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Estimating the Timeline for Green Hydrogen's Viability for Captive Power Generation Compared to Grid Power for the Indian Industrial Sector

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Abstract

The transition to sustainable energy is vital for reducing carbon emissions and mitigating climate change. This study provides a quantitative analysis to forecast the viability timeline of green hydrogen as an alternative to conventional fossil fuels for captive industrial power generation in India, aiming to reduce Scope 1 emissions and support net-zero targets. Green hydrogen, produced via electrolysis using renewable energy, offers a zero-emission substitute to natural gas. However, high production costs, infrastructure limitations, and technological challenges hinder widespread adoption. This research applies Value Web and techno-economic analyses to evaluate current and projected costs of green hydrogen, technological advancements, and infrastructure scalability. Using data from industry reports, policy documents, and academic studies, the paper models cost-reduction scenarios in green hydrogen production and electrolysis efficiency. It determines the Levelised Cost of Green Hydrogen (LCOH) and assesses transport costs to industrial sites. Further, it examines onsite captive power generation to calculate the Levelised Cost of Electricity (LCOE) from green hydrogen, comparing it to grid electricity over time. Sensitivity analyses explore the effects of carbon tax and discount rate changes on green hydrogen's competitiveness. Findings indicate that green hydrogen could reach cost parity with grid power for industrial use by 2032 without policy incentives. With favourable government policies and sustained technological progress, this parity could be achieved earlier. The study highlights the strategic role of green hydrogen in India's energy transition, emphasizing the importance of investment in renewable energy infrastructure and supportive policies. It offers valuable insights for policymakers, industry leaders, and researchers into the challenges and opportunities of adopting green hydrogen for industrial power, contributing to national and global climate goals.

Major Findings: *Green hydrogen for 24x7 captive power generation in India could become viable by 2032, particularly in coastal states, like Gujarat, Maharashtra, and Tamil Nadu, that are rich in renewable energy. A carbon tax of $100/ton CO_2 could accelerate adoption by another couple of years, with financing and discount rates playing a crucial role in cost competitiveness. Government incentives like import duty waivers and Production-Linked Incentives (PLI) can further boost market adoption of Green Hydrogen. While Green Hydrogen competes with natural gas, advancements in carbon capture technologies could enable carbon-neutral power generation from natural gas. The choice between Green Hydrogen and carbon capture investments will depend on market dynamics and natural gas availability.*

Keywords: *Captive Power Generation, Green Hydrogen, Natural Gas, Net Zero, Sustainability*

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1.0 Introduction

Sustainability is a vital paradigm for the world now, and with the increasing impact of climate change not just on daily life but also on business operations, sustainability has not just remained a buzzword but has translated into actionable goals for countries and corporations alike[1]. The most noticeable impact of climate change due to its repetitive impact is, for instance, the East African drought that was experienced in 2011, 2017, and 2019, affecting millions of people and is primarily attributed to higher sea temperatures affecting the natural seasonal cycle in the East African region[2]. According to a report by the National Oceanic and Atmospheric Administration (NOAA), there have been more than 23 separate weather-related events in the year 2023, resulting in losses running into billions of US$[3]. India ranks 4th globally in terms of countries impacted by climate change[4] India has experienced a temperature rise of 0.7°C between the year 1901 to 2018, which is significant. This is estimated to impact glaciers and ice melting in the Himalayan regions and cause flooding and droughts. The agricultural yield is estimated to be impacted and reduced if the impact continues till the year 2100. Due to these noticeable impacts of climate change on business and the economy, countries have started taking this matter with utmost seriousness and have initiated their respective climate action plans.

Over the past three decades, India's energy needs have tripled. In the year 2000, the nation's total energy needs were approximately 400 million tons of oil equivalent (Mtoe)[5]. To meet these needs, the nation has relied heavily on fossil fuels, specifically coal, petroleum, and natural gas. In contrast to oil and natural gas, coal has been sourced domestically for the past 20 years, outpacing its imports.

While the first country to commit to a net zero target was Sweden in 2017[6], Table 1 represents 5 major economies that are diverse in their business operations, *i.e.,* a mix of countries from the United States being energy-independent, the Kingdom of Saudi Arabia being a net exporter of energy to countries like Japan, South Korea and India who are net importers of energy sources from across the globe[7].

From the data represented in Table 1, it is also significant to observe that markets like the USA, Japan, and South Korea have taken early net-zero targets of 2050, while KSA and India have the targets of 2060 and 2070, respectively. This is also because KSA currently has very low adoption of renewable energy, whereas though India has a 23% (year 2023) share of renewable energy in its power-generation mix, it still has a significant reliance on coal-based power generation[7]. While this provides a significant amount of time for India to plan and adapt to net-zero goals, it is also important to understand how much time all stakeholders, particularly the industry in India, may require to achieve the net-zero target.

Table 2 is indicative that the targets set by major companies of India Inc. are very steep compared to national targets, which also means that they need to be ahead of the curve in adopting future and carbon-neutral technologies by two to three decades.

Table 1. Net zero targets vs % of renewable energy in electricity mix[8,9]

Country	Net Zero Target	% of renewable in Power Generation US$2023
USA	2050	40.35
India	2070	22.99
Kingdom of Saudi Arabia	2060	0.21
Japan	2050	26.97
South Korea	2050	36.45

Table 2. Net Zero targets by major corporations in India[9]

Indian Company	Web address	Net Zero Target
Reliance Industries Limited	https://www.ril.com/	2035
Tata Consulting Services	https://www.tcs.com/	2030
Infosys Limited	https://www.infosys.com/	2040
ONGC	https://ongcindia.com/web/eng	2038
Mahindra Group	https://www.mahindra.com/	2050

2.0 Aims of the Study

While each industry has its operations aligned to the sector it operates in, the impact of its manufacturing operations on the environment may vary. Also, as industries look forward to reducing their carbon footprint on their Scope 1 emissions, one major contributor to these is captive power generation. There have been endeavours to utilise green hydrogen for captive power generation reliably, thus addressing the abatement of Scope 1 emissions from onsite power generation.

This study aims to identify a timeline by which green hydrogen shall be a viable and cost-effective alternative in comparison with natural gas in India, especially for industry users. This study emphasises identifying the landed cost of green hydrogen, to be utilised for power generation on-site for industrial customers, and empirically estimates the potential of adopting this path of sustainability and a timeline by which it would be economically viable in India.

3.0 Significance of this Study

While there are a good number of articles and research papers on green hydrogen generation technologies and utilisation technologies[10], only sporadic work on the 'economics of generating green hydrogen' is available[11]. Existing research work mostly focuses on the utilisation of green hydrogen for hard-to-abate segments like Iron and Steel manufacturing, fertilisers, and transportation in India. However, this study deals with an integrated techno-economic analysis to predict the life cycle landed cost of green hydrogen and utilise it for the identification of the levelised cost of electricity using green hydrogen as fuel, which has not been done previously for the Indian market. This analysis is termed as power-to-power cycle (Techno economics of generating green fuels using renewable electricity and electrolyzing water, the generated fuel is consumed at a different location and time for power generation using a fuel cell or a combustion technology with the generated green fuel as feed energy) deals with techno-economic analysis for the Indian market, specifically where initial green power generation is offshore as renewable electricity (or non-captive where the reliability is low), while the final usable green power is generated as captive onsite for the highest order of reliability.

4.0 Rationale of the Study

The study provides a quantitative perspective on Scope 1 emissions reduction by opting for green hydrogen as a fuel for captive power generation. The study contributes to the analysis of the green hydrogen value chain, hydrogen generation technology analysis, and hydrogen consumption technology analysis from an industrial user perspective. This study helps decision makers plan their sustainability goals and timeline estimation of this technology to best fit economically for their business. The analysis, though, is not without certain limitations that can slightly alter the results in terms of time to adoption of the technology.

5.0 Structure of the Paper

Starting with a brief introduction, aims, significance, and rationale of the study, this paper contains a contextual literature review that helps identify the prospective research gap and consequent research questions of the study. Further, with the help of operational definitions, the green hydrogen value chain contextual to the study has been explained. This enables us to envisage the components that are involved in the identification of the landed cost of green hydrogen for industrial users. Next, the paper discusses the research framework (including research gap identification, research questions, and the methodology to address the research questions). The research framework is utilised to identify the levelised cost of green hydrogen, after which, the levelised cost of electricity is calculated. This calculated levelised cost of electricity using green hydrogen is then compared with the estimated levelised cost of grid electricity to identify the timeline by which there is a possibility to attain parity of LCOE (Levelised Cost of Electricity) between power generation from the grid and that produced from green hydrogen. Since the grid power would still contribute to carbon emissions, and the economic viability of (generally) high-capex green hydrogen technologies depends on the (relevant) discount rate, a sensitivity analysis is thus run to identify the impact of these two components on the adoption of green hydrogen for captive power generation. The paper then mentions a case where green hydrogen generation at a location (Mundra Port, Gujarat state of India) is utilised at another location far from the generation site (near Ahmedabad in the same

state of Gujarat, India) and then discusses the outcomes of quantitative analysis, possible alternatives like carbon capture for net- zero onsite power generation and concludes with findings of the study, further applicability of the study and possibilities to improve the accuracy of the study.

6.0 Literature Review

A literature review was conducted to understand the value chain of green hydrogen, technical aspects, economic aspects, and the studies on correlating green hydrogen and net-zero 24x7 on-site renewable power generation.

Dell and Rand[12] evaluated the prospects of green hydrogen as a global future fuel. The areas covered include pathways to hydrogen production, prospects for carbon capture and storage, and options for hydrogen storage on vehicles, fuel cells, and fuel cell vehicles. A report by the Hydrogen Council[13] discusses an evidence-based path for the cost competitiveness of hydrogen fuel and provides firm ground on which to base financial and non-financial support that will unlock the economic value of hydrogen and to develop adequate policy frameworks. IEA[14] has tracked hydrogen production and demand worldwide. Two important reports estimate the potential for green hydrogen production as a function of land availability, considering exclusion zones such as protected areas, forests, wetlands, urban centres, slopes and water scarce regions[15,16]. A study by Lazard[17] provides an analysis of the LCOH to provide greater clarity to Industry participants on the potentially disruptive role of hydrogen across a variety of economic sectors. A work by Quarton & Samsatli[18] provides a unique model for optimising integrated value chains for CCUS (Carbon capture, utilisation and storage), renewables & hydrogen. A study compares Green Ammonia with CCS (Carbon capture and storage) and nuclear energy for dispatchable green electricity. The study concludes that Green Ammonia warrants further exploration in electricity system modelling[19]. Hwang, Maharjan, & Cho[20] have carried out a comprehensive review on hydrogen production and utilisation. They have also discussed in detail the technical challenges in hydrogen utilisation. Colbertaldo *et al.*[21] have worked out a model that simulates the hourly balance of demand and supply in the power grid. The study, among others, also discusses the role of storage, focusing on hydrogen storage via Power-to-Gas Options for 100% renewable electricity in California.

7.0 Operational Definitions

The given section provides operational definitions of various activities and terms relevant to this study. The following operational definitions have been dealt with:

- Green Hydrogen Value Chain
- Standard Equation to calculate the landed cost of Green Hydrogen
- Green Hydrogen Production Cost
- Green Hydrogen Preparation Cost
- Green Hydrogen Distribution Cost
- Green Hydrogen Storage& Reformation Cost
- Levalised Cost of Green Hydrogen
- Levalised Cost of Electricity
- Electrolyser Types for Green Hydrogen Production
- Power Generation Technologies using Green Hydrogen
- Hydrogen-based Fuel Cell Technologies

7.1 Green Hydrogen Value Chain

The value chain begins with water or steam upstream and ends with power generation through fuel cells or direct combustion downstream. To interpret the standard equation for calculating the total landing cost of green hydrogen for power generation, it is crucial to have a thorough understanding of the various components of the green hydrogen value chain, as illustrated in Figure 1.

The total landed cost of green hydrogen for customers for power generation described in Figure 1, can be expressed in an equation as:

7.2 Standard Equation to Calculate Landed Cost of Green Hydrogen

Total landed Cost of Green Hydrogen, *i.e.*, TDC (T) = P+Q+R+S –Equation 1

7.3 Green Hydrogen Production Cost (P)

In order to produce green hydrogen, electrolyser equipment is used to split water or steam and use renewable electricity as the main source. The LCOH model is used to

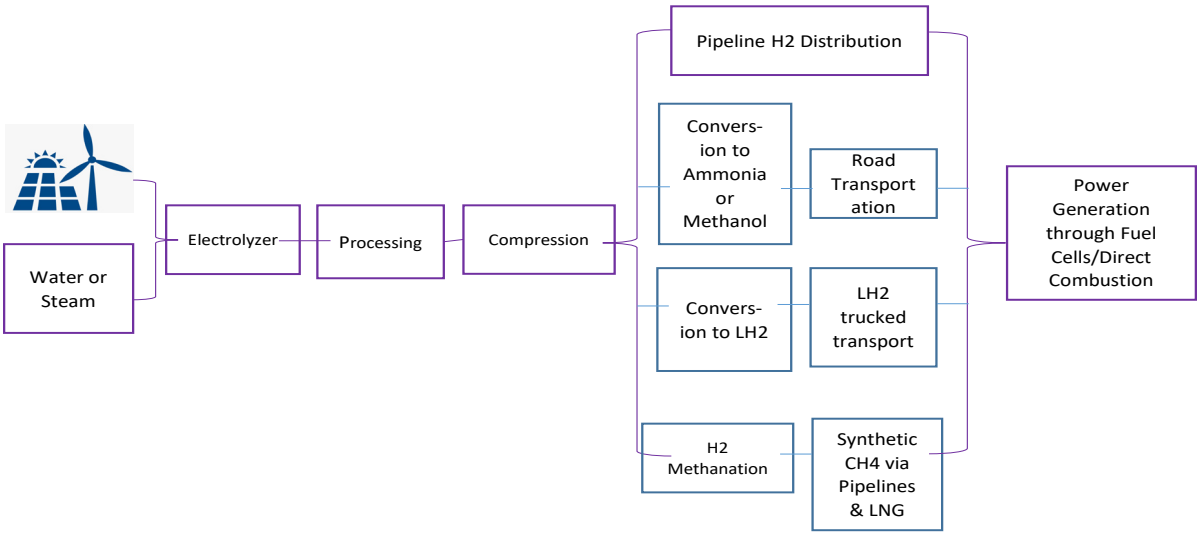


Figure 1. Green Hydrogen Value Chain[22].

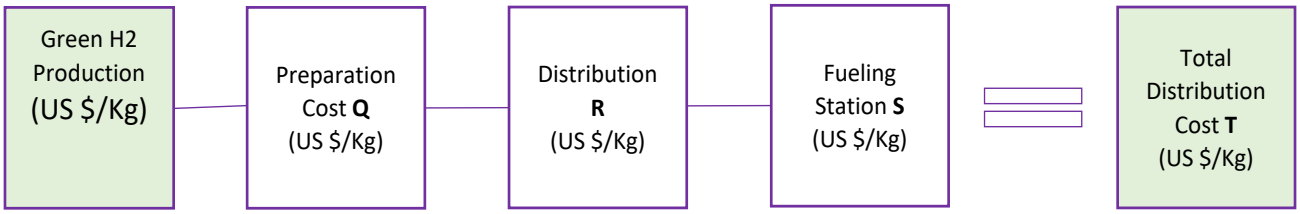


Figure 2. Landed Cost of Green Hydrogen[22].

assess an electrolyser technology's yield. Throughout the assessment, this offers inputs on the green hydrogen (P) project's production cost.

7.4 Green Hydrogen Preparation Cost (Q)

Green hydrogen must be conditioned using procedures like chilling, drying, compression, and conversion if the market requires that. However, the cooling process is solely related to the creation of green hydrogen from solid oxide electrolysers that operate at high temperatures. As a result, the electrolyser's output is likewise at a higher temperature, necessitating cooling before the drying and compression stages. Since green hydrogen is produced by electrolysing water and contains up to 20% moisture in its raw form, these two steps are shared by all technologies. Drying is a crucial step in getting green hydrogen ready for distribution since it removes moisture before compression.

7.5 Green Hydrogen Distribution Cost (R)

Green hydrogen must be compressed at high pressure to be distributed. Three methods are primarily used for the local distribution of green hydrogen (GH2): (i) Compressed GH2, which is delivered in high-pressure tube trailers after being compressed at pressures of up to 350 bar[23]. This is a cost-effective choice for distribution within a 200–300 km radius. (ii) Liquefied GH2 tankers, in which GH2 is carried to its destination after being liquefied using cryogenic methods. Although the liquefaction process is costly, it makes it possible to transport hydrogen over greater distances by truck, train, ship, or barge more effectively (in comparison to high-pressure tube trailers). Liquid hydrogen must be compressed to 82 bar of pressure to be distributed using this technique. The technique may transport higher amounts in a trip, but it also uses electricity up to 6.4 kWh/kg of liquid hydrogen. 3) Gas pipelines are the final

distribution option; GH2 can be mixed up to 18% with already-existing natural gas pipelines. As an alternative, GH2 can also be transmitted by installing specialised gas pipes, which could ultimately be more cost-effective but require a large CAPEX[13].

7.6 Storage Reformation Cost (S)

The storage component, targeted distribution component, and conversion from hydrogen vector to pure hydrogen are the costliest. However, with rising demand and an increase in the number of purchasers, this component could improve. However, bulk storage, compression/pumping, high-pressure buffer storage, and pre-cooling devices are among the cost components in the case of industrial users purchasing GH2 with the options mentioned above in R[24]. As a result of higher demand, the cost of fueling station components decreased by 87% in 2020 compared to 2012 levels, and this trend is predicted to continue through 2030.

7.7 Levalised Cost of Green Hydrogen

The LCOH is a method used to evaluate the total expenses involved in producing hydrogen throughout its entire lifecycle, including both Capital (CAPEX) and Operational Costs (OPEX).

7.8 Levalised Cost of Electricity

The rate of the total energy output of the energy system to build and operate it over its lifetime, to the average total cost of the system over that lifetime.

As also referred to in the proposed methodology framework, the abovementioned operational definitions will be used to identify the cost range of Q, R, and S to identify the pricing range of Green Hydrogen based on secondary data and derive rates for estimating their values over the time range.

7.9 Electrolyser Types for Green Hydrogen Production

Given the importance of electrolysis in the creation of green hydrogen, it is crucial to take note of the various kinds of electrolyzers that have been created worldwide, as well as the variations in their design and functionality. The following Table 3[25-33] lists the many kinds of electrolyzers in different green hydrogen scenarios.

According to the analysis, there are a number of different electrolyzer technologies in different phases of product development, which is reflected in their prices. However, each of these technologies will have a distinct clientele and demand base based on how important lower capital expenditure, increased efficiency, and reduced water use are. Nevertheless, each technology

Table 3. Analysis of electrolyzer technologies

S. No.	Electrolyzer type	Technology maturity	Electrode material (Cathode - reduction side, H2)	Electrode material (Anode - Oxidation side)	Stack efficiency (kWh/kgH2)	System efficiency (kWh/kgH2)
1	Alkaline	Matured	Nickel, Nickel Molybdenum Alloy	Nickel, Nickel Cobalt Alloy	45-55	50-78
2	Polymer Electrolyte Membrane	Commercialised	Platinum, Platinum - Palladium Alloy	Ruthenium Oxide, Iridium Oxide	45-50	50-83
3	Solid Oxide	Commercialised	Nickel, YSZ	YSZ	34-40	45-55
4	Anion Exchange Membrane	Prototype	Nickel and Nickel Alloy	Nickel, Ferrous Cobalt Oxides	NA	57-69

will eventually progress toward its goals of increased efficiency, lower capital expenditures, and extended stack availability.

7.10 Power Generation Technologies using Green Hydrogen

The development of the steam engine, diesel engine, gas engine, steam turbines that run on coal, natural gas, biomass, and combined cycle power plants that run on natural gas fuel are just a few of the technologies that have evolved and been used for industrial power production over time. All of these have been working to show the best electrical efficiency that may be achieved with traditional power generation systems[34]. Table 4 lists conventional stationary power generation along with the best demonstrated efficiencies and average performance efficiencies at the time of its introduction.

Table 4. Conventional power generation technologies[34-40]

Technology	Fuel	Electrical Efficiency (LHV) Average
Steam Turbine	Pulverized Coal	36%-45%
Steam Turbine	Coal	32%
Simple Cycle Turbine	Natural Gas	35%-45%
Combined Cycle Gas Turbine	Natural Gas	44%
Engine	Oil	30%
Engine	Natural Gas	35%-45%

7.11 Hydrogen-based Fuel Cell Technologies

Fuel cells have come a long way from their first creation in 1850 and their use in space applications in the 1950s. Today, they are being used in every application where power was previously supplied by traditional technologies like turbines and engines. Electric vehicles, power applications such as forklifts, backup power generation, captive power production, utility-scale power generation, space applications, and marine applications, such as cruise ships, submarines, and LNG carriers, are among the current uses for fuel cells. Power generation in stationary applications, such as utility-scale power generation, backup power generation, and primary power generation, is one of the main uses of fuel cells, which have found extensive use. The best quality power production with qualities like high dependability, power plant scalability, and better economics—that is, high efficiency, fuel flexibility, and adaptability from present market demand to future fuel adaptability needs—is always sought by industries.

Table 5 indicates fuel cell technologies that have seen market acceptance and can use hydrogen for power generation.

Table 5. Hydrogen-based fuel cell technologies

S. No.	Fuel cell type	Abbreviation	Technology maturity	Direct usable fuels	Average LHV efficiency
1	Alkaline Fuel Cell	AFC	Matured	Hydrogen	47%
2	Polymer Electrolyte Membrane Fuel Cell	PEMFC	Matured	Hydrogen	39%
3	Solid Oxide Fuel Cell	SOFC	Matured	Natural gas, biogas, hydrogen, ammonia, methanol	58%
4	Phosphoric Acid Fuel Cell	PAFC	NA	Hydrogen	40%
5	Molten Carbonate Fuel Cell	MCFC		Natural gas, syngas, hydrogen	50%

8.0 Research Gap

The literature review provides multiple contents on technical and economic aspects of the generation, transportation, and application of green hydrogen. However, each of these aspects of green hydrogen has been worked out only in isolation. An integrated approach that encompasses analysing the value-web of green hydrogen, identifying the levelised cost of generation of GH, cost of transportation and storage of green hydrogen, and ultimately techno-economic analysis of the utilisation of green hydrogen is missing.

Existing research mostly identifies the application of green hydrogen in hard-to-abate segments like fertiliser, iron, and steel and its application in marine or road transport. There is a limited techno-economic analysis of utilising green hydrogen for 24x7 onsite renewable electricity generation with a predictable cost and reliable availability.

The integrated approach of identifying *power-to-power* cycle effectiveness and adaptability of green hydrogen for the Indian market, which is important for concerned entities looking forward to achieving their net-zero goals and also needing reliable onsite power generation for their operations, has not been conducted yet.

9.0 Research Questions

The identified research gap throws up three significant research questions as follows:

1. How to identify the landed levelised cost of green hydrogen for captive power generation?
2. What goes into the calculation of the levelised cost of electricity for captive power generation using green hydrogen as a fuel?
3. How sensitive is the adoption of green hydrogen to the following two variables:
    - Carbon taxes
    - Discount rate for capex on green hydrogen generation and utilisation equipment.

10.0 Methodology

The methodology involves secondary research to collect data points for techno-economic analysis, along with the analysis of the value chain of green hydrogen with cost components at each stage of generation and utilisation of green hydrogen. A deep dive into technologies involved in the generation of green hydrogen and in the utilisation of green hydrogen has been undertaken to realise future performance developments and potential cost reductions. Secondary data for each cost component is identified and studied, and then reflected in a mathematical model that first identifies the LCOH, then it identifies the delivered cost of green hydrogen, which becomes a feed to captive power generation technology. And eventually, it identifies the LCOE using the identified LCOH + cost of delivering fuel, as a price feed for fuel. The identified LCOE using green hydrogen as fuel is compared with conventional grid-based power and its CAGR escalation curve to estimate the time for reaching the commercial viability of captive green hydrogen-based power generation for industrial consumers in India. The methodology also entails performing a sensitivity analysis about the impact on adoptability with respect to other variables like lending rate and carbon tax (which also impacts the viability of cleaner sources of power generation). The results shall help identify the impact/benefit of adopting green hydrogen-based power generation with time as the factor on the x-axis. The quantitative analysis helps maximise economic return while meeting Net Zero goals.

The research question 1 shall be attempted to be answered by conducting secondary research as indicated in Figure 3 in association with the calculation of LCOH, as also mentioned in Figure 3 (Methodology diagram) and the corresponding equations. The outcome of the same is termed as step 1.

Research question 2 is addressed by applying the landed cost of green hydrogen generated along with the output of research question 1, and then using them further along with the LCOE model for Green Hydrogen (equation 5) described in the upcoming section. By applying this LCOE model across the time series for projects starting in the next decade, it provides the expected economic performance and derives LCOE for those projects over time. This facilitates quantitative analysis and answers research question 2. This is represented in the results section as step 2. Further, by running a sensitivity analysis

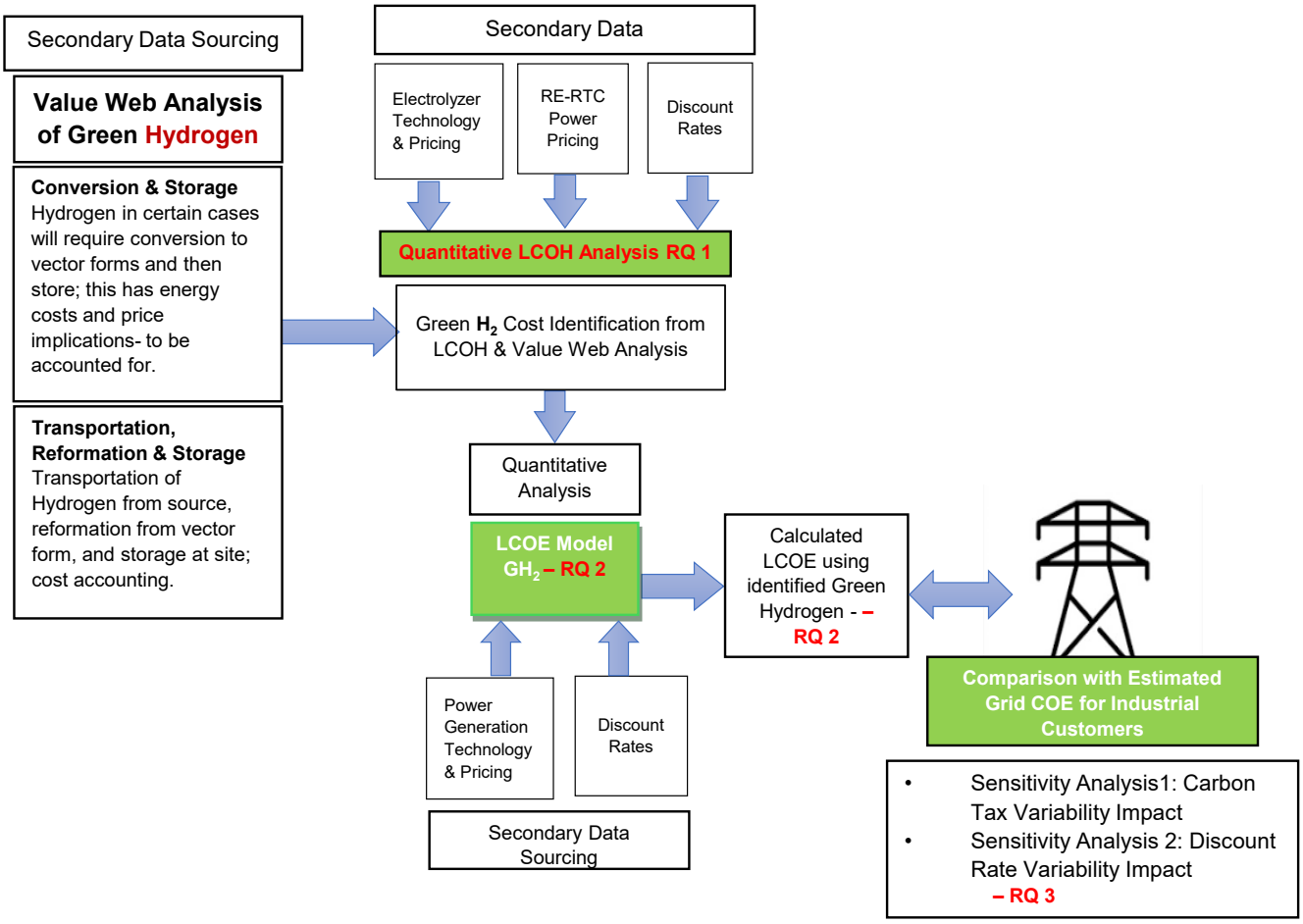


Figure 3. Research framework.

and varying the inputs of these variables, like carbon tax and discount rate of green hydrogen technologies, the sensitivity of derived natural gas pricing can be found and analysed. This analysis provides the answer to Research Question 3 and is termed as step 3.

The methodology is also described in Figure 3**:**

10.1 Equations and Variables for Quantitative Analysis

Developing LCOH Model of Green Hydrogen: This shall be accomplished by using equations 2, 3 and 4 below, and the result/finding is termed as step 1. The generalised equation for calculating the levelised cost of hydrogen is as indicated[41].

$$LCOH = \frac{Net\ Present\ Value\ of\ all\ project\ costs\ during\ project\ duration}{Net\ Present\ Value\ of\ H2\ Generated\ in\ total\ project\ duration} \quad (2)$$

$$LCOH = \frac{\sum_{n=1}^{N} \frac{Costs_{(n)}}{(1+r)^n}}{\sum_{n=1}^{N} \frac{Hydrogen_{(n)}}{(1+r)^n}} = \quad (3)$$

The customised equation on which the LCOH model operates is as explained in the equation below, followed by an elaboration of each component of the equation:

$$LCOH_n = LHV_{H2} \frac{\sum_{n}^{n+N}\left[\left(\frac{Capex_n^{FE} + O\&M\&R_{n+N}^{FE}}{cf*8760h}\right) + \left(\varepsilon_{n+N}^{FE} + \omega_{n+N}^{FE} + CCUS_{n+N}^{FE} - r_{n+N}^{FE}\right)\right] dr_{n+N}}{\eta_n \sum_{n}^{n+N} \Delta_{n+N} * dr_{n+N}} \quad (4)$$

10.2 Developing LCOE Model using Green Hydrogen as fuel

The green hydrogen landed cost (T) derived from the analysis above is used as fuel feed for the power generation; this provides with resultant levelised cost of electricity for continuous generation of renewable electricity for utility and industrial captive power requirements. Equations 5-7 shall be used to develop this model, and the model development is termed as step 2.

$$LCOE = \frac{Net\ Present\ Value\ of\ all\ project\ costs\ during\ project\ duration}{Net\ Present\ Value\ of\ electricity\ Generated\ in\ total\ project\ duration} \quad (5)$$

Table 6. Description of parameters for equation 4 for LCOH

Parameter	Unit	Description
$LCOH_t$	US$/kg	Levelised cost of hydrogen
t	Years	Project construction time
t+T	Years	Project construction and operation duration
FE	-	Final Energy, *i.e.*, electricity
LHV_{H2}	$\frac{kWh_{H2}}{kg_{h2}}$	Lower heating value of hydrogen, *i.e.*, 33.33
$Capex_t^{FE}$	$\frac{\$}{kW_{FE}}$	Capex investment for the project per unit capacity across the project duration
$O\&M\&R_{t+T}^{FE}$	$\frac{\$}{kW_{FE}}$	Total operations, maintenance, and cumulative reinvestment across the project duration
ε_{t+T}^{FE}	$\frac{\$}{kW_{FE}}$	Final Energy, *i.e.*, electricity across the project duration
ω_{t+T}^{FE}	US$/kg	Water or steam expense across the project duration
$CCUS_{t+T}^{FE}$	$\frac{\$}{kW_{FE}}$	Cost of CO_2 emissions per kWh of final energy for the project duration
Γ_{t+T}^{FE}	$\frac{\$}{kW_{FE}}$	Savings from sales of byproducts like oxygen from the Anode across the project duration
η_t	$\frac{kWh_{H2}}{kWh_{FE}}$	Conversion efficiency of the complete plant to generate a single unit of hydrogen at LHV
dr_{t+T}	%	Discount rate
Δ_{t+T}	%	Reduction in the efficiency of the system across the project duration
cf	%	Capacity factor/Utilisation factor of the system

$$COE = \frac{\sum_{n=1}^{N} \frac{Costs_{(n)}}{(1+r)^n}}{\sum_{n=1}^{N} \frac{Electricity_{(n)}}{(1+r)^n}} \quad (6)$$

- Where N is the project duration and n is the year under consideration
- Costs are all the costs associated with the generation of hydrogen across the project duration.
- R is the discount rate for the project duration

$$LCOE_{kWhel_{GH_2}} = \frac{\sum_{n}^{n+N}\left[\left(\frac{Capex_n^{FE} + O\&M\&R_{n+N}^{FE}}{cf * 8760h}\right) + (\zeta_{n+N}^{FE} + \omega_{n+N}^{FE} + CHP_{n+N}^{FE} - \gamma_{n+N}^{FE})\right] dr_{n+N}}{\eta_n \sum_{n}^{n+N} \Delta_{n+N} * dr_{n+N}} \quad (7)$$

10.3 Data Tables

For performing quantitative analysis using the equations

Table 7. Description of parameters for Equations 5*, 6* and 7*

Parameter	Unit	Description
$LCOE_{kWhel_{GH_2}}$	US$/kWh	Levelised cost of electricity
$\boldsymbol{n}$	Years	Project construction time
$\boldsymbol{n+N}$	Years	Project construction and operation duration
FE		Final Energy, *i.e.*, Fuel consumption
$Capex_n^{FE}$	$\frac{\$}{kW_{FE}}$	Capex investment for the project per unit capacity across the project duration
$O\&M\&R_{n+N}^{FE}$	$\frac{\$}{kW_{FE}}$	Total operations, maintenance, and cumulative reinvestment across the project duration
ζ_{n+N}^{FE}	$\frac{\$}{kg_{FE}}$	Fuel Consumption, *i.e.*, Green Hydrogen, across the project duration
ω_{n+N}^{FE}	US$/kg	Water or steam expense across the project duration
CHP_{n+N}^{FE}	$\frac{\$}{kW_{FE}}$	Cost of operating CHP equipment across the project duration
γ_{n+N}^{FE}	$\frac{\$}{kW_{FE}}$	Savings from secondary utility generation using CHP equipment across the project duration
η_n	$\frac{kWh_{H2}}{kWh_{FE}}$	Conversion efficiency of the complete plant to generate a single unit of hydrogen at LHV
dr_{n+N}	%	Discount rate
Δ_{n+N}	%	Reduction in the efficiency of the system across the project duration
cf	%	Capacity factor/Utilisation factor of the system

*Used for calculating LCOE with green hydrogen as fuel

Table 8. Intended markets for research and its US$2023 electricity mix

S. No.	Country	Mean grid cost of electricity (US$/kWh)	Grid COE escalation (CAGR)	Grid emission factor (kg/ MWh)	Probable hydrogen source	RE-RTC renewable power cost	RE-RTC power CAGR	Solar power cost	Carbon Tax *Indirect ^Direct/ ETS
1	India	US$0.13	4%	633	Domestic Production	$0.05	-6%	0.03	$ 1.6*
Sources		42	43	44	45	44,47	48-50	51	52

Note: RE-RTC: Renewable Energy-Round the Clock

Table 9. Commercialised electrolyser technology contextual for this study and its performance parameters for the generation of green hydrogen[53-55]

Electro-lyzer Type	Project Capex ($/kW)	Electro-lyser Cost as % of total Project Cost	System Efficiency	Lifetime (1000 Hours)	O&M Cost (% of Capex)	Stack Replace-ment Cost	Learning Rate	Average Water/ Steam Consum-ption (kg/ kgh_2)	Efficiency Degra-dation per Year
Solid Oxide	>$2,300 -$5,600, $2,300	45%	45%-55%, 42%	50-80	3%	20 - 40%	28%, 17%	20	0% for 5 years, 5% per year after that

Table 10. Commercialised fuel cell technology is contextual for this study, and its performance parameters for the electricity generation using green hydrogen as fuel

Technology	Project Capex (US$/kW)	System Efficiency (LHV)	All-inclusive O&M Cost (% of Capex)	Learning Rate	Sources
Solid Oxide	$5,400, $2,859	58%	5%	17%	56,57

Table 11. Hydrogen processing cost

	Compression for Pipeline Transfer (US$/kg)	Conversion to LH2 (US$/kg)	Conversion to Vector of H2 (Ammonia, etc.) (US$/kg)	Sources
Source 1	NA	$1.6	$0.8	16
Source 2	NA	$0.7-$1.0	NA	58
Source 3	NA	$1.1227	$1.1118	59
Source 4	$0.08-0.45	NA	NA	60

Table 12. Hydrogen transportation cost (compressed)

	Distance <300km (US$/kg)	Distance <1000km (US$/kg)	Distance >1000km (US$/kg)	Sources
Source 1	$0.06-0.19	$0.2.0-1.4	$2.0	[16]
Source 2	$0.1.0-$2	$0.1.0-1.0	$1.0-2.0	[58]
Source 3	NA	NA	$1.0	[61]

Table 13. Hydrogen transportation cost (liquid hydrogen) in US$

	Distance <300km ($/kg)	Distance <1000km ($/kg)	Distance >1000km($/kg)	Sources
Source 1	$0.55 - 0.75	$0.75 - 1.5	$1.5-2.6	[16]
Source 2	$1.0-2.0	$1.0-$2.0	$1.0-$2.0	[58]
Source 3	$1.10	$1.25	$1.50	[61]
Source 4	$0.96	$0.96	$0.96	[59]

Table 14. Hydrogen Transportation Cost (Vector Form) in US$

	Distance <300km ($/kg)	Distance <1000km ($/kg)	Distance >1000km ($/kg)	Sources
Source 1	NA	NA	$0.20	[16]
Source 2	NA	NA	$1.0-2.0	[58]
Source 3	NA	NA	$0.12	[59]

Table 15. Hydrogen reconversion/storage cost (from vector form and liquid hydrogen to gaseous hydrogen) in US$

	Reconversion from vector ($/kg)	Reconversion from LH2 ($/kg)	Sources
Source 1	$1.40	$0.40	[16]
Source 2	$1.23	$0.02	[59]

derived earlier, the India market data is used as an input in the model, and that has been detailed in this section. The data are from relevant secondary sources.

11.0 Application of the Quantitative Model: The Case of Green Hydrogen Generation and Usage at Two Indian Locations

The quantitative model developed in this study and secondary data collected are used to analyze the Indian market considering two locations for generation and usage of Green Hydrogen respectively- where it is envisaged that the green hydrogen generated will be utilised domestically- to become less energy dependent, getting 24x7 renewable power and subsequently moving towards achievement of net-zero goals in a fast-tracked manner- as listed in Table 16.



Figure 3. Image of location for green hydrogen generation (Mundra) and location of utilisation (Ahmedabad) - India.

Table 16. Domestic GH2 generation and utilisation for power generation

Details	Market: India	Comments
GH_2 Plant Location (indicated in Figure 3)	Mundra, Gujarat	Huge Renewable Potential and Near Port
GH_2 Utilisation (indicated in Figure 3)	Ahmedabad, Gujarat	Business Hub, Gujarat
Distance (km)	300	Distance Measured
Mode of GH_2 Transport Envisaged	Pipeline	As per research
Avg. Compression Cost for Pipeline Transport (US$/kg) (A)	$ 0.27	As per the research data
Avg. Transportation Cost Via Pipeline (US$/kg) (B)	$ 0.59	As per the research data
Avg. Distribution Cost (US$/kg) (C)	NA	Not applicable for pipeline distribution
Avg. Reconversion Cost (US$/kg) (D)	NA	Not applicable for pipeline distribution
Levelised cost of Green Hydrogen Production (LCOH) (E)	Outcome 1 of the analysis	This is the result 1 of the analysis and is calculated in Table 14
Net Levelised Cost of Green Hydrogen for Customer (A+B+C+D+E)	Outcome 2 of the analysis	This is result 2 of the analysis and is calculated in Table 15

11.1 Step 1: Quantitative Analysis – Identification of LCOH

The data aggregated for Electrolyser technology and market-related inputs for the Indian market are utilised to run the LCOH model; the variables utilised are as mentioned in Table 17.

The variables listed above and the quantitative analysis methodology provide the levelised cost of green hydrogen

Table 17. Addressing the research question 1

Key Assumptions	Unit	Value
Electrolyzer Technology	Scale	SOEC
Capacity	kW	100000
Existing Project EPC Capex	US$/kW	$3,400.00
Stack Replacement Cost	%	30%
Learning Rate	%	23%
Average Stack Life	Years	5.71
Stack Degradation	%/year	0% for 5 years, 5% per year after that
Project lifetime	Years	25
Plant utilisation factor	%	85%
Water Consumption	kg/kg	10.54
Electrolyzer Efficiency	kWh/kgh_2	37.5
Electrolyser System Efficiency	kWh/kgh_2	47.00
Operating cost		
Annual GH_2 generated	kg	19,856,000
Water/Steam Cost	US$/kg	$0.0016
Energy Cost (Re RTC)	US$/kWh	$0.0540
Energy Cost (Re RTC) CAGR	%	-6%
Annual Energy Consumption	MWh	14,707
Annual Water/Steam Consumption	kg	209,282,240
Electrolyser Component as % of Project Capex		45%
Electrolyser Ancillary Learning Rate		9%
O and M (% of Capex)	%	3%
Annual Inflation	%	5.0%
Capital structure		
Debt	%	40%
Cost of Debt	%	8%
Equity	%	60%
Cost of Equity	%	12%
Tax Rate	%	25%
WACC/Discount Rate	%	9.60%
LCOH GH_2	US$/kWh	0.24

Table 18. Landed cost of green hydrogen for end use (US$)

Project Start Year (25-year project)	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**
GH_2 Production LCOH (US$/kg)	$5.17	$4.78	$4.47	$3.76	$3.56	$3.40	$3.26	$3.14	$2.58	$2.50
Landed LCOH of GH_2 for end users (US$/kg)	$6.02	$5.63	$5.33	$4.61	$4.41	$4.25	$4.11	$4.00	$3.43	$3.35
Landed LCOH of GH_2 for end users (US$/MMBtu)	$52.87	$49.45	$46.77	$40.50	$38.75	$37.31	$36.10	$35.09	$30.12	$29.40

Note: 1MMBtu of hydrogen is equal to 8.78kg of hydrogen

for projects starting in the next 10 years and are listed in Table 18. This provides the desired output and identifies the future landed levelised cost of green hydrogen for captive power generation and answers research question 1.

11.2 Step 2: Identification of Levelised Cost of Electricity using Green Hydrogen as Fuel

The landed LCOH of green hydrogen calculated in step 1 is utilised as feed in step 2 to derive the levelised cost

Table 19. Assumptions considered for identifying the levelised cost (in US$) of generating electricity using GH2

Parameter	Scale	SOFC Fuel Cells
Capacity	kW	10000
EPC Capex	US$/kW	$ 4,130
Learning rate*	%	17%
Fuel Cell as % of Project Capex	%	85%
Learning rate on BOP Components	%	1%
Reduction in learning rate with maturity	%	1% per year
Plant lifetime	Years	25
Plant utilisation factor	%	95%
Plant efficiency (average Lifetime)	% LHV	52%
Operating cost		
Annual kWh generated	kWh	83,220,000
Annual GH_2 consumed	kg	5,657,541
GH_2 Cost	US$/kg	As per the feed from Step 1
O&M (% of Capex)	%	5%
Annual Inflation	%	6.7%
Annual Inflation Applied to Technology	%	2.0%

Conventional grid electricity		
Starting Grid CoE (US$/kWh)	$	$0.13
Grid CAGR	%	4%
Grid Baseline CO_2 emission	kg/MWh	633
Grid Baseline Emission CAGR	%	-3%
Capital structure		
Debt	%	40%
Cost of Debt	%	8%
Equity	%	60%
Cost of Equity	%	12%
Tax Rate	%	25%
WACC	%	9.60%

of 24x7 green and clean electricity for the captive power generator in an Industry in Ahmedabad, Gujarat (India). For the avoidance of complications arising out of water consumption in combustion-based turbine technologies, accounting for NOx emissions and relative calculation of greenhouse gas emissions or consumption of amines for scrubbing of flue gas to avoid NOx emissions, it is assumed that Solid Oxide fuel cells are utilised for 24x7 reliable power generation. Assumptions of variables are as given.

11.3 Results

Table 20 provides the desired output and identifies future LCOE using green hydrogen as fuel for comparison with the grid cost of electricity and answers to Research Question 2.

11.4 Sensitivity Analysis: Addressing the Research Question 3

The analysis has two assumptions that, if applied, can change the results. These are:

Carbon Tax: This is the role of the institution/government in accelerating the adoption of green hydrogen in the energy mix; this can either be looked at as an incentive for adopting green fuel or a penalty for consuming fossil fuels. In either case, it improves the economic adaptability of green fuels, an economic choice

Table 20. Identification of LCOE for a project using GH2 as fuel for a 25-year duration

Project start year	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
LCOE of the Project for 25 Years	$0.45	$0.41	$0.39	$0.34	$0.32	$0.30	$0.29	$0.28	$0.24	$0.24
Expected Grid LCOE for the same 25 years (US$/kWh)	$0.18	$0.19	$0.20	$0.20	$0.21	$0.22	$0.23	$0.24	$0.25	$0.26
Expected Levelised Grid Emissions for project duration (kg/MWh)	511.20	495.86	480.99	466.56	452.56	438.98	425.81	413.04	400.65	388.63

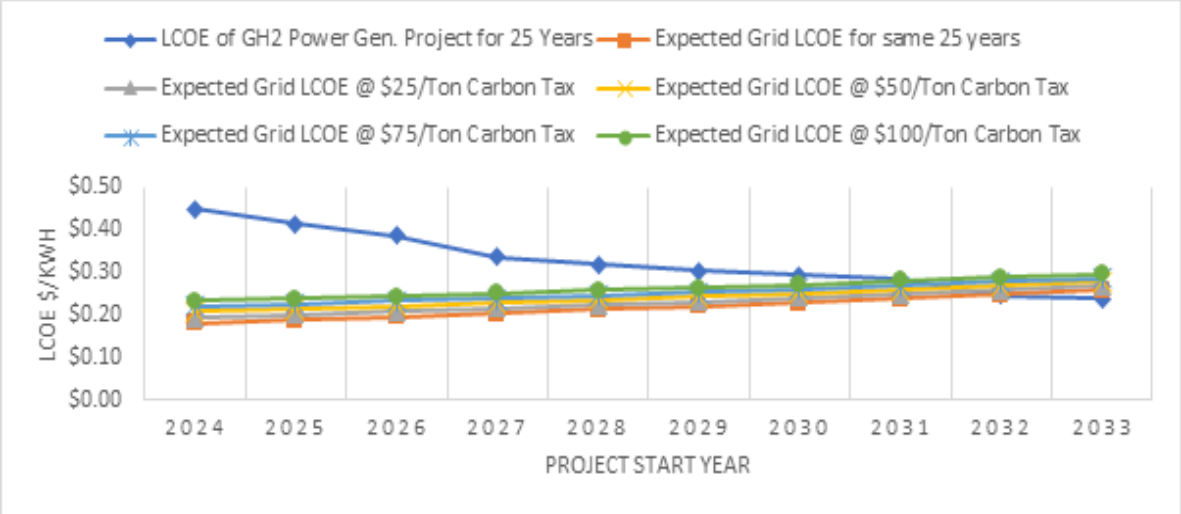
Discount Rate: Discount rate plays a significant role in capital-intensive future fuel generation and utilisation technology adaptability. The result of this analysis provides a direction to make the adoption of green fuel faster by making capital accessible at lower discount rates.

11.4.1 Carbon Tax Variability Impact

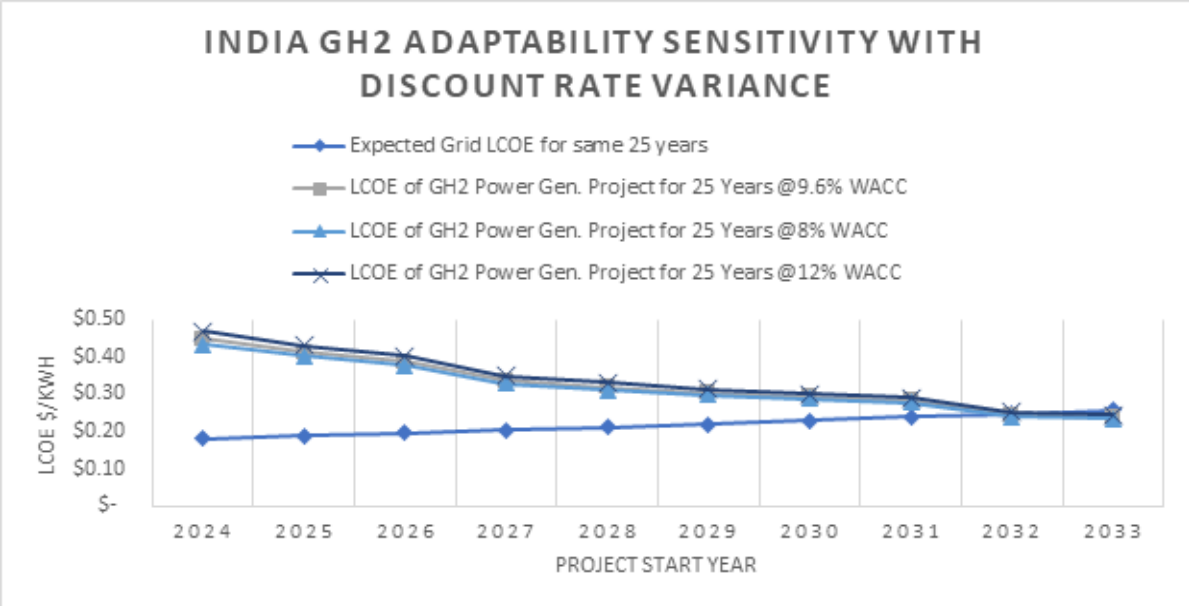
India's market scenario was analysed for carbon taxes at $25/ton, $50/Ton, $75/Ton, and $100/Ton to identify improvement in the adoption of green hydrogen for power generation.

11.4.2 Changes in Discount Rate

The Indian market scenario is analysed for discount rates of 8% and 12%, apart from the already evaluated discount rate of 9.6%, to identify the impact on the adoption of green hydrogen for power generation.



Graph 1. India GH2 adaptability sensitivity with change in carbon tax vs grid LCOE (India Market; unit US$).



Graph 2. India GH2 adaptability sensitivity with change in WACC for project vs grid LCOE (Unit: US$).

12.0 Discussion and Managerial Implications

The current market dynamics and development in the ecosystem of green hydrogen generation are indicative that, in cases where green hydrogen transportation is in the sub-500 Km range, it is estimated that the viability of using green hydrogen for 24x7 captive power generation can be as early as from year 2032 for India. This analogy can be drawn for most coastal Indian states with good renewable energy resources like Gujarat, Maharashtra, Karnataka, Tamil Nadu, Andhra Pradesh, and Orissa, as they have a blend of wind and solar renewable energy. While the impact of introducing a carbon tax is limited, and an improvement in adoption can be seen from 1 to 2 years, *i.e.*, introduction of $100/Ton of CO_2 can incentivise the adoption of green hydrogen for captive power generation by the year 2030.

Financing will also play a major role in the early adoption of green hydrogen; the lower the discount rate better the LCOH and LCOE for green hydrogen projects. Anticipating a sub-10 % discount rate will improve the adoption of green hydrogen in captive power generation by a couple of years. All these estimates are without considering any government incentives. The incentives can be provided in multiple forms, *i.e.*, import duty waiver, PLI (production-linked incentives), and even a higher carbon tax to boost the market offtake activities of green hydrogen.

Green hydrogen is eyeing a spot in captive power generation as a fuel that can provide 24x7, reliable and on-site power generation. However, it is competing with a traditional fuel with a robust supply chain, *i.e.*, Natural Gas. But, natural gas being a fossil fuel, the power generated from utilising natural gas as feed cannot be termed as 100% green/renewable power. However, as there are technological and commercial advancements in the production of green hydrogen, and simultaneously there are advancements in carbon capture, storage and utilisation technologies, this enables economic viability and the possibility of generating captive power also using natural gas as fuel and with carbon capture technologies. This will help corporate entities generate carbon-neutral power onsite using conventional fuel, utilising a conventionally available supply chain of natural gas.

It is worth mentioning that the impact of natural gas-based power generation with carbon capture being implemented will have on the adoption of green hydrogen as the preferred fuel for onsite power generation. It is also to be evaluated how markets with extensive natural gas reserves will react to the adoption of green hydrogen versus investment in the development of carbon capture technologies -as the development of carbon capture and storage technologies enables those markets to maximize leveraging of natural resources available while also addressing carbon footprint impacts of using natural gas.

13.0 Exclusions and Limitations of the Study

- Taxes and customs duties are not assumed as variables for the research work.
- Changes in the price margins by the Original Equipment Manufacturers (OEMs) of technology over the period are not part of the analysis.
- Both hydrogen generation equipment and power generating equipment are operating at the desired capacity factor across the project duration; it is assumed that there is no decline in the output.
- Carbon intensity of hydrogen transport through ships, pipelines, or other means is not considered in the study.
- The study assumes that the hydrogen generation in the case of post-production export is at a location close to the port and thus excludes post-production inland transportation.
- Land acquisition costs for green hydrogen and power generation projects are excluded from the study.
- CHP (combined heat and power) solution is not considered for the analysis; additional heat availability has the potential to improve economics.

14.0 Conclusion

The study deals with performing quantitative analysis for captive power generation using green hydrogen in India for industrial customers with the following three pre-conditions:

- GH_2 fuel can be transported using pipelines from the source of generation to the point of utilisation
- Comparison with the current CAGR for the grid cost of electricity
- Inclusion of techno-economic advancements anticipated for green hydrogen generation, transport, and utilisation

The study provides a result that the projects starting operations in the year 2032 in India can look at exploring captive power generation using domestically generated green hydrogen for their need of reliable 24x7 renewable power generation at their respective sites. This will enable corporates and industries to achieve their net-zero targets and focus on their Scope 1 emissions without compromising the resiliency requirements of their facilities.

However, the sites that are situated at a larger distance will find it expensive to utilise green hydrogen for captive power generation. This implies that the government should enable (with appropriate policy initiatives) multiple nodes of domestic green hydrogen generation. In the short term, while it is lucrative to install green hydrogen generation plants in the coastal areas for ease of shipping for international customers, in the longer term, it will also aid in the domestic utilisation of green hydrogen cost-effectively.

Early investments in green hydrogen pipelines will also enable infrastructure for the transport of green hydrogen from land-locked Indian states to coastal states, and hence higher volume of green hydrogen will be available for export purposes. An effective national grid of green hydrogen will help maximise the economic utilisation of green hydrogen.

The research work can be further enhanced with relatively better precision by implementing multi-variable linear programming for the precise identification of various cost components in the green hydrogen value chain[62]. Such precise analysis in association with the methodology of this study may provide results with greater accuracy for a 'power to power' cycle of green hydrogen.

Corporations with aggressive net-zero targets can look up to the government for policies that provide capital incentives for generating and utilising green hydrogen, classify them as the preferred technology for lower discount rates and longer duration, and also bring carbon tax policies that will help improve economic viability for green hydrogen in captive power generation.

The methodology used here for captive power generation can be replicated to identify the viability of green hydrogen replacing conventional fuels for the transport segment in India and can be implemented for global markets. It is envisaged that green hydrogen will play a significant role in marine transport and heavy-duty vehicles, replacing diesel and natural gas as conventional fuels.

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Abbreviations

BCM Billion Cubic Meter

CAPEX Capital Cost

CCUS Carbon Capture, Utilisation and Sequestration

CH_4 Methane

CHP Combined Heat and Power

CO_2 Carbon Dioxide

CAGR Compounded Annual Growth Rate

EU European Union

FCC Foreign Component Charge

GH_2 Green Hydrogen

GW Giga Watts

H_2 Hydrogen

IEA International Energy Agency

IMF International Monetary Fund

KMS Kilometers

KSA Kingdom of Saudi Arabia

kW Kilo Watts

LCOE Levelised Cost of Electricity

LCOH Levelised Cost of Hydrogen

LH_2 Liquid Hydrogen

LNG Liquified Natural Gas

Mtoe Million tons of Oil Equivalent

MT Million Tons

MW Mega Watts

NA Not Available/Not Applicable

NG Natural Gas

NH_3 Ammonia

NO_x Nitrous Oxide

NPV Net Present Value

O_2 Oxygen

OPEC Oil Producing and Exporting Countries

OPEX Operating Cost

PPA Power Purchase Agreement

PEM Polymer Electrolyte Membrane

Re-RTC Renewable Round-the-Clock Power

SCC Social Cost of Carbon

SOEC Solid Oxide Electrolyser Cell

SOx Sulphur Oxide

SMR Steam Methane Reformation

UPS Uninterrupted Power Supply

USA United States of America