evaluation plan and participating in the peer review process

This involves developing a detailed outline of the evaluation methodology, data collection procedures, analysis techniques, and reporting structure. Participating in the peer review process established for the plan entails having the plan reviewed by other evaluators to ensure its rigor and adherence to best industry practices.

Phase 5: Conducting the impact evaluation

Step 16. Perform sampling, data collection, and measurement and verification

This involves gathering relevant data and conducting measurements to assess the performance and impact of the project or program being evaluated. This can include conducting on-site inspections, utilizing monitoring equipment, and verifying the actual energy savings.

Step 17. Monitor the evaluation during the implementation

Monitoring the evaluation during the implementation phase involves regularly tracking and overseeing the progress and execution of the evaluation activities. This includes ensuring that data collection is on track, monitoring the quality and reliability of the data being collected, addressing any issues or challenges that arise, and maintaining communication with stakeholders involved in the evaluation process.

Step 18. Complete data analyses and calculations

This involves analyzing the collected data to derive insights and evaluate the performance of the project or program. This may include conducting statistical analyses, calculating energy savings, and cost-effectiveness ratios depending on the type of evaluation conducted. These results help in determining the effectiveness of the energy efficiency measures.

This paper focuses on the impact evaluation of energy efficiency. The flowchart for the impact evaluation process is presented in Figure 2. The evaluation of energy efficiency measures is energy savings in terms of kWh and kW reduction. Energy Savings are calculated in terms of Gross savings, which refer to the total energy savings achieved as a direct result of program interventions, without considering any adjustments or factors that might influence the actual energy consumption. Various methods like actual measurement & verification, deemed savings using TRM, or billing analysis can be used to determine the gross savings.

Measurement & Verification procedures and standards are provided by the International Performance Measurement and Verification Protocol (IPMVP), which are necessary for the verification of energy savings. IPMVP provides four options to quantify the savings (Option A, Option B, Option C and Option D) [21]

Net savings represent the energy savings achieved after accounting for any rebound effects, free ridership (a portion of program's energy savings that would occur without program intervention or incentive), spillover (energy savings that occur because of the program but are not part of the program's verified savings) or other factors that might influence the actual energy consumption and overall program effectiveness.

Step 19. Identify key findings

Identifying key findings involves summarizing the most significant and relevant results from the data analyses and calculations. These findings highlight the main outcomes, trends, successes, challenges, and insights gained from the evaluation. These findings provide information for decision-making and reporting purposes.

Step 20. Prepare draft and final report

Preparing a draft and final report entails compiling the evaluation findings, analyses, and key insights into a comprehensive document. The draft report serves as an initial version that undergoes review and feedback, while the final report incorporates any revisions and additions based on the feedback received. The report presents the overview of the evaluation process, findings, and recommendations, which in turn helps with the decision-making process for the energy efficiency program.

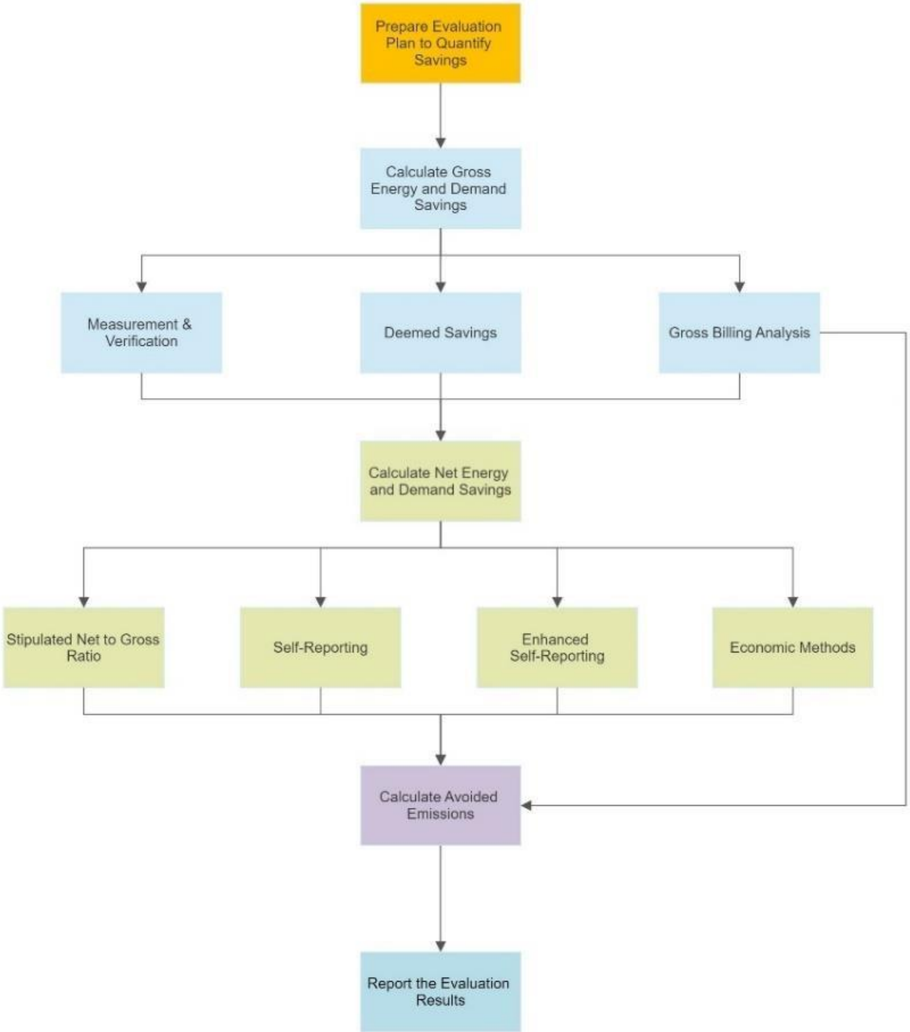

Figure 2: Flowchart for impact evaluation process of energy efficiency program [20]

Phase 6: Reporting the impact evaluation results

Step 21. Participate in peer review of draft evaluation report

Participating in the peer review of a draft evaluation report involves independent experts or evaluators in the field. These peers review the report for accuracy, rigor, methodology, and overall quality, providing valuable insights and recommendations to enhance the report's credibility and ensure that it meets the best industry standards practice.

Step 22. Publish final report

Publishing the final report involves making the completed evaluation report publicly available to relevant stakeholders, organizations, and the wider audience. This can be done through various channels, such as online platforms, project websites, industry publications, or government reports.

Phase 7: Using the impact evaluation findings

Step 23. Use the results to make decisions about the future program

Using the results to make decisions about the future program entails examining the evaluation findings and leveraging them to inform strategic choices for program improvement. This can include addressing the identified challenges and updating the program objectives to enhance the program's impact in the future.

Assumptions

1. The energy efficiency charge is considered to be 0.0011 US$/kWh [14]. Assuming a conversion rate of 80₹ per US$, the energy efficiency charge becomes ₹0.088 per kWh.The average electricity tariff of India was ₹6.15 per kWh in 2020 [22]. Using the historical average electricity tariff from 2009 to 2020, the electricity tariff for 2022 was extrapolated to ₹6.706 per kWh. The percentage of energy efficiency charge levied to customers will be 1.3%. So, a rounded value of 1% increase in electricity tariff, i.e., ₹0.067, is assumed as an energy efficiency charge.

2. The determination of rebate amounts is contingent upon several factors, including the sector in which the energy-saving equipment is deployed, its type, and other relevant considerations. Generally, rebates are calculated based on the amount of energy saved in kilowatt-hours during the first year of implementation. This approach ensures a straightforward and transparent payment mechanism directly linked to the actual energy savings achieved. By offering rebates based on per kWh saved, energy efficiency programs can effectively encourage customers to embrace energy-saving practices and technologies.
3. The determination of rebate amounts per kilowatt-hour (kWh) hinges on various factors, such as the incremental cost associated with energy-efficient equipment or processes. However, for the purpose of this paper, an alternative criterion is adopted due to the topic's scope. The primary rationale behind this alternative approach is rooted in the notion that the cost of saving one kWh of electricity is typically lower than the cost of generating or procuring an additional kWh of electricity. By employing this rationale, the selected criteria for rebate calculation ensures that the incentives provided align with the objective of promoting energy efficiency and optimizing resource utilization.
4. The average cost of procurement of electricity by DISCOMs of Maharashtra, Gujarat, and Tamil Nadu is assumed as the rebate amount.
5. Evaluation cost and management and other expenses are both considered as 5% of the total revenue generated.

Table 2: Case study: Energy savings and reduction in CO_2 emissions for FY 2022-23

Sr. No.	Parameters	Units	Maharashtra	Gujarat	Tamil Nadu
1	Annual electricity consumption for FY 22-23 [23]	Million Units	190,281	140,887	106,704
2	Energy efficiency charge in the tariff	₹/kWh	0.067	0.067	0.067
3	Annual revenue generated from the additional energy efficiency charge	₹ Crores	1,275	944	715
4	Management and other expenses (assumed)	%	5%	5%	5%
5	Evaluation expenses (assumed)	%	5%	5%	5%
6	The net amount available for rebate	₹ Crores	1,147	850	643
7	Rebate amount per kWh saved	₹/kWh	4.82 [24]	4.55 [25]	5.86 [26]
8	Total energy saved based on rebate amount	Million Units	2,380	1,868	1,098
9	Average demand reduction (24 hours and 365 days of operation)	MW	272	213	125
10	Percentage of energy savings compared to annual electricity consumption	%	1.3%	1.3%	1.0%
11	Weighted average carbon dioxide emission factor (incl. RES and Imported energy) [27]	Ton/MWh	0.711	0.711	0.711
12	Avoided CO_2 emissions for FY 22-23	Million Tons	1.692	1.328	0.780

Conclusion

In conclusion, this paper has examined the energy demand-supply gap in India and emphasized the importance of implementing energy efficiency measures to address the increasing electricity demand and inadequate power generation. It has recognized the significant role played by SERCs, DISCOMs, and SDAs at the state level in improving energy efficiency and implementing demand-side management activities. The focus has been on Maharashtra, Gujarat, and Tamil Nadu, providing an overview of their energy efficiency initiatives and incentive programs. Furthermore, the paper has clarified the expanded definition of demand side management (DSM) to encompass energy efficiency and energy conservation activities. The study has delved into the DSM activities in the mentioned states as well as by EESL and BEE, and explored different incentive programs available, including government-funded and rate-payer-funded initiatives. The introduction of a rebate-based incentive program has been proposed as a strategy to scale up energy efficiency efforts, and estimates have been made to determine the potential electricity savings achievable in the selected states. The importance of program evaluation has been discussed, highlighting its aims and necessity. The paper has also presented the various steps involved in an energy efficiency program for downstream customers, covering program planning, rebate payment, independent evaluation, impact evaluation planning, execution, reporting, and utilization of findings. Lastly, a case study has been presented, calculating the revenue generated, energy savings, and CO_2 emissions reduction for Maharashtra, Gujarat, and Tamil Nadu. Overall, this paper provides valuable insights and recommendations for advancing energy efficiency and achieving sustainable energy goals in the studied regions and all over India.

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Assessment of Energy-Efficient and Clean Energy Technology in the Cold Chain Sector

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Highlights

- The cold-chain infrastructure in India is anticipated to expand dramatically over the next few years, increasing the cooling demand and corresponding energy consumption.
- It uses cutting-edge technology to keep temperature regulation at a precise level. Assessing current technologies and encouraging efficient technology is crucial to lowering energy demand.
- The findings from the study will be helpful to government agencies involved in developing the cold-chain sector. Technology providers, researchers, and cold-chain owners will benefit by understanding the technologies present in the sector.

Abstract

There is a growing need for the cold-chain sector due to the demand for fresh and frozen products. With the increase in growth of the cold chain sector, the related energy consumption will increase, and to address the issue, emphasis needs to be given to energy-efficient and clean energy technologies. By utilizing these methods, expenses can be decreased, increasing the cold-chain industry's profitability and sustainability. The authors aim to identify the available technologies and focus on adopting efficient technologies to improve the cold chain's efficiency, reduce costs, and ensure product quality and safety in the cold-chain sector by reviewing relevant literature, stakeholder consultation, and case studies.

Keywords: Cold chain, Horticulture, Food Loss, Cooling Technologies

Introduction

India has witnessed an increase in horticulture production over the last few years. The production of horticulture crops in 2021-22 has been pegged at a record 341.63 million tonnes, 2.9 percent higher than the final estimate for 2020-21. The production of vegetables alone is estimated to be 204.61 million tonnes, while fruit production is estimated to be 107.10 million tonnes [1]. Horticulture contributes 30.4 percent of agriculture's gross domestic product (GDP), using only 13.1 percent of the gross cropped area [2]. Over the years, total horticulture production in the country has surpassed the total food grains production, achieving a higher production record every year. Despite all these achievements, the horticulture sector faces substantial post-harvest losses, a lack of storage infrastructure, price seasonality, and market volatility.

Furthermore, small-holder farmers, who account for 86% of all farmers in India and own half of the arable land, still struggle with low-income levels and huge food losses throughout the supply chain [3]. These farmers fail to benefit from post-harvest management facilities because of the limited access to cold-chain logistics and other financial barriers, further shortening the lifespan of their horticulture produce. Subsequently, the reduced lifespan causes a significant loss in their production value and livelihoods. Due to this, a considerable part of the population continues to face challenges related to food insecurity and malnutrition. A comparative study by the Centre Institute of Post-Harvest Engineering and Technology (CIPHET, 2015) reported that about 16 percent of fruits and vegetables are lost post-harvest [4]. Thus, urgent steps are needed to integrate and revamp the horticulture production and value chain system, promoting healthier and more nutritious foods and improving farmers' income.

To address these issues, the Government of India recognizes that cold-chain infrastructure is thus one of the crucial factors in the post-harvest process because it is where the commodity can sustain most of its lifetime. However, storage infrastructure is particularly pertinent for India because of inferior coordination between supply and demand, seasonality, and the perishable nature of horticulture crops. The cold-chain infrastructure mainly consists of three essential pillars: a static infrastructure for aggregating and storing the produce, reefer transport for connecting the link between the post-production and pre-market stage, and market channels for the transaction of the crop. The integrated development of the cold chain facilities in the country needs to be more robust, with major essential components of the cold chain needing to be adequately developed.

The development of cold chains is crucial for preserving product quality, preventing spoilage, and ensuring the safety of perishable items. As per ICAP, around 500 packhouses are there in India at present consuming 0.02 TWh electricity; the number is likely to grow to 55,000 by 2027-28 and to 1,25,000 by 2037-38, attributing to the energy consumption of 2.4 TWh and 5.2 TWh, respectively. The growth of reefer vehicles is related to an increase in the packhouse, and their estimated numbers are 1,35,000 units in the next decade and 4,00,000 units in the subsequent decades from the present 15,000 units with related energy consumption of 4000 TJ at baseline and 40,000 TJ by 2027-28 and 1,25,000 TJ by 2037-38 [5]. Energy consumption in the cold chain primarily stems from packhouse refrigeration systems, including refrigerated trucks, warehouses, and display units. The growth in the development of infrastructure is necessary. However, there are challenges such as high energy cost, operational efficiency, high cost of technology, and unskilled workforce. Addressing these challenges will be essential for the cold chain sector to realize the benefits of scaling up the technology and meet the growing demand for temperature-sensitive products.

Energy consumption in the cold chain is involved within each component of the cold chain in terms of fuel or electricity. Due to the insufficiency of data, the author has focused primarily on the packhouse and shared a few details on reefer trucks. The authors aim to identify the available technology used in sorting, grading, packing area, pre-cooling chamber, staging room, and reefer truck through an evaluation framework model which would improve efficiency, reduce costs, and ensure product quality and safety in the cold chain sector by reviewing relevant literature, stakeholder consultation, and case studies. Consequently, the research paper also highlights some of the plug-in technologies that can be used to make the cold chain sector more robust.

The model will focus on technologies available in the following categories:

- Cooling Technology
- Refrigerant
- Insulation
- Plug-In Solution
- Energy Sourcing

Each of these categories will be evaluated based on appropriate parameters.

Methodology

The research paper is intended to be a comprehensive study that builds upon a thorough understanding of the best available industry knowledge. The document has tried to plug some information gaps through a multi-source methodology adopted by the author, which triangulates inputs from existing government databases, market intelligence reports, secondary research from other reliable sources, and interviews with subject matter experts. The data was obtained through consultations with refrigeration system manufacturers such as Danfoss, Carrier, Voltas, Blue Star, etc., Cold room manufacturers such as Inficold, Pluss Advance Technologies, New Leaf Dynamics, etc., refrigeration institutions like RAMA, ISHRAE, and service provider such as Standard Refrigeration, Ice Make Refrigeration, etc.

The technology used in each component of the cold chain was identified and compared based on relevant parameters. Significant inputs are sourced from consultations with various technology providers, and efforts were made to consolidate data obtained and assess each technology.

Cold Chain and its components

According to the NCCD definition, a cold chain is a temperature-controlled environment logistic chain, ensuring uninterrupted handling of products from source to user, consisting of storage and distribution-related activities in which the inventory is maintained within predetermined ambient parameters. The cold chain essentially serves two primary purposes, namely maintaining a product’s quality and prolonging a product’s life without changing the core features of the product handled.

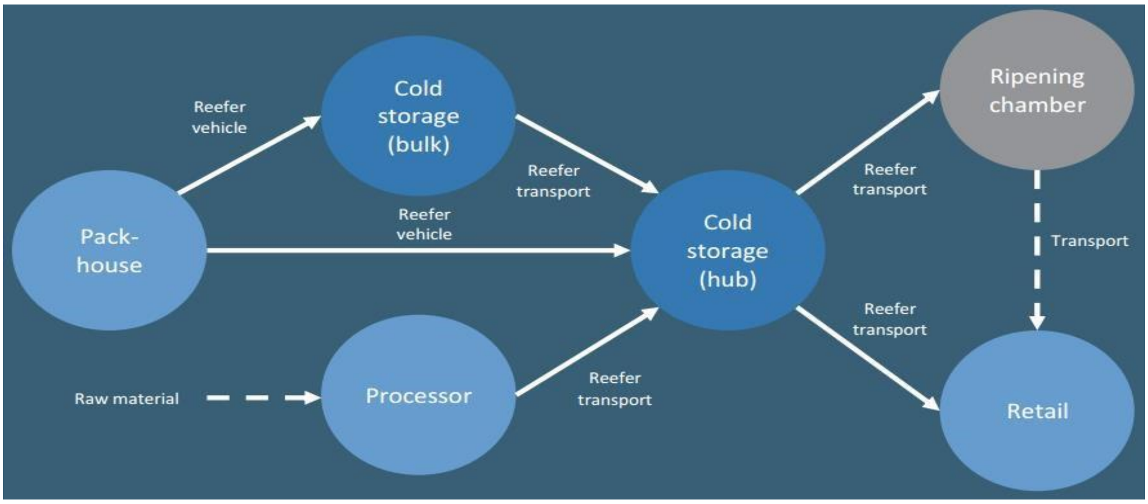

Figure 1: Flow of process in a cold chain

In the case of fresh fruits and vegetables, the cold chain infrastructure must offer a more precisely controlled environment regarding humidity and microbial conditions, oxygen level, monitoring and control of degenerative gases, and segregation to avoid tainting between living tissue and maintaining a precise temperature. According to ICAP 2019, the flow of products in a typical cold chain is shown in Figure 1. Data shows that most food losses related to fruits and vegetables are between the farm gate and post-harvest handling. To reduce these losses, a packhouse facility is an appropriate solution for correctly handling, pre-cooling, and packaging the produce. In the product's supply chain, the reefer or refrigerated trucks are crucial in transporting the produce at a required temperature.

Integrated pack house

This component refers to a modern integrated pack-house with facilities for a conveyor belt system for sorting and grading, washing, drying, and weighing. A modern integrated pack-house unit enables small lot sourcing of horticulture produce and should be built close to the farming area. The "Integrated Pack-house" component includes a covered receiving area, an enclosed covered sorting and grading area, sorting and grading conveyors, washing/drying equipment, a packaging area, an electricity generator, etc. Additionally, washing, drying, and weighing equipment can be installed to read the product for packaging.

Pre-cooling unit

The component Pre-Cooling Unit is a specialized cooling room that rapidly removes field heat from fresh produce after harvest, preparing the cargo for subsequent shipping. The temperature differential between the harvested crop's temperature and the produce's ideal storage temperature is called the "field heat." Generally, the temperature should be lowered until 88% of the current temperature difference from its ideal storage temperature [6]. The humidity depends on the produce storage requirements, which may vary from 80% - 95% RH in the case of fresh fruits and vegetables. The "Pre-cooling unit" component includes an insulated room, pre-cooler unit, evaporating and condensing unit, electronic controller, electricity generator, etc. The refrigeration system uses the majority of the energy in the pre-cooling room; therefore, it is crucial to evaluate the cooling technology applied in the pre-cooling unit.

Cooling technology for pre-cooling unit

Field heat must be removed from freshly picked perishable vegetables to slow metabolism and deterioration before storage. The amount of produce that needs to be chilled, the air temperature, airflow rate, relative humidity, the packing configuration and stacking arrangement of the produce, the energy efficiency of the method, the availability of a skilled operator, and the economic viability of the pre-cooling all play a role in the decision of which pre-cooling technique to use for fruits and vegetables. Some of the significant pre-cooling methods are compared based on specific parameters in Table 2.

Table 1: Comparison of pre-cooling methods

Technology	Refrigerated Room cooling	Forced air cooling	Hydro cooling	Ice cooling	Evaporative cooling
Typical cooling time (h)	20 to 100	1 to 10	0.1 to 10	0.1 to 0.3	0.3 to 2
Product moisture loss (%)	0.1 to 2	0.1 to 2	0 to 0.5	No data	No data
Water contact with the product	No	No	Yes	Yes, unless bagged	Yes
Potential decay	Low	Low	High	Low	High
Capital cost	Low	Low	Low	High	Medium

Energy efficiency	Low	Low	High	Low	Medium
Water-resistant packaging needed	No	No	Yes	Yes	Yes
Portable	No	Sometimes	Rarely done	Common	Common
Feasibility of in-line cooling	No	Rarely done	Yes	Rarely done	No

Note- Source: ASHRAE Handbook 2021

Refrigerated room cooling techniques are typically used in traditional cold storage; however, this technology demands more energy due to comparatively higher cooling time. Evaporative cooling technology is humidity-dependent technology. The cooling effect diminishes in areas with high humidity, making evaporative cooling less effective. However, it works best in dry climates with a low humidity range. In comparison, hydrocooling is an efficient technology for pre-cooling with low capital cost. The system's potential decay is much higher than other technologies. Forced air cooling is primarily used technology in pre-cooling rooms as it uses a rapid cooling technique, although it demands higher energy for the cooling process.

A few parameters, such as capital cost, efficiency, and potential decay of these technologies, are defined as low, medium, and high due to data insufficiency. The operational cost depends on various factors such as system efficiency, ambient temperature, usage patterns, type of produce stored, etc.

Staging cold-room

This component is an insulated and refrigerated chamber, a necessary combination for the pre-cooling unit. It serves as a temporary storage while allowing the pre-cooler to be utilized for the next batch load of incoming produce. The "Cold room (staging)" component includes an insulated room, associated refrigeration equipment, staging area, etc.

Cooling technologies for staging

Two principal types of technologies are found in the cold chain sector: (1) Vapour Compression Refrigeration (VCR) and (2) Vapor Absorption Machine (VAM). VCR technology makes up most cooling systems used in staging areas or for bulk storage.

VCR uses mechanical energy as the driving force for refrigeration to remove heat through the evaporation of refrigerant at low pressure and condensation of the refrigerant at high pressure. The compression refrigeration cycle consists of circulating a liquid refrigerant through four stages of a closed system. As the refrigerant circulates through the system, it is alternately compressed and expanded, changing its state from a liquid to a vapor. As the refrigerant changes state, heat is absorbed and expelled by the system, lowering the temperature of the conditioned space.

VAM belongs to the class of vapor cycles similar to the Vapour compression refrigeration system. However, unlike VCR, the required input to the absorption system is in the form of heat. Hence, these systems are also called heat-operated or thermal energy-driven systems. The method of creating the pressure difference and circulating the refrigerant is the primary difference between the two cycles. The performance of cold storage only depends on the temperature. The lower the temperature inside the cold chamber, the greater the performance. Table 3 compares both cooling technologies based on parameters such as capacity range, CAPEX, OPEX, COP, and skill required for operation.

Table 2: Comparison of cooling technologies for staging

Technology	**VAM**		**VCR**	
	Min	Max	Min	Max
Commercially available Range (Temperature of refrigeration-TR)	50	1,550	1	2,800
CAPEX (INR Lakhs)	60-70 (25 TR)		65 (50TR)	
OPEX (INR Lakhs/year)	5-15 (approx.)		15-20 (approx.)	
Coefficient of performance	1.45 - 1.50		2 - 3.60	
Maintenance/skill required	High		Low	

Note- Source: The data mentioned in the table is for direct-fired VAM. The COP of the system may vary depending on various factors, such as load condition, ambient temperature, etc.

VCR systems are generally more energy efficient than VAM when used for small to medium-scale cooling applications. VAM systems tend to have lower energy efficiency; however, they have advantages in specific niche applications where waste heat or low-grade heat sources are readily available, making them more cost-effective.

Insulation

Insulation minimizes heat transfer and protects the stored product from external temperature fluctuation. It is typically achieved through specialized materials with high thermal resistance, such as foam panels or polyurethane foam. These materials are placed in the refrigerated storage areas' walls, floor, ceiling, reefer truck, and cold storage warehouse. Insulation plays a significant role in reducing overall energy consumption by decreasing the load on the refrigeration system. Insulating the pre-cooling and staging room with optimal thermal performance could save around 3-5% of the overall refrigeration (cooling) energy consumption [7].

Table 3: Comparison of insulation materials used in cold storage

Sr. No.	Panel	Thermal conductivity (W/m. K)	Fire resistance	Panel density (kg/m^3)	Water absorption rate	Cost (INR/m^2)	Lifespan (years)
1	Polyurethane foam (PU or PUF)	0.022-0.028	B2, B1	35 - 45	2.5% - 3%	1,300	25
2	Extruded polystyrene foam pane (XPS)	0.025-0.040	A	22-26	0.03%	840	Building lifetime
3	Expanded polystyrene foam pane (EPS)	0.030-0.040	B1	10-26	2% -4%	600	35-50
4	Mineral wool	0.020-0.040	A	32-100	0.3%	500	Building lifetime
5	Glass wool	0.023-0.040	A	16-48	<2%	450	Building lifetime

Insulation panels should have five essential characteristics: (i) excellent thermal insulation, (ii) perfect sealing, (iii) strong anti-compression, (iv) anti-bending, and (v) vapor barrier (anti-condensation insulation). Prefabricated panels, an emerging standard material, can serve as permanent walls and insulation for roofs. These panels act as vapor barriers and resist moisture flow from both sides.

Additional energy efficiency measures

Energy efficiency improvement in the packhouse can also be implemented through intervention in building design, equipment and system design, and packhouse operation and maintenance. The table below presents the energy efficiency measures that can be used for improving efficiency along with its energy-saving potential:

Table 4: Energy efficiency measures for packhouse

Energy efficiency measures	Energy saving potential	Remarks
Natural lighting, proper orientation, and Shading	Indicative energy saving potential can be 1-2% of total energy consumed. The reduction in cooling demand is around 1%.	The orientation of the building should be such that the longer façade faces North-South and the short façade faces East-West.
Wall and Roof Insulation	The energy-saving potential is 1-2% of the total energy consumed in a packhouse	Insulation will reduce heat gain inside the building by reducing the conductive heat transfer from the wall and roof.
Cool roof treatment	The energy saving potential is estimated at around 0.5-1% of total energy consumed.	Cool roof treatment using low-cost interventions like highly reflective china-mosaic tiles.
Air-tight doors for pre-cooling and cold rooms	The saving potential in overall energy consumed in cooling is around 2%.	Use of gaskets, hinges, and latches made of industrial-grade stainless steel materials.
Fast roll-up doors to prevent hot/moist air infiltration	The saving potential in overall energy consumed in cooling is estimated to be around 6-8%.	
Low-energy evaporative cooling system for temperature control in the packing hall	The energy-saving potential of evaporative cooling over an airconditioned space can be up to 40-50%	Suitable for the hot & dry and composite climatic conditions.
Energy-efficient refrigeration system configuration for pre-cooling and staging room	Semi-hermetic reciprocating or scroll compressors in a rack system can potentially reduce energy consumption by 15-20%. A water-cooled/Evaporative condenser can potentially reduce energy consumption by 20% over the air-cooled system.	The compressor rack system works more efficiently compared to the independent one-to-one compressor.
Energy Management System	The accurate setting of plant operation parameters, including the right suction pressure and discharge pressure, can potentially improve the overall system efficiency by 8-10%	PLC-based refrigeration plant operation will enable real-time monitoring and help optimize the cooling demand

Plug-in solution / Micro cold room

Technology development has accelerated in India in recent years due to a rise in demand for storing fruits and vegetables at the farm gate. Governments realize the necessity of farm-gate storage of fresh produce to increase their shelf life; hence, the plug-in solution/micro cold room is being promoted. Some start-ups have arisen with their creative approaches to preserving produce at the farm gate. These products represent some intriguing market advancements. Since most of these solutions are off-grid capable, they work best when implemented in regions with highly erratic grid electricity supply.

Table 5: Comparison of plug-in solutions

Parameter	Ecozen	Inficold	CoolCrop	Promethean Power System	Oorja	New Leaf Dynamics
Key Products	Eco frost – solar cold storage room	Solar cold room	Cold storage solutions	Cold storage solutions	Solar powered refrigeration	Green chill
On/off Grid	On-grid	On-grid	On-grid	On-grid	On-grid	Biomass
Storage capacity range	5-10 MT	5-10 MT	2-10 MT	0.50-2 MT	5-10 MT	10-20 MT
Temperature range	4-10 °C	4-20 °C	0-18 °C	2-4 °C	4-10 °C	-2-25 °C
Electrical backup	NA	NA	NA	Yes	NA	NA
Thermal backup	PCM plates	Water	PCM lined Walls	PCM	PCM plates	NA
Digital platform	Predictive diagnostics- AI & Data Science	Cloud-based management & Inventory management	Crop Management Platform, Market Analytics	App-based management for the system Performance	Predictive diagnostics- AI & Data Science	NA
Financial model	Lease model, Sales model	Sales model	Lease model, Sales model, Cooling as a Service model	Lease model, Sales model	Cooling as a service – uses Eco Frost model	Sales model
CAPEX	7.50-10 lakhs/unit	11-12 lakhs/unit	4.50-5 lakhs/unit	8-10 lakhs/unit	Tariff: INR 0.30 per kg per day Membership fee: INR 1,000	15-20 lakhs/unit

Note: The data is obtained through consultation and companies' websites

Energy Sourcing

In the cold chain, which involves storing and transporting temperature-sensitive goods, energy sourcing plays a crucial role in maintaining proper temperature conditions and ensuring product integrity. The majority of the packhouses in India source energy from the grid and use diesel generators as a backup system. However, the owners of packhouses face significant difficulties due to the high energy cost through the grid and its dependability in remote places. As a result, it is essential to explore renewable energy sourcing methods as a substitute energy source for the packhouse. The grid may serve as a balancing source when there is either an excess or a lack of onsite renewable energy generation.

Table 6 provides a high-level distributed renewable energy generation technology assessment. Solar PV is commercially and financially the most attractive distributed energy generation technology today. Biogas and biomass technologies with a competitive Levelized Cost of Electricity (LCOE) and unintermittent generation potential are attractive options, provided that an adequate type and quantity of feedstock at an affordable rate is available.

Table 6: Technology assessment of renewable energy sourcing

Technology	Solar PV	Biogas	Biomass	Solar Thermal1
LCOE range	INR 4.15-5.05/kWh	INR 7.13-14.25/kWh	INR 4.5-21.75/kWh	INR 13.65-32.25/kWh
Commercial availability	1 kWp and onwards	3 kW and onwards	10 kW – and onwards	6 kW and onwards
Technology readiness (TRA)	Fully Commercialized	Fully Commercialized	Fully Commercialized	Partially Commercialized
Resource	Solar Irradiance (No minimum value)	Feedstock with moisture	Dry feedstock	Solar Irradiance (Minimum 350 W/m^2)
Area required	10 m^2 for 1 kWp	560 m^2 for 40 kW	NA	16 m^2 aperture area & 35 m^2 shadow free are for 6 kW
Intermittency	Hourly	NA	NA	Hourly

Conclusion

The cold-chain sector plays a vital role in preserving the quality and safety of perishable goods, such as food and pharmaceuticals. However, it is also associated with significant energy consumption and high operating costs. To address these challenges, the report identifies and evaluates various efficient and innovative technologies that can be integrated into cold-chain operations to reduce energy consumption and minimize environmental impact. These include efficient cooling solutions, advanced insulation materials, building design and orientation, energy-sourcing options, etc.

Primary and secondary research carried out under this study indicates that there is untapped potential for energy performance improvement in the cold-chain sector. Cross-cutting technologies such as solar-based cold rooms are invented to reduce grid reliability in remote areas, making farm gate storage accessible to marginal and small farmers. A Low-energy evaporative cooling system can be deployed for temperature control in the packing hall. It can effectively provide favorable post-harvest environmental conditions required for fruits and vegetables. Energy efficiency measures include proper orientation and shading, insulating roof and wall, cool roof treatment, air-tight doors, etc. play a vital role in energy savings. The research paper focuses mostly on farm gate storage, which includes the micro cold room and packhouse; reefer trucks and large cold storage facilities are not included. The upcoming study will address the broad elements of the cold chain.

The report underscores the urgent need for efficient and sustainable solutions in the cold-chain industry. By leveraging energy-efficient technologies and innovative approaches, stakeholders can reduce operating costs, minimize environmental impact, and improve the overall efficiency of cold-chain operations.

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Implementing Dynamic Tariffs for Residential Consumers: A Literature Review

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Highlights

- Discoms must have a deep understanding of consumer attributes before implementing dynamic tariffs.
- Income, education, household composition, and grid characteristics determine the distribution effects of dynamic tariffs.
- The decision to adopt new tariffs needs sustained consumer engagement.
- Technologies can play a pivotal role in helping consumers adapt to new tariffs.

Abstract

Dynamic retail tariffs are expected to be a cost-effective method to integrate variable renewable energy into the electricity grid while leading to higher social welfare. However, the global uptake of dynamic tariffs among residential consumers has been tepid due to complexities in implementing tariffs that match consumer preferences and uncertainties around their distributional effects, leading to unrealized welfare gains for consumers, utilities, and society. With a renewed interest in implementing dynamic tariffs in India following the large-scale rollout of smart consumer meters, this paper reviews recent literature on the attributes that affect the distribution of gains and losses among consumers and influence their uptake of dynamic tariffs. We propose a three-stage implementation framework that starts with getting a deeper understanding of the heterogeneous residential consumer segment and delineates the complementary steps required along with a change in tariff design to increase the likelihood of consumer participation.

Keywords: Dynamic tariffs, literature review, residential consumers

Introduction

There is a growing focus on using demand-side management (DSM) to manage the electricity system reliably with the increasing share of variable renewable energy in the grid. While longer-term DSM strategies like energy efficiency can help manage the multi-year demand growth, real-time strategies such as demand response (DR) can help manage grid operations. Dynamic or time-varying retail tariffs are one such method to mobilize DR. Along with its utility for RE integration, dynamic tariffs can also increase welfare by exposing consumers to charges that reflect system conditions [1]. However, few residential consumers globally use dynamic tariffs. By 2021, only about 8% of all residential customers in the USA had enrolled for any dynamic tariff [2]. In Europe, less than half of the households are supplied under dynamic tariffs where they are offered [3]. In India, out of the 29 states and Union Territories that offer dynamic tariffs to retail consumers, only 9 have optional dynamic tariffs for low-volume or mandatory dynamic tariffs for high-volume residential consumers [4].

There is a renewed push from the Government of India to implement dynamic tariffs for residential consumers with the target of installing smart meters for 250 million non-agricultural consumers by March 2026 [5] and implementing dynamic tariffs for all smart metered consumers from April 2025 [6]. But, given the tepid uptake of such tariffs among residential consumers globally, it is crucial to understand the factors that determine the outcomes of such a move.

This paper reviews the literature on the consumer attributes that affect the distribution of gains and losses from dynamic tariffs among consumers and influence their uptake. The review provides an implementation framework for dynamic tariffs, which starts with improving the understanding of the consumer segments that are likely to respond to time-varying tariffs and delineates the steps required along with a change in tariff design to increase the likelihood of consumer participation. The paper also identifies areas of future research on this theme. Unless specifically mentioned, we use the term "dynamic tariffs" or "time-varying tariffs" to refer to the dominant dynamic tariff designs shown in Table 1 [7].

The paper is structured as follows: Section 2 lays out the methodology used to identify the literature to be reviewed, Section 3 characterizes the identified literature, Section 4 presents a discussion of the reviewed literature with the recommendations drawn from it, and Section 5 concludes.

Table 1: Types of dynamic tariffs and their design features

Tariff design	Features
Time-of-day (ToD) or Time-of-use (ToU)	Pre-defined buckets of hours have higher or lower rates. Where two (peak and off-peak) or three (base, peak, and off-peak) different rates are applicable, they are referred to as two-tier or three-tier ToD/ToU tariffs, respectively.
Critical peak pricing (CPP)	Pre-defined high prices are imposed during severe system constraints or contingencies for a limited number of hours or days, such as during peak summer periods. CPP is usually an overlay on ToD or flat-rate tariffs.
Real-time pricing (RTP)	Retail prices can change hourly or more frequently based on the wholesale electricity prices on a day-ahead or hour-ahead basis.

Methodology

We identified 51 papers for the review using a three-step methodology (Figure 1).

Step 1: We did an initial search for academic papers having the keywords "dynamic tariffs," "dynamic electricity tariffs," "dynamic electricity pricing," and "time of use tariffs," among others, in their titles using Google Scholar. We limited our search to papers published in English in 2013-2023. We extracted 526 papers with the keywords in their title using the 'Publish or Perish' software [8] and removed 74 duplicate records.

Step 2: We retained papers from journals published by Elsevier, Springer, Wiley, SAGE, and MDPI to focus on high-quality, full-text published papers. We did two rounds of screening on this filtered set of articles. In the first screening, we included abstracts that indicated a clear focus on implementing rather than designing dynamic tariffs for residential consumers. Papers that focused on dynamic tariffs in the wholesale market were excluded. In the second round, we categorized studies based on the aspect of implementing dynamic tariffs that they focused on. This strategy yielded 62 papers for the full-text review relevant to our research question.

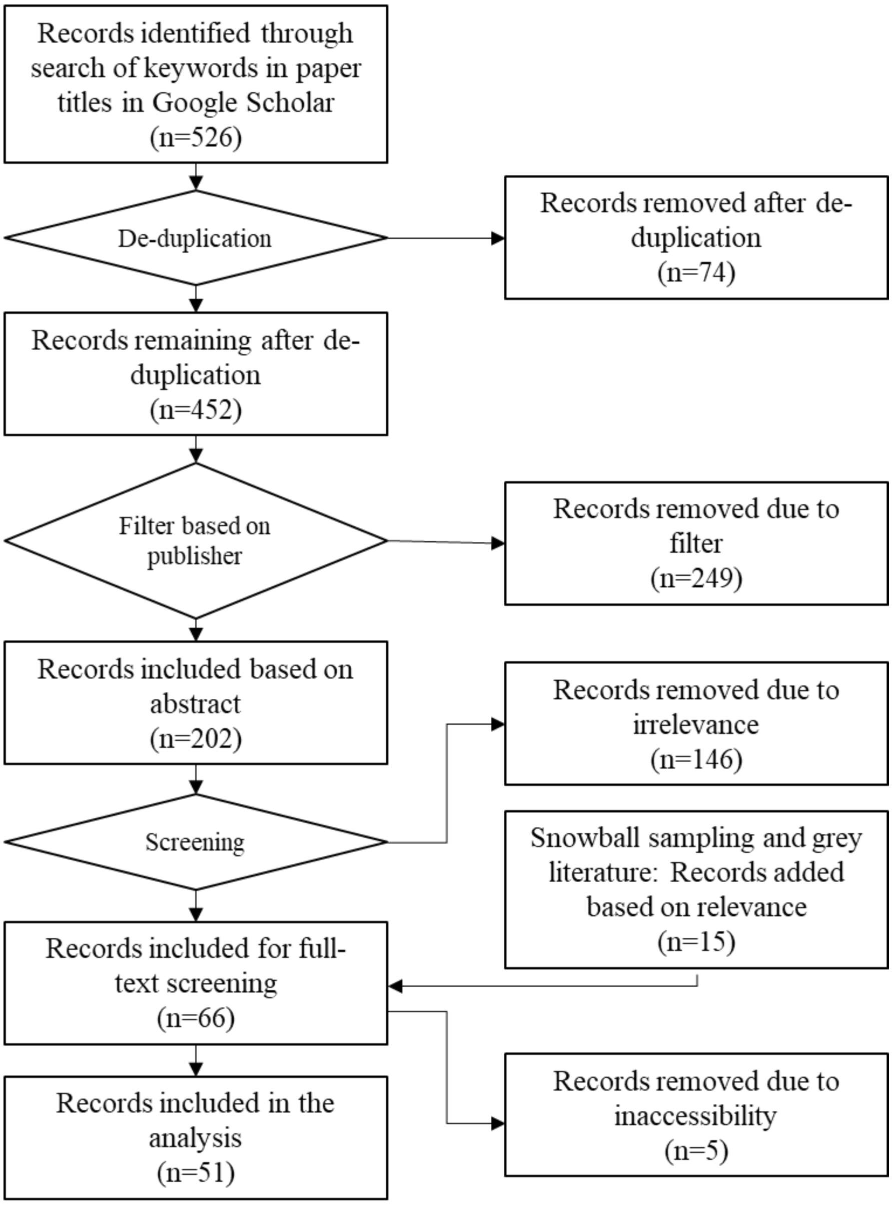

Figure 1: Methodology followed to identify papers for review

Step 3: We cross-checked our results with the database of the selected publishers and added the papers that were missed during the Google Scholar search due to the limitations of relying on Google Scholar alone. For example, Google Scholar shows only the first 1000 results and may return different results based on the timing of the search, limiting the search's reproducibility. We could not access five papers and added 15 papers obtained through snowball sampling, such as through the "related articles" option on Google Scholar, by referring to the citations of the selected papers, and by including relevant grey literature on India (see next section). We excluded papers that were found to be irrelevant during the full-text review from the final review.

Results

Geographical spread of empirical studies

Figure 2 shows the geographical spread of a sub-sample of reviewed papers based on field experiments, pilots, or modelling studies that use consumer data from a specific country. It excludes meta-analyses and literature reviews to avoid double counting and purely theoretical agent-based modelling studies. The geographical spread provides clues about the dominant sources of empirical data in the literature and the applicability of findings to Indian consumers.

Almost 40% of the included empirical studies are from Europe and North America. This may be because of the easier availability of consumer data from smart meters in the USA and European countries and a longer history of offering dynamic tariffs to retail consumers than in other regions [9]–[11]. Using English as the publication language as an inclusion criterion may have also affected the distribution across regions. Among Asian countries, Japan figures prominently in the literature, followed by India, China, and Korea. The validity of findings from studies based in developed countries in the Indian context needs to be carefully examined.

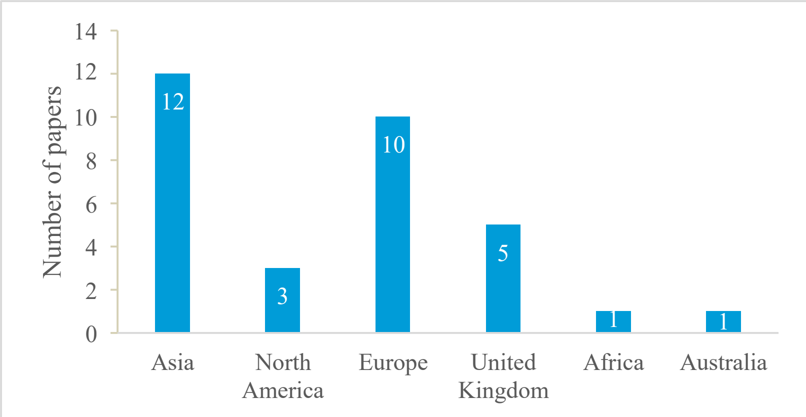

Figure 2: Geographical spread of included empirical studies.

Sparse literature on implementing dynamic tariffs in India

Academic literature from or based on India is sparse, with only four papers included in our review [12]–[15]. A simulation study [12] finds that a three-tier ToD tariff with net metering/feed-in tariffs could lead to zero cost of energy due to demand shift and the earning opportunity from selling energy to the grid. While the study finds a strong economic case for solar rooftop systems for residential consumers with ToD tariffs and net metering, it does not evaluate the impact of ToD tariffs on the economic case for solar rooftop systems by drawing a comparison with flat-rate tariffs. The study [13] conducted an experiment to assess the impact of dynamic pricing on off-grid solar systems and found that when electricity demand is low relative to the available supply, dynamic pricing would not be necessary and would not have the desired impact. Therefore, dynamic pricing for consumers who have higher peak demand would be more effective. The study [14] uses a discrete choice experiment to find that high-income consumers' willingness-to-adopt (WTA) a three-tier ToD is higher than for RTP and that environmental benefits are weaker decision influencers than bill savings and enhanced supply reliability. Finally, The study [15] is an interesting example of how discoms can optimize tariff structures for profit by forecasting consumer behaviour under a large number of potential tariff structures using advanced computational techniques.

Given the sparse academic literature in the Indian context, we also included grey literature in our search and found four more results [16]–[19]. The study [16] is an early report that explores the considerations in designing ToD tariffs and assumes that consumers would exhibit cost-minimizing behaviour under time-varying tariffs. However, a more recent survey of consumers in the study [19] shows that most consumers across categories declined to change consumption behaviour even if lower electricity rates were offered, indicating that cost minimization behaviour should not be assumed. Based on a review of 17 pilot projects globally, the study [17] recommended implementing pilots among consumers with homogenous consumption patterns to gather more information on the benefits and the required infrastructure. Similarly, based on a review of 82 papers, the study [18] stressed the importance of understanding the demand-price relationship and customer segmentation for implementing dynamic tariffs. However, it does not discuss how these variables impact consumer response to dynamic tariffs. Overall, the studies [17]–[19] reiterate the importance of enabling technology and the need for consumers to change their electricity consumption pattern but do not explore it in depth.

Methods used

Based on the review of the included studies, four important themes emerge for implementing dynamic tariffs for domestic consumers. The review documents the various methods and data that can be used to investigate questions related to these themes. Literature reviews on dynamic pricing have previously taken stock of developments and learnings as new technologies are deployed and more data becomes available. Choice experiments are a popular method to estimate consumers' WTA, preferences between types of dynamic tariffs, and the factors that influence these preferences. Pilots, experiments, and historical load data help to estimate or forecast how consumers change their behaviour in response to time-varying price signals. Algorithmic techniques, simulation studies, linear/mixed programming, and optimization models have been used to determine optimal schedules for loads, the information that can nudge consumers to shift loads, barriers to moving loads, and impact on bills.

Qualitative techniques such as interviews, surveys, and focus group discussions aid in identifying consumers' habits, practices, and lifestyles that influence their perceived ease of responding to dynamic tariffs and, therefore, the WTA and potential for load-shifting. Time use surveys comprise data on energy-related habits of households, including leisure, laundry, cooking, ironing, cleaning, etc., along with socio-demographic characteristics of households like occupancy, overall income, household type, employment status, etc. Table 2 presents these themes, the papers that address them, and the methods used.

Table 2: Methodologies used in the reviewed articles

Theme	Papers	Methods used
Segmentation of consumers and distributional effects	[12], [13], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34]	• Surveys, FGDs, simulation trials • Field experiment and/or statistical analysis on historical consumption data • Based on historical load data and time-use surveys • Sequence network analysis • Cost optimization through mixed linear integer programming • Analysis of tariff design through models calibrated using consumption data • Systematic review
Willingness-to-adopt	[14], [29], [35], [36], [37], [22], [38], [39], [40], [41], [42], [43], [44], [45], [46]	• Open source LORETTA model • Partial equilibrium model • Survey, interviews, mixed methods • Modelling appliance control • Choice experiments • Based on historical load data • Consumer cost optimization problem coupled with load flow calculations • Systematic review
Closing the intention-action gap	[22], [23], [20], [29], [37], [44], [47], [30], [48], [49], [50], [51], [52], [53], [54], [55]	• Survey and interviews • Statistical analysis of historical consumption data • Mixed integer linear or nonlinear programming • Choice experiments • Agent-based modelling/simulation • Modelling of appliance control • Deep Learning-based bi-level hybrid demand modelling framework • Systematic review
Consumer response to dynamic tariffs	[15], [22], [44], [34], [56], [57], [58], [59], [60]	• Survey and interviews • Permutation equivariance-enabled attention mechanism • Agent-based modelling/simulation • Field experiment and/or statistical analysis on historical consumption data • Utility functions of households to study subsistence during different hours

Important factors for implementing dynamic tariffs

Based on the literature, we divide each of the identified themes into factors that affect the implementation and uptake of and consumer response to dynamic tariffs.

Consumer segmentation and distributional effects

From an operational perspective, segmenting residential consumers is an important preliminary step to identify consumer groups that are likely to be able to shift load in response to price signals. From an economic perspective, segmentation helps estimate how a given dynamic tariff design would impact different kinds of consumers within the utility consumer base. The factors in this theme represent the *ex-ante* information about the consumer base used in the literature for segmentation and estimating distribution effects.

Income: Consumers across income levels are likely to be impacted by dynamic tariffs differently. For example, the study [21] found that a uniform ToU applied across the UK is expected to benefit high-income consumers in the urban area of London and low-income consumers in rural North East England due to divergent lifestyles. Consumers in poorer socio-economic areas respond less to different peak and off-peak prices [25], [31], which can result in an unfavourable perception of peak pricing by these consumers [38].

Education: Higher education levels positively correlate with the willingness to switch [23], [25], [40]. Beyond general education levels, the studies [30] and [32] find that consumers with lower levels of energy literacy do not opt for dynamic tariffs as they fail to understand their potential benefits. Energy literacy comprises the capacity to read and understand electricity bills and the extent of understanding the electricity market.

Household composition: Shifting energy use is likely to be more difficult for households with multiple members, households with children, and consumers with an inherent inflexibility in their tasks, such as child care or elder care [22], [26], [34], [44], [61]. These consumers would demonstrate a greater unwillingness or inability to shift their consumption across hours a day and could be disadvantaged by dynamic tariffs.

Grid characteristics and objectives: Depending upon the elasticity of consumption and rate of penetration of decentralized energy sources such as rooftop solar systems, the impact of dynamic tariffs on overall economic efficiency may vary [28]. Tariffs determine how consumers who own decentralized energy sources bear capacity, energy, and network charges versus those who do not. Therefore, the tariff design may vary depending on the utilities' objectives of promoting or limiting the uptake of decentralized energy.

Consumers' WTA dynamic tariffs

Even without wide adoption by consumers, dynamic tariffs can improve grid utilization, leading to a reduced need for grid expansion [46]. However, not adopting dynamic tariffs results in unrealized welfare gains [35] or increased tariffs for residential consumers in the long run [36]. A granular understanding of the reasons for not adopting dynamic tariffs can help chart a strategy to enhance adoption.

Tariff design: The choice between ToD, RTP, and CPP can affect consumers' decision to switch to a dynamic tariff. The study [20] found that the uptake of RTP across a sample of developed countries is 13% lower than ToU tariffs. Studies in Germany, Sweden, and the UK reveal a lower consumer preference for CPP and RTP than ToU [37], [41], [62]. In the Indian context, the study [14] also found a low preference for RTP in high-income households in Delhi. This is partly because dynamic tariffs are more complex than flat rate tariffs, adding to an individual's cognitive burden and decreasing their WTA [41], [48]. Some studies also report consumer preference for a three-tier tariff over a two-tier tariff [14], [20], [22].

Awareness: Higher awareness about the benefits of adopting dynamic tariffs can increase WTA. The expected reduction in power outages is a positive motivator for high-income Indian consumers to opt for time-varying tariffs even at a higher cost [14]. Positive environmental benefits, such as reductions in carbon emission at the system level, may effectively increase WTA among some consumers, even if it means diminished monetary benefits [43], [63].

Loss aversion: Loss aversion is when downward deviations from a reference point (mostly the status quo) are given a higher weightage than potential upward deviations [64]. A higher risk of bill increase or perception of loss in comfort results in a heightened tendency to maintain the status quo, i.e., not adopting a new tariff. 93% of billpayers were found to be loss-averse in a nationally representative sample survey of 2020 British energy billpayers [40].

Familiarisation: Given the factors discussed above, trials or pilots can aid in making consumers feel more confident about changing their energy consumption practices [44]. Providing incentives during pilots can drive energy-saving habit formation [57]. The importance of familiarisation is demonstrated by the fact that consumers in the UK who are already on two-tier ToU tariffs have a greater willingness to switch to other time-varying tariffs [29], [40].

Gap between willingness and action

A meta-analysis in the study [20] found that the median share of domestic consumers who expressed willingness to sign up for dynamic tariffs was five times higher than the median actual sign-up rates across studies. Therefore, despite expressing willingness to adopt a new tariff, obtaining a high uptake rate requires further interventions.

Decision lead time: An agent-based model in the study [51] showed that if more time elapses between consumers becoming aware of a new tariff and deciding to adopt it, the gap between willingness and adoption rates increases due to the action of other personnel, local and global factors such as feedback from peers and advertising. The model in the study [51] also shows that adoption of new tariffs is initially likely to happen in small clusters, which are essential to form a momentum for broader adoption. Thus, following a proposal of tariff change, reinforcement of the positive aspects of the new tariff would be required so that a positive opinion of the new tariff is sustained.

Switching mechanism: Utilities need to make a rollout decision of whether to keep the program as 'opt-in' or 'opt-out.' In implementation trials in various countries, opt-in recruitment led to uptake levels as low as 1% without any efforts on consumer engagement; uptake was higher (43%) with concerted efforts on awareness, promoting assistive technologies such as smart meters and thermostats, etc. [20]. In the case of an opt-out mechanism where a tariff becomes the default option, recruitment is likely to exceed 57% and go up to 100% [20].

Access to technologies: In case of multiple tariff options to select from, consumers may struggle to match tariffs to their electricity usage, resulting in sub-optimal decisions. Providing an easy-to-use digital tool that compares flat-rate and time-varying tariffs helps consumers make more informed choices [29], [48].

Consumer response under dynamic tariffs

Several dynamic tariff pilots observed peak demand reduction in the range of 13-35%, with higher reduction levels where enabling technology was provided [17]. ToU can also lead to a reduction in wholesale market prices if consumers respond. On average, with a 5% reduction in consumption by consumers during the base and peak tariff periods, retailers could reduce the energy price by 1.5%, increasing retailers' returns and lowering consumer tariffs [56]. Notwithstanding, there are limits to price-responsiveness by shifting activities from peak to off-peak periods for households, as the subsistence levels may be higher during the peak and need to be met regardless of the electricity price [60].

Appliance and dwelling characteristics: Actual response to price is higher for households with more appliances, more flexible appliances, and better-insulated houses that can maintain indoor temperatures without active energy use for longer [61]. Consumers that own energy-efficient appliances [25], electric vehicles [29], [40], [65], and flexible space conditioning devices like heat pumps with thermal storage [24] may be able to provide a steeper response to time-varying tariffs and save on their electricity bills. The evidence on ownership of solar rooftop systems is mixed. While the study [12] finds that solar rooftop systems are economic under ToD if demand is shifted to lower price periods, the study [31] does not observe any impact of solar photovoltaics' ownership on the difference between peak and off-peak consumption.

Access to information: The availability of timely and actionable information determines the extent of consumer response to tariffs. Real-time feedback on in-home displays with colour signals to indicate peak hours or display the electricity intensity of appliances is useful in the short run [30], [37], [44]. Reports that indicate the level of consumption relative to peers can prompt consumers to shift tasks in response to electricity tariffs [22]. Information assisting recall can also help. For example, suppose consumers recall that prices during peak hours are higher than the previous day. In that case, the reduction in energy consumption is greater than when prices are lower than the previous day [39]. Therefore, even after post-consumer enrolment, utilities must empower consumers to respond to tariffs by sharing relevant information.

Appliance automation and smart meters: Scheduling appliances help reduce the cognitive burden on consumers to shift demand and help achieve bill savings [27]. Appliances can be scheduled to meet objectives like minimizing peak load, minimizing bills, or ensuring thermal comfort [50], [53]. Home energy management systems or appliances like dynamic thermostats can help schedule appliances based on the nature of tasks and individual routines [49], [54]. Electricity suppliers can also use automation algorithms to account for consumer behaviour and offer optimal day-ahead prices [55]. In this context, smart meters are a critical technology. The study [34] demonstrates that smart meter data can be leveraged to predict load profiles based on historical load data, which can help design optimal prices. Table 3 summarises the themes and indicators extracted from the literature.

Table 3: Factors impacting the implementation of dynamic tariffs

Consumer segmentation and distributional effects	Consumer WTA	Intention-action gap	Consumer response
1. Income 2. Education 3. Household composition 4. Grid characteristics and objectives	1. Tariff design 2. Awareness of benefits 3. Loss aversion 4. Familiarisation	1. Decision lead time 2. Switching mechanism 3. Access to enabling technologies	1. Appliance and dwelling characteristics 2. Access to information 3. Automation and smart meters

Discussion

Each theme in Table 2 represents an important aspect of the effective implementation of dynamic tariffs, and each factor provides the information required to understand how it impacts implementation. It is obvious that some information should precede subsequent implementation steps. For example, utilities must determine the consumer category that can provide a price response before deciding on the switching mechanism to offer. Thus, we arrange the themes in a chronological sequence to propose a three-stage implementation framework for dynamic tariffs (Figure 3): (1) **Design** the tariff based on consumer segmentation, an assessment of distributional impacts, and consumers' WTA, (2) **Rollout** the designed tariff following consumer engagement and pilots using an appropriate switching mechanism, and (3) **Sustain** impact by improving tariff offerings and consumer empowerment through technology.

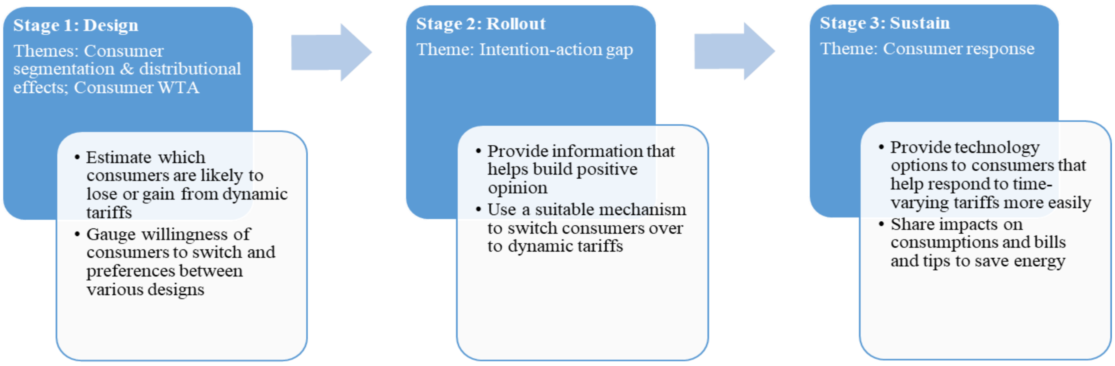

Figure 3: Three-stage implementation framework for residential dynamic tariffs

Stage 1: Design

In the first stage, discoms must determine the objective of implementing dynamic retail tariffs, the consumers to be targeted, and the appropriate tariff design. For example, is the objective to shift the load from peak hours to other hours on a regular basis or only to contain demand during extreme supply shortages? What are the policy targets for promoting the adoption of solar rooftop units or EVs? Accordingly, discoms must segment the consumer base for targeting and choose the appropriate tariff design. For example, which consumers primarily drive the peak demand and would change consumption behaviour under a ToD or CPP tariff? Or which consumers are expected to adopt solar rooftop units or EVs, and what price signals do they require to do so? Load research studies are critical to determine system-level objectives and carry out consumer segmentation. Demand-side data such as hourly load profiles, sanctioned load, and billing demand can be used to identify seasonal and daily peaks and the consumers driving the peak. This must be combined with supply-side data on the power supply position and costs to estimate the appropriate tariffs for cost recovery [66], [67].

Once a suitable tariff type is chosen and cost-reflective prices are estimated, discoms should map its potential impacts on the consumer base. Consequences may vary based on the characteristics of its consumer base, such as income and education levels, family sizes and habits, weather across its control area, etc. Expected gains and losses and consumers' perception of them are essential in communicating with consumers and getting their buy-in.

While existing consumption slabs and data may help in the segmentation process, discoms may have to overlay information from other sources, such as time-use surveys, to design the finer features of tariffs, for example, the number of tiers in a ToD tariff. Time-use surveys can help generate synthetic demand profiles of various types of consumers, map the impact of electricity prices, and identify the activities that need to be shifted or reduced to respond to time-varying tariffs. Forty countries have carried out time-use surveys at a national scale [68], including India [69]. Consumer's WTA has to be determined to estimate the likelihood of consumer uptake of dynamic tariffs. Information obtained during segmentation can help design samples for a WTA exercise, such as through choice experiments. Estimating WTA would also provide critical insights into consumers' perceptions of dynamic tariffs. For example, do consumers prefer a two- or three-tier ToD, or is CPP perceived to be more complex and riskier than ToD due to loss aversion? Finally, discoms may have to conduct pilots among homogenous consumer groups to collect detailed information on the effectiveness of tariff designs and increase consumers' familiarity with time-varying tariffs.

Stage 2: Rollout

Based on the information gathered for design, discoms should focus on consumer engagement since high WTA for dynamic tariffs may not translate into high recruitment rates. Engagement should help consumers form and sustain a positive opinion about the proposed tariff design by assisting them in understanding it and communicating its potential benefits. Information about the characteristics of the consumer base gathered during stage 1 can help design engagement strategies, which can be tailored for the different consumer segments and emphasize various benefits, such as bill savings, environmental benefits, reduced power outages, etc. Pilot projects can be used to familiarise consumers with the new tariff. The option to switch to the new tariff should follow at a time such that enough consumers have formed a positive opinion about the new tariff. The switching needs to manage the trade-off in making the process easier for consumers and garnering wider consumer acceptance. Once a few clusters of uptake are formed, social comparisons, such as through home energy reports [70], can be used to facilitate wider uptake. The dissipation of reliable and helpful information about the tariff is even more important in cases where consumers distrust the discom due to unreliable power supply [71].

Stage 3: Sustain

The final stage is ensuring demand response via continuous engagement and leveraging technologies. Consumers who already own energy-efficient appliances, EVs, and better-insulated homes are likely to modulate demand in response to price signals. Consumer engagement in this stage should focus on providing tips and strategies to consumers that can help them use these assets to benefit from dynamic tariffs. Response strategies include 'recrafting' how practices are done to reduce their energy intensity, like using gas for cooking during peak hours instead of electricity, 'substituting' unsustainable practices with more sustainable ones, like using a thermos to keep tea hot, and 'changing how practices interlock' or changing practice sequencing through automation [59], [72]. Technologies that provide feedback, such as in-home displays and digital comparison tools, also enable consumers to respond to dynamic tariffs comfortably and should form the focus of subsequent DSM strategies by discoms.

Conclusion

This paper has provided a three-stage framework for a sustainable and effective implementation of dynamic tariffs for residential consumers. Since residential consumers are not a homogenous category, a deeper understanding of the willingness of consumers to adopt dynamic tariffs and their impacts on consumers is important. Regular and robust load research studies can help the discoms identify the appropriate tariff design. The proposed framework can help target the consumer segments that drive peak demand, make dynamic tariffs more palatable for consumers, and, where required, provide bill protection. Beyond installing smart meters, regulators and discoms need to understand consumer preferences and attitudes and cater to these via information and technology to ensure dynamic tariffs are acceptable.

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Learnings from Thermal Comfort Adaptation of Jain Ascetics During Heat Waves

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Highlights

- Severe heat waves are affecting a large vulnerable population in India, impacting their health and well-being.
- The Jain monks and nuns in India have been leading their lives without electricity use for hundreds of years.
- This study went beyond the India Model for Adaptive Comfort range for indoor operative temperatures.
- 90% of the surveyed subjects expressed acceptability of the thermal conditions in the strong heat stress range. of UTCI
- Improved adaptive thermal comfort range can help bring down the cooling related energy consumption significantly.

Abstract

Climate change is leading to severe heat waves in India, affecting a large vulnerable population and impacting their health and well-being. The recent adaptive thermal comfort research for Indian climates suggested that the people living in residential buildings can adapt to indoor temperatures upto 35 °C. The Jain ascetics in India have been leading their life without the use of electricity for hundreds of years, irrespective of the temperatures. In this study, thermal comfort surveys with 20 monks and nuns were carried out during summer for the composite climate of Delhi. 90% of the subjects expressed acceptability of the thermal conditions while the indoor operative temperatures varied between 35 °C and 40 °C. This study should offer hope to people globally that if we can gradually adapt to the rising temperatures, we may be able to move on with our lives without affecting our comfort or health.

Keywords: Adaptive thermal comfort, ascetics, UTCI, health and wellness, heat waves

Introduction

Climate change is leading to severe heat waves in India, with higher temperatures that arrive earlier and last longer in recent times [1]. These heat waves could break the human survivability limit in the coming years. More than two-thirds of the Indian population earns less than USD 2 per day, and it may not be able to afford active cooling. Temperatures beyond the thermal comfort range [2] could result in extreme heat stress and severely affect the health and well-being of individuals. Even those who may be able to afford active cooling solutions may suffer from sick building syndrome with the use of cooling systems such as split air-conditioners, as these systems reduce the fresh air delivery in indoor spaces.

The science to combat climate change for energy use in buildings the world over has focussed broadly on the three principles of passive solar architecture, energy efficiency of equipment, and using clean sources of energy [3]. The science should also urge people to reduce energy consumption, which is also related to UN sustainable development goal no. 12 of “Responsible consumption and production” [4]. Prof Chetan Singh Solanki [5] recently suggested that human beings should avoid one-third of their energy consumption by changing their lifestyles. The Jain monks and nuns in India have been leading their lives without the use of energy for thermal comfort for hundreds of years [6]. In an experiment carried out on Tibetan monks by Mind/Body Medical Institute at Beth Israel Deaconess Medical Centre in Boston [7], the monks performed G Tummo meditation and were able to dry up ice-cold water sheets from the heat being radiated from the monk’s body. G tummo yoga technique trains the mind to regulate the internal body temperature to attain thermal comfort. Wim Hof [8] has also designed a self-tested three-step method – breathing, cold therapy and commitment to adapt to extreme cold conditions and the same is taught to other individuals.

People feel thermally comfortable in buildings when they don't feel hot or cold. ISO standard 7730 definition [9] suggests thermal comfort to be the "condition of mind which expresses satisfaction with the thermal environment". It is assessed using subjective evaluation in the form of surveys about a person feeling hot or cold [10]. Two types of approaches to thermal comfort have been studied over the past decades - the heat balance and the adaptive thermal comfort approach. The heat balance approach was led by Prof Fanger [2] in the early 1970s. It is based on climate chamber experiments and indicates that the thermal sensation is related to the thermal load on the human thermoregulatory system. It helps the HVAC engineers to design the optimum thermal environment by working with air temperature, humidity, mean radiant temperature and air speed. The concerns with this approach have been about the chamber experiments not reflecting the real world experience of the occupant or taking into account the cultural, climatic, and social contexts of the occupants. Moreover, this approach relies on mechanical ventilation systems to provide thermal comfort, which is energy-intensive [11]. The adaptive thermal comfort approach suggests that the past thermal history and context can influence occupants' thermal preferences. People living in warmer climates would prefer higher indoor temperatures than cold climatic zones. The thermal adaptation lessens the human response to continuous environmental stimulation. It can be behavioural (clothing, windows), physiological (acclimatization), and psychological (cultural and social context) [12]. The perception can also vary depending on whether the buildings are naturally ventilated, air-conditioned, or in mixed mode. This approach helps with reducing the need of energy for heating and cooling, thereby helping with the issue of global warming. This approach has been based on field studies using regression models relating the indoor temperature as a function of outdoor air temperature. India's model of adaptive thermal comfort (IMAC) was developed based on the adaptive thermal comfort model [13]. It was based on field surveys in three seasons and five different climatic zones of India. It found that the occupants in naturally ventilated offices in India were more adaptive than the existing ASHRAE and EN models. It found the neutral temperature in naturally ventilated buildings to vary from 19.6 to 28.5 °C for 30-day outdoor running, with mean air temperatures ranging from 12.5 to 31 °C. Another adaptive model was constructed for Indian residences – the India Model for Adaptive Comfort - Residential (IMAC-R) based on year-long field surveys across five climate zones of India [14]. It found that more than 80% of the residential occupants in India experienced a neutral temperature in the indoor temperature range of 16.3–35 °C for a 5.5–33 °C variation in the 30-day outdoor running mean temperature.

There have been limited studies of people being able to withstand colder temperatures wilfully without any active means of heating and no scientific studies of people being able to withstand higher temperatures beyond the adaptive thermal comfort range to the best of our knowledge. In this paper, we would like to study the adaptive thermal comfort-based lifestyles of Jain monks and nuns to learn from them. Why do they live without the use of any energy for heating or cooling? How are they able to persevere? Is the wider thermal comfort range acceptable to them? Do they feel uncomfortable? Is it possible to have a higher adaptive thermal comfort range for Indians than what is suggested by IMAC-R? This research would help the vulnerable populations in India to increase their adaptive thermal comfort range thereby helping them to be in a better situation to sustain the effects of heat waves. It would also help the world in general to reduce the consumption-based lifestyles [15].

Methods

The research design, field surveys, and data analysis are based on the ASHRAE RP-884 document [12]. This paper is based on the data collected over a survey campaign in residential buildings in the composite climate of Delhi [14], lasting for two consecutive days in the month of May, which has hot and dry weather. The surveys were administered in naturally ventilated buildings. The subjects were interviewed in six buildings, with three of them being multi-storied residential buildings and three of them being Jain Sthanaks, buildings specially designed for the stay of Jain monks and nuns. The Jain Sthanaks have been designed for natural ventilation and have higher window to wall ratios, typically over 65%. The building material for the Jain Sthanak appeared to be similar to that of other typical buildings.

The thermal comfort point in time surveys were based on the surveys in [14] and were conducted with occupants to have responses from them about their thermal sensation vote, thermal preference vote, thermal acceptance vote, air movement acceptance vote, air movement preference vote, and overall comfort. The surveys also had questions about their age, gender, weight, height, and activity 15, 30 and 60 minutes before the survey. Building information was also sought. Indoor

Table 1: Instrumentation details

Device	Indoor parameters	Range	Accuracy	Resolution
Testo 400 CO_2 probes	CO_2 (ppm)	0-10000 ppm	±(50 ppm + 3 % of mv) (0 to 5000 ppm) ±(100 ppm + 5 % of mv) (5001 to 10000 ppm)	1 ppm
Testo 400 CO_2 probes	Air Temperature (℃)	0 to 50 ℃	±0.5 ℃	0.1 ℃
Testo 400 CO_2 probes	Relative Humidity (%)	5 to 95 %	±3 %rH (10 to 35 %rH) ±2 %rH (35 to 65 %rH) long-term stability: ±1 %RH/ year Hysteresis: ±1.0 %rH ±3 %rH (65 to 90 %rH) ±5 %rH (Remaining Range) ±0.06 %RH/K (0 to +50 °C)	0.10%
Testo 400 hot wire probe	Air velocity (m/s)	0 to 50 m/s	±(0.03 m/s + 4 % of mv) for (0 to 20 m/s) ±(0.5 m/s + 5 % of mv) for (20.01 to 30 m/s)	0.01 m/s
Testo 400 globe	Globe Temperature (℃)	0 to 120 ℃	Type K thermocouple, class1. Approximately 30 minutes adjustment time	0.1 ℃

climate measurements were recorded using hand-held devices placed near the occupant while the survey response was taken, meaning that each set of measurements was spatio-temporally coincident with the occupant's location. All instruments were ensured of calibration before each campaign. Table 1 provides details of the sensors used for measurement. Testo 400 transmitter was used with 2 wireless Testo CO_2 probes that measured CO_2, air temperature, and Rh, another wired Testo probe measured globe temperature, and two other wireless Testo probes measured air speed. The average value of the measurements was taken for each parameter. ASHRAE Standard 55-2017 [10] methodology was used for operative temperature calculations. Meteorological data for air temperature and relative humidity was publicly available and was obtained from the closest Central Pollution Control Board (CPCB) Air Quality Monitoring Station (AQMS) in Rohini, Delhi, to the sites for the TCS surveys. The CPCB AQMS was about 5 km away from the sites. The raw data was checked for errors, after which the survey responses and the measured sensor data were merged using a time stamp to create a single row of data corresponding to each subject. This led to one set (row) per survey of results in the final data matrix which was used for the thermal comfort analysis. PMV, PPD thermal comfort indices for each survey entry were calculated using the ASHRAE Thermal Comfort Tool developed by UC Berkeley [16] with indoor air temperature, relative humidity, mean radiant temperature, air speed, clothing insulation, and metabolic rate as the inputs. The UTCI thermal comfort index was computed using the UTCI calculator [17].

Results and Discussion

The interviewed subjects were monks and nuns from the Jain Sthanakvasi sect of Shvetambara Jainism [18]. The subjects had vowed not to use any electricity from the time of their monkhood. The average years of monkhood in the subjects was 24 years. The monks and nuns wear white clothes, as shown in Figure 1. The clo values for the clothing for the monks were interpolated from the clo values for the existing garments from ASHRAE Standard 55-2017 and were assumed to be 0.54 clo for monks. The clo values for nuns was assumed to be 0.62 based on the research done for finding clo values for an Indian sari [19]. The checklist of activities was provided in the TCS form to document the subjects' activities in the hour preceding the survey, divided into three time brackets of 15/30/60 minutes before the interview. Most of the subjects were sitting for most of the time before the interview. Some of them were standing, walking, or washing utensils or clothes during or before the interview. The activities were translated into metabolic rates based on the tables published in ASHRAE Standard 55-2017.

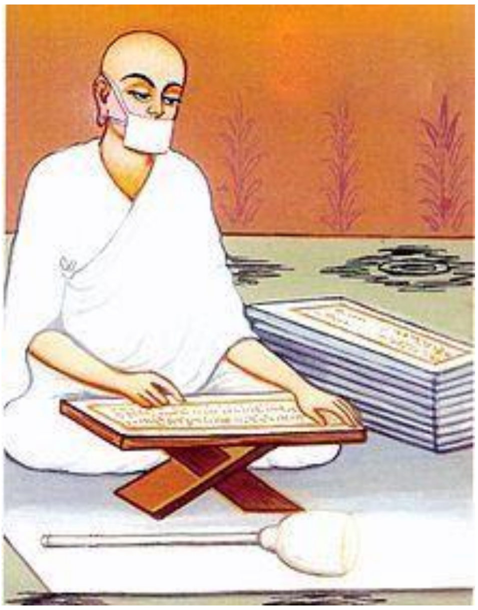

Figure 1: Painting of a Jain Sthanakvasi Monk [18]

The thermal comfort surveys (TCS) and the measurements of indoor climate parameters of the monks and nuns surveyed went hand in hand. The measured parameters included air temperature, relative humidity, and air speed. The globe temperature was measured for the first case, and it was found to be similar to the air temperature so it wasn't measured for the rest of the surveys as there seemed to be a general absence of sources of radiation across all the buildings surveyed. For the indoor spaces where there is no direct solar radiation coming from the survey location, the mean radiant temperature can be assumed to be equal to the air temperature. A brief interview was also conducted with the willing monks and nuns to understand how they managed thermal comfort over the past five years since they didn't use any electricity, irrespective of the weather conditions. A total of 20 TCS were gathered from 6 buildings. Of the 20 TCS, 11 were gathered from monks and 9 from nuns. Table 2 describes the surveyed residential buildings. All the subjects were staying on a higher floor of the building. The survey campaign lasted for two days during a heat wave condition in Delhi. 9 out of 20 subjects were females in the age groups of 22 to 64 years. 11 out of 20 subjects were males in the age groups of 18 to 84 years. The BMI of the subjects varied between 18 and 33. The surveys were conducted during the morning, afternoon, and evening, with the majority of them during the afternoon.

For both days of the survey campaign, three researchers were involved. The team approached the willing occupants and asked if the time was convenient for the survey. Two of the researchers interviewed the monks and the nuns for the instantaneous survey and the long-term thermal comfort management, while the other researcher took environmental measurements as close to the position of the respondent as feasible. Additional information about the building was also recorded, and the respondent's location was marked on the floor plan.

Table 2: Description of surveyed residential buildings

Building type	Floor	Surveyed Monks	Surveyed Nuns	Total subjects surveyed	Survey Time	Survey Date
Multi-storied residential building	Second	3	2	5	3:15 pm to 5:15 pm	22nd May 2023
Jain Sthanak	Second	0	3	3	7:15 pm to 7:45 pm	22nd May 2023
Multi-storied residential building	Second	1	2	3	10:30 am to 11:15 am	23rd May 2023
Jain Sthanak	Second	4	0	4	1 pm to 2 pm	23rd May 2023
Jain Sthanak	First	3	0	3	3:30 pm to 4:45 pm	23rd May 2023
Multi-storied residential building	First	0	2	2	6:15 pm to 6:35 pm	23rd May 2023

The surveys happened during the heat wave in Delhi. Figure 2 shows the outdoor air temperature and the outdoor relative humidity variation for the days of the survey. The minimum outdoor air temperature was calculated as 27.4℃, the mean as 37.5 ℃, and the maximum as 43.5℃. The minimum outdoor relative humidity was recorded as 26.1%, the mean as 31.6%, and the maximum as 56.6%. The weather in the evening of 23rd May 2023 became windy with higher chances of rain, which cooled down the temperatures. The minimum indoor operative temperature was calculated as 35.1℃, the mean as 37.7 ℃, and the maximum as 39.9℃. The minimum indoor relative humidity was recorded as 23.8%, the mean as 32.7%, and the maximum as 41.7%. The indoor air velocity was below 0.2 m/s for 95% of the cases since the fans were not used. For most of the cases, the indoor operative temperature was below the outdoor air temperature.

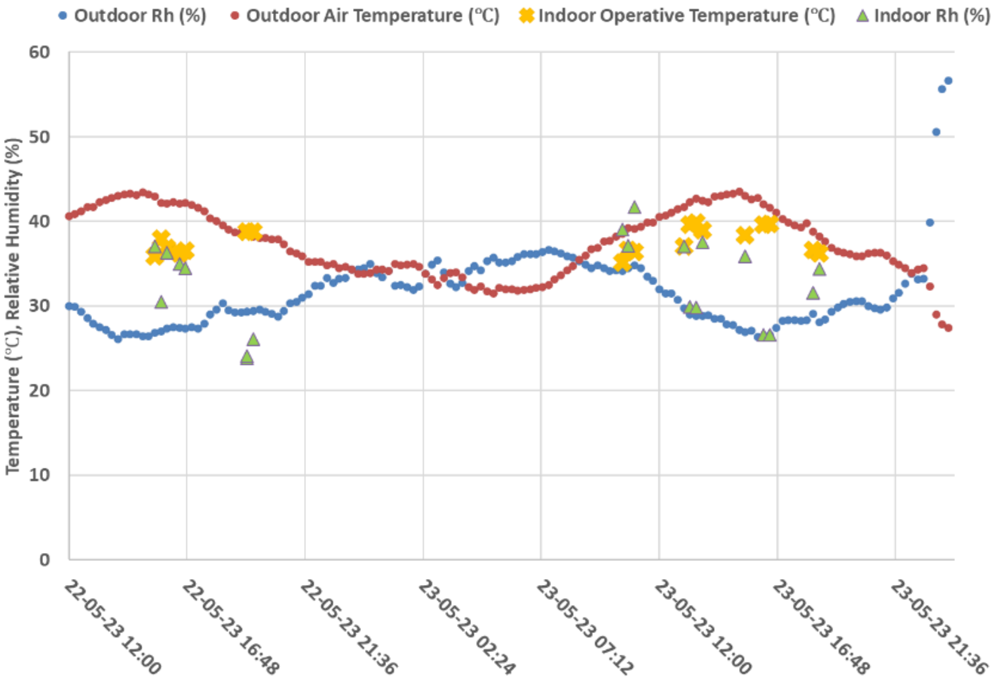

Figure 2: Indoor and outdoor temperature and relative humidity data

Figure 3 shows the results from the TCS point in time survey when the indoor operative temperatures ranged from 35 ℃ to 40 ℃. 60% of them expressed a neutral thermal sensation (Figure 3(a)), with 45% of them suggesting no change in thermal preference (Figure 3(b)) and 90% of them finding the thermal conditions to be acceptable (Figure 3(c)).

PMV was computed using the Berkeley thermal comfort tool, with the minimum PMV being 1.8, the mean PMV being 3.7, and the maximum PMV being 4.6. The percentage of people dissatisfied (PPD) was above 98% for 90% of the subjects. Figure 4 shows that the calculated PMV had a statistically significant non-zero slope in the equation with the indoor operative temperature (T_{op}). Figure 4 also shows that the observed TSV had a zero slope in the equation with T_{op}. 30-day outdoor running mean temperature ($T_{out\text{-}30DRM}$) was computed with $\alpha = 0.8$ [14]. The neutral temperature was computed by using those indoor operative temperatures for TSV=0 and performing a linear regression with $T_{out\text{-}30DRM}$.

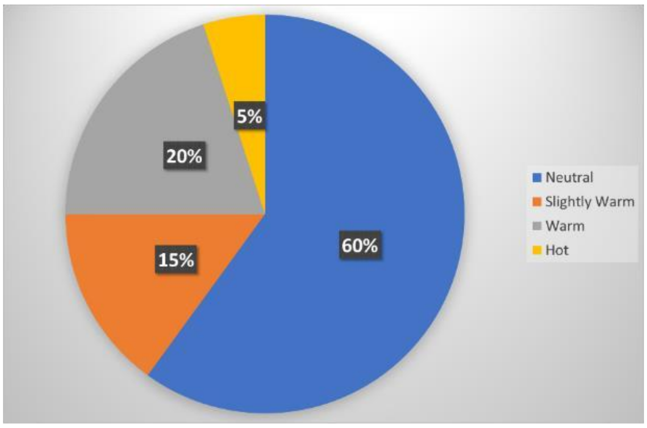

Figure 3(a): Thermal Sensation Votes (TSV)

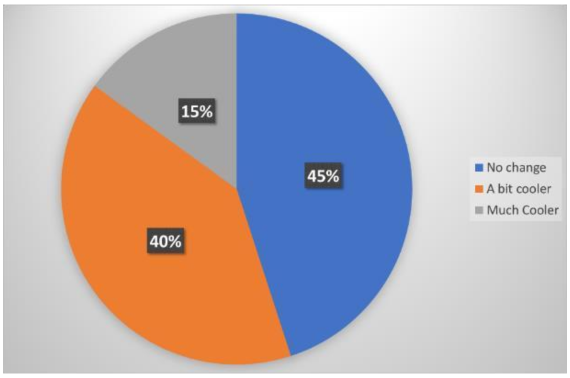

Figure 3(b): Thermal Preference Votes (TPV)

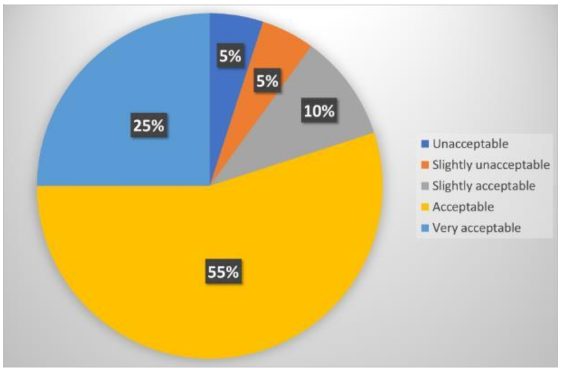

Figure 3(c): Thermal Acceptability Votes (TAV)

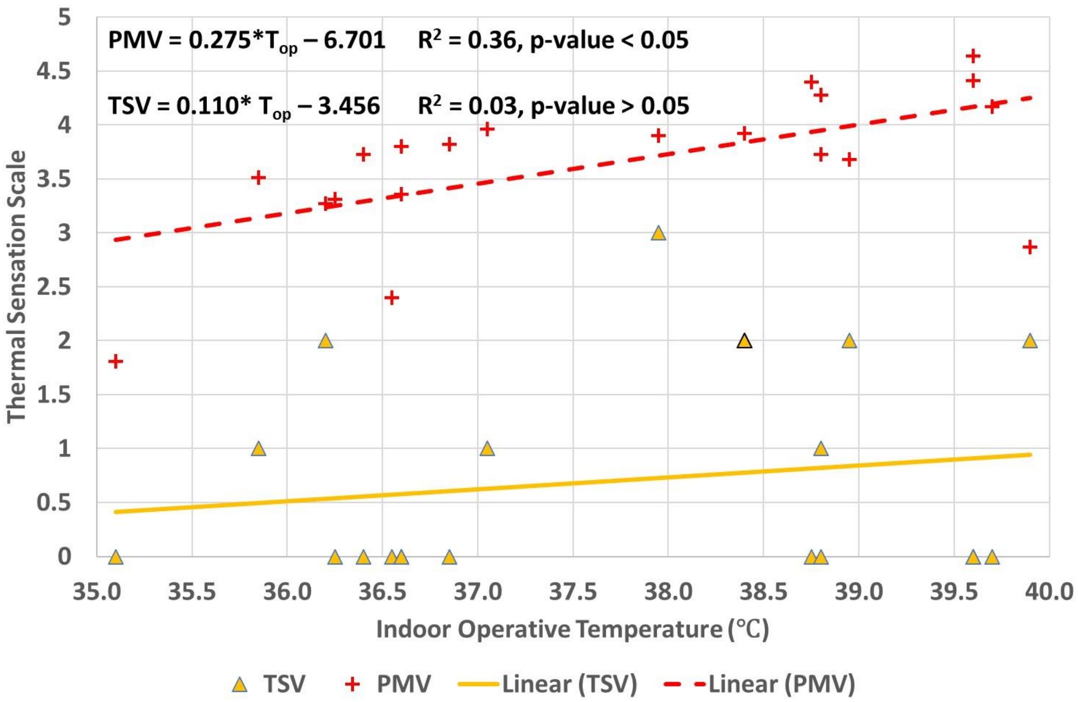

Figure 4: Comparing observed TSV and calculated PMV with Indoor Operative Temperature

Figure 5 shows that the adaptive thermal comfort model with the neutral temperature as a function of $T_{out\text{-}30DRM}$ is not statistically significant with a zero slope. Figure 6 shows the points on the UTCI vs. TSV graph marked separately for monks and nuns. Most of the subjects expressed a neutral thermal sensation even though the UTCI was in the range of strong to very strong heat stress.

IMAC-R model [14] suggests that 80% or more occupants from Indian residential buildings in naturally ventilated or mixed mode buildings felt a neutral thermal sensation for the indoor operative temperature of 16.3–35 °C for a 5.5–33 °C variation in the 30-day outdoor running mean temperature. Our survey data for neutral thermal sensation for indoor operative temperatures (Figure 5) from 35.1 °C to 39.7 °C is beyond the range of the IMAC-R adaptive thermal comfort model. One of the two data points for the outdoor running mean temperature is also greater than 33 °C. But observing the data for $T_{out\text{-}30DRM}$ of 32.6 °C, we are able to find 4 out of 8 cases having a neutral thermal sensation for a T_{op} up to 38.8 °C. Figure 4 shows that the linear regression model of TSV as a function of T_{op} had a zero slope since there were many neutral thermal sensation points among the data. On the contrary, the PMV predicted a thermal sensation beyond 3 ('Hot') for 17 out of the 20 subjects. PMV underpredicted the adaptability of the subjects significantly when compared to TSV. The UTCI, which takes into account the effect of air temperature, mean radiant temperature, relative humidity, and air speed for the neutral thermal sensation, also ranged in the strong to very strong heat stress range (Figure 6), suggesting that there is scope to work on the UTCI index for subjects from tropical climates.

We may wonder why we are getting neutral thermal sensations for these subjects in the strong heat stress range. We may want to think of these subjects as the exceptions not falling in the 80% acceptability range of the adaptive thermal comfort model with them being more adaptive thermally. The surveyed Jain monks and nuns have vowed not to use electricity from monkhood, and so they must have gone through behavioural, psychological, and physiological adaptation over the years. When asked the question about the thermal sensation they had for the present temperature corresponding to their TSV, some of them said that they remain equanimous no matter what the thermal conditions are. In our case, equanimity would translate to a neutral thermal sensation. They have been living without electricity for many years so they must have become acclimatized physically and accustomed psychologically. During a survey, one of them mentioned that 50-60 years ago, many villages in India didn't have access to electricity, and people lived comfortably without it. The heat waves and urbanization may not have been so intense earlier, but it did get hot in the hot and dry climates of India. A couple of them also mentioned that due to past health conditions, they are not able to withstand so much heat. Others said that mentally, they are neutral with the thermal sensation, but physiologically, they did feel slightly warm or warm. They said that physiologically, they have similar experiences as the rest of us, but psychologically, they are more adaptive. However, we can also think of these subjects as an inspiration to the country and the world to improve our thermal adaptation.

The ascetics have taken it as a constraint to live in sync with nature and not use any electricity. Within this constraint, they explore behavioural adaptation methods to feel better, such as moving to a room that is cooler in a building or going to a place that is breezy, or using the evaporative cooling from a wet cloth put on the body when it gets hot. Some of the subjects suggested that the use of a wet cloth for cooling was typically done during the night time to get a better sleep. The ascetics also preferred to stay on higher floors of the building as there is a greater probability of the higher floors being airy. The Jain Sthanaks, where the ascetics prefer to stay, have a much higher window-to-wall ratio, typically 65% or higher. Some of the Sthanaks had such high window-to-wall ratios on two or more facades. This building architecture

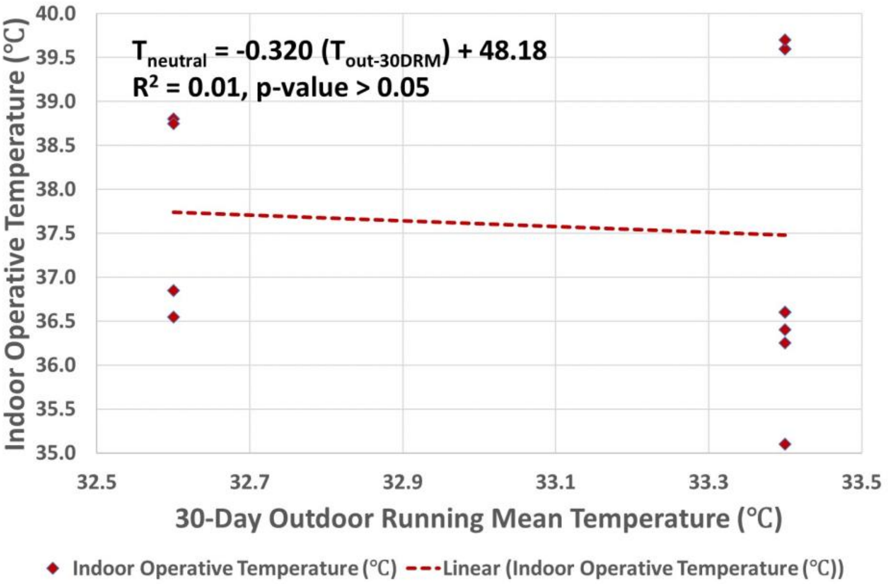

Figure 5: The adaptive thermal comfort model with neutral temperature = f($T_{out\text{-}30DRM}$)

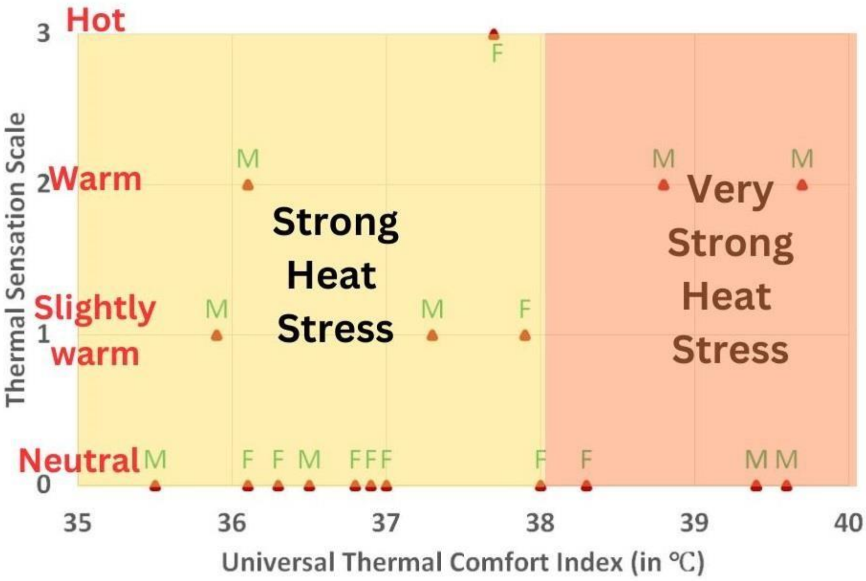

Figure 6: TSV vs. UTCI for monks and nuns

leads to higher cross-ventilation rates and may help them with higher comfort levels without the need of energy. It raises a question about the architecture of the buildings designed for air-conditioning. These buildings would have lower window-to-wall ratios to reduce the cooling loads, and it may be more difficult to operate them in natural ventilation mode. Further studies are suggested to compare the impact of window-to-wall ratios on the thermal comfort of the occupants.

These behavioural adaptations can help the vulnerable populations in India to adapt to the heat waves when they can't afford active cooling. The vulnerable populations would include the poor people suffering from the heat waves amidst the increased urban heat island effect due to rapid urbanization in India. It would also include the labourers who have to work in hot temperature conditions without access to cooling. It could also include the prisoners who may not have access to thermal comfort for cooling. This can also help the folks living in the colder climates in the West to know that there are human beings who can withstand higher temperatures in the heat stress range comfortably. Increased thermal adaptation can bring energy consumption down to meet the world's cooling needs. The research scholars conducting the surveys also felt that they were surprised that they could withstand such a high temperature without even the use of fans. Not using the fans is another notable difference from the IMAC-R model, where the air speed from the fans would have helped the subjects to be comfortable. They only get higher air speed due to the occasional wind from the windows. The survey was done during the heat wave, and during this time of the year, the wind that comes during the day time is hot, which doesn't provide comfort, so most of the surveyed subjects didn't prefer the wind.

This study also shows how significant the effect of culture can be in adaptive thermal comfort. One of the principles followed by the Jain ascetics is not to harm any living beings or the environment. They think that using electricity harms living beings. This vow helps them with improving their adaptive thermal comfort. On a minor note, it also can create discomfort for some of them. One of the nuns said that it can be more discomfortable during the night time over day time during this time of the year. The reason is that during this time of the year, there are insects affecting their sleep. Since culturally they wouldn't kill them so, some of them would use mosquito nets to prevent insects from biting them. This, however, reduces the airflow to them and makes it uncomfortable for them to sleep. It is important to have a way to make these measurements during the night time as well as to capture the thermal sensations at that time. A monk suggested doing an outdoor thermal comfort study with them since that might be more intense since they walk barefoot. They don't cook their food and some of them have to go out barefoot and walk on the hot asphalt roads during the days in the summer to get their food. They also don't cover their heads while walking in the summer sun in north India, so they would be experiencing high mean radiant temperatures due to the effect of the sun. Studying their outdoor thermal comfort can help understand their adaptation amidst high mean radiant temperatures and high metabolic rates. It is also worth noting that the Jain ascetics eat lacto-vegetarian food that they get from their households. They don't keep leftover portions for the night, so they tend to take smaller portions of food per person. They also tend to fast more often. It would be worth studying the impact of their food intake on their thermal comfort in the future.

While the lifestyle of these ascetics is inspiring, can we generalize the results we have achieved to the larger population of India, having diverse lifestyles interlinked with varied cultural and religious backgrounds? For instance, the food intake and the activities of vulnerable groups such as labourers may be quite different, so an in-depth study would be needed to find out how the lifestyles of these ascetics would help the other population groups to improve their thermal adaptation. This study was the first step to find out through scientific methods if they lead an extremely adaptive thermal comfort based lifestyle by correlating the TCS and the interview scripts with actual measurements. As a next step, we need to have a bigger sample size and study these subjects in other seasons as well to have an informed understanding of their adaptation. After that, we can conduct experiments with typical people in controlled conditions after letting them know about the lifestyle of these ascetics. Based on the findings from these experiments in controlled conditions, TCS could be performed in the field where people actually live their lifestyles in the real world. These people could be introduced to some of these behavioural and psychological adaptations of the ascetics before the survey, and they could be observed longitudinally to find out if they are able to adapt better than before. However, it is possible that the ascetics living a lifestyle of choice of not using energy may not work for the vulnerable population with a lifestyle that is "given" to them. Even the people who can afford cooling may not be able to get rid of mechanical cooling altogether, but it is possible that they may be able to reduce their cooling needs from before. It might be difficult for people who can afford air-conditioning to give it up as opposed to our grandparents who lived in times when it didn't exist. When the ascetics were asked for advice on how other people could reduce their cooling needs, some of them suggested that they could start by reducing their cooling needs by 5%, and then, depending on their adaptation, they could keep on widening their thermal comfort range. The objective of this study is not to interfere in the lifestyles of people but to take cues from these findings to know what is possible to improve adaptation and reduce energy consumption since climate change is a serious concern, and we have to explore all the ways that can help.

Conclusion

This study helped in understanding the thermal comfort adaptation in the heat wave conditions of Jain monks and nuns. Their thermal comfort was in the heat stress range as per the present thermal comfort indices. The sample size for this study was 20, and the study was done in the composite climate of Delhi during the hot and dry summer days. Future studies should be done to capture the effect of monsoon and winter on their thermal comfort indoors as well as outdoors. These studies should also be conducted in other climates of India with them. This study would also open doors for exploring other aspects of their lifestyles and comparing them with people leading a conventional life through the life cycle assessment framework to help the majority of our population to find sustainable ways of living through scientific understanding. It is also suggested to study other communities and professionals who undergo thermal adaptation and learn from them. The objective of this study was to show that it was humanly possible in the present times to have a neutral thermal sensation during heat waves in tropical cities such as Delhi when the cooling demand is much higher. It should offer hope to people from all around the world that if we can gradually adapt to the rising temperatures, we may be able to move on with our lives without it affecting our comfort or health.

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Nomenclature

BMI: Body Mass Index

PMV: Predicted Mean Vote

PPD: Percent People Dissatisfied

TAV: Thermal Acceptability Vote

TCS: Thermal Comfort Surveys

TSV: Thermal Sensation Vote

TPV: Thermal Preference Vote

Top: Indoor operative temperature

$T_{out-30DRM}$: 30 day outdoor running mean temperature

UTCI: Universal Thermal Climate Index

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Market Transformation in Energy Efficiency: A Success Story of the MSME Sector in India

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Highlights

- Successful models for scaling up energy efficient technologies in the MSMEs
- Cost reduction- Bulk procurement
- Model for scale-up and replication

Abstract

This paper illustrates successful cases of financing through bulk procurement for the scale-up of standard energy-efficient technologies in the MSME sector via innovative business models. The study analyses success factors and implementation methods seen in the UNIDO-EESL-MoSME programme “Promoting Market Transformation for Energy Efficiency in the MSME Sector” under GEF-5 and will highlight its achievements, with Surat and Jorhat clusters as examples. The authors attempt to highlight the challenges and mitigation mechanisms involved while exploring opportunities for involving private sector ESCOs similarly. Secondary research methods and stakeholder consultations were adopted during paper development. There is potential to scale-up these technologies in MSME clusters pan-India through programmatic models resulting in substantial emission reductions, development of indigenous supply chains, job creation, and creation of green-growth pathways, making it crucial for India’s net-zero and NDC targets. A similar model, developed by GGGI with EESL, addressing the barriers for replication and scale-up, is also showcased.

Keywords: MSME sector decarbonization, energy efficient technologies, demand aggregation, innovative business models, bulk procurement

Introduction

India’s Micro, Small & Medium Enterprises (MSME) sector is also known as its backbone and growth engine for good reason, contributing 26.83% to its GDP and being responsible for 40% of its exports [1]. While responsible for one-third of the country’s total manufacturing output, the sector is also highly emission-intensive owing to the usage of fossil fuels and its unorganized and informal nature of operations, which makes it a regulatory nightmare. Currently, the sector accounts for nearly 25% of the total energy consumption by the industrial sector in India, wherein 15% is consumed as electricity, and the remaining 85% is consumed from thermal energy sources [2].

As part of India’s NDCs, the government has committed to a reduction in emissions intensity by 45% by 2030 from 2005 levels and 50% cumulative electric power installed capacity from non-fossil-fuel-based energy resources by 2030, with the help of the transfer of technology and low-cost international finance [3]. Significant reductions in energy consumption and emissions from India’s MSMEs, particularly the adoption of newer, more energy-efficient technologies, will be necessary to achieve this. Initially, the states with the highest number of key MSME clusters in India may be targeted for implementation. It can be noted that more than 70% of the MSME clusters are based in the states of Uttar Pradesh, West Bengal, Tamil Nadu, Maharashtra, Karnataka, Bihar, Andhra Pradesh, Gujarat, Rajasthan, and Madhya Pradesh [4]. Various energy audits by leading organizations like BEE, TERI, UNDP, NPC and Industry Associations, etc., have revealed that there are energy savings to the tune of 10-30% with less than 2 years payback period in the MSME sector. It is also observed that maximum energy saving is possible by retrofitting or replacement of conventional technologies with energy efficient technologies. It is interesting to note that many of the technologies are “standardized,” i.e., with similar technical specifications that may be applicable to various MSME clusters. This gives us an opportunity for the demand aggregation of these identified Standard Energy Efficient Technologies (SEET) that may be taken for bulk procurement. Such an approach has immense potential for enabling technology cost reduction, the benefit of which may be passed on to the consumers.

The cost reduction through demand aggregation and bulk procurement has been well established in India through national programs like UJALA (Unnat Jyoti affordable LED for all) and LED street light national program (SLNP) implemented by Energy Efficiency Services Limited (EESL) during the last 8 years. Riding on the high success of these 2 programs, wherein a cost reduction of around 50-70% was observed, EESL intended to expand a similar approach to the industrial sector, i.e., MSMEs [5]. Accordingly, EESL, in partnership with UNIDO, initiated a project called "Market Transformation through Energy Efficiency in MSME" in 2017, intending to create an ESCO ecosystem in the sector.

This paper is an attempt to highlight the success stories of the above project in terms of technology identification, deployment, and business model design, thereby creating a possible pathway for scaling up. Further, it highlights the challenges faced during the implementation along with recommendations for possible interventions. A similar project, developed with GGGI's SEET programme focusing on replication in 3 clusters in Kundli, Panipat, and Karnal, is also explored as a model for addressing the challenges in the scale-up.

Methodology

The study will analyze the key success factors and method of implementation seen in the UNIDO-EESL-MoSME programme "Promoting Market Transformation for Energy Efficiency in the MSME Sector" under GEF-5 and will further highlight the savings achieved under this programme. Recommendations for scaling up and replicating the above programme in a sustainable manner with funding from other sources are explored through GGGI's existing model.

The study is structured into 3 parts: analysis, results and discussion, and conclusion. The analysis gives a brief introduction to the programme and delves into the description of the clusters, their energy scenarios, the key interventions identified, and an example of technology intervention that was followed in each. The results and discussion look at the energy savings and the overall impact of bulk procurement on the savings. It also delves into the succeeding project developed by Global Green Growth Institute (GGGI) with Energy Efficiency Services Limited (EESL) and how the replication and scale-up may be carried forward.

This study is primarily based on secondary data. The relevant data is collected from various sources, including a number of industry reports, the annual report for 2022-23 of 'Ministry of Micro, Small and Medium Enterprises', the official website of the EESL MSME project, and other EESL project reports (including, but not limited to, various detailed project reports, survey reports and statistics on the relevant projects), Ministry of Statistics, research reports on the MSME sector, and GGGI's annual project reports on SEET.

Analysis

A brief introduction to the programme and methodology adopted for implementation

The programme, "Promoting Market Transformation for Energy Efficiency in the MSME Sector," was developed under GEF-5 (Global Environment Facility). Implemented under the technical guidance of the United Nations Industrial Development Organization (UNIDO) in collaboration with Energy Efficiency Services Ltd. (EESL) and MoMSME (Ministry of Micro, Small and Medium Enterprises), the project was also co-financed by the Bureau of Energy Efficiency (BEE) and Small Industries Development Bank of India (SIDBI) and aims to deploy selected standard EE technologies in various MSME clusters across India.

As per the survey reports, technology selection was carried out by identifying critical parameters to ensure ease in the implementation, energy-saving potential, availability of indigenous manufacturing and local service providers (LSPs), and potential for replication and eliminating those that did not make the cut. A careful step-by-step process was carried out. This included gap assessment through surveys of LSPs and technology vendors, detailed energy audits for the industries (carried out for a sample of 5% of the representative industries in each cluster), stakeholder consultations, and preparing a benchmarking matrix to identify replicable technologies. A technology toolkit was developed, and a mobilization workshop was carried out in each cluster. This was followed by a unit survey, at the end of which 35 technologies were identified for 10 MSME clusters. The MSME clusters were also selectively chosen based on the potential for maximum energy savings and replicability across the sector.

The preparation for demonstration in the units was carried out in a streamlined manner and included the identification of units for the same. 2 demonstration projects per unit were chosen, and the business model was finalized based on the ESCO (Energy Servicing Company) model, wherein the investment is expected to be recovered through the implementation of a Pay-As-You-Save (PAYS) model, which works by monetizing energy savings through the technology used in the cluster. Baseline energy audits were conducted as part of the demonstration in order to finalize the technical specifications and the monitoring and verification protocol. The procurement of technology and the process of identification of the vendor for implementation of the demonstration will be elucidated in detail through the case studies.

The process was documented to ascertain the benefits. The final stage included the initiation towards replication in other clusters.

Quality control was ensured for the entire process, from decision-making, implementation, the review of the work plan, and the scrutiny of technical details such as technologies and business models to other project-related activities by carrying it out in consultation with and alongside the strategic guidance of a Project Steering Committee and a Working Technical Advisory Committee. Members included representatives from MoMSME, Bureau of Energy Efficiency (BEE), EESL, the Small Industries Development Bank of India (SIDBI), as well as representatives from GEF and other relevant bodies [6].

The Key stakeholders of the project were identified as [6]:

- Global Environmental Agency - Donor Agency
- Bureau of Energy Efficiency - Guiding agency
- MoMSME
- MoEFCC
- United Industrial Development Organization (UNIDO) - Implementing agency
- Energy Efficiency Services Limited (an entity under MoP) - Executive agency
- SIDBI - Financing guide and Partner
- MSME units and their cluster associations

Based on data available from the EESL MSME website, the project was successful despite the COVID-19 pandemic with 24 technologies being demonstrated in various clusters during the period of 2018 to 2022 [6]. Out of these, 2 successful clusters were chosen for analysis in this paper based on the availability of information and the demonstrated energy savings observed. The following section of this paper explains the approach and methodology adopted in 2 clusters, mainly Surat (textile) and Jorhat (tea processing), and the impact created through bulk procurement and the ESCO mechanism.

Surat "Textile" Cluster demonstration

About the cluster: Surat, also known as "the Silk Capital of India", hosts more than 600,000 power looms and is known for its dyeing and printing industries. Its strength lies in the production and export of fabric and fibre, accounting for 40% of India's total man-made fabric production, 28% of its total man-made fibre production, and 18% of its total man-made fibre exports. Along with the presence of nearly 400 printing and dyeing industries in the cluster, the majority of these are concentrated in the industrial area of the city and have been operational for almost 15 to 30 years. Of these, nearly 60% belong to the MSME sector *(Refer to Figure 1)*. The raw material most used is grey polyester which is procured from local producers. The key point to note is the cost of energy, which ranges between 12% and 15% of the total manufacturing cost. This share is due to the fact that the majority of industries apply the wet process, which makes use of a large amount of thermal energy via hot water and steam. Before the UNIDO-EESL-MoMSME programme, the textile industry in Surat, dominated by the processing (dyeing and printing) industries, mainly relied on local technologies, which were generally of poor quality and energy intensive. This was mainly due to the lack of investment initiatives for the same.

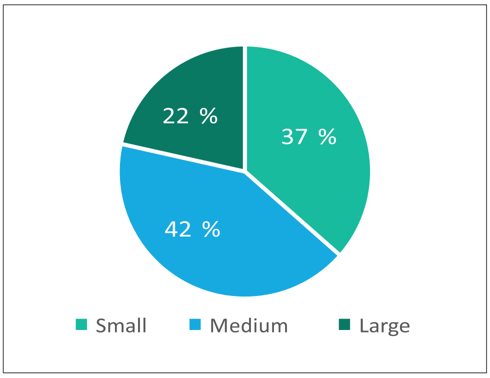

Figure 1: Percentage of textile industries in Surat by scale

The industrial association taking care of the legal and welfare concerns for the Surat cluster is currently the South Gujarat Textile Processors Association (SGTPA), which operates in and around Surat, i.e., in Pandesara, Sachin, Kadodara and Palsana. Part of their mission includes reducing production costs and promoting awareness among the units regarding energy efficient practices and technology. The areas in and around Surat have a number of Common Effluent Treatment Plants (CETPs), making them suitable for textile processing units, which have a significant amount of effluent waste. Major equipment used for wet processing includes jet dyeing machines and jigger machines for dyeing processes, stenter machines for stretching fabrics, heat setting and applying the finishing chemicals, printing machines for colouring patterns, rotary drums, and loop machines. Of the 400 units surveyed based on production facilities, around 65% had both dyeing and printing facilities, while 27% had only dyeing facilities, and the remaining 8% had only printing facilities.

Energy Scenario in the cluster: Energy consumption in the cluster happens through both fuel and electricity. The majority of the fuel consumed was coal, which accounted for nearly 94% of energy consumption, while 6% came from electricity. In contrast, nearly 45% of the total energy cost share came from electricity consumption. The electricity was purchased from Dakshin Gujarat Vij Company Limited (DGVCL) - a state-owned power distribution utility or generated using microturbines or DG sets. An outline of the fuel and electricity use in each stage of the processing is shown in Figure 2.

Energy-intensive equipment and processes: Based on the surveys of 100 units that were conducted (Annexure 1), the major energy-intensive equipment were found to be the stenter machine, the printing machine, the U jet dyeing machine, and the drum machine. These had a connected load of around 60% of the total connected load from equipment. The energy consumption from the textile dyeing and printing units was seen to depend on the production capacity and type of process used. Based on the electricity bills and the equipment being used, a savings potential of up to 10 to 15% per unit could be ascertained. The thermal energy use share was observed to be the biggest from losses during condensate recovery, process drying, heating, the heat released from equipment, and exhaust losses.

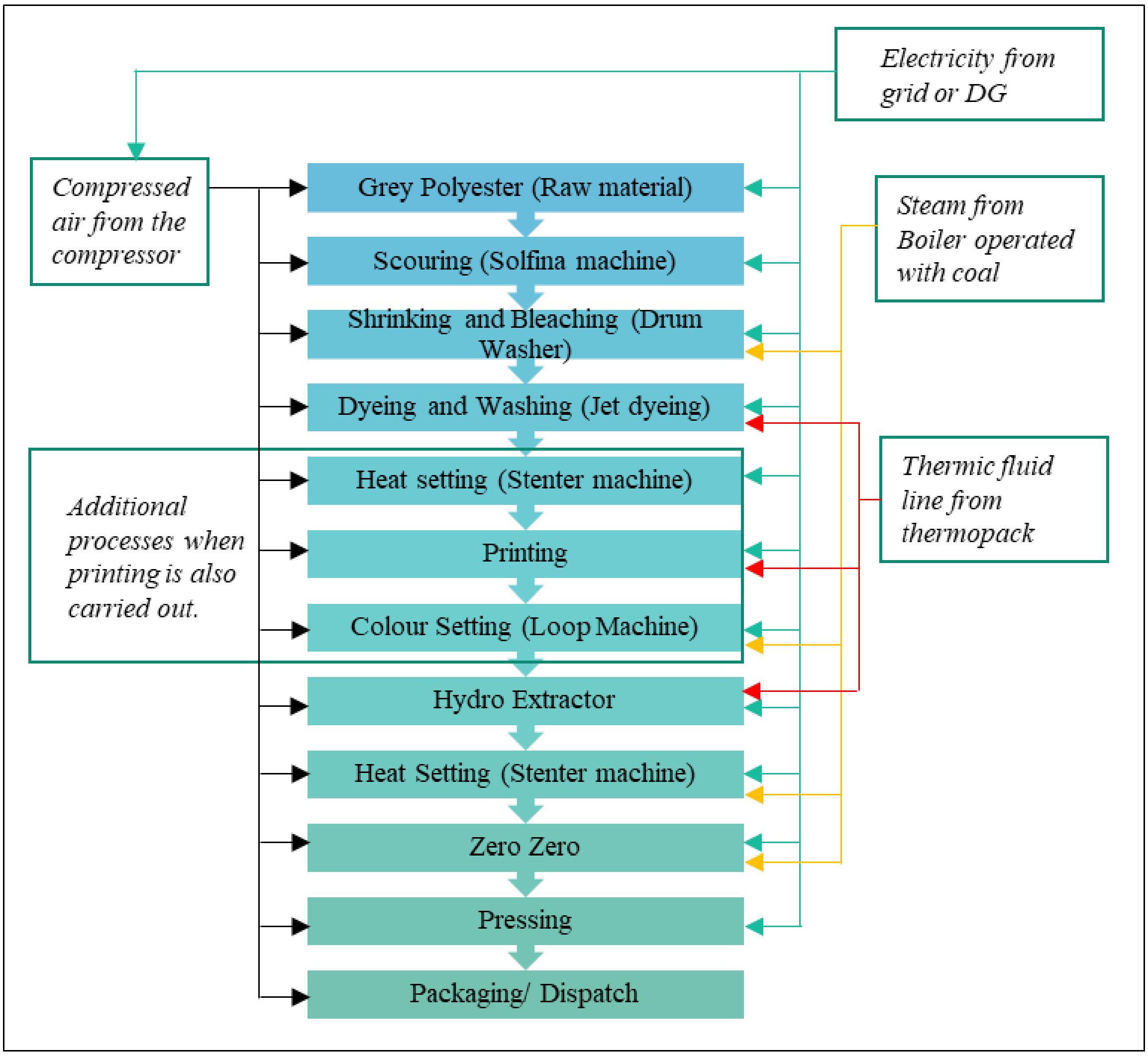

Figure 2: Process flow diagram (Textile dyeing and printing) and energy consumed

Critical equipment and processes identified: These include boilers for producing steam, thermic fluid heaters, jet machines wherein the amount of water and chemical depends on the manual operation, and air compressors such as reciprocating and screw compressors. Based on the energy audits and stakeholder consultations, 5 technological interventions were identified for implementation in the Surat cluster:

1. Replacement of existing reciprocating compressors with a VFD-enabled screw compressor with a Permanent magnet (PM) motor
2. PLC based automation system in Jet Dying machine
3. Steam Condensate Recovery System for indirect heating system

4. PLC based automation and control system for boilers and thermic-fluid heaters
5. Installation of Micro Turbine for power generation (Parallel to PRV system)

Technology willingness was determined for the above, and the replication potential was assessed.

EE Technology chosen for bulk procurement in Surat: Jet dyeing was one of the processes identified for targeted energy efficiency interventions. The process involves pressurized dyeing of the raw cloth in an even manner. The key here is to use a relatively small amount of chemicals without damaging the cloth. It is a water-intensive process and depends on manual control, which may lead to an excessive use of water and steam if not done right. The project thus envisaged savings by introducing automated control of the Jet Dyeing Process. A PLC system was introduced to operate the jet based on a logic programme, allowing it to optimize the water intake during the cycles, reducing the overall batch time as well as the amount of steam required to raise the temperature if required. This ultimately reduced fuel consumption and enhanced the overall production capacity of the jet dyeing machines.

Jorhat "Tea" Cluster demonstration

About the cluster: Jorhat, a town in the state of Assam, which is globally known for its teas, has a cluster of tea gardens with in-house factories for tea leaf processing. A lot of these factories were set up prior to independence and are owned and inherited by families or by group companies like APPL Williamson & Magor. It also has several 'bought leaf tea factories' (BLTF), which aggregates tea leaves from various gardens and process it together. These factories are newer and owned by first generation entrepreneurs. Overall, Jorhat has around 150 tea factories which produce more than 100,000 tonnes of tea annually. Manufactured products include black tea varieties made either by orthodox or CTC tea processing methods. CTC, in general, is less energy-consuming than orthodox methods and accounts for 44% of the production units, while orthodox methods account for 55%. The remaining 1% are dual-based units. It is important to note that tea production is seasonal, and tea is usually plucked and processed in the factories, often round-the-clock (RTC) during the peak season, i.e., from spring (March- April) to autumn (October- November). The CTC process generally involves the manual plucking of soft top leaves and buds during this period, followed by withering to remove surface moisture and break down the tea juices. The tea leaves are then crushed, torn, and curled (CTC) with cylindrical rollers, fermented, dried further, sorted, packed, and then dispatched. Based on the quantity of tea produced yearly, nearly 70% of Jorhat's industries fall into the MSME sector classification.

Jorhat's tea industries have formed four associations to support tea processing, i.e., the Assam Branch of Indian Tea Association (ABITA), Tea Association of India (TAI), Assam Tea Planters Association (ATPA) and North-east Tea Association (NETA). Part of their mission includes the reduction of production costs for tea, energy conservation, and the implementation of energy efficiency measures. However, the dearth of local technology providers makes this difficult, with most of the upgraded technology being sourced from LSPs in Kolkata, Tinsukia, and Dibrugarh.

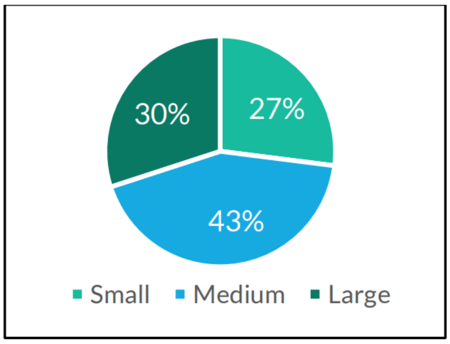

Figure 3: Percentage of tea industries in Jorhat by scale

Energy Scenario in the cluster: Energy consumption in the cluster largely depends on the supply of electricity from the grid for the electrical equipment and the use of coal or natural gas for their thermal energy needs. 85% of this energy comes from thermal energy, making it the dominant source of energy. However, electricity accounts for a larger share of 59% in terms of costs. The electricity is sourced from the Assam State Electricity Board (ASEB) grid. However, due to a lack of stable supply, the actual availability is only 70% of the time, leading to a dependence on DG sets. Thermal energy is consumed during the drying and withering processes. Currently, the cost of energy ranges between 12% - 15% of the manufacturing cost. Further, since most units are over 40 years old, they use old machinery and equipment, making them more inefficient. An outline of the fuel and electricity use in each stage of the processing is shown below.

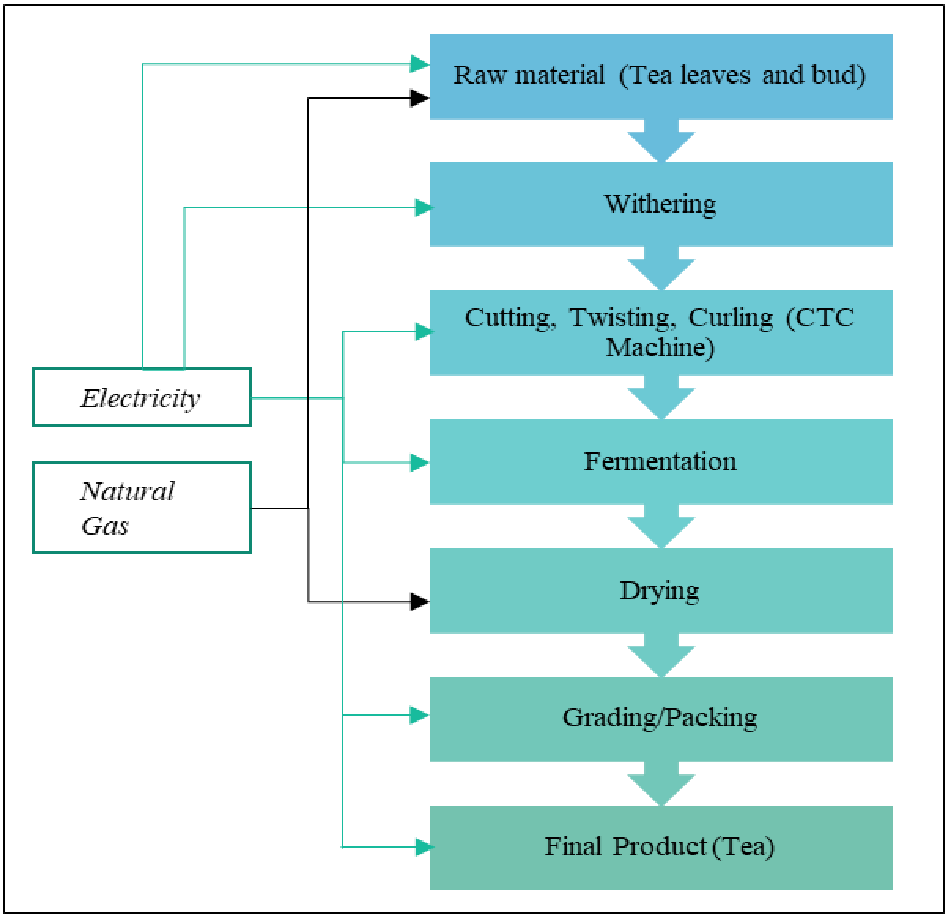

Figure 4: Process flow diagram (Tea processing) and energy consumed

Energy-intensive equipment and processes: Surveys of 100 units were conducted, and the major energy-intensive equipment was found to be the CTC machine with a connected load accounting for 60% of the total. The rest of the connected load included the withering machine, the fermentation machine, the sorting and dispatch processes, and the dryer FD/ID fan. The energy consumption from the tea units was seen to depend on the production capacity and type of process used. Based on the electricity bills and the equipment being used, a savings potential of up to 10 to 15% per unit could be ascertained. The thermal energy was seen to be largely sourced from coal and natural gas to generate hot air for the drying and withering of tea leaves.

Critical equipment and processes identified: These include the withering machine, CTC machine, and dryers. Based on the energy audits and stakeholder consultations, 4 technological interventions were identified for implementation in the Jorhat cluster:

1. Withering Process Automation with PLC
2. Installation of Temperature based Modulating Burner
3. Replacement of CI/AL with FRP-based withering fan having VFD-driven PM motor
4. PLC based Dryer Automation and Control System

Technology willingness surveys were carried out, and the replication potential was assessed and extrapolated for the entire cluster.

EE Technology chosen for bulk procurement in Jorhat: Withering of tea leaves, the first step in the tea manufacturing process, involves the reduction of moisture in the leaves by 30%. The axial fan used for this process provides the necessary airflow for this. Currently, most of the units use non-IE-3 motors, and CI/CS/A1 bladed withering fans in enclosed/ open withering troughs. It was proposed that this be replaced with fibre glass reinforced plastic (FRP) fans instead. FRP fans are more energy efficient due to their designed aerodynamic properties and thus allow more air flow with less power consumption. Lighter and smoother than CI/CS/A1 fans, this provides leeway for greater savings. Added to this, since withering fans are run on electrical energy but operate 12-14 hours per day, this intervention would deliver immense savings.

Results and discussion

Stakeholder workshops regarding energy efficient technologies and meetings with the association were conducted to get the expression of interest (EOI) for the identified technologies. Based on the number of EOIs received, as well as the aggregated demand from the MSME unit, procurement was initiated through a tendering process. Bulk procurement was identified as the method to achieve economies of scale. Savings results were also found to be very encouraging in terms of potential for showcasing to other potential clusters as well as other MSMEs. In this manner, the market for local technology providers was enabled, and it further encouraged them to drastically reduce their prices to match the tendered price.

Results of bulk procurement in Surat cluster:

One of the major contributing factors to the success of the implementation was the delivery of a well-organized bulk procurement strategy, wherein a 32% reduction in cost was achieved in comparison to the market price, i.e., from a cost of Rs. 2.95 lakhs per unit to Rs. 2.28 per unit. Demand aggregation was carried out for 500 PLCs, and the procurement process was carried out via a single tender. The successful process can be largely attributed to the standardization of specification in the tender, along with the provision of an additional warranty of 3 years, as well as a careful quality control process. Some of the major challenges included developing the technology standardization and selection criteria in such a manner as to ensure quality while avoiding alienation of the local vendors.

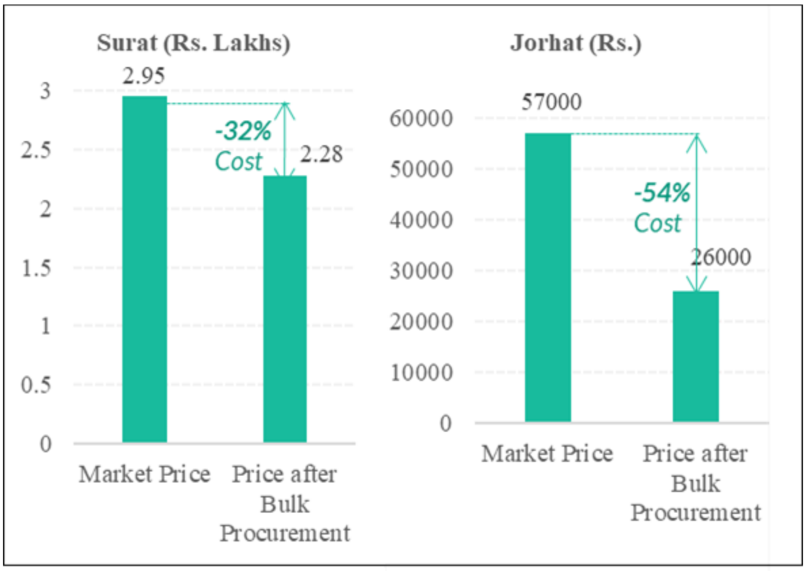

Figure 5: Price reduction as a result of bulk procurement in Surat and Jorhat clusters

Results of bulk procurement in Jorhat cluster:

During the demonstration, the unit replaced 39 CI-based fans with FRP withering fans instead. Once again, a well-organized bulk procurement strategy was a key contributing factor that allowed a 54% reduction in cost compared to the market price, i.e., from a cost of Rs. 57,000 per unit to Rs. 26,000 per unit. Demand aggregation was carried out for 600 fans through a single tender procurement process. A standardization of tender specifications and an additional warranty of 3 years was ensured, along with strict quality control procedures.

Challenges and way forward:

The procurement process was a success despite the difficulty of standardizing the technical specifications. Once specifications were set, the next issue was that local vendors reduced their prices to compete with the tender outside the tendering process. While this was not as big a concern since energy efficient technologies were adopted, convincing units to share their data while risking their monopoly in the local area and concerns about losing jobs due to automation were also brought up. However, this situation varied across the industries.

Scaling up of investments through the ESCO mechanism by deploying standard energy-efficient technologies (SEET): Although the technology demonstration was successful in the programme, several challenges thwarted the scale-up, mainly a lack of awareness, structured and effective demand aggregation, and a lack of investments to carry it forward. Keeping this in mind, GGGI developed a project, "Scaling up of investments through the ESCO mechanism by deploying standard energy-efficient technologies (SEET)", to support EESL's efforts. Additional funding from the Korean Green New Deal Fund (KGNDF) was obtained to facilitate this. The project was envisioned with the goal of transforming the MSME sector to be energy efficient by means of technology deployment/ transfer while creating a sustainable ecosystem for all relevant stakeholders, be it ESCOs, MSMEs, industry associations, financial institutions, technology providers, governmental institutions or energy auditors. It further aims to establish a National Framework for Implementation (NFFI) of standard energy efficiency solutions in MSMEs through proof-of-concept leading, with the intention of accelerating investments and setting up an Energy Efficiency Revolving Fund (EERF) to mobilize investments. Furthermore, in the 10 clusters chosen by EESL, having 2 successfully completed demonstrations, it was observed that an estimated investment potential of 30 million USD could be translated into a larger investment if scaled up to other MSME clusters as well. While the EERF was proposed by UNIDO and EESL under GEF-5 with the intention of mobilizing investments with SIDBI as the fund managing entity, it has yet to be formally institutionalized. However, EESL cannot be the sole investor capturing the entire market. Hence it was proposed that proof of concept would be necessary in order to get other ESCOs to invest, thus achieving the target of opening up the ESCO market to MSMEs. This would have to go parallel with awareness building for financial institutions, which will make financing easier for both MSMEs and ESCOs.

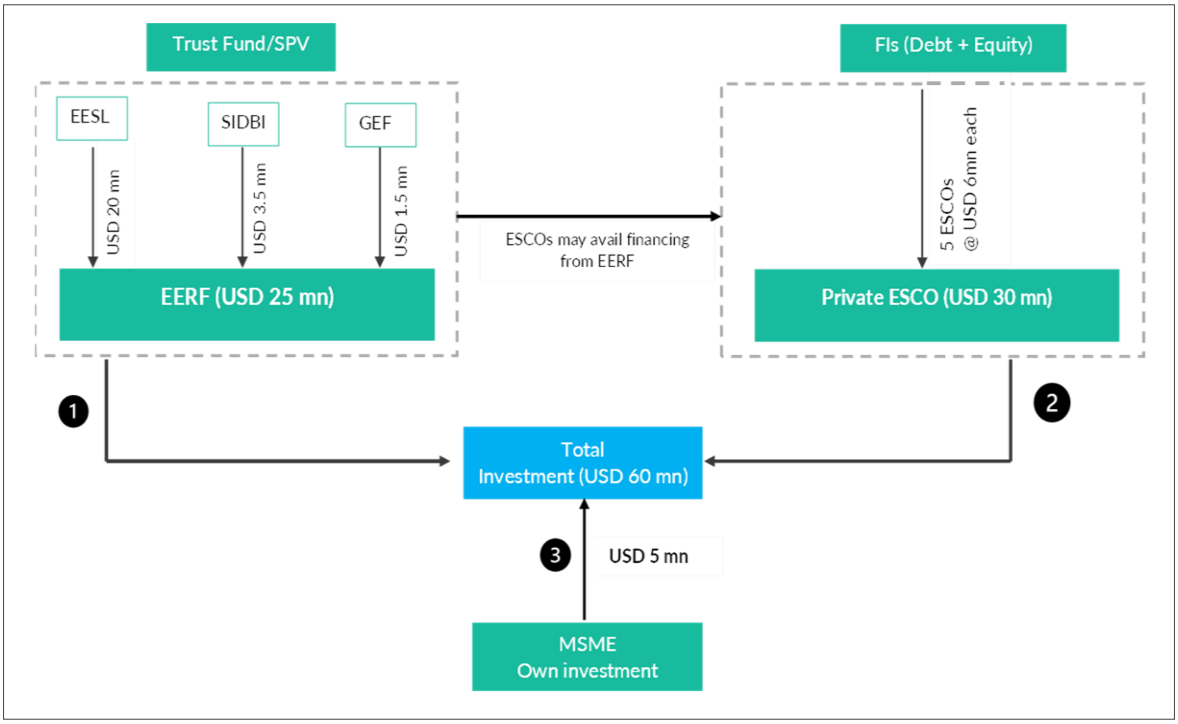

Figure 6: Investment Mobilization expected to be achieved before 2025 under SEET

As an extension of the earlier programme, 3 clusters- the Karnal rice cluster, the Panipat textile cluster, and the Kundli mixed cluster were selected under SEET. Studies were performed to identify energy efficient technologies, and based on the EOIs received from the industries, 7 technologies were identified with the potential for increased energy efficiency, scale-up, and replication. In terms of investments alone, a potential 0.4 to 0.5 million USD of investment was ascertained from baseline surveys conducted in around 20 initial industries in the chosen clusters *(Refer to Table 1 for calculation)*. Having assessed the demand, the next step is to raise awareness for financial institutions and ESCOs. SIDBI was chosen to be the primary financial institution to set up the EERF, and the next step is the empanelment of ESCOs, technology providers, and the mapped financial institutions and lenders by means of an IT platform in order to ensure that the data and matchmaking is easier overall. Overall, SEET is expected to be followed as a model for future replications of the UNIDOEESL-GEF programme in other MSME clusters across India.

Table 1: Technologies identified for replication potential based on EoIs received under SEET and the total investment.

Technology Name	Interest (no)	Technology Cost (INR Lakhs)	Total Investment (INR Lakhs)
EE Screw compressor	10	9.34	93.4
IE3 Motors	545	0.21	114.46
Boiler automation	6	11.3	68
BLDC Ceiling fan	423	0.045	19
Jet dyeing machine automation	8	6	48
Flash steam condensate recovery	2	5	10
Low grade waste heat recovery	3	5	15
Total	997	36.895	367.86

Conclusion

Altogether, this paper focused on the case studies conducted in 2 clusters among the 10 identified clusters, but the overall aim of this paper is to look into recent developments and strategies for transforming the market for energy efficiency in the MSME sector by adopting the best practices and by replicating the proven tested business models under this paper on a pan-India basis that could help in achieving India's NDC and net-zero targets. This paper will assist policymakers in developing new policies for opening up the MSME sector to energy efficiency and aiding the increased penetration of the identified energy efficient technology in the MSMEs, subsequently increasing demand for the technology in the clusters. The barriers identified for the implementation of energy efficient technologies, like a lack of financing options for the MSME sector, a lack of after sales service support from suppliers, and the lack of institutional support for MSMEs were mainly mitigated by providing easy financing through the ESCO mode and by enhancing the competitive market by means of demand aggregation thus leading the creation of cluster level technology support centres in the form of ESCOs and technology suppliers/local service providers, and also by creating peer-to-peer networks between units, association, suppliers, governments, etc. and enabling enhanced support from Central/ State governments to MSMEs, LSPs, and ESCOs.

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Annexure 1

Table 2: Unit Survey Formats for identifying energy-intensive technologies

Sl.No.	Parameter	Details		
1	Name of the unit :			
2	Address of the unit :			
3	Contact details :			
	Name:			
	Designation :			
	Mobile:		Email :	
5	Year of Establishment :			
6	Registered under MSME Act (Please Tick) : Yes		No	
7	UAM No. / MSME Reg No. :			
8	Annual audited turn-over (last financial year) :			
9	Whether the company is profitable in last 3 financial years : Yes		No	
10	Current profit margin (range) :			
11	Total Investment on plant and machinery:			
12	Process (Please Tick) : Dyeing	Printing	Both	
13	Raw Material :		Finished Product :	
14	Electricity Consumption			
a	Average monthly electricity consumption (kWh/month):			
b	Average monthly expense towards electricity (Rs in lakhs /month) :			
15	Fuel consumption			
	Type of Fuel	Average monthly consumption	Average monthly expenses (Rs in lakh/ month)	
	Coal (Imported)	t/month		
	Coal (Indian)	t/month		
	Diesel	l/month		
	Natural Gas	Nm^3/month		
	Others ( )			
16	Monthly production (meters / month) :			
17	Specific energy consumption per ton of textile processed:			

Sl.No.	Parameter	Details		
18	Major Utilities			
a	Boiler	Make:	Nos.:	Type:
		Capacity (t/h) :	Fuel:	
		FD Fan (hp) :	ID Fan (hp):	
		Fuel Consumption (tpd) :	Operating hours per day :	
b	Thermic Fluid Heater (TFH)	Make:	Nos.:	Type:
		Capacity (t/h) :	Fuel:	
		FD Fan (hp) :	ID Fan (hp):	
		Fuel Consumption (tpd) :	Operating hours per day :	
c	VFD in Boiler / TFH : Yes		No	
d	Automation & Control system in Boiler / TFH : Yes		No	
e	Steam System	Steam Consumption (tph) :	Process Pressure (kg/cm^2):	
f	Condesate Recovery : Yes		No	
g	Condesate Recovery pump :	Type (Reciprocating / Pressurized) :		
		Percentage of condensate recovery (%) :		
h	Steam Traps :	Yes	No	
		No. of TD Trap:	No. of float trap:	

i	Compressor								
	Make	Type	Motor (hp)	VFD (Y/N)	CFM	Operating hours per day	Design Pressure (kg/cm^2)	Receiver Pressure (kg/cm^2)	SPC (kW/cfm)

19	Process Equipment			
a	Drum Washer	No. of units:	Make:	Capacity:
		PLC based system :	Yes	No
b	Stenter	No. of units :	Make:	Capacity:
		No. of batches:		
c	Soflina	No. of units:	Make:	Capacity:
		No. of batches:		
d	Jet Dyeing	No. of units:	Make:	Capacity:
		PLC based system :	Yes	No
		No. of batches:		
e	Zero-Zero	No. of units :	Make:	Capacity:
		No. of batches:		
f	Printing	No. of units:	Make:	Capacity:
		No. of batches:		
g	Loop Ager	No. of units:	Make:	Capacity:
		No. of batches:	Fuel Used:	

20	Willingness for technology implementation	
	Please rate the following technologies (1 to 5) based on your willingness to adopt the same	
	Technology	**Rating**
	Automation & Control System in Boiler / TFH	
	Condensate Recovery system	
	Replacement of reciprocating compressor with screw compressor with VFD	
	PLC based automation system in Jet Dyeing Machine	
	Installation of back pressure turbo-generator for power generation	
	Any other technology (please mention)	

21	Any potential risk the unit foresee in the above technologies:

21	Willingness for Business Model
	I certify that the business model (tentative) for financing under ESCO mode has been explained to me.
a	I have understood the business model and am interested to participate under the project, as per its terms and objectives
b	____
c	I am not interested to participate in the project

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New Education Policy and Energy Efficiency: Understanding through the Lens of a Solar Decathlon India Team

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Highlights

- Academic Institutions are encouraged to leverage energy efficiency and water conservation goals in future planning to cut on operation costs.
- 81.27% reduction may be achieved by a combination of rainwater harvesting and use of fixtures.
- 220 MWh renewable energy generation potential exists with the envisaged building.
- Government of India's New Education Policy 2020 is not only curricula change but also invites new building concepts.
- Solar Decathlon India's Educational Building Contest is an important avenue for idea generation.

Abstract

Academic institutions are excited about the opportunities that are showcased by the Government of India's New Education Policy 2020 regarding the potential impact that it can have on learners. Inspired by this important development, a team of engineering and architecture students took the initiative to consider exploring energy-efficient building designs through the Solar Decathlon India contest in support of the new policy. The team contributed to developing a concept for a "Student Life Centre" - a building that particularly deals with student activities to enable them to pursue their passions along with their studies. This idea was a unique concept for an educational building as participating students got an opportunity to visualize and appreciate the economic aspects. From the author's analysis, before introducing coursework based on the New Education Policy in curricula, academic institutions may benefit if they visualize the options that the built environment may offer in accelerating learning.

Keywords: Education, Solar Decathlon India, Energy-Efficient Buildings, Governance, Building Science

Introduction

The New Education Policy (NEP) envisaged by the Government of India offers opportunities to inculcate skills like: "scientific temper and evidence-based thinking; creativity and innovativeness; aesthetics and art; communication; health and nutrition; physical education and sports; collaboration and teamwork gender sensitivity; environmental awareness including water and resource conservation, sanitation and hygiene" amongst the student community. In the pursuit of developing the eight new IITs envisioned by the Ministry of Education (MoE), Government of India in 2008 to expand the reach and enhance the quality of technical education in the country, the Indian Institute of Technology Ropar has emerged to be one of the flagship institutions [1]. It was envisaged in 2020 that the Solar Decathlon India contest might be leveraged to initiate and accelerate the dialogue of linking energy efficiency with student wellness, engagement, and learning.

The Solar Decathlon India is an annual competition that intends to inculcate skills in emerging students and architects to build net-zero buildings with the eventual aim of addressing climate change through the building sector. The contest is organized by the Indian Institute for Human Settlements (IIHS) and Alliance for an Energy Efficient Economy (AEEE) under the aegis of the Indo-US Science and Technology Forum (IUSSTF). It is supported by the Department of Science and Technology, Government of India.

Under the 2020 Solar Decathlon India Competition Team, the Indian Institute of Technology Ropar contributed to developing a concept for a "Student Life Centre" - a building that particularly deals with student activities so that they can pursue their passions along with their studies [2]. The building will help in integrating life skills as desired by the curriculum revisions of the New Education Policy. From an educational building category contest entry viewpoint for Solar Decathlon India, this proposal was a unique concept as participating students got an opportunity to visualize and work out the economics of developing the educational building. The entry was one of the finalist entries in the Solar Decathlon India 2020 contest.

Methods

The conceptualization of the Student Life Centre brings an innovative concept of an educational building that envisages being "Of the students, for the students, and by the students". The Student Life Centre is proposed to be an educational building in the campus of an academic institution with the Government of India, which operates primarily on a non-profit basis. The possibility of inviting Corporate Social Responsibility funds to help student activities may be explored, provided a "backbone" infrastructure is present on campus to encourage investments. An important consideration is that operational expenses are expected to be minimized, and capital -intensity is a concern as the possibility of revenue generation is less as compared to a commercial building. Table 1 provides the salient site characteristics associated with the Student Life Centre. As can be seen, the hours of operation and the site location (e.g., Seismic Zone IV) influenced some of the design decisions, like having a Ground Floor Level and three additional floors. For furthering the analyses, the team used tools like Design Builder (Provided by Solar Decathlon India), Climate Studio (Provided by Solar Decathlon India), AutoCAD, Photoshop, Sketchup, and MS Excel-based programs (e.g. CBE Comfort Tool).

Table 1: Salient design features of the student life centre (proposed)

Climate zone:	Ropar has a tropical, semi-arid, hot, and subtropical monsoon type of climate with cold winter and hot summer
Occupant Profile:	Students involved in various activities like technical, cultural, sports etc.
Site Specifications:	Site has loose alluvial soil. It comes under seismic zone IV.
Hours of Operation:	24*7, Peak Hours: 4 PM - 10 PM daily
Occupancy expected	840
Building purpose:	Build-own-operate building dedicated to student activities

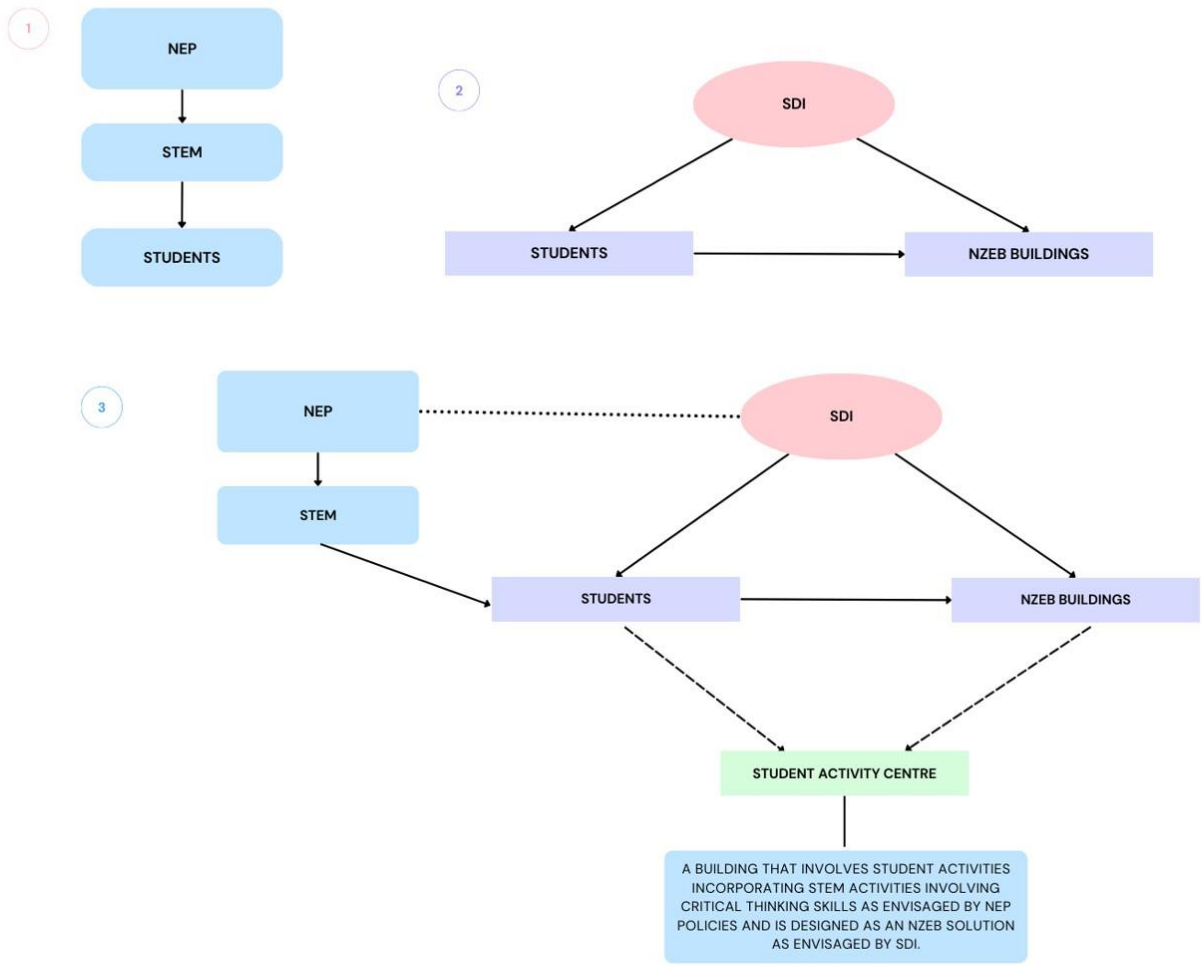

Figure 1: The triumvirate between New Education Policy, Teaching and Learning, and Energy Efficient Buildings

Understanding the triumvirate between New Education Policy, Teaching and Learning, and Energy Efficient Buildings

The triumvirate between New Education Policy, Teaching and Learning, and Energy Efficient Buildings (or NetZero Energy Buildings) may be best understood with the help of Figure 1. The New Education Policy envisaged by the government of India has promoted multidisciplinary education and acknowledgment of Science, Technology, Engineering, and Mathematics (STEM) as one of the core principles. At the other end of the spectrum, the Solar Decathlon India contest has emerged as a connector between enunciating building science principles based on net zero, addressing sustainability, climate change, and energy efficiency, and the student community.

The Student Life (or Activity) Center is one of the important buildings in any institution where students would like to spend most of their time after their classes. The implementation of the New Education Policy shall require the planning of new learning spaces. In the author’s opinion, Solar Decathlon India may serve as a remarkable opportunity to inculcate the need for net zero and sustainable buildings by involving students in providing design input to their academic institutions.

Recent literature in andragogy related to sustainability and energy efficiency has acknowledged the role of “learning by doing” in sustainability education [3], the role of developing clean energy communities to promote education [4], and recognizing the need to impart education beyond the formal learning environment [5]. The educational impact of Solar Decathlon competitions in the European editions [6-7], Middle East [8,9], and Latin America [10] has been very well acknowledged in the research literature. The literature also acknowledges the role of participatory design student competitions as a vehicle to foster advances in building science education [11-13]. To the best of the author’s knowledge, this conference paper is one of the first to document the potential impact of Solar Decathlon India in providing important input to the New Education Policy envisaged by the Government of India.

Results

The architectural thought process was initiated by a stakeholder survey with students, which revealed that “privacy and individuality” were some of the key considerations that the students may like to experience in a building that aims to bridge the community. On further exploration, it was identified that students appreciate spaces for science and technology that are helped by a less noisy environment and, hence, were provided at the top of the building so that focus and attention may be maximized. The sports area and auditorium were planned on the ground floor so that they are easily accessible without much disturbance. Figure 2 represents the elevation and side views of the Student Life Centre.

The plan of the Student Life Centre in Figure 3 shows the cultural activity areas that were provided in the centre of the building, which acts as the inner atrium and helps in acoustics. The cultural areas are expected to provide a lot of interaction space and are not at the entrance, which is likely to create an atmosphere of anticipation before getting immersed in the event atmosphere. Since the Student Life Centre is expected to be a building that may serve as the heartbeat of the institution by hosting various events and participation from other academic institutions is also expected hence, luggage rooms, an auditorium, and an associated audio-visual room were also provided.

The Student Life Centre on its first floor encompasses a defense art room, badminton court, and common playroom. The second floor has a dedicated space for music and dance, drama and fine arts, and a digital lab. The emphasis on Science, Technology, Engineering, and Mathematics (STEM) activities like aero modelling, robotics, astronomy, and the automotive club were provided on the third floor. The idea was how the experiential learning envisaged by the New Education Policy may be integrated into one dedicated building.

Figure 2: Elevations and side views of student life centre

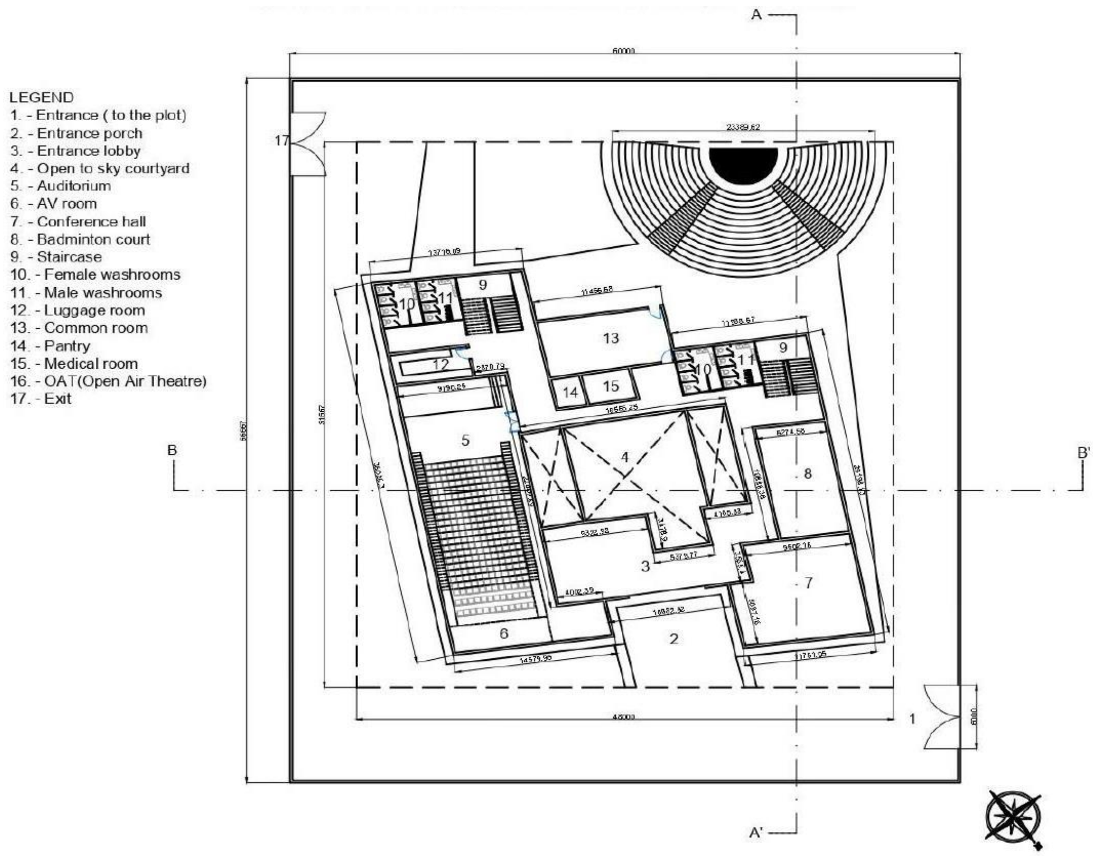

Figure 3: Ground floor of the student life centre

Table 2 provides the salient design features of the Student Life Centre. The opportunity to use energy efficient lightning. Rainwater harvesting based systems promoting renewable solar energy are very strong. If a nation has to showcase novel technologies and promote their use, then in the opinion of authors, all future educational buildings should lead the way in showcasing these concepts. It was calculated that 220 MWh of renewable energy generation potential exists with the envisaged building.

Table 2: Salient design features of the student life centre (proposed)

Built-Up Area	2600 m^2
Lighting (LPD)	2.7 watts per square foot(building)
Electrical (EPD)	1.38 watts per square foot
Water systems	Annual Consumption- 17,28,536.2 L Annual Greywater Treatment- 6,09,938.9 L Annual Blackwater Treatment- 3,25,300.8 L Annual Rooftop Rainwater Harvesting- 5,75,503.0 L Annual Hardscape Rainwater harvesting- 15,01,567.2 L Underground Tank Capacity (with partitions)- 9,589 L (rooftop rainwater) + 25,019.1 L (hardscape rainwater) + 4275 L (municipal water) Overhead Tank Capacity (with partitions)- 9,589 L (rooftop rainwater) + 27,523.9 L (recycled greywater + hardscape rainwater) + 4275 L (municipal water) Surface Area of Root Zone Bed- 79.5 m^2
HVAC	System type - air cooled VRF CoP - 3.5 EER - 12 Star-rating - 5
Renewable energy (system type, generation capacity)	Solar panel system of capacity 165 kW is installed, with 450 pvs and each p.v of 350 W, mix of roof and ground mounted. Annual Generation: 220 MWh

Discussion

The analysis of energy consumption of the Student Life Center is shown in Figure 4 which reveals important engineering possibilities. As identified in the detailed analysis in the report, the overall energy consumption could be significantly reduced by changing from Single glazed, 30% WWR, wooden frame with no local shading to Double glazing, 15% WWR with UPVC frame along with overhang changed from 693 MWh to 541.96 MWh, i.e, a drop of 22%. Other considerations include looking into roof-top insulation with a U-value of 0.175 and external wall insulation with a U-value of 0.27, which further leads to a reduction in the consumption to 324 MWh, i.e., a further drop of 30%. Adoption of mixed mode ventilation and further attached radiator surface in the ceiling along with VAV water-cooled chiller may facilitate reduction of energy consumption by 13 MWh. However, adopting air-cooled VRF systems led to a potential reduction from 324 MWh to 193 MWh, i.e., a drop of 40.4%. The adoption of an air-cooled VRF system as an HVAC Solution for the three buildings with cooling capacities 85 kW, 31 kW, and 154 kW, with maximum terminal side airflow rates of 1.34m^3/s, 0.62 m^3/s and 1.34 m^3/s respectively may be considered in the design.

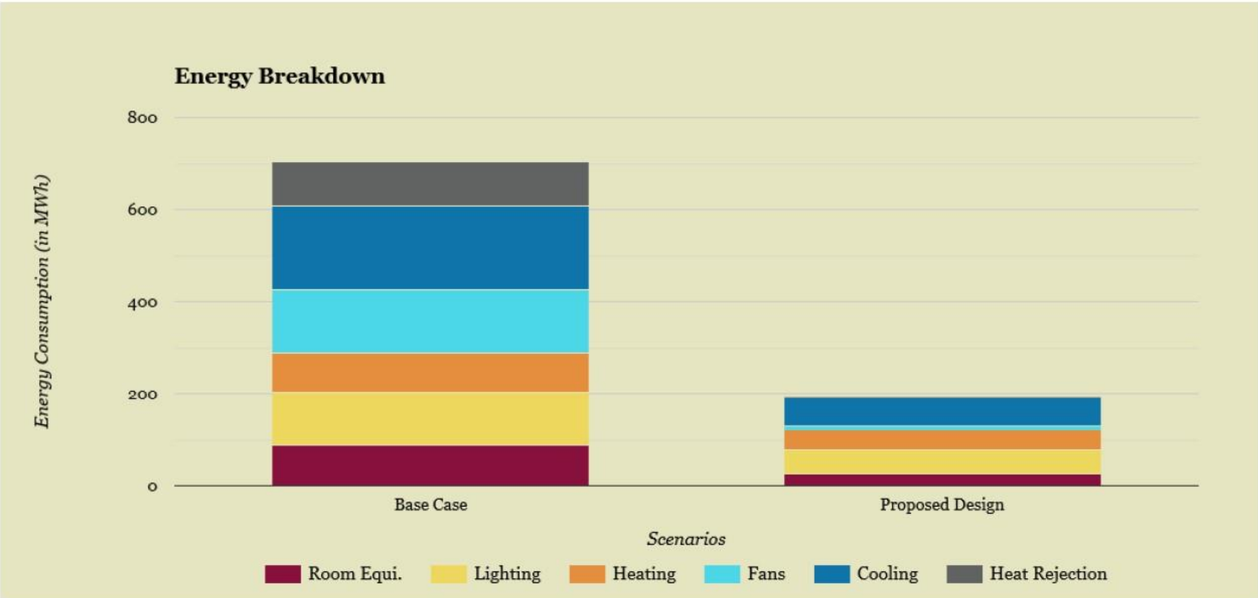

Figure 4: Estimation of energy consumption in the student life centre

Table 3 highlights the role in the reduction of energy in cooling, use of fans, lighting, and the significant savings that can be achieved through building energy efficiency measures in the Student Life Centre. The Lighting simulations on Design-Builder software revealed that for the base case scenario, lighting consumption was on the very high side (112.83 MWh). With the reduction of power required for lighting, the obvious choice was to go with LED lighting fixtures, as LEDs are far more efficient and have a higher luminescence-to-power ratio than traditional lighting fixtures (A luminous efficacy of 150 lm/W for LED vs. 35 lm/W) and may have a significant impact.

Table 3: Energy end use breakdown for base case and proposed case

Demand	**Base Case Scenario (Energy in MWh)**	**Proposed Energy Efficient Case (Energy in MWh)**
Room Equipment	89	27
Lighting	113	51
Heating	86	43
Fans	139	10
Cooling	181	62
Heat Rejection	95	0

Figure 5 gives the analysis of water consumption in the Student Life Centre. The calculations were performed by assuming the same amount of rainfall and taking into account. Annually, 575503 L of rainwater can be harvested from the building roof and used for potable needs. A decision was made to reduce the irrigation area, which resulted in more space for walkways and other hardscape areas. The water falling on these surfaces will be carried to treatment systems installed to make them fit for non-potable uses instead of being disposed of. This results in the collection of an additional 1501567 L annually. Although the total harvested rainwater (2077070.3 L) is greater than our total consumption of 1728536L, thereby resulting in a net positive water performance, there is a deficit of potable water. Hence, 465459L of municipal water (an offsite resource) is needed. Thus, it is evident that the use of efficient systems and rainwater harvesting has heavily reduced our dependence on offsite resources (a reduction of 81.27%). Furthermore, the utility of having greywater and blackwater treatment systems may easily be witnessed in Figure 6, which shows the flow of water to and from tanks and different use locations. The junction number and annual use/capacity have been mentioned for each location and system as an illustration.

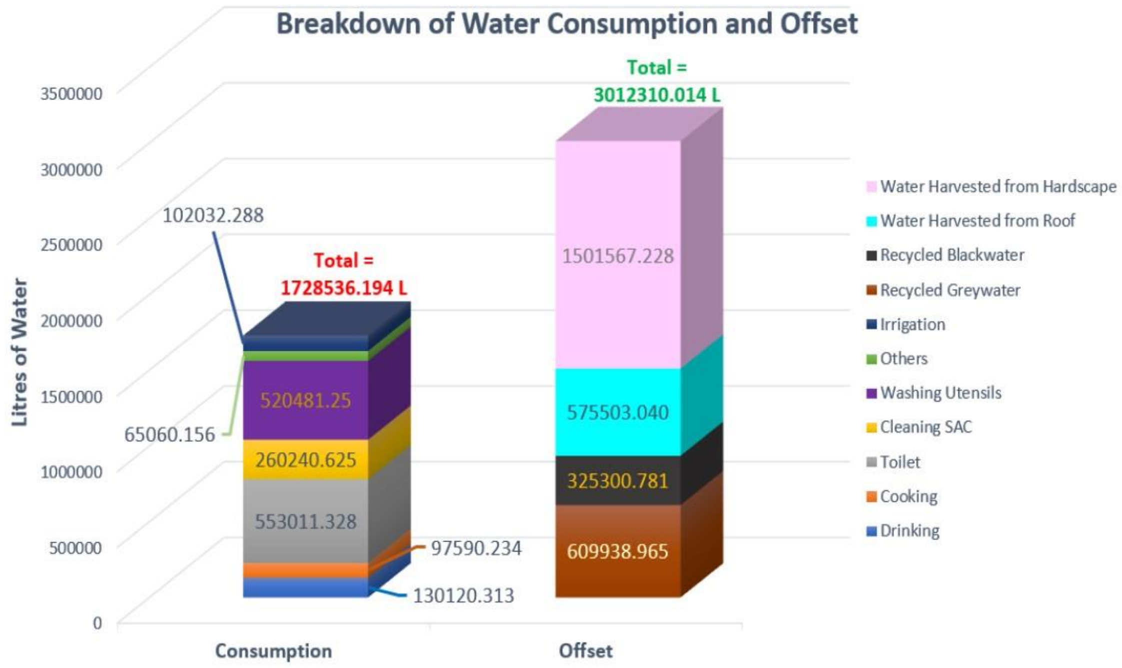

Figure 5: Estimation of water consumption in student life centre

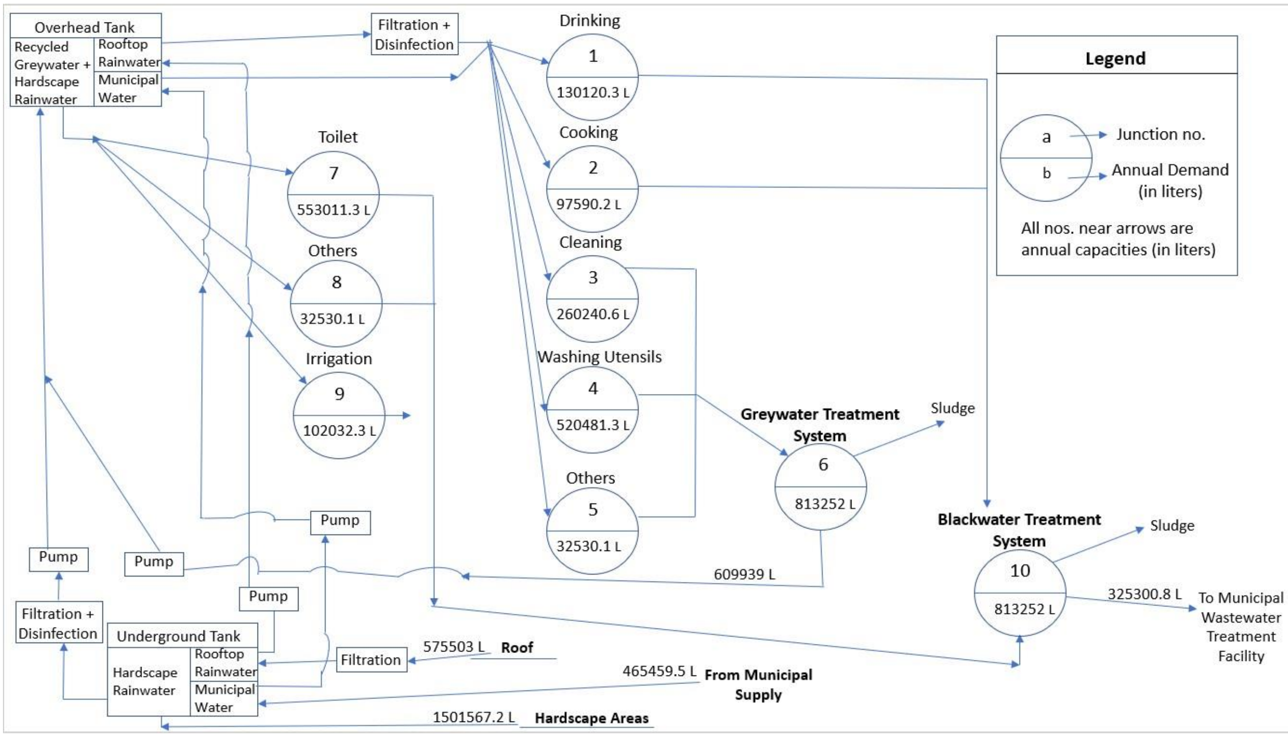

Figure 6: Water flow diagram in student life centre

Other innovations that can be considered in campuses include grid-based PV installations, the use of aerators, piezoelectric flooring, and the conversion of plastic waste into bituminous material for the construction of roads. If students are able to explore the various facets of life at a campus like the Indian Institute of Technology Ropar, which is in a semi-urban area, then this concept can be adopted nationwide and help in generating revenue. One of the ideas that we would like to work on in further development is that sections of the building be sponsored through Corporate Social Responsibility (CSR) funds. A notable effort is MPower to promote mental health and well-being in the most holistic manner conceivable, which was founded by Ms. Neerja Birla [14]. As funding for higher education is getting reduced globally, and economic hardships have been severe on millennial and Generation Z students (e.g., the 2008 Crisis, Corona Economic Slowdown), concepts of integrating energy and water efficiency, low operation cost, modern architecture, and student life are essential. An important aspect is that if education becomes a symbol of energy efficiency, then it can impact the economic outcomes of an educational institution significantly as money can be diverted into research and development and improving academic infrastructure.

Conclusions

Through a Solar Decathlon India design competition entry, it has been demonstrated how academic institutions may be able to leverage new building concepts involving energy efficiency, incorporation of renewable energy, and water conservation measures into future planning. As educational institutions work eagerly to explore their transition to multidisciplinary institutions, leveraging "Promotion of Indian Languages, Arts, and Culture", and identifying avenues for mechanisms and opportunities for enabling clubs and activities organized by students as some of the goals, the need for a building like the "Student Life Centre" exists.

From an academic point of view, the analysis in this paper clearly presents the case of the need for careful planning of an academic community of students. Prestigious Universities like Harvard [15] have leveraged the services of reputed firms like Hopkins Architects, Bruner/Cott Architects (Cambridge, MA) Arup, Faithful+Gould, Simpson Gumpertz & Heger, and Michael Van Valkenburgh Associates on their Smith Campus Center project. Stanford University is currently undergoing a consultative process involving the design of its Town Center, whose elements shall discover the depth and range of endeavor across the university through direct, spontaneous exposure of the institution's intellectual diversity, and is engaging LMN Architects as a partner [16]. Another fascinating academic building concept is EPFL's Rolex Learning Center, which has novel architectural elements with gentle slopes and terraces undulating around a series of internal 'patios', with almost invisible supports for its complex curving roof, which has required innovative methods of construction. The building is known as Forum Rolex, wherein the conference and event venue has a seating capacity of 600, arranged around a collapsible circular stage of 70 m^2 [17].

In light of important developments across prestigious academic institutions, it is high time that new policies in education should be synergized with leveraging equivalent advancements in energy efficiency, water conservation, and renewable energy. The Solar Decathlon India contest is a great avenue to ideate the buildings of the future through students under the guidance of experienced mentors and drive a conversation that has the potential to significantly transform Indian Academia by reducing operation costs and promoting a living and demonstrable example of sustainability and energy efficiency.

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https://doi.org/10.62576/LLTY6708

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Study on Evaluating Net-Zero Energy Potential for a Proposed Apartment Building

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Highlights

- The purpose of the study is to assess net-zero energy potential for a proposed apartment building.
- The study is conducted for a proposed G+12 apartment building located in Sonipat, NCR.
- After applying three different identified internal profiles (low-mid-high consumption) the BAU case EUI is in the range of 92 to 88.
- ECM's - IMAC MM 90% temp. setpoints, shading, NV, efficient envelope, efficient PTAC system were identified as energy conservative measures (ECM’s).
- After all ECM's were applied one upon another the EUI is in the range of 37 to 31 (66% reduction from BAU case). Which gives a payback period of 8 months.

Abstract

The floor area of residential buildings in India is evaluated twofold (16.0 billion m2 to 31.6 billion m2) and the residential energy consumption is assessed to trifold (246 TWh/y to 748 TWh/y) between 2017 and 2030, as per NITI Aayog (2015). This development of residential floor space, combined with an increment in electricity production, leads to critical energy demand within the up-and-coming decades.

The purpose of the study is to assess net-zero energy potential for a proposed apartment building, suggest effective energy conservative measures, and see the financial achievability of the same by reporting the payback period and internal rate of return (IRR).

Keywords

Net-zero energy, Residential buildings, Internal rate of return, simulation, energy savings, incremental cost, Eco-Niwas Samhita.

Introduction

Background

India — the second-most populous (1.37 billion in 2019) nation of the world [1] - is anticipated to have the biggest population in the world by the year 2030 [2]. Concurring to the 2011 census information, India’s number of households was 246 million with a population of 1.2 billion [3]. Under the 2011 average household measure (4.9) suspicion, there will be 307 million households in 2030.

Significance

The study would contribute in terms of providing the proposed option which can achieve net-zero energy residential building and its feasibility & added extra investment. The relationship between reduction in energy performance index (EPI) reduction, energy conservative measures (ECM’s) & added extra investment will also help to understand/draw some conclusions for any building developers/contractors/architects.

Research objectives

- To find the IRR of net-zero energy residential buildings and to compare/analyze it with the savings with existing residential energy codes.
- To analyze the relationship between energy conservative measures, & added extra investment cost for net-zero energy residential buildings.

Scope of the study

The study will cover the economic feasibility of each energy conservative measure and the potential of photovoltaics at present state of art technology to combinedly achieve potential net-zero residential building. The plug load data to calculate equipment power density is gathered by conducting a survey and the study is done for a specific G+12 apartment.

Limitations and challenges of the study

- As the study is done for a specific building the results of this study might not represent/capture the entire residential building scenario.
- The study will propose energy conservative measures (ECM's) based on the climate and sensitivity analysis and reports IRR or the same. Hence the study doesn't capture all the possible ranges of ECM's.

Literature review

Development process for net-zero energy buildings

Net Zero Energy graph

A base case will be developed based on the architecture & service drawings, construction specifications, and usage schedules. After that the pathway to a Net ZEB is given by the balance of two actions:

- Reduce energy demand (x-axis) employing energy conservative measures (ECM's)
- Generate electricity as well as thermal energy carriers using energy supply options to get enough credits (y-axis) to achieve the balance.

In most circumstances, major energy conservative measures are needed as on-site energy generation options are limited, e.g. by suitable surface areas for solar systems, especially in high-rise buildings [4].

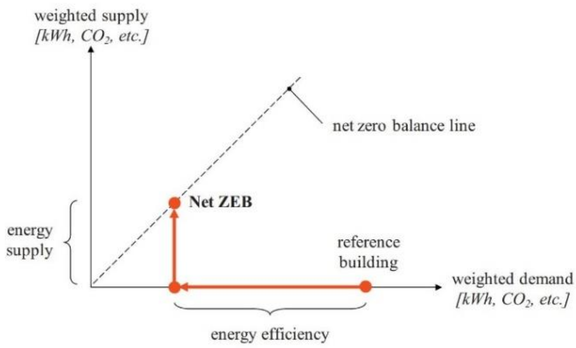


Figure 1 - Graph representing the Net Zero Energy concept

Building energy simulation input data

BES models require the input of building conditions, much of which is specific to a building or analysis objective, such as geometry, internal loads, system configuration, and control. Other input data is obtained from external sources, which define properties of building materials, system performance coefficients, and the local weather conditions [5]
Input data of the residential building's appliance usage is a critical element for the BES model as for the same the methods to collect appliance usage data have been gathered/studied.

Methods to collect appliance usages patterns

Among these strategies, it was expressed that in situ estimation can give high-quality comes about with point-by-point data on energy consumption and the usage pattern. In situ measurement was the strategy utilized in a few studies such as the end-use metering program (Sweden, 2005–2008), the family power overview (the UK, 2010–2011), and STANDBY control (France, 1997–1999), the REMODECE (12 European nations, 2006–2008). [6]

So, the proposed equipment/plug load survey is conducted via hand-given survey forms. The parameters collected were occupancy Density (W/m^2-person), lighting power density (W/m^2),& equipment power density (W/m^2). The electricity consumption of each type of appliance was theoretically calculated by formula.

Equation 1 - Electricity consumption

Electricity consumption (kWh) = power rating * working hours * number of items

Internal Rate of return (IRR)

Internal Rate of Return (IRR) is a financial metric that helps estimate the profitability of a potential investment. It is the discount rate that makes the net present value of the cash flows equal to zero. In other words, NPV equals zero. It is widely used in discounted cash flow analysis. It is ideal for analyzing capital budgeting projects. [7].

Equation 2 - Net present value

$$NPV = (Cash\ flows / (1+r)^n) - Initial\ investment$$

Where
r = IRR
n = time period.
The initial investment is the first investment made into the project.
Cash flows = All the cash flows during the period of investment.

IRR can't be used as a standalone measure for one project. One can use IRR to compare two projects/design options. A project with a higher IRR will be more desirable.

Methodology

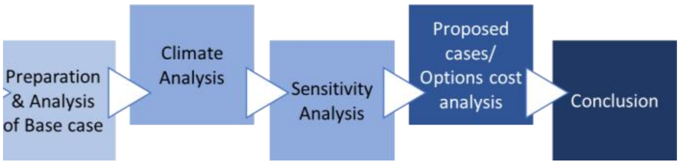


Figure 2 - Methodology

Part 01: Preparation & Analysis of Base case
The base case is developed by using proposed building architectural drawings, Equipment Plug load survey results (for internal conditions), building as usual (BAU) construction assemblies, and packaged terminal air conditioner (PTAC) as an HVAC system.
Base case results analysis: Rooftop PV potential analysis (to arrive at target EPI), Residential Daylight anatomy (RDA), Comfort hours (Heating/Cooling), Primary energy breakdown, energy consumption by different end uses, and ENS compliance check for BAU case.

Part 02: Climate Analysis
Environmental parameters chart (to understand the high humidity and high-temperature zones), Climate Categorization into nine modes (to arrive at potential thermodynamic strategy).

Part 03: Sensitivity analysis
The following sensitivity analysis is conducted to analyze/forward on design stages.

- Standardized regression coefficient (SRC) for the cooling load (kWh), SRC for the Heating load (kWh), SRC for total site energy (kWh), Comfort hours percentage vs Window open %.
- Once the design stages are generated, comfort hours percentage vs different design stages analysis is conducted by simulating without any HVAC system to analyze/compare comfort hours as per IMAC 90% acceptance band.

Part 04: Design stages/Proposed case cost analysis
For each option/case incremental cost is calculated upon BAU case, payback period, and internal rate of return (IRR) is calculated to analyze the feasibility of the option. Parametric analysis for the ENS compliance case analysis is done to demonstrate the savings & IRR of ENS compliance cases.

Part 05: Conclusion
Proposed design option – their savings, payback period, and IRR with further discussion.

Results & Analysis

Preparation & results from the Base case

Project Data

The location for the faculty housing is in Sonipat, Delhi. The As-Is case is modelled as the base case. The building has a total of Ground +12 floors.

The Equipment/Plug load survey is conducted to derive the electrical plug load (EPD) and Lighting plug load (LPD) values. A functional faculty housing (apartment) adjacent to the proposed apartment building is chosen for the survey as the occupants can be of the same economic class.

Table 1 - Building Typology

Building Type	Residential
Location	Sonipat, Delhi
Built-up Area	8,244 m^2
Number of Floors	Ground + 12
Floor Height	3.15
Window Wall Ratio (WWR)	18%
Orientation	E-W long axis
Floorplate	687 m^2

Table 2 - Climate Typology

Climate Type	Composite climate
Summer Months	March to June
Winter Months	November to February
Monsoon Months	July to October

Software/Tools used

Table 3 - Software's/Tools used

Energy simulation	EDLS Tas (version 9.5.1), DesignBuilder v6.1.6 (EnergyPlus v8.9)
Lighting simulation	LightStanza
Result's analysis	DesignBuilder results in the viewer, Microsoft Excel

Input values for the base case

Table 4 - Envelope values used for making the base case

Parameter	**Value**	**Units**
BAU Wall U-value	2.10	W/ m^2.k
BAU Roof U-value	3.70	W/ m^2.k
BAU Glazing U-value	5.70	W/ m^2.k
SHGC	0.70	Ratio
VLT	0.75	Ratio
Model Infiltration	0.70	ac/h

Weather file

For the entire analysis, the weather file used is,
"IND_DL_New.Delhi-Safdarjung.AP.421820_TMYx.2004-2018".
The weather file is downloaded for the source https://climate.onebuilding.org/WMO_Region_2_Asia/IND_India/index.html

Input values for the base case

The survey results/responses are used to make the schedules and input parameters /data like EPD, LPD, and occupancy density.
Three different profiles (low-mid-high consumption) were identified and are used to get the range of EPI's for BAU case and at each ECM's analysis. The Electrical power density (EPD value is changed in these profiles from 4W/m^2 to 7 W/m^2 (after adjusting no. of hours of usage).but the Lighting power density is kept as constant with 0.7 W/m^2 (derived from the LED usage response).
For all the service spaces like corridors/staircase and lift spaces, a scheduled EPD of 19 W/m^2 has been used. For the primary use areas (Living area/Hall, bedroom) PTAC system has been used as an HVAC system.

Best case results

Table 5 - Standard design results

Parameter	Value
Energy Performance Index (kWh/m^2.year) range	88 to 92
Unmet Hours (Cooling)	15
Unmet Hours (Heating)	0

Table 6 - Performance summary

Parameter	Value
Max. Heating Load (kW)	15.98
Max. Cooling Load (kW)	36.28

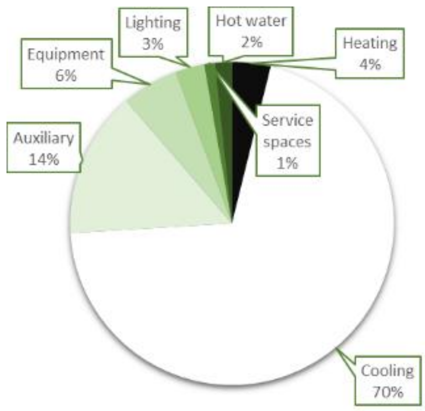
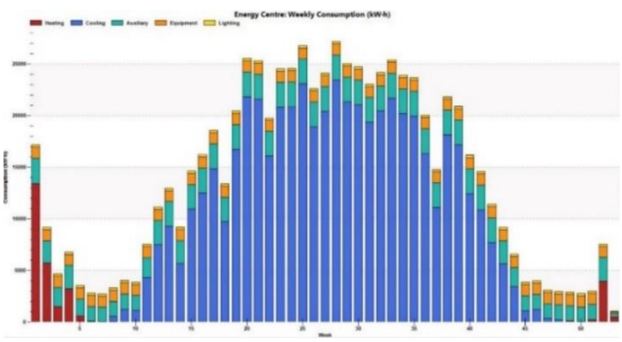


Figure 3 - Energy breakdown

Figure 4 shows the weekly energy breakdown, here equipment load has service spaces (corridor lift), Hot Water Consumption energy within it. A peak of cooling load in the months of March, April May, June, July, Aug, Sep, and peak of cooling load in the months of Dec, Jan is observed.

ECM which will reduce the predominant loads (Cooling & Heating) will result in a higher energy reduction.



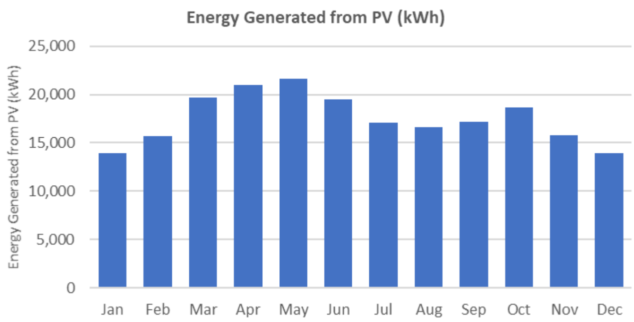


Figure 4 - Monthly energy Consumption (kW-h), Figure 5 - Rooftop PV generation

Renewable Potential (Photovoltaic generation)

To calculate Rooftop PV potential 80% of rooftop area is considered and for each month solar radiation of the surface (kWh/m^2) is calculated. 18% is chosen as the efficiency of the PV panel as per present technology. Figure 5 shows the PV generation for each month.
For the base case, the rooftop PV can offset 28% of the total building EUI, as per the generation if the EUI gets less than 26 (kWh/m^2.year) then the building becomes net-zero.
To calculate Rooftop PV potential 80% of rooftop area is considered and for each month solar radiation of the surface (kWh/m^2) is calculated. 18% is chosen as the efficiency of the PV panel as per present technology. Shows the PV generation for each month. 18% is chosen as the efficiency of the PV panel as per present technology. Shows the PV generation for each month.

Compliance check for the base case

The compliance for ENS of the apartment building is checked using the compliance check tool for ENS code (Version 1.6). The following are the details used and results from the tool.

Table 7 - Project Information

Project Name	Faculty Housing (Ashoka University)
State	New Delhi
City	New Delhi
Climate	Composite
Latitude	>= 23.5° N
Total No. of Residential Blocks	1

Table 8 - Dwelling Unit Details

S/No.	Type of Dwelling Unit	No. of Units	Carpet Area (m^2)	Total Area (m^2)
1	1 1BHK (Type 01)	47	50.0	2350.0
2	2 1BHK (Type 02)	14	54.0	756.0 3
3	2BHK	14	115.0	1610.0
4	3BHK	10	170.0	1700.0
Total carpet area (m^2)				6416.0

ENS Compliance Results

Table 9 - ENS results

S/No.	Requirement	Calculated	Criteria	Status
1	WFR_{op}	11.08	12.5	Non-Compliant
2	VLT %	80	27	Compliant
3	U_{roof}	1.8	1.2	Non-Compliant
4	RETV	20.25	15	Compliant

Observations

- WFR_{op} requirement got non-compliant status which will suggest that window wall ratio of the building should be increased, which is addressed above by daylight options.
- U_{roof} requirement also got non-compliant status where the U-value of the roof should be less than or equal to 1.2, which suggests having a roof assembly with insulation as an option.
- RETV for the base case not following the Eco-Niwas Samhita compliance, U-value of the wall & window can be further brought down to reduce energy consumption and to get ENS compliance.

Results from the climate analysis

Environmental parameters chart

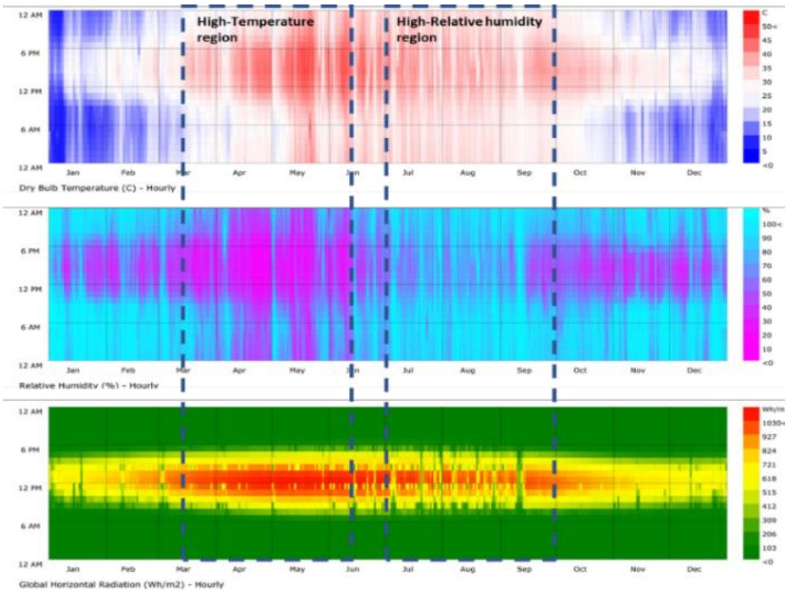


Figure 6 - Environmental Parameters DBT, RH & GHR,

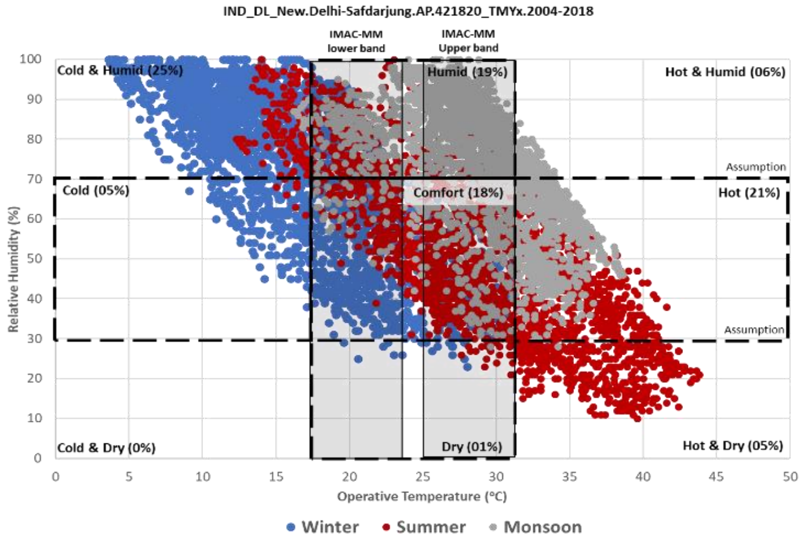


Figure 7 - Climate Categorization

Climate Categorization

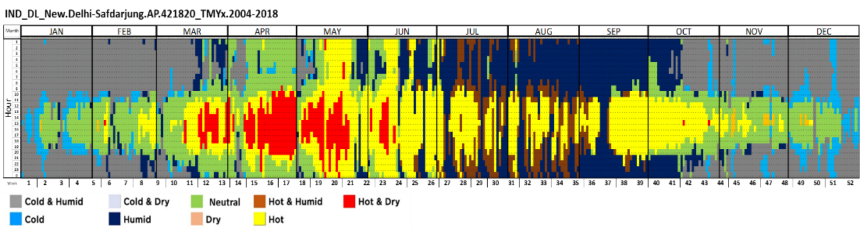


Figure 8 - Heat map showing the distribution of each mode

Observations

Table 10 - shows four major modes, percentage (%) during occupied hours, the required process to bring those modes to comfort bands, and the potential strategy by which it can be done.

Table 10 - Percentage of each mode during occupied hours & potential strategy

NO	MODE		%	REQUIRED PROCESS	POTENTIAL STRATEGY
1	Cold & Humid		25	Heating & Dehumidification	Electric heating coil, DX heating system
2	Hot		21	Sensible Cooling	Indirect Evaporative cooling
3	Humid		19	Dehumidification	Humidistat control, DX cooling system
4	Neutral		18	NIL	Mixed mode, DAOS
5	Hot & Humid		6	Cooling & Dehumidification	Indirect Evaporative cooling, DX system
6	Cold		5	Heating	Electric heating coil
7	Hot & Dry		5	Cooling & Humidification	Direct Evaporative cooling
8	Dry		1	Humidification	Direct Evaporative cooling
9	Cold & Dry		0	Heating & Humidification	Electric heating coil

Indian Model for Adaptive Model (IMAC)

IMAC mixed-mode buildings neutral temperatures were calculated using the IMAC assistant.

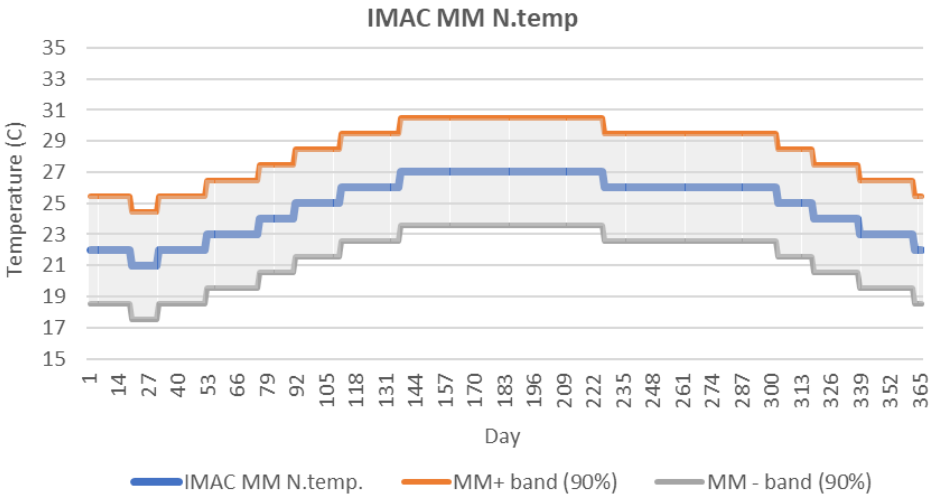


Figure 9 - IMAC Neutral temperatures and 90% acceptability bands

Limitation

As the internal temperature in a room is based on several local factors the study on climate will only help to understand/capture the main ECM's and thermodynamic process required in that climate, a specific room indoor environmental metrics (Operative temperature (OT), Relative humidity (RH) will be observed to access proposed ECM's)

Results of the Sensitivity analysis

Standardized regression coefficient (SRC)

To understand the sensitivity of main components specific to the cooling load, heating load, and total site energy analysis is done via standardized regression coefficient (SRC). The below graphs shows the sensitivity of each component.

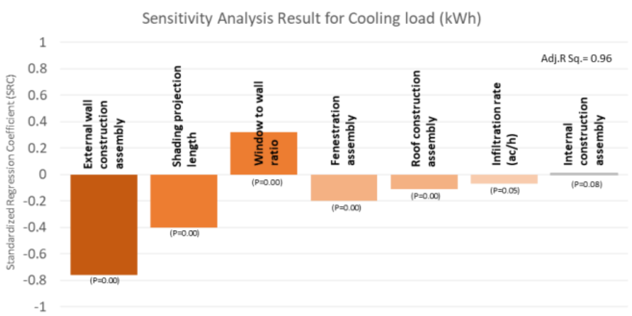


Figure 10 - SRC for Cooling load,

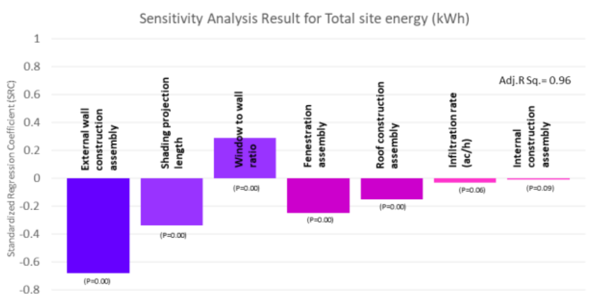


Figure 11 - SRC for Total site energy

Observations

- External Wall construction assembly has the maximum effect on both cooling and heating load followed by shading projection length for cooling load and fenestration assembly for the heating load.
- For total site energy window to wall ratio (WWR) is also contributes to maximum effect.
- Roof construction assembly has shown a medium effect on cooling and heating loads whereas internal partition construction assembly and infiltration rate have shown the least among other components.

Further, to understand the sensitivity of window opening percentage to comfort hours as per IMAC 90% acceptable range the sensitivity analysis for comfort hours (hr) vs Window Open (%) is analyzed.

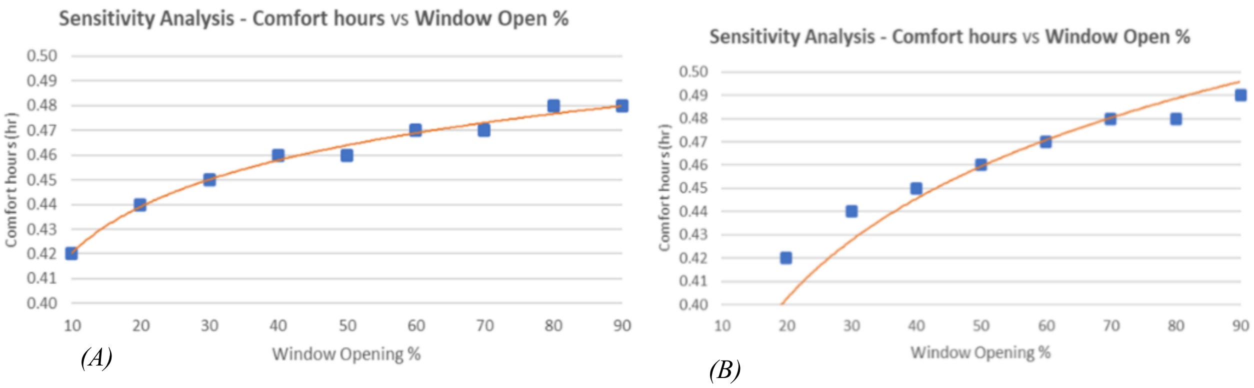


Figure 12 - Sensitivity analysis window opening %

Two text rooms A & B which are facing east, and west were chosen to do the analysis and it is observed that as the window open % increases comfort hours are also increasing. From this study, all the windows were replaced with the casement windows with mosquito mesh resulting in an effective 70% opening of windows.

The ECM's from the climate and sensitivity analysis used in different design stages

Table 11 - ECM's used at diff. design stages

Option	Discerption
Base case	Base case
Design stage 01	Basecase + IMAC
Design stage 02	Basecase + IMAC + Shading
Design stage 03	Basecase + IMAC + Shading + Natural ventilation
Design stage 04	Basecase + IMAC + Shading + Natural ventilation + Envelope optimisation
Proposed design	Basecase + IMAC + Shading + Natural ventilation + Envelope optimisation + 5-star PTAC system

Energy savings and incremental costs of individual ECM's

<u>Reduction of EPI and comparison of incremental cost</u>

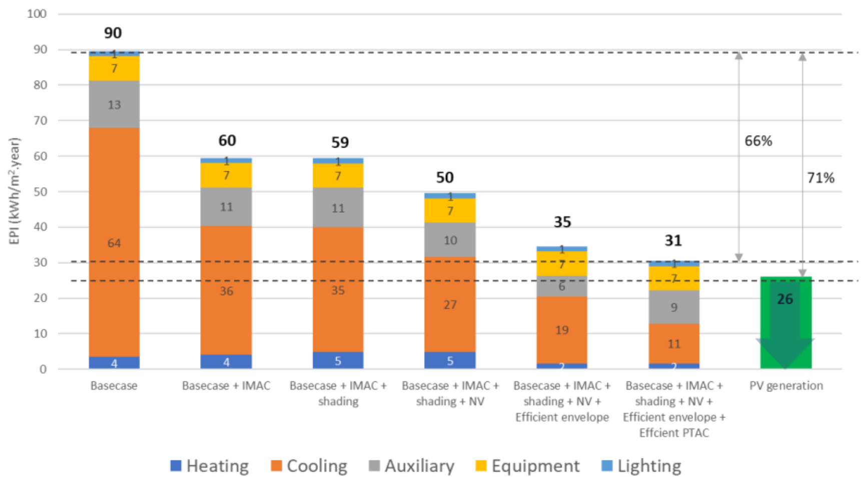


Figure 13 - Reduction of EPI

Table 12 - Incremental cost for diff. cases

Option	Discerption	Incremental cost (₹)
Base case	Base case	0.00
Design stage 01	Basecase + IMAC	0.00
Design stage 02	Basecase + IMAC + Shading	59,736.00
Design stage 03	Basecase + IMAC + Shading + Natural ventilation	0.00
Design stage 04	Basecase + IMAC + Shading + Natural ventilation + Envelope optimisation	-16,34,446.2
Proposed design	Basecase + IMAC + Shading + Natural ventilation + Envelope optimisation + 5 star PTAC system	4300 per ton
ENS case	Basecase + AAC block (exterior wall) + efficient roof assembly	-29,70,555

Unmet hours at each design stage

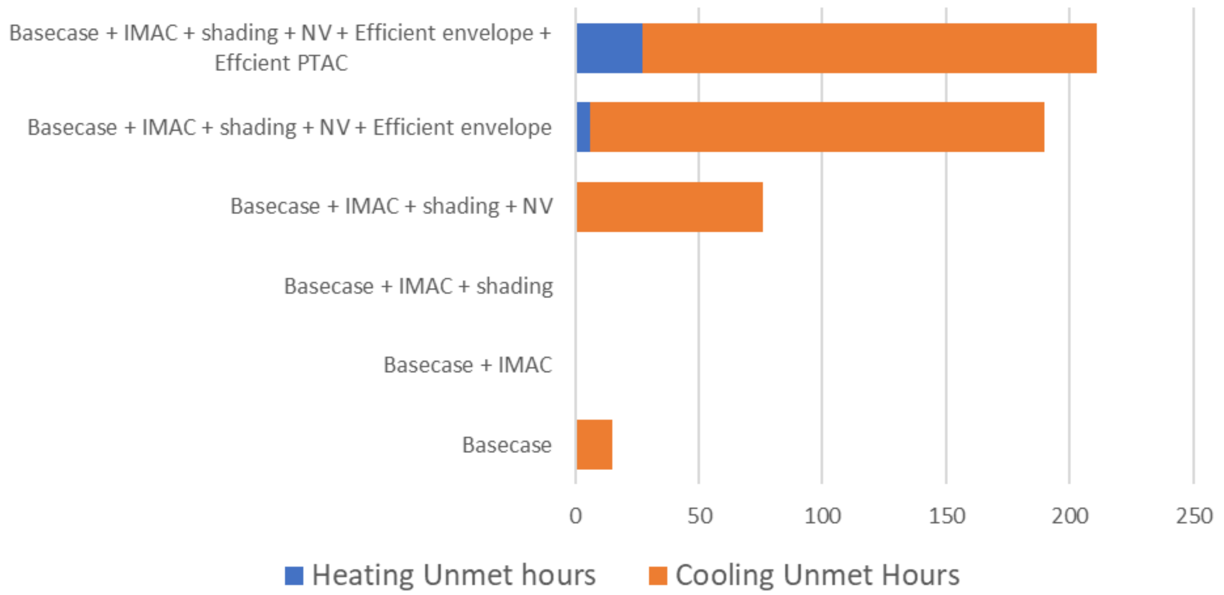


Figure 14 - Unmet hours

Parametric study on Eco-Niwas Samhita compliance cases

Parametric analysis of ENS Compliance cases

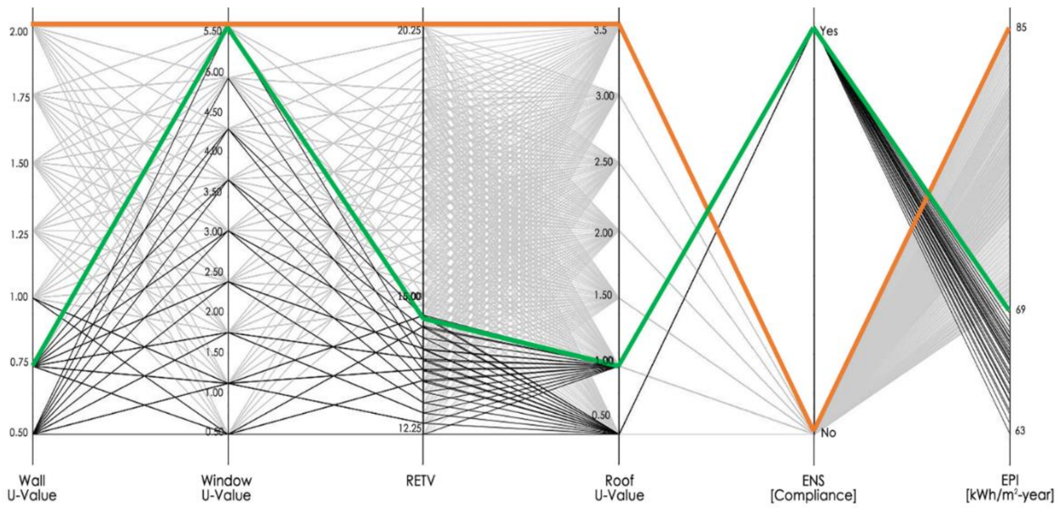


Figure 15 - Parametric analysis of ENS Compliance case

Building as usual case
One of the ENS compliance case (with AAC block used in exterior walls as the only change)

Note: Window U-value is changed and SHGC is kept constant for the analysis.

Observations

- The ENS compliance case with a low payback period is found and this case has the EUI range of 69 to 72 (19% reduction from BAU case) with savings from day 01 as the incremental cost is also less than BAU and has higher efficiency.
- The BAU case has the RETV of 20.25, by changing exterior wall assembly to AAC block the RETV came to 14.98 and just meets the ENS compliance of 15 RETV
- U-value of the wall and roof have a major impact on the RETV as the WWR in this building is at 18%.

Proposed case ECMS's and respective Internal rate of return (IRR) (for 20 years)

Table 13 - IRR for diff. cases

Option	Discerption	IRR (%)
Base case	Base case	-
Design stage 01	Basecase + IMAC	-
Design stage 02	Basecase + IMAC + Shading	60.89%
Design stage 03	Basecase + IMAC + Shading + Natural ventilation	-
Design stage 04	Basecase + IMAC + Shading + Natural ventilation + Envelope optimisation	26%
Proposed design	Basecase + IMAC + Shading + Natural ventilation + Envelope optimisation + 5-star PTAC system	46%
ENS case	Basecase + AAC block (exterior wall) + efficient roof assembly	30.98%
Renewable	Roof top PV	46.13%

Table 14 – Payback period for diff. cases

Option	Discerption	Payback period (years)
Base case	Base case	From Day 01
Design stage 01	Basecase + IMAC	From Day 01
Design stage 02	Basecase + IMAC + Shading	1 year 9 months
Design stage 03	Basecase + IMAC + Shading + Natural ventilation	From Day 01
Design stage 04	Basecase + IMAC + Shading + Natural ventilation + Envelope optimisation	From Day 01
Proposed design	Basecase + IMAC + Shading + Natural ventilation + Envelope optimisation + 5-star PTAC system	0years 2 months
ENS case	Basecase + AAC block (exterior wall) + efficient roof assembly	From Day 01
Renewable	Roof top PV	2years 4 months

Conclusion

The Net-Zero Energy Potential and main outcomes are as follows.

- After applying three different identified internal profiles (low-mid-high consumption) the BAU case EUI is in the range of 92 to 88.
- ECM's - IMAC MM 90% temp. setpoints, shading, NV, efficient envelope, efficient PTAC system were identified as the energy conservative strategies.
- After all ECM's were applied one upon another the EUI is in the range of 37 to 31 (66% reduction from BAU case). Which gives a payback period of 8 months.
- A 73kWp of rooftop PV is installed which offset 26 kWh/m2-year EUI with a payback period of 2.1 years
- The ENS compliance case with a low payback period is found and this case has the EUI range of 69 to 72 (19% reduction from BAU case) which payoff from day 01.
- AAC Blocks is identified as a very effective ECM as it has lesser construction cost and higher energy efficiency than BAU case.

Further discussion

- Efficient central HVAC systems like VAV, VRF will further reduce the EUI to reach Net-zero energy building.
- Renewable systems like Building integrated photofloods (BIPV) will also offset the required EUI to reach Net-zero energy building.
- As the study is conducted for a specific building, the same study can be done for typical residential building layout types and in different cities to further increase the study of net-zero energy residential buildings.

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Annexure 1

Envelope constructions

Table 15 - Envelope construction costs

Constructions	**U-value**	**Cost/m²**
BAU-Wall (10mm cement plaster + 230mm brunt brick + 10mm cement plaster)	2.19	2400
Autoclaved aerated concrete (AAC) block wall with plaster on both sides	0.70	2000
150 mm RCC Roof [RCC slab]	3.27	1800
White reflective tile; 40mm PUF insulation; 150mm RCC slab	0.73	2650
AIS Solar Control Glass – 6 mm (Spring)	5.70	886
AIS 6 mm (Solar Control Glass) - 12 mm (Air Gap) - 6 mm (Clear Glass) (Spring)	2.80	1926
AIS 6 mm Double Low-E Glass – 12 mm Air Gap – 6 mm Clear Glass (Clear Vivid)	1.60	2264
AIS 6 mm Low-E Glass – 12 mm Air Gap – 6 mm Clear Glass (Green Essence Plus)	1.80	2100

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Incorporating Energy Efficiency and Sustainable Energy Practices in the Renovation and Retrofitting of a 50-Year-Old Independent House

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Highlights

- Incorporating Energy Efficiency in retrofitting of a 50-year-old Building
- Rooftop solar in renovated building
- Renovated buildings can be sustainable.

Abstract

The authors, a homeowner and an architect without in-depth technical knowledge of energy efficiency, embarked on the renovation of a 50-year-old house in Bangalore, India. The result was a design that combined family needs with energy efficiency and sustainability. The 3000 m^2 property underwent a comprehensive retrofit, encompassing energy-efficient practices and renovation with renewable energy solutions, showcasing a blending of architectural design and sustainable systems.

Load reduction strategies included double-glazed windows, solar chimneys for stack-effect cooling, cool roofs, plants for shading, and energy-efficient appliances. Efficient systems, such as a VRF system, BLDC fans, LED lights, and home automation with sensors, have been installed for improved cooling, ventilation, and lighting. The house generates and uses renewable energy through a 4.89 kW rooftop solar array, a 200-liter solar water heater with a heat pump, and a 300-liter storage tank. Additional sustainability efforts also included rainwater harvesting and material reuse to reduce embodied energy.

Keywords: Renovation, Retrofit, Independent House, Energy Efficiency, Rooftop Solar

Introduction

In the face of growing energy demands and concerns about climate change, there is an increasing need to focus on energy efficiency and sustainability in residential buildings [1,2]. The building sector accounts for a significant portion of global energy consumption and greenhouse gas emissions. As such, improving the energy performance of both new and existing buildings is crucial for reducing the environmental impact of the built environment [3].

In countries like India, where most residential plots fall outside the purview of building codes, such as the Eco Niwas Samhita, there is a vast untapped potential for energy efficiency improvements in independent single-family homes. With rapid urbanization and a growing population, the renovation of older residential buildings presents a unique opportunity to incorporate energy efficiency measures and renewable energy systems, ultimately contributing to India's Nationally Determined Contribution [4].

This paper presents the case study of a 50-year-old independent house in India, renovated and retrofitted, with a focus on energy efficiency and sustainability. The homeowner, an advocate of energy efficiency with limited technical expertise, collaborated with a talented architect to transform the house into a beautiful, energy-efficient, and sustainable home that met the family's requirements. The retrofit process incorporated load reduction measures efficient systems, and the renovation process included renewable energy systems to achieve the desired energy performance.

The primary objectives of this paper are to:

- Share the experiences and challenges faced during the renovation process to demonstrate the feasibility of incorporating energy efficiency measures and renewable energy systems in an older, independent house.

- Provide costing of the energy efficiency measures and renewable energy systems implemented during the renovation. Also, it will highlight the challenges of calculating ROI due to the lack of BAU of the retrofitted energy-efficient equipment.
- Offer valuable insights to industry professionals, policymakers, and homeowners interested in energy-efficient renovation of independent single-family homes.

Background

The paper presents the case study of a 50-year-old independent house in Bangalore, India, renovated and retrofitted with a focus on energy efficiency and sustainability. The homeowner, an advocate of energy efficiency with limited technical expertise, collaborated with a talented architect to transform the house into a beautiful, energy-efficient, and sustainable home that met the family's requirements. The renovation process incorporated load reduction measures, efficient systems, and renewable energy systems to achieve the desired energy performance.

Background and Design Considerations

The architect's brief was to modernize a 50-year-old building with two residential units into a single-unit home for a multigenerational family of three and their three pets. The 30x60 site was in an urban residential area, featuring a G+2 story load-bearing structure. The renovation maintained the external walls and roof slabs while reconfiguring internal spaces to accommodate the family's needs. Older internal walls were carefully removed and replaced with new ones, supported by structural steel members.

Energy Efficiency Measures and Renewable Energy Systems

This transformation featured:

Renovation introduced a solar chimney for passive cooling, reduced window sizing to decrease cooling load, and installed a rooftop solar power system and heat pump. To maintain energy efficiency, local materials were used, and existing teak doors were repurposed, and cool roof tiles were used on the terrace and inner courtyard. The final design incorporated individual preferences while ensuring the home remained comfortable for the family's pets.

The measures undertaken can be classified into three main categories:

- Load Reduction
- Efficient Systems and
- Renewable Energy Systems Each of these measures are detailed below:

Measures: Each of the Measures are detailed below:

Load Reduction:

- The 3000 m2 house building envelope was largely kept intact.
- Windows were sized to maintain a 15-20% window to floor area ratio
- The windows were replaced with double-glazed units with uPVC window frames
- A solar chimney was installed in the atrium to create stack-effect cooling.
- A cool roof was installed, along with plants for shading
- Energy-efficient appliances such as a microwave, oven, dishwasher, washing machine, refrigerator, and dryer were installed in the kitchen and utility

The implementation of load reduction measures, including proper window sizing and the use of double-glazed windows, contributed to improved thermal performance and reduced cooling loads. The solar chimney and cool roof further enhanced the building's thermal performance by providing natural ventilation and minimizing heat gain. The energy-efficient appliances contributed to an overall reduction in energy consumption.

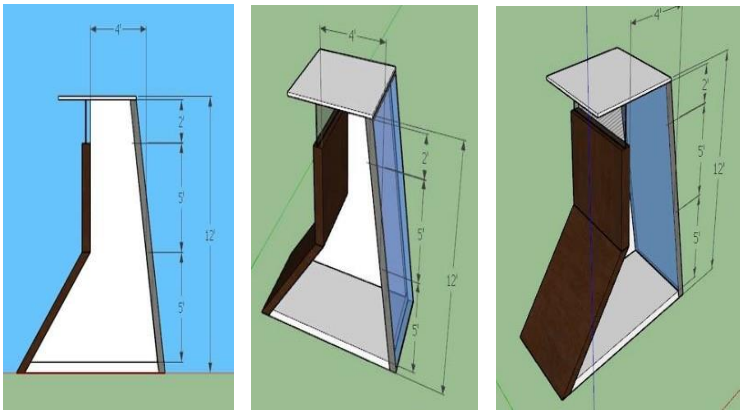

Figure 1: Drawings of Solar Chimney

Figure 2: Photo showing the constructed Solar Chimney

Efficient systems for providing cooling, ventilation, and light. They are:

- VRF system – ODU 10 HP with R410A refrigerant
- BLDC fans – 9 nos
- LED lights and home automation with sensors and dimmers

The VRF system, BLDC fans, and LED lights with home automation sensors and dimmers have significantly improved the efficiency of cooling, ventilation, and lighting systems. The VRF system offered better zoning capabilities and improved temperature control while minimizing energy consumption. The BLDC fans provided energy savings of up to 50% compared to conventional fans, and the LED lights, coupled with home automation, led to a reduction in energy usage for lighting.

Renewable energy systems:

- The terrace has been fitted with 4.89 kW of rooftop solar panels
- There is also a 200-liter solar water heater with a heat pump and a 300-liter storage tank

The installation of a 4.89 kW rooftop solar panel system and a solar water heater with a heat pump contributes to the production of clean, renewable energy for the house. The aim is to reduce the overall grid electricity consumption, resulting in lower energy bills and a smaller carbon footprint.

Others:

- Green cover with plants on all 3 floors of the house; small water bodies in the form of two aquariums and a small tank
- Rainwater harvesting
- Repurposing old teak doors into new doors
- Energy-efficient pumps and motors for pumping water

The green cover, rainwater harvesting, and repurposing of materials further enhanced the sustainability of the house. The green cover provides natural shading and helps maintain a comfortable microclimate within the house. Rainwater harvesting has enabled water conservation, while the reuse of old teak doors and energy-efficient pumps and motors have contributed to reduced embodied energy and operational energy consumption, respectively.

Figure 3: Image of the house before renovation and retrofit, 1971

Figure 4: Image of the house before renovation and retrofit, 2021

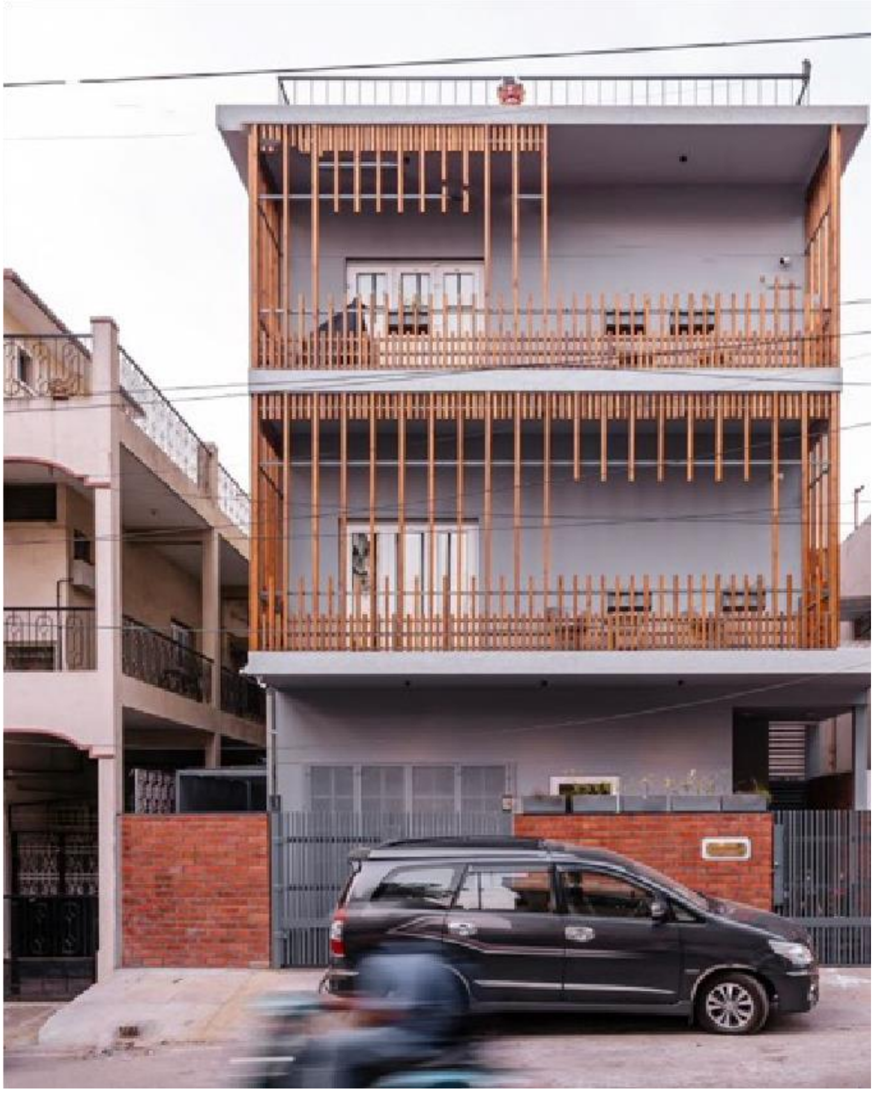

Figure 5: Image of the house after renovation and retrofit, 2023

Figure 6: Interiors Now

Costing

The determination to make the house energy efficient, combined with discounts negotiated for the equipment and appliances, aided in implementing energy efficiency measures. The costs are detailed below.

Table 1: Costing of Energy-Efficient Equipment

Appliance	Discount	Cost for EE Appliance in INR After Discount +GST	Cost of Business-As-Usual (BAU) Appliance	Incremental Cost of Appliance	Energy Savings Compared to BAU
VRF (including 8 units)	30%	4,25,000	1,72,000	2,53,000	20%
Home Automation	37%	2,00,000	0	2,00,000	10%
uPVC with double glazed windows	27%	13,00,000	6,50,000	6,50,000	NA
Kitchen Appliances	25%	5,95,000	1,85,000	4,10,000	NA
BLDC (9 Fans)	-	33,000	12,600	20,400	NA
Efficient pumps, motor, solar water heater,	-	4,39,000	2,50,000	1,89,000	Pumps 15%, water heater 50%.
heat pump and storage tank					
Total		**29,92,000**	**12,69,600**	**17,22, 400**	

The total cost for implementing energy efficiency measures and renewable energy systems during the renovation was INR 29,92,000. The incremental cost was INR 19,53,400.

Unclear Return on Investment (ROI):

To calculate the return on investment (ROI) for each energy efficiency measure (not including the renewable energy system), the annual energy cost savings need to be estimated; only then can the payback period be determined.

As seen in Table 1, various vendors gave only percent savings estimates compared to a Business As Usual (BAU) appliance or equipment. Also, for windows, kitchen appliances, and BLDC fans, the vendors did not provide even the percentage of energy savings.

If the BAU energy consumption numbers for each equipment or appliance were provided by the vendors, the ROI or payback calculation could have been done.

The 4.89 kW rooftop PV system cost INR 4,31,000, and no discounts were provided for that system.

Challenges

The homeowner and the architect faced several challenges during the renovation period:

- The payback for the entire suite of efficiency improvements is unknown despite the percentage savings numbers provided by some vendors and the significant discounts received from manufacturers. The incremental cost of appliances, energy efficiency, and renewable energy measures are nearly 1.5 times the cost of generic appliances. But for the passion of the homeowner, the incremental cost would have been a strong deterrent to implementing energy efficiency.
- Coordination among various vendors: A lack of clear communication and coordination among the different vendors involved in the renovation process led to work being redone. Ensuring smooth communication and collaboration among vendors is crucial for successful project execution.
- GRIHA rating: Applying for a GRIHA rating (Green Rating for Integrated Habitat Assessment) was considered to certify the energy efficiency and sustainability of the house. However, the cost of obtaining the rating – Rupees 1 lakh was deemed better spent on implementing energy-efficient measures. The decision to prioritize actual improvements over certification reflects a focus on tangible benefits. The homeowner was also unclear about the benefits of obtaining a GRIHA rating for a renovated house.
- Limited material recycling facilities: The architect discovered information about material recycling facilities relatively late in the renovation process. Additionally, there are not many such facilities in the city, making it challenging to incorporate recycling and reuse strategies in the project. Increased awareness and access to material recycling facilities can significantly improve the sustainability of renovation projects.
- Lack of Electricity Bills: Since the solar panels were installed and commissioned, BESCOM has yet to issue an electricity bill.

These challenges highlight the importance of effective communication, prioritizing investments, and increasing awareness of sustainable construction practices.

Addressing these challenges can help homeowners and architects to navigate the renovation process and achieve the desired outcomes in terms of energy efficiency and sustainability.

Conclusion

This paper has demonstrated that renovating and retrofitting an older, independent house with energy efficiency and sustainability in mind is not only achievable but also possible, even with limited technical expertise and a strong determination. The renovation of the 50-year-old house resulted in a beautiful, energy-efficient, and sustainable home that met the family's requirements.

The cost analysis and unclear return on investment calculations provide an understanding of the financial issues associated with implementing energy efficiency measures and renewable energy systems during the renovation process. With an unknown payback period, the energy efficiency measures and renewable energy systems cannot be scaled up in a retrofit and renovation process where limited technical expertise is available to the owner. Integration of costs and savings of various appliances and equipment needs to be presented clearly to the owner. Perhaps a simple calculation tool that empowers the owner to ask for the relevant information would help building owners make informed choices.

We recognize that the energy efficiency and environmental benefits contribute to the overall value of the investment. Furthermore, such measures can improve the comfort and indoor air quality of the building, enhancing the occupants' well-being and overall satisfaction with their living environment. However, these may not be considerations entertained by less motivated homeowners.

As India strives to meet its Nationally Determined Contribution, the findings and observations of this paper are highly relevant to the large market of independent single-family homes that currently fall outside the scope of residential building codes. The experiences and costs associated with implementing energy efficiency measures in the renovation process offer valuable insights for industry professionals, policymakers, and homeowners interested in making their homes more sustainable and energy-efficient in the renovation process can provide valuable information for industry professionals, policymakers, and homeowners.

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