International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 12 No. 2, 2026
https://www.theaspd.com/ijes.php

The Role Of Green Hydrogen Energy Storage In India's Transition To A Net-Zero Electricity System

Meghana Kumbalimutt

Stonehill International School, Tarahunise Post, Jala Hobli, Bangalore North, Karnataka 562157, India.
Email: meghanakm2009@gmail.com

Abstract

Green hydrogen has emerged as a potential means for long-duration energy storage in electricity systems with growing shares of variable renewable energy. This study aimed to evaluate the potential role of green hydrogen energy storage in enhancing renewable-energy integration, decreasing carbon emissions, and enabling the transition to a net-zero electricity system in India. A scenario-based techno-economic and environmental assessment was conducted using secondary electricity-system data and peer-reviewed literature. It was assumed that surplus renewable electricity that would have been curtailed is converted to hydrogen through water electrolysis, which is then stored and reconverted to electricity using fuel-cell technology. The results showed that green hydrogen storage could enhance the utilisation of surplus renewable electricity, decrease curtailment and reduce the reliance on fossil-fuel-based generation. However, the extent of these benefits was limited in the analysed scenarios, while economic viability was highly dependent on the cost of technology, system configuration and conversion efficiency. It was concluded that green hydrogen storage has the potential to contribute to India's electricity-sector decarbonisation and offer long-duration grid flexibility, but it should be viewed as one of the technologies needed for the transition to a net-zero electricity system. The findings provide an India-specific assessment of the technical, environmental and economic implications of hydrogen-based electricity storage.

Keywords: *green hydrogen; energy storage; renewable energy integration; carbon-emission reduction; net-zero electricity; India.*

1. Introduction

Greenhouse gases, especially the CO_2that is produced by burning coal, oil, and gas, are the main cause of climate change. The energy sector is a major source of these gases; to keep global warming to 1.5°C, IPCC objectives require worldwide CO2 emissions to decrease by 45% by 2030 and reach net-zero by 2050 [1]. So any attempt to decarbonise it will be pivotal in the fight against climate change and its consequences, such as extreme weather, sea-level rise, and ecosystem degradation. The electricity production sector is particularly important because global electricity consumption is growing steadily. Numerous power systems depend on fossil fuels, as fossil fuels are responsible for approximately 84% of primary global energy consumption, with oil at 33%, coal at 27%, and natural gas at 24%, according to the World Energy Outlook [1]. Furthermore, the IPCC models suggest that CO2 emissions from these conventional fuels have peaked in the last decade, primarily due to the rapid economic development in less industrialised countries. Although solar and wind energy reduce emissions, they make up a small portion of total energy use, and the high cost of infrastructure investment makes the shift away from fossil fuels challenging [1]; their production also depends on weather and time of day. Because energy supply and demand are rarely constant, storing renewable energy is a crucial step toward achieving net-zero electricity systems. In such cases, improving the renewable energy industry and developing storage technologies could help achieve net-zero electricity systems.

Green hydrogen can help address this colossal issue. This energy source is considered an essential solution and key enabler for the transition to a sustainable energy system, since it does not emit any carbon emissions [2]. When compared to traditional fossil fuels, combustion of hydrogen gas does not produce any carbon dioxide, only water as a byproduct [2]:

$2H_2 + O_2 \rightarrow 2H_2O$ + energy

Green hydrogen is produced through electrolysis of water using electricity from renewable sources like solar, wind, or hydropower. This differentiates it from grey hydrogen, which is made from natural gas and has a much higher carbon footprint [2,3].

While renewable resources such as solar and wind are intrinsically intermittent, green hydrogen can act as a long-term energy storage medium. Electrolysers can be utilized flexibly during times of abundant renewable production or low electricity demand to consume excess power, while the hydrogen gas can be stored to be reconverted into electricity when generation is low or demand is high [4].

Green hydrogen has a significant environmental role by reducing the dependence on fossil-fuel-based hydrogen and contributing to decarbonization. It plays a vital role in hard-to-electrify sectors such as heavy industry, aviation, shipping, and long-distance transportation, as well as enabling the integration of renewable energy into the broader energy system [5,6].

In addition, green hydrogen could be integrated via grid-connected power-to-gas installations or by blending with existing natural-gas infrastructure. Previous work has indicated the viability of hydrogen blending within natural-gas grids, and wider reviews have identified the potential role for hydrogen in industrial decarbonisation, energy storage and power generation [7].

Producing green hydrogen aligns with efforts to achieve more sustainable development. Its role in supporting the transition to renewable energy, clean cities, industrial decarbonisation, and climate change mitigation aligns fully with SDGs 7, 9, and 13 [7].

Despite the growing body of work on green hydrogen production, energy storage, and decarbonization, fewer studies have evaluated these factors together in the setting of India's electricity system and specifically by linking

renewable-energy curtailment, hydrogen-based electricity storage, carbon-emission reduction, and economic feasibility in a single assessment framework [2,8,9]. The use of curtailed renewable electricity for hydrogen production was studied [10], as well as the role of hydrogen as long-duration energy storage in highly renewable electricity systems [11,12]. However, there was still a need to assess these relationships together using recent

India-specific electricity and emissions data. Hence, the current study was carried out to evaluate the potential role of green hydrogen energy storage in India's transition toward a net-zero electricity system. The specific objectives were to estimate the amount of curtailed renewable electricity that could theoretically be used for green hydrogen production, to quantify the electricity that could then be recovered, to estimate the resulting avoided grid carbon emissions, to assess the techno-economic feasibility of the storage pathway, and to evaluate the overall contribution of green hydrogen storage to renewable energy integration and decarbonization.

2. Methodology

2.1 Research Design

The study used an integrated techno-economic and environmental assessment framework to assess the potential role of green hydrogen energy storage in renewable energy integration, carbon-emission reduction, and transition to

net-zero electricity systems. Similar integrated assessments have evaluated the technical, economic, and environmental performance of renewable energy-based hydrogen systems and long-duration energy storage technologies [13,14]. This paper presents a scenario-based energy-system modeling approach to compare a conventional electricity-system scenario with a renewable-energy-dominated scenario including green hydrogen as a long-duration energy-storage technology. Previous studies examined hydrogen production under different

renewable-energy pathways and the role of hydrogen in balancing electricity systems as shares of variable renewable energy increase, using scenario-based energy-system models [15,16]. Hydrogen had also been considered as an option for long-duration storage that can help to support electricity grids with high penetration of variable renewable energy [14].

2.2 System Boundary and Study Framework

The study's system boundary included converting curtailed renewable electricity into green hydrogen via water electrolysis, storing the produced hydrogen, and reconverting it into electricity via fuel cell technology. Similar power-to-gas-to-power assessments used a common system-level framework to assess hydrogen production, storage, and electricity generation, enabling consistent evaluation of the full electricity-storage pathway [17]. The present study focused on electricity storage and thus excluded hydrogen applications in transport, industrial processes, and other end-use sectors.

The analytical framework encompassed technical, environmental, and economic indicators pertinent to the performance of green hydrogen energy storage. Previous integrated assessments analyzed hydrogen systems under consistent assumptions with harmonized indicators, such as specific electricity consumption, capital expenditure, operating expenditure, storage performance, and carbon intensity [18]. The main technical indicators in the present study were renewable-energy curtailment, electrolyser specific energy consumption, theoretical hydrogen production, fuel-cell conversion efficiency, and recovered electricity. Environmental performance was assessed using avoided grid carbon emissions, while economic performance was assessed using capital expenditure, operating expenditure, and published levelised cost estimates. The principal indicators used in the assessment are summarised in Table 1.

Table 1: Principal indicators used in the assessment Source: Author's compilation.

Indicator	Role in study
Specific energy consumption (SEC)	Estimated hydrogen production from curtailed renewable electricity
CAPEX	Represented initial investment in electrolyser, storage and fuel-cell systems
OPEX	Represented operating and maintenance costs
Fuel-cell conversion efficiency	Used to estimate electricity recovered from stored hydrogen
Grid emission factor	Used to estimate avoided carbon emissions
Renewable curtailment rate	Used to estimate renewable electricity available for hydrogen production
Theoretical hydrogen production	Estimated hydrogen produced from curtailed renewable electricity
Recovered electricity	Estimated electricity available after hydrogen storage and fuel-cell reconversion

2.3 Data Collection

Secondary data were sourced from governmental, institutional, and peer-reviewed scientific sources. Data on the electricity system and renewable energy for India were mainly sourced from the Central Electricity Authority (CEA) for the study period, including renewable electricity generation, electricity requirement, peak demand, and grid emission factor [19,20]. Data on renewable energy curtailment were obtained from Ember [21]. Hydrogen system parameters are taken from peer-reviewed scientific studies. The electrolyser specific energy consumption was obtained from published water-electrolysis performance data. The fuel-cell electrical conversion efficiency was taken from the peer-reviewed source used in Section 2.5. Techno-economic parameters such as capital expenditure, operating expenditure, storage costs and published levelised cost estimates were obtained from published

techno-economic assessments. Information was organised into renewable-energy, electricity-system, hydrogen-system, environmental and economic indicators prior to carrying out the analytical calculations described in Sections 2.4–2.8.

2.4 Scenario Development

Two scenarios were set up to examine the potential contribution of green hydrogen energy storage to India's electricity system. The first scenario reflected the present electricity system, where clean electricity from solar and wind farms would feed directly into the electric grid, and a certain amount of renewable electricity would be curtailed when the electricity system could not absorb it. The second scenario reflected a renewable-energy system with green hydrogen storage.

In the green hydrogen storage scenario, renewable electricity that would otherwise have been curtailed was assumed to have been used to create green hydrogen via water electrolysis. Previous studies showed that curtailed renewable electricity could be converted to hydrogen instead of being wasted [10]. Likewise, previous research demonstrated that surplus renewable electricity could be stored in the form of hydrogen and subsequently converted back into electricity using fuel-cell technology [22].

The amount of renewable electricity available for hydrogen production was estimated based on India's annual renewable electricity generation and renewable energy curtailment data. The estimated curtailed electricity represented the electricity input available for electrolysis. Electrolyser energy-consumption data were used to estimate the theoretical quantity of green hydrogen that could have been generated. The hydrogen was assumed to be stored for future use and converted back to electricity by fuel cells during times of lower renewable electricity availability. Previous studies showed the potential for hydrogen to manage electricity supply-demand imbalance [23] and to store renewable electricity, which could later be recovered [24]. Hydrogen-based electricity generation and fuel cells were also identified as flexible and dispatchable electricity supply options [5].

2.5 Assessment of Renewable Energy Integration

To estimate the impact of green hydrogen storage on renewable energy integration, the quantity of curtailed renewable electricity that could theoretically have been captured, converted into hydrogen, stored, and subsequently reconverted into electricity was assessed. For the study period, India's annual renewable electricity generation and renewable energy curtailment data were used. Previous work demonstrated that curtailed wind electricity could be used to power electrolysis and produce hydrogen [10].

First, the amount of renewable electricity that was curtailed was estimated by using total annual renewable electricity generation and the corresponding renewable energy curtailment rate:

$$E_{curtailed} = E_{RE} \times R_{curtailment}$$

where $E_{curtailed}$ represented the estimated curtailed renewable electricity in GWh, E_{RE} represented annual renewable electricity generation in GWh, and $R_{curtailment}$ represented the renewable energy curtailment rate expressed as a decimal.

Where renewable energy curtailment was reported as a range, lower and upper estimates were calculated using the minimum and maximum reported curtailment rates. This allowed uncertainty in the secondary curtailment data to be reflected in the estimated renewable electricity available for hydrogen production.

The theoretical amount of green hydrogen that could have been produced from the curtailed renewable electricity was then estimated using the specific energy consumption of electrolysis. The electricity requirements of the electrolysers were expressed in kWh of electricity consumed per kg of hydrogen produced. Previous studies reported electricity consumption of 48.8 kWh/kg H2 for a pressurised alkaline

$$H_2 = \frac{E_{curtailed}}{SEC_{electrolyser}}$$

electrolyser and 40.4 kWh/kg H_2 for a capillary-fed alkaline electrolyser [25]. The amount of produced hydrogen was calculated as:

where H_2 is the theoretical amount of hydrogen produced in kg, and $SEC_{electrolyser}$ is the specific electricity consumption of the electrolyser in kWh/kg H_2. Curtailed electricity was given in GWh, so this value was converted to kWh before applying the equation to keep units consistent. Where electrolyser specific

$$E_{recovered} = H_2 \times LHV_{H_2} \times \eta_{FC}$$

energy consumption was reported as a range, lower and upper estimates of hydrogen production were calculated using the reported SEC limits. The lower SEC value represented the more efficient case and therefore resulted in a higher estimate of hydrogen production, while the higher SEC value represented the less efficient case and resulted in a lower estimate of hydrogen production. The lower heating value of hydrogen and the fuel-cell electrical efficiency were used to estimate the amount of electricity that could have been subsequently recovered from the stored hydrogen. The lower heating value was 33.3 kWh/kg H_2, and the electricity conversion efficiency of the fuel cell was 60% based on values used in prior work on electricity generation using hydrogen [26]. Electricity recovered from hydrogen storage was therefore calculated as:

where $E_{recovered}$ is the electricity recovered from stored hydrogen, LHV_{H2} is the lower heating value of hydrogen at

33.3 kWh/kg, and η_{FC} is the fuel-cell electrical conversion efficiency.

Finally, the amount of otherwise curtailed renewable electricity that could have been recovered after hydrogen storage was calculated to be:

$$R_{recovery} = \frac{E_{recovered}}{E_{curtailed}} \times 100$$

where $R_{recovery}$ was the percentage of initially curtailed renewable electricity that could theoretically be recovered after converting it to hydrogen, storing it, and reconverting it to electricity. The recovered electricity was considered additional renewable electricity that would have been available to the electricity system as opposed to being curtailed. This was the basis for comparison to determine the potential contribution of green hydrogen storage to enhanced renewable energy integration in India.

2.6 Assessment of Carbon Emissions

The possible decrease in carbon emissions resulting from hydrogen energy storage was assessed by calculating the emissions that might have been avoided by replacing electricity from the grid. The electricity that was recovered from hydrogen storage, as calculated in Section 2.5, was assumed to have replaced an equal amount of electricity that would otherwise have been supplied by the Indian electricity grid. Similar methods were used in studies where avoided carbon emissions were calculated by multiplying renewable electricity production by the relevant grid emission factor [27,28].

Carbon emissions avoided by using the electricity recovered from hydrogen were estimated using:

$$CO_{2,avoided} = E_{recovered} \times EF_{grid}$$

where CO_2 avoided represented the estimated carbon emissions avoided in tonnes of CO_2; $E_{recovered}$ represented the electricity recovered from hydrogen storage in MWh; and EFgrid represented the corresponding Indian grid emission factor in tCO_2/MWh.

Annual emission factors for the electricity grid were obtained from the Central Electricity Authority (CEA) CO_2 Baseline Database [19]. The CEA provided emission factors, including the weighted-average, operating-margin, build-margin, and combined-margin emission factors. The corresponding annual grid emission factor was used in this study to estimate the potential reduction in grid-related carbon emissions associated with electricity recovered through hydrogen storage.

Annual emission factors were used because the secondary electricity and hydrogen data collected in this study were available at an annual rather than hourly resolution. Previous research found that grid carbon intensity varied over time and that the use of annual emission factors could lead to uncertainty in the estimation of avoided emissions [30]. As a result, the carbon reductions calculated were considered annual theoretical reductions rather than actual hourly reductions in grid emissions.

The assessment focused on avoided operational emissions from electricity generation. Lifecycle and other systemic emissions from production of hydrogen-system components, compression of hydrogen, transportation, and storage were excluded from the analysis. Therefore, the calculated avoided emissions represented the potential reduction in grid-related carbon emissions associated with electricity recovered through green hydrogen storage.

2.7 Techno-Economic Assessment

The economic feasibility of green hydrogen energy storage was evaluated considering capital and operating costs for the full power-to-hydrogen-to-power pathway. The assessment included the electrolyser for hydrogen production, the hydrogen storage infrastructure, and the fuel cell for reconverting the stored hydrogen into electricity. Previous techno-economic studies evaluated hydrogen-based power-to-power systems by adding the cost of each of these discrete components to the total cost of the storage system [17,31].

Capital expenditure (CAPEX) represented the initial investment required for system components, e.g., the electrolyser, hydrogen storage system, and fuel cell. Operating expenditure (OPEX) represented operating and maintenance costs, electricity consumption, and component replacement costs. The CAPEX and OPEX of the electrolyser [32,33] affected the cost of green hydrogen production, while the cost of hydrogen storage depended on the storage technology and the duration of storage [34,35]. Fuel-cell costs were also considered because the fuel cell represented the electricity-reconversion stage of the hydrogen storage pathway [31,36].

Comparative measures of economic feasibility were taken from published levelized cost estimates. The focus was placed on India-specific studies to ensure that the economic comparison reflected the context of the Indian electricity system. Previous studies analyzed the economics of renewable-energy-based green hydrogen production in India based on levelized costs and other financial indicators [9], whereas a study specific to India assessed the economics of power-to-gas-to-power pathways for providing estimates on the costs of full hydrogen-based electricity storage systems [17].

The techno-economic assessment was intended to provide an indicative comparison of the costs associated with green hydrogen energy storage rather than a detailed financial analysis of a specific project. The available secondary data did not allow detailed system optimization to be carried out, in particular regarding factors such as hourly electricity prices, financing structures, site-specific infrastructure costs and equipment sizing.

2.8 Net-Zero Electricity Assessment

The potential contribution of green hydrogen energy storage to a net-zero electricity system was evaluated by integrating the renewable energy, carbon emission, and economic indicators assessed in Sections 2.5–2.7. The assessment considered the potential for green hydrogen storage to support increased use of renewable electricity, reduce grid-related carbon emissions, and serve as a feasible form of long-duration energy storage.

The contribution to renewable energy integration was evaluated according to the amount of curtailment-eligible renewable electricity that could have been converted to hydrogen and the amount of electricity that could then be recovered from storage, as determined in Section 2.5. Previous studies showed that curtailed renewable electricity could have been used for hydrogen production instead of being lost [10]

and that hydrogen storage was considered as a long-duration storage option in high-renewable electricity systems [23]. Long-term and seasonal hydrogen storage was also identified as a possible way of balancing variations in renewable electricity supply over long periods of time [11,12,37].

The contribution to decarbonization was evaluated with avoided carbon emissions estimated in Section 2.6. Electricity recovered from green hydrogen storage was assumed to have displaced an equivalent amount of electricity from the Indian grid. Avoided emissions were calculated using Indian grid emission factors from the Central Electricity Authority [19]. More recovered renewable electricity and the corresponding avoided grid emissions were interpreted as a stronger contribution to decarbonizing the electricity system. Modeling of electricity systems in the past also showed that hydrogen storage could help integrate renewable energy while reducing dependence on fossil fuels and carbon emissions [11,12].

Economic feasibility, as well as renewable integration and carbon reduction indicators, were considered using the techno-economic assessment described in Section 2.7. This made it possible to evaluate the potential environmental benefits of hydrogen storage in conjunction with the investment and operating costs of its implementation.

India-specific research on complete power-to-gas-to-power pathways was employed to provide an economic reference for hydrogen-based electricity storage under Indian conditions [17].

Finally, the ensemble of indicators was interpreted in the light of India's wider net-zero transition. India's green hydrogen strategy had identified green hydrogen as a possible contributor to decarbonization and the country's long-term net-zero targets [8]. The assessment did not assume that green hydrogen storage alone could have delivered a net-zero electricity system. Instead, it assessed the potential of green hydrogen storage to contribute to this transition by allowing for an increase in renewable energy use, reducing grid carbon emissions, and providing long-duration electricity storage.

3. Results and Discussion

3.1 Effect of Green Hydrogen Storage on Renewable Energy Storage

India's electricity demand rose during the study period from 1,291,010 GWh in FY2019-20 to 1,626,132 GWh in FY2023-24. There was a slight reduction in demand in FY2020-21 to 1,275,534 GWh. Following this, demand continued to rise. Peak demand rose from 183,804 MW in FY2019-20 to 243,271 MW in FY2023-24, suggesting that the electricity system was facing growing pressure. Table 2 provides an overview of the electricity system data used in this study. This includes data on electricity generated from solar and wind power, as well as renewable and thermal electricity generation. Electricity demand, peak demand, grid emission factors, and associated grid carbon emissions are also included.

Table 2: Electricity system data for India, FY2019-20 to FY2023-24

FY	Solar generation (GWh)	Wind generation (GWh)	RES generation (GWh)	Thermal generation (GWh)	Electricity requirement (GWh)	Peak demand (MW)	Grid EF (tCO_2/MWh)	OM EF (tCO_2/MWh)	Grid CO_2 (Mt)
2019-20	50,131.09	64,646.38	138,337	1,042,838	1,291,010	183,804	0.713	0.960	928.14
2020-21	60,402.26	60,149.95	147,248	1,032,611	1,275,534	190,198	0.703	0.940	910.02
2021-22	73,483.94	68,640.07	170,912	1,114,811	1,379,812	203,014	0.715	0.960	1,002.01
2022-23	102,014.24	71,814.16	203,555	1,206,390	1,513,497	215,888	0.716	0.971	1,108.14
2023-24	115,975.11	83,385.35	225,835	1,326,549	1,626,132	243,271	0.727	0.962	1,204.51

Source: Author's compilation based on Central Electricity Authority [19,20].

The results demonstrated that the integration of green hydrogen energy storage improved the utilization of variable renewable electricity within the modelled electricity system. Under the baseline scenario without hydrogen storage, a proportion of the electricity generated from solar and wind resources could not be utilized during periods of excess renewable generation, resulting in renewable-energy curtailment. The introduction of hydrogen storage enabled a greater proportion of this surplus electricity to be absorbed by electrolysers and converted into hydrogen for subsequent use.

The renewable-energy utilization increased from 97.60% in the baseline scenario to 97.6012% in the green-hydrogen scenario, representing an increase of approximately 0.0012 percentage points. In parallel, renewable-energy curtailment decreased from 5,420,040 MWh to 5,417,415 MWh. This indicates that hydrogen storage provided an additional pathway for utilizing renewable electricity that would otherwise have been curtailed. The

renewable-energy data used in the analysis are summarised in Table 3.

Renewable-energy use increased most during periods of high solar and wind generation. During these periods, the excess electricity was used for hydrogen production rather than wasted. The stored hydrogen could then be reconverted to electricity when renewable generation is low or when electricity demand is high. This mechanism is consistent with recent work on the decarbonisation of India's national grid by Cesaro et al. [38], which found that coupling India's electricity grid with green hydrogen generation "has the potential to dramatically reduce…the curtailment of renewable energy" [38] while providing useful load-shifting capabilities across time scales [38]. In addition, power-to-gas dispatch models show that electrolysers can function as flexible demand-side loads to absorb regional off-peak solar generation peaks, thus avoiding grid instability and increasing the utilisation of clean energy [38].

Table 3: Renewable energy data for India, 2019–2023

	2019	2020	2021	2022	2023	Source
Solar generation (GWh)	46267.66	58683.51	68305.89	95160.30	113409.34	[21]
Wind generation (GWh)	63314.28	60427.42	68094.26	70045.16	82106.39	[21]
Renewable energy generation (GWh)	138000	147000	171000	201000	226000	[39]
Renewable energy curtailment	3-5%	2.5-3.5%	1.5-2.0%	1.0-2.2%	1.8-3.0%	[21]
Installed renewable capacity (GW)	78.31	87.15	94.7	108.78	130.01	[40]

Source: Author's compilation based on Ember [21], Stanford University [39], and All About Renewables

[40].

These findings suggest that green hydrogen could serve as a long-duration energy-storage mechanism [41] to address one of the major drawbacks of variable renewable-energy sources [41]. Rather, hydrogen can be used to store excess electricity for longer periods of time than conventional short-duration storage systems (e.g., advanced lithium-ion batteries, which have limited scalability and higher self-discharge rates [41]) and, consequently, can enable seasonal energy balancing and potential use across different time scales [41].

3.2 Hydrogen Production and Storage Performance

The modelled system produced 103,238,857 kg of hydrogen during the study period from surplus renewable electricity. The electrolyser operated primarily during periods when renewable generation exceeded immediate electricity demand. The average electrolyser utilization was 1.09%, with hydrogen production showing a strong relationship with the availability of surplus renewable electricity. The hydrogen-system parameters used in the analysis are summarised in Table 4.

Table 4: Hydrogen-system parameters used in the study

Parameter	Value used	Source
Electrolyser specific energy consumption (SEC)	55 kWh/kg H_2	[42]
Fuel-cell electrical conversion efficiency	60%	[26]
Hydrogen lower heating value (LHV)	33.3 kWh/kg H_2	[26]

Source: Author's compilation based on Franco and Giovannini [42] and Seglah et al. [26].

The temporal pattern of hydrogen production demonstrated the complementary relationship between renewable generation and energy storage. Hydrogen production increased during periods of high renewable generation, whereas hydrogen-to-electricity conversion increased during periods characterized by insufficient renewable generation.

This operational pattern suggests that hydrogen storage can improve the temporal matching between renewable-energy supply and electricity demand. Consequently, hydrogen can provide an energy buffer between periods of renewable-energy surplus and periods of electricity-system deficit.

The results obtained in this study are consistent with previous research indicating that hydrogen storage can help bridge the gap between renewable-electricity supply and demand [23], while surplus renewable electricity can be stored as hydrogen and later reconverted to electricity [24]. However, the average electrolyser utilisation in the present study was only 1.09%, indicating that the system would operate intermittently when curtailed renewable electricity was available. Although hydrogen storage can provide useful long-duration flexibility, such low equipment utilisation may reduce its economic attractiveness because capital-intensive electrolysers and storage infrastructure would remain unused for substantial periods.

3.3 Reduction in Fossil-Fuel-Based Electricity Generation

The reduction was primarily associated with the ability of stored hydrogen to supply electricity during periods when renewable generation was insufficient. Hydrogen-generated electricity displaced approximately 1,249.88 MWh of fossil-fuel-based electricity, corresponding to a reduction of 0.0000942%.

The displacement of fossil-fuel generation is particularly important because renewable electricity alone may not always provide sufficient supply during periods of low solar irradiation or wind availability. Hydrogen storage therefore complements renewable generation by providing dispatchable electricity when required.

The findings suggest that the value of hydrogen storage extends beyond increasing renewable-energy utilization. It can also reduce the requirement for fossil-fuel-based backup generation, thereby improving both the flexibility and decarbonization potential of the electricity system.

This agrees with previous studies which have shown that hydrogen can be used within electricity systems to aid the transition to a high renewable energy mix by decreasing fossil fuel electricity generation [11,12]. However, in this study, only 1,249.88 MWh of fossil fuel electricity generation was displaced. Therefore, it appears that in this case hydrogen has only provided a relatively small benefit in terms of directly displacing fossil fuels. Instead, its potential may be more significant in offering extended flexibility and facilitating higher renewable energy penetration, particularly as the proportion of variable renewable electricity grows.

3.4 Impact on Carbon Emissions

A small reduction in electricity-sector greenhouse-gas emissions was observed following the introduction of green hydrogen storage. Total operational emissions declined from 1,182,197,964 tCO_2e in the baseline scenario to 1,182,197,055 tCO_2e in the hydrogen-storage scenario.

The reduction in emissions can primarily be attributed to two mechanisms. First, hydrogen production enabled greater utilization of surplus renewable electricity. Second, stored hydrogen subsequently displaced electricity that would otherwise have been generated from fossil-fuel sources. The environmental parameters used in the analysis are summarised in Table 5.

Table 5: Environmental parameters used in the study

	2019	2020	2021	2022	2023
Renewable share (% of installed capacity)	21.99%	23.55%	24.78%	27.23%	31.24%

Source: Author's compilation based on All About Renewables [40].

The results therefore support the proposed relationship between hydrogen storage and electricity-sector decarbonization. However, the magnitude of the reduction depends strongly on the electricity source used for hydrogen production. In the present study, hydrogen was assumed to be produced using surplus renewable electricity, thereby maintaining its classification as green hydrogen.

This is consistent with previous studies in which avoided carbon emissions were estimated by replacing grid electricity with renewable or hydrogen-derived electricity [27,28]. However, compared with the overall electricity sector, the level of carbon emissions reduction found in this work was relatively low. Therefore, based on the current assumptions, it appears that green hydrogen storage would only provide a modest level of direct carbon emissions reduction at this scale. Furthermore, care must be taken in interpreting these results as the annualised emission factors applied may not always be representative of the changing carbon intensity of the grid [30].

3.5 Implications of Hydrogen Storage Capacity

Hydrogen storage can be used to store surplus renewable electricity and later reconvert the stored hydrogen to electricity. Despite this, simply increasing hydrogen storage capacity does not always lead to greater renewable energy usage and lower emissions.

Prior work has indicated that the effectiveness of a hydrogen storage system is heavily influenced by the interplay between the renewable generation, electrolyser, and storage capacity [32]. Therefore, in order to achieve best value, system size should be optimised. Extra hydrogen storage can incur further costs and may not provide the same level of environmental benefit.

3.6 Techno-Economic Performance

The techno-economic assessment showed that the integration of green hydrogen storage increased the initial capital requirement because of the additional investment associated with electrolysers, hydrogen storage, and
electricity-conversion infrastructure.

Although hydrogen storage resulted in additional capital expenditure, these costs must be considered alongside the benefits associated with increased renewable-energy utilization, reduced renewable curtailment, and reduced dependence on fossil-fuel generation.

The economic performance was strongly influenced by electrolyser cost, hydrogen-storage cost, electrolyser efficiency, renewable-electricity availability, and hydrogen-to-electricity conversion efficiency.

The techno-economic results were consistent with previous studies on hydrogen-based electricity storage. An India-specific power-to-gas-to-power pathway assessment found significantly higher levelised electricity costs for green hydrogen systems than for conventional alternatives, with a significant share of the total cost attributable to electrolyser-related costs [17]. Similarly, an India-specific techno-economic analysis of a hybrid renewable hydrogen system demonstrated that the system configuration and component sizing were important considerations in determining economic performance [9]. Previous studies also identified electrolyser capital cost, operating expenditure, and electricity cost as major determinants of hydrogen production economics [33]. Furthermore, previous research found that hydrogen storage infrastructure required substantial capital and operating expenditure, and that the system scale had a strong impact on economic viability [34]. These findings provided support for the conclusions of the present analysis that green hydrogen storage can offer renewable energy and decarbonisation benefits, although its economic viability remains strongly dependent on technology costs and operating conditions, as also reported in previous power-to-power hydrogen studies [31].

Overall, these findings indicate that the main issue surrounding hydrogen energy storage is an economic one. Although hydrogen storage can provide renewable-energy integration and decarbonisation benefits, the system is highly dependent on the costs of the electrolyser and storage, as well as the efficiency of the hardware. As has been shown in prior work, the initial investment, running costs and size of the electrolyser are key factors that will influence the economics of hydrogen storage [33,34]. Thus, further technological and systems advances would be key to enhancing the economic attractiveness of green hydrogen.

3.7 Contribution to Net-Zero Electricity Systems

The modelled hydrogen-storage scenario demonstrated that green hydrogen storage can contribute to progressive decarbonisation of electricity systems by enabling higher shares of variable renewable energy while reducing fossil-fuel generation.

The renewable-energy share increased from 31.24% in the baseline system to 31.241% under the hydrogen-storage scenario, while electricity-sector emissions declined from 1,182,197,964 tCO_2e to 1,182,197,055 tCO_2e.

These results suggest that hydrogen storage can contribute to closing the gap between high renewable-energy
penetration and the reliability requirements of a low-carbon electricity system.

Importantly, hydrogen storage should not be considered a standalone pathway to net zero. Rather, its contribution depends on its integration with renewable generation, demand management, transmission infrastructure, energy efficiency, and other storage technologies. The results indicate that hydrogen is particularly valuable where
long-duration or seasonal energy storage is required.

This is in line with previous literature, which has suggested that green hydrogen could be used as both long-duration and seasonal energy storage in electricity systems with high shares of renewable energy [11,12,37]. Research has also highlighted that India's electricity system can further reduce its carbon footprint and increase renewable energy penetration by integrating it with green hydrogen [38]. Nevertheless, the marginal improvements in renewable

energy mix and emissions in this study suggest that hydrogen storage would not alone be able to facilitate a net zero electricity system. More probably, hydrogen will work alongside initiatives including increased renewable energy deployment, electricity transmission infrastructure, demand response schemes and energy efficiency to further advance decarbonisation.

4. Conclusion

This study evaluated the potential of using green hydrogen for electricity storage to improve renewable-energy integration, reduce carbon emissions, and enable the transition to a net-zero electricity system in India. The results demonstrated that surplus renewable electricity that would otherwise be curtailed could be converted to hydrogen via electrolysis, stored, and then reconverted to electricity when renewable sources were less abundant. This process enhanced renewable-energy utilization, reduced curtailment, and displaced a small amount of fossil-fuel electricity generation.

The results also showed that the environmental benefits of hydrogen storage were associated with significant economic challenges. The viability of the system was strongly dependent on the costs of the electrolyser, hydrogen-storage costs, the configuration of the system, and conversion efficiency. Although the reductions in curtailment and emissions were relatively small in the modelled scenarios, the results suggest that green hydrogen has the potential to offer valuable long-duration storage and grid flexibility in electricity systems with growing shares of variable renewables. Green hydrogen should not be considered as a stand-alone option to decarbonise

electricity, but rather as part of a broader portfolio of options that includes renewable-energy expansion, transmission upgrades, demand-side management, energy efficiency and other storage technologies.

Findings must also be considered alongside these constraints. Annual secondary data were analysed, and generic system scenarios were assumed without high temporal granularity. Furthermore, there was no consideration of lifecycle emissions or in-depth economic modelling. Additional work could improve understanding by considering finer-grained electricity data, different hydrogen storage technologies, and in-depth economic modelling along with lifecycle emissions. Practically, the results indicate that green hydrogen is likely to be of greatest added value as an augmenting long-term storage technology within power systems which are becoming increasingly reliant on variable renewables, rather than as a sole means to achieve a net-zero power system.

5. Acknowledgments

I would like to express my sincere gratitude to Dr. Neha Pandey and Dr. Roshan A for their invaluable guidance and feedback throughout this study.

6. Conflict of Interest

The author declares no conflict of interest.

7. Funding

This research received no external funding.

8. References

[1] Alagoz, E., and Alghawi, Y., 2024, "The Future of Fossil Fuels: Challenges and Opportunities in a Low-Carbon," International Journal of Earth Sciences Knowledge and Applications, 5(3), pp. 381–388. https://doi.org/10.13140/RG.2.2.16763.49442/1

[2] Elegbeleye, I., Oguntona, O., and Elegbeleye, F., 2025, "Green Hydrogen: Pathway to Net Zero Green House Gas Emission and Global Climate Change Mitigation," Hydrogen, 6(2), 29. https://doi.org/10.3390/hydrogen6020029

[3] Kumar, S. S., and Lim, H., 2022, "An Overview of Water Electrolysis Technologies for Green Hydrogen Production," Energy Reports, 8, pp. 13793–13813. https://doi.org/10.1016/j.egyr.2022.10.127

[4] Boettcher, S. W., 2024, "Introduction to Green Hydrogen," Chemical Reviews,

124(23), pp. 13095–13098. https://doi.org/10.1021/acs.chemrev.4c00787
[5] Zhang, J., and Li, J., 2024, "Revolution in Renewables: Integration of Green Hydrogen for a Sustainable Future,"
Energies, 17(16), 4148. https://doi.org/10.3390/en17164148
[6] Marouani, I., Guesmi, T., Alshammari, B. M., Alqunun, K., Alzamil, A., Alturki, M., and Hadj Abdallah, H., 2023, "Integration of Renewable-Energy-Based Green Hydrogen into the Energy Future," Processes, 11(9), 2685. https://doi.org/10.3390/pr11092685
[7] Sakthimurugan, V., Lakshmikanth, G., Balaji, N., Roopashree, R., Kumar, D., and Devarajan, Y., 2025, "Green Hydrogen Revolution: Advancing Electrolysis, Market Integration, and Sustainable Energy Transitions Towards a Net-Zero Future," Results in Engineering, 26, 104849. https://doi.org/10.1016/j.rineng.2025.104849
[8] Sambasivam, B., and Narayana Sarma, R., 2024, "India's National Green Hydrogen Mission: An Analysis of the Strategies, Policies for Net-Zero Emissions and Sustainability," Environmental Research: Energy, 1(4), 045015. https://doi.org/10.1088/2753-3751/ad8fb2
[9] Goel, S., and Sharma, R., 2026, "Green Hydrogen Production from Hybrid Renewable Energy Systems: A Techno-Economic Analysis in Rural India," International Journal of Sustainable Energy, 45(1), 2630464. https://doi.org/10.1080/14786451.2026.2630464
[10] Aburziza, A. A., Naderi, M., and Gladwin, D. T., 2026, "A Detailed Analysis of Long-Term Modelling Method of Power-to-Gas Hydrogen Generation Using Curtailed Wind Energy," Energies, 19(9), 2232. https://doi.org/10.3390/en19092232
[11] Upadhyay, A., Tröndle, T., Ganter, A., Petkov, I., Gabrielli, P., and Sansavini, G., 2025, "The Role of Energy Storage Towards Net-Zero Emissions in the European Electricity System," Energy Conversion and Management, 338, 119887. https://doi.org/10.1016/j.enconman.2025.119887
[12] Elberry, A. M., Thakur, J., and Veysey, J., 2021, "Seasonal Hydrogen Storage for Sustainable Renewable Energy Integration in the Electricity Sector: A Case Study of Finland," Journal of Energy Storage, 44, 103474. https://doi.org/10.1016/j.est.2021.103474
[13] Gado, M. G., 2024, "Techno-Economic-Environmental Assessment of Green Hydrogen and Ammonia Synthesis Using Solar and Wind Resources for Three Selected Sites in Egypt," E-Prime – Advances in Electrical Engineering, Electronics and Energy, 10, 100780. https://doi.org/10.1016/j.prime.2024.100780
[14] Hunter, C. A., Penev, M. M., Reznicek, E. P., Eichman, J., Rustagi, N., and Baldwin, S. F., 2021, "Techno-Economic Analysis of Long-Duration Energy Storage and Flexible Power Generation Technologies to Support High-Variable Renewable Energy Grids," Joule, 5(8), pp. 2077–2101. https://doi.org/10.1016/j.joule.2021.06.018
[15] Thaler, B., Pirker, G., and Wermuth, N., 2025, "Hydrogen Production with Grid-Connected Electrolysis: Scenario-Based Analysis of the EU Criteria for Renewable Fuels," Environmental Research Letters, 20(2), 024017. https://doi.org/10.1088/1748-9326/ada16d
[16] Tatarewicz, I., Skwierz, S., Lewarski, M., Jeszke, R., Pyrka, M., and Sekuła, M., 2023, "Mapping the Future of Green Hydrogen: Integrated Analysis of Poland and the EU's Development Pathways to 2050," Energies, 16(17), 6261. https://doi.org/10.3390/en16176261
[17] Thatte, A. A., Kogekar, P., Malyan, A., Choudhary, S., and Ningthoujam, J., 2026, "A Comparative Techno-Economic Assessment of Utility-Scale Power-to-Gas-to-Power Pathways Involving Green Hydrogen: An Indian Case Study," Next Energy, 13, 100889. https://doi.org/10.1016/j.nxener.2026.100889
[18] Patunkar, M., Bhojwani, V. K., Sidheshware, R., Tipole, P., and Mahesh, G., 2026, "Advancing the Green Hydrogen Economy: A Techno-Economic and Environmental Assessment," Next Energy, 12, 100631. https://doi.org/10.1016/j.nxener.2026.100631
[19] Central Electricity Authority, 2024, CO_2Baseline Database for the Indian Power Sector: User Guide, Version
20.0, Ministry of Power, Government of India.
[20] Central Electricity Authority, 2025, Growth of Electricity Sector in India from

1947–2025, Ministry of Power, Government of India.
[21] Ember, n.d., "India Electricity Data Explorer," available at: https://ember-energy.org/data/india-electricity-data-explorer/
[22] Tetik, H., and Kirkil, G., 2024, "The Role of Hydrogen in the Energy Mix: A Scenario Analysis for Turkey Using OSeMOSYS," Energies, 17(24), 6348. https://doi.org/10.3390/en17246348
[23] Cui, J. Z., Xie, C., Wu, W., Widijatmoko, S. D., Hong, Y., Li, Y., and Leeke, G. A., 2024, "Techno-Economic Analysis of Deploying a Short or Mixed Energy Storage Strategy in a 100% Green Power Grid," Journal of Energy Storage, 99, 113333. https://doi.org/10.1016/j.est.2024.113333
[24] Rezk, M. R. A., Piccinetti, L., Saleh, H. A., Salem, N., Mostafa, M. M. M., Santoro, D., El-Bary, A. A., and Sakr, M. M., 2023, "Future Scenarios of Green Hydrogen in the MENA Countries: The Case of Egypt," Insights into Regional Development, 5(4), pp. 92–114. https://doi.org/10.9770/ird.2023.5.4(7)
[25] Ajeeb, W., Baptista, P., and Costa Neto, R., 2024, "Life Cycle Analysis of Hydrogen Production by Different Alkaline Electrolyser Technologies Sourced with Renewable Energy," Energy Conversion and Management, 316, 118840. https://doi.org/10.1016/j.enconman.2024.118840
[26] Seglah, P. A., Wang, Y., Wang, H., Wobuibe Neglo, K. A., Zhou, K., Sun, N., Shao, J., Xie, J., Bi, Y., and Gao, C., 2023, "Utilization of Food Waste for Hydrogen-Based Power Generation: Evidence from Four Cities in Ghana,"
Heliyon, 9(3), e14373. https://doi.org/10.1016/j.heliyon.2023.e14373
[27] Ahmadullah, A. B., Mubashir, S. M., Irshad, A. S., Muslih, N. M., Rahel, H. A., Qudah, A., Serat, Z., Karimi,
B. A., and Senjyu, T., 2026, "Regional Techno-Economic Assessment of Integrated PV-Powered Electricity, Hydrogen, and Freshwater Production Systems in Afghanistan," International Journal of Sustainable Energy, 45(1), 2708540. https://doi.org/10.1080/14786451.2026.2708540
[28] Akbar, D., 2026, "Techno-Economic and Environmental Assessment of Grid-Connected Solar Photovoltaic Systems Across Five Climate Zones in Turkey," International Journal of Energy Research, 2026(1), 4265358. https://doi.org/10.1155/er/4265358
[29] Alikhani, P., Brinkel, N., Schram, W., Lampropoulos, I., and van Sark, W., 2023, "Marginal Emission Factors in Power Systems: The Case of the Netherlands," Proceedings of the 12th International Conference on Smart Cities and Green ICT Systems, 1, pp. 50–57. https://doi.org/10.5220/0011855700003491
[30] Zou, A., Raftery, P., Roberts, M., Wang, Y., Lv, G., Duarte, C., Brager, G., and Schiavon, S., 2026, "Temporal Resolution Matters: Evaluating Carbon Emission Factors for Accurate Accounting in Commercial Buildings,"
Applied Energy, 412, 127655. https://doi.org/10.1016/j.apenergy.2026.127655
[31] Pera, L., Gandiglio, M., and Marocco, P., 2025, "Techno-Economic Assessment of Hydrogen-Based Power-to-Power Systems: Operational Strategies and Feasibility Within Energy Communities," Energies, 18(13), 3254. https://doi.org/10.3390/en18133254
[32] Mendler, F., Fragoso Garcia, J., Kleinschmitt, C., and Voglstätter, C., 2024, "Global Optimization of Capacity Ratios Between Electrolyser and Renewable Electricity Source to Minimize Levelized Cost of Green Hydrogen,"
International Journal of Hydrogen Energy, 82, pp. 986–993.
https://doi.org/10.1016/j.ijhydene.2024.07.320
[33] Nicholas, A. E., Sabastine, A. N., and Aminaho, F., 2025, "Techno-Economic Assessments of Electrolyzers for Hydrogen Production," Applied Energy, 399, 126515. https://doi.org/10.1016/j.apenergy.2025.126515
[34] Saberi Mehr, A., and Carton, J. G., 2025, "Techno-Economic Analysis of Green Hydrogen Storage in Salt Caverns: Evaluating Cycling Effects and Cavern Scaling on the Levelized Cost of Hydrogen Storage in Ireland's Power-to-X Landscape," Journal of Energy Storage, 136, 118439. https://doi.org/10.1016/j.est.2025.118439

[35] Moran, C., Moylan, E., Reardon, J., Gunawan, T. A., Deane, P., Yousefian, S., and Monaghan, R. F. D., 2023, "A Flexible Techno-Economic Analysis Tool for Regional Hydrogen Hubs – A Case Study for Ireland," International Journal of Hydrogen Energy, 48(74), pp. 28649–28667. https://doi.org/10.1016/j.ijhydene.2023.04.100
[36] Alshammari, M. S., Awad, M., Attya Saa, M., and Omar, A. I., 2026, "A Comprehensive Review of Fuel Cell Technologies for Renewable Power Systems: Fundamentals, Materials, System Integration, Techno-Economics, Standardisation, and Middle Eastern Stationary Deployment," IET Renewable Power Generation, 20(1). https://doi.org/10.1049/rpg2.70380
[37] Zeng, Y., Zhou, T., Wang, T., Zhang, M., Zhang, S., and Yang, H., 2025, "Long-Duration Energy Storage: A Critical Enabler for Renewable Integration and Decarbonization," Energies, 18(3), 466. https://doi.org/10.3390/en18030466
[38] Cesaro, Z., Bramstoft, R., Bañares-Alcántara, R., and Ives, M. C., 2025, "Facilitating India's Deep Decarbonisation Through Sector Coupling of Electricity with Green Hydrogen and Ammonia," Energy Storage and Applications, 2(2), 4. https://doi.org/10.3390/esa2020004
[39] Stanford University, 2026, "Understand Energy in India," Understand Energy Learning Hub, January 27, 2026, available at: https://understand-energy.stanford.edu/news/understand-energy-india
[40] All About Renewables, n.d., "Installed Capacity," available at: https://allaboutrenewables.com/installed-capacity.html
[41] Thakkar, N., Paliwal, P., Kaliyaperumal, D., Pandi, V. R., Gupta, N. P., and Merlo, M., 2025, "Sensitivity Analysis of Reliability Constrained, Eco Optimal Solar, Wind, Hydrogen Storage Based Islanded Power System,"
Scientific Reports, 15(1), 9743. https://doi.org/10.1038/s41598-025-92893-x
[42] Franco, A., and Giovannini, C., 2023, "Recent and Future Advances in Water Electrolysis for Green Hydrogen Generation: Critical Analysis and Perspectives," Sustainability, 15(24), 16917. https://doi.org/10.3390/su152416917