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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%

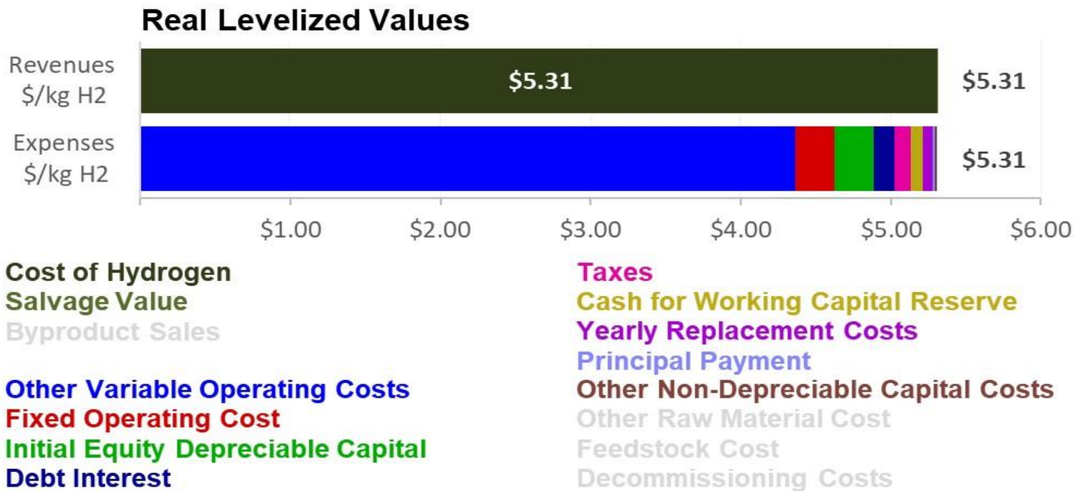

Figure 1: Cost breakdown of PEM electrolysis

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.

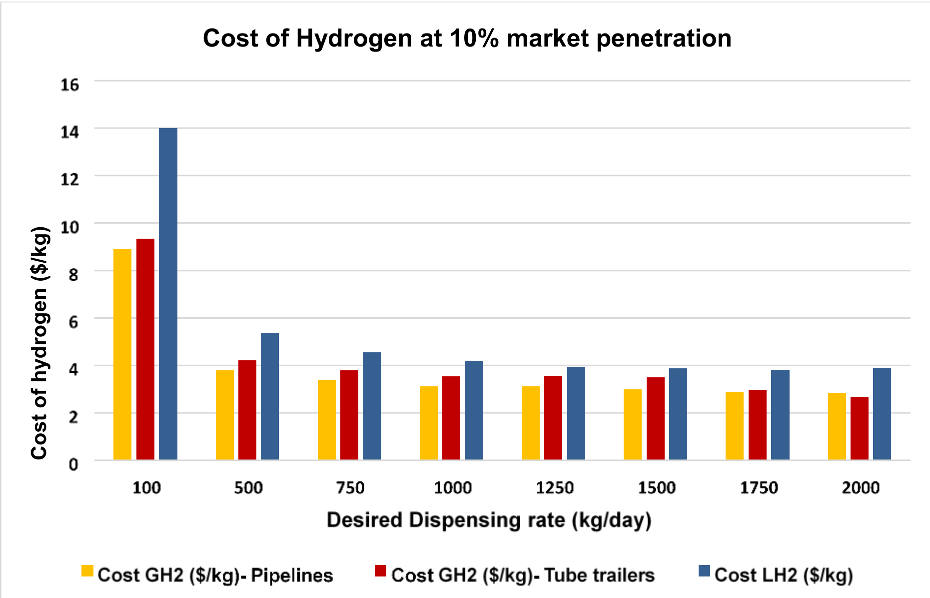

Figure 3: Delivery cost of hydrogen at 10% market penetration

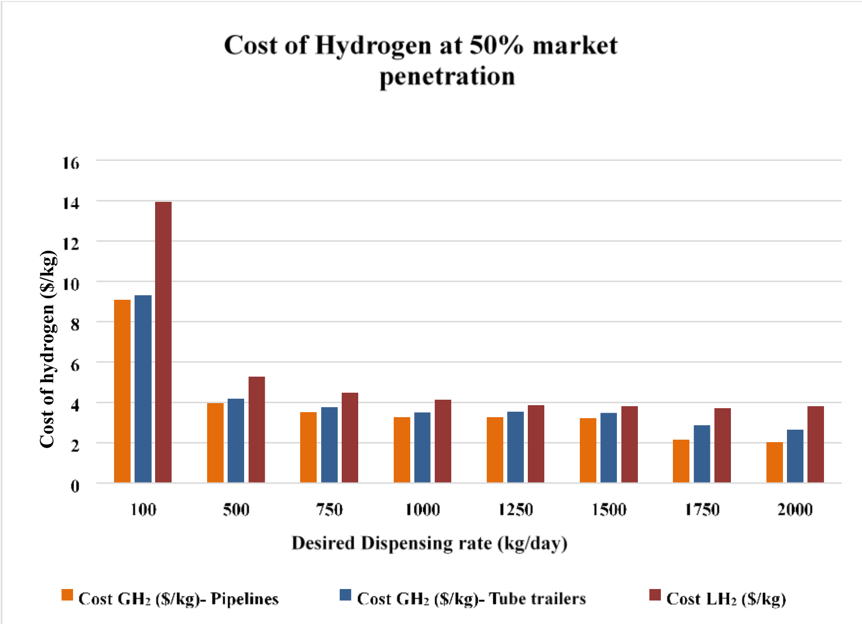

Figure 4: Delivery cost of hydrogen at 50% market penetration

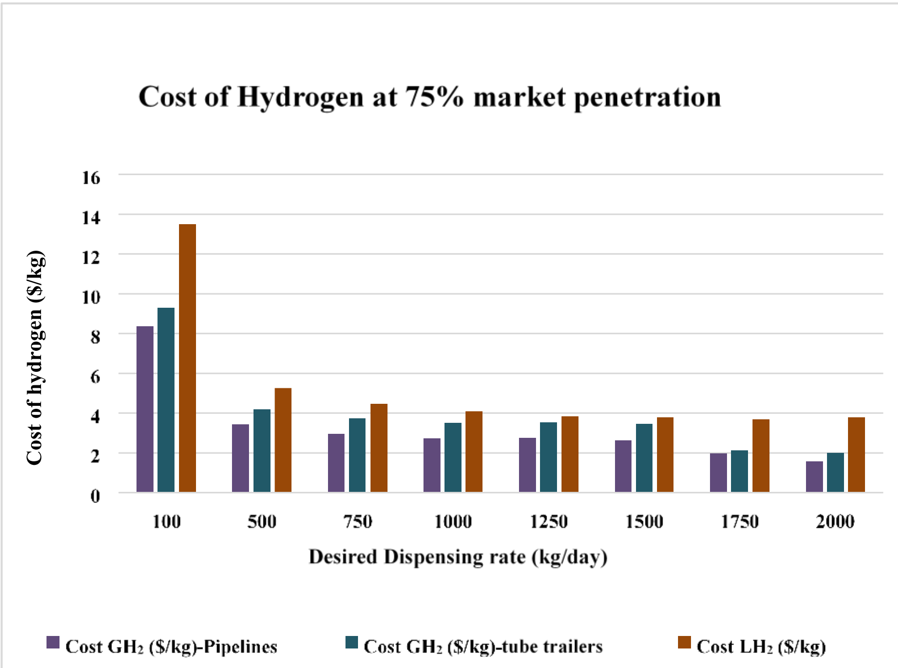

Figure 5: Delivery cost of hydrogen at 75% market penetration

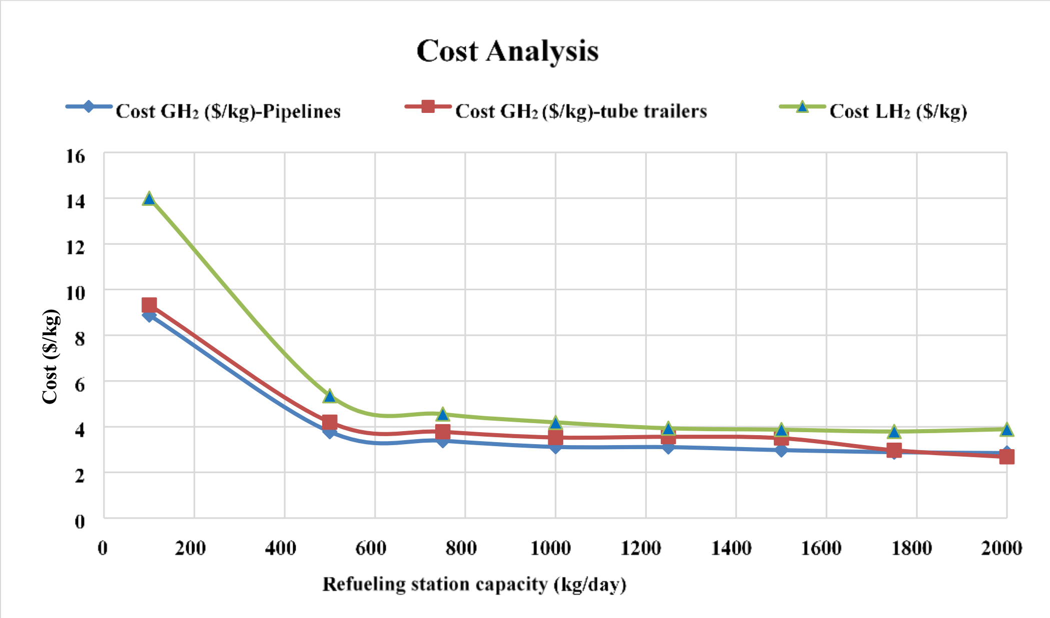

Figure 6: Delivery cost of liquid and gaseous hydrogen

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

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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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