# Synergistic Enviro-Economic Evaluation of a Solar-Green Hydrogen Hybrid System (SGHHS) for Continuous Clean Energy Using a Region-Specific Techno-Economic and Environmental Framework

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**Abstract.** This study assesses the techno-economic and environmental feasibility of a Solar–Green Hydrogen Hybrid System (SGHHS) designed for Rawalpindi, Pakistan. The system combines a 22.75 MWp photovoltaic array, a 2.25 MW Proton Exchange Membrane (PEM) electrolyzer, 450 kg hydrogen storage, and a 1 MW fuel cell to supply a continuous 1 MW daytime and 0.6 MW nighttime load. High-resolution climatic data and HOMER Pro simulations guided component optimization and validation. Results indicate a capital cost of USD 19 million and a levelized cost of electricity (LCOE) of USD 0.10/kWh, competitive with fossil-fuel benchmarks. Over a 25-year lifespan, the system avoids approximately 157,542 metric tons of $CO_2$ emissions. Seasonal analyses confirm hydrogen storage as an effective buffer during winter deficits. The findings highlight SGHHS as a viable pathway to enhance energy security, reduce fossil fuel dependence, and contribute to Pakistan's decarbonization targets.

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## 1 Introduction

The global energy landscape is undergoing a definitive shift driven by the essentials of sustainability, decarbonization, and energy security [1]. Escalating energy demand, depleting fossil fuel reserves, and the urgency to mitigate climate change have accelerated the transition to renewable energy [2]. Among the variety of renewable resources, solar energy has emerged as fundamental due to its ease of availability and infiniteness. However, the inherent intermittency of solar irradiance poses significant challenges to its integration into electrical grids which requires a continuous and reliable power supply [3]. While this transition is globally relevant, it is particularly crucial for countries like Pakistan, where energy shortages and climate conditions present unique challenges.

Pakistan, like many other regions across the globe, with its diverse geography and high solar irradiance, presents an opportunity for deploying solar-hydrogen hybrid systems to address its ongoing energy crisis [4]. The country faces energy shortages and a strong reliance on imported fossil fuels, intensifying economic instability and environmental harm [5]. To address these issues, Pakistan has developed several policies aimed at promoting renewable energy and reducing carbon emissions. The Alternative & Renewable Energy Policy (ARE 2019) sets ambitious targets for increasing the share of renewables in the energy mix[6] , and Pakistan's National Climate Change Policy underscores the importance of low-carbon technologies, including hydrogen energy solutions[7]. Furthermore, the country's Nationally Determined Contributions (NDCs) under the Paris Agreement commit to reducing greenhouse gas emissions by 50% by 2030, with hydrogen and solar energy playing a key role in achieving this target [8]. Given these policy initiatives, Rawalpindi, a key city in Punjab's Pothohar Plateau with a semi-arid climate and significant solar potential, offers an ideal location for implementing and assessing solar-hydrogen hybrid systems. This study evaluates the techno-economic feasibility of such a system, aligning with Pakistan's long-term energy security and climate mitigation strategies. [9]

In this context, hydrogen has contracted significant traction as a high potential energy carrier capable of bridging the inequalities between energy supply and demand [10]. The incorporation of solar photovoltaic (PV) systems with hydrogen production, storage, and reconversion technologies constitutes a archetypal for achieving a sustainable and resilient energy infrastructure. This solar-hydrogen hybrid system uses surplus solar electricity to produce hydrogen during periods of peak irradiance [11]. The produced hydrogen can be stored and subsequently utilized in fuel cells to produce electricity during periods of low or nonexistent solar generation, resultantly ensuring a continuous power supply.

The technoeconomic and environmental assessment of renewable energy systems, particularly solar-hydrogen hybrids, has been extensively explored in prior studies. Researchers have evaluated the feasibility of integrating solar photovoltaics (PV) with hydrogen production through electrolysis, highlighting the role of electrolyzers and fuel cells in ensuring grid reliability and energy security [12]. These studies primarily focus on theoretical modeling and general performance assessments without tailoring system configurations to specific regional climatic and economic conditions. Moreover, research has identified key challenges such as high capital costs, efficiency losses across the energy conversion chain, and policy limitations that hinder widespread adoption [13]. Although prior studies have demonstrated the feasibility of solar-hydrogen hybrid systems, they often overlook region-specific factors such as high-resolution solar irradiance data, local economic conditions, and life-cycle environmental impacts [14]. This study addresses these gaps by focusing on Rawalpindi's unique climatic and economic conditions. Furthermore, existing works tend to overlook real-world constraints such as degradation rates, seasonal variations in hydrogen production, and site-specific deployment challenges [15]. Addressing these gaps, this study offers a comprehensive enviro-economic analysis of a solar-green hydrogen hybrid system (SGHHS) tailored to Rawalpindi's climatic conditions, integrating advanced technoeconomic modeling, high-resolution climate data, and environmental impact assessments to ensure a regionally optimized and sustainable energy solution.

This research provides a synergistic enviro-economic analysis of an SGHHS designed to deliver a stable 1 MW power load in the Rawalpindi region. It explores the intricate aspects of system design, component integration, and performance optimization to offer a comprehensive understanding of its functionality [16]. In addition, this study serves as a foundational step in a broader research initiative aimed at evaluating the efficiency and economic viability of SGHHS across different regions. By first analyzing Rawalpindi's climatic conditions, the findings will provide a benchmark for future comparative studies in other subregions. There is a lack of research focusing on the integration of these systems in the specific context of regional climatic conditions and economic landscape [17]. The analysis of the research comprises finding requisite potential of solar PV , electrolyzers, hydrogen storage units, and fuel cells while taking into account system efficiencies, degradation rates, and operational parameters which includes CAPEX, OPEX, and LCOE over a 25-year project lifespan, integrating discount rates, cost projections of equipment, and maintenance cost.

In addition, the study accounts carbon emissions which are avoided by replacing fossil fuel-based power generation through a comparative assessment using emissions factors and life cycle considerations.

Advancements in hydrogen storage technologies and policy incentives can further enhance its feasibility as a dispatchable renewable energy source. Such systems can alleviate the need for fossil fuel-based peaking plants, reduce transmission losses by enabling decentralized generation, and enhance energy security [18]. Moreover, progression in electrolyzer and fuel cell technologies have better efficiency and reduced costs, making solar-hydrogen hybrid systems increasingly viable to be implemented.

To achieve these objectives, the research subjects to a multidisciplinary approach that integrates utilization of high-resolution solar irradiance data to evaluate the probable energy generation from the PV system, electrolyzer, hydrogen storage, and fuel cell components accurately and objectively. This includes taking into account inefficiencies, losses, and degradation over time. It also incorporates conducting a thorough financial assessment using LCOE calculations, sensitivity analysis, and discounted cash flow models to ascertain the economic feasibility under various scenarios, as well as applying life cycle assessment methodologies to estimate the environmental benefits, particularly in terms of carbon emissions reduction.

The findings of this research will potentially guide policy makers in developing and defining strategies and incentives in order to promote renewable energy adoption, addressing both energy reliability and environmental carbon cutting objectives. The research methodology defined will act a blue print for following up studies in various climatic zones, which will resultantly facilitate a comparative analysis that can lead to optimized system designs fabricated to regional characteristics. Given these insights, the widespread implementation of SGHHS requires strong policy interventions, infrastructure support, and financial incentives to drive large-scale adoption.

While the benefits of SGHHS are significant, several challenges must be addressed before large-scale implementation. Key obstacles include high capital costs, hydrogen storage complexities, and policy limitations [19]. Although PEM electrolyzers and fuel cell technologies have advanced, challenges related to durability, efficiency, and maintenance remain [20]. Similar issues exist in fossil fuel-based systems, but unlike conventional energy infrastructure, hydrogen technologies face additional barriers such as limited availability and regulatory constraints in many regions [21]. The absence of robust regulations and standards for hydrogen technologies can impede deployment and acceptance at government level [22].

## 2 Literature Review

The deployment of solar-hydrogen hybrid systems represents a convergence of multiple advanced technologies each with its own set of complexities and interdependencies [23]. This section investigates the technical groundworks of the key components—solar photovoltaic systems, hydrogen production via electrolysis, hydrogen storage technologies, and fuel cell systems. Additionally, it evaluates pertinent literature to contextualize the current state of research and development in the discussed field, highlighting gaps that this study aims to address and resolve.

The environmental impact of solar-hydrogen systems has been widely acknowledged, but many studies lack quantitative assessments of carbon mitigation potential**.** Studies have demonstrated that solar-hydrogen hybrid systems can significantly reduce carbon emissions, but their analyses did not incorporate lifecycle $CO_2$ reduction quantifications [24]. This study builds upon these findings by quantifying metric tons of $CO_2$ emissions reduction over a 25-year operational period**,** providing a direct comparison with fossil-fuel-based power generation systems. Additionally, this research integrates findings with Pakistan's National Hydrogen Policy, ensuring that results are aligned with real-world policy frameworks. By addressing both economic feasibility and environmental sustainability, this study provides actionable insights for decision-makers in energy policy and investment planning**.**

Many previous studies on solar-hydrogen hybrid systems have examined their feasibility in various climatic and economic conditions [25]. Research has highlighted challenges in energy efficiency, cost trade-offs, and storage limitations [26]. Studies have also pointed out the reliance on generalized solar irradiance datasets rather than localized, high-resolution environmental data. Some researchers have attempted economic modeling, but sensitivity analyses accounting for market fluctuations remain limited [27]. Additionally, while the environmental benefits of solar-hydrogen systems have been acknowledged, detailed carbon mitigation assessments are lacking [28]. This study builds upon previous work by incorporating region-specific solar irradiance and climate data for Rawalpindi, offering a more precise performance assessment. Furthermore, it integrates comprehensive economic modeling and quantifies the environmental impact through avoided carbon emissions, providing valuable insights for renewable energy policy discussions.

The critical aspect with regards to the subject is Energy management [29]. The phenomenon of balancing the intermittent generation from PC with persistent demand resultantly requires advanced control systems. Efficiency cascades also play a role, with sequential losses in each component—such as PV efficiency, electrolyzer efficiency, and fuel cell efficiency—compounding to reduce the overall system efficiency. Additionally, economic trade-offs must be carefully considered, as achieving higher efficiencies often comes with increased capital costs, necessitating optimization strategies to minimize the levelized cost of electricity (LCOE) and maximize system performance [30].

This research addresses several gaps identified in previous studies. Many previous studies on solar-hydrogen hybrid systems have relied on generalized solar irradiance datasets rather than localized, high-resolution environmental data [31]. In contrast, this study enhances accuracy by incorporating region-specific solar irradiance and climate conditions in Rawalpindi, improving the reliability of the system's performance assessment [32]. Additionally, it incorporates a comprehensive economic analysis, integrating up-to-date cost metrics and economic modeling, along with sensitivity analyses to account for market fluctuations. Another key contribution is the detailed quantification of the environmental impact, specifically the assessment of avoided carbon emissions, which provides valuable insights for policy discussions on renewable energy incentives. Literature highlights the potential of solar-hydrogen hybrid systems while highlighting the challenges related to efficiency, cost, and integration. By building upon existing knowledge and addressing identified gaps, this study contributes to advancing the understanding of how such systems can be effectively deployed in regions like Rawalpindi, ultimately supporting the global transition to sustainable energy.

## 3 Materials and Methods

The methodology adopted in this research encompasses a laborious and wholesome multi-disciplinary approach which is designed to evaluate the technical feasibility, economic viability, and environmental impact of the proposed solar-hydrogen hybrid system in a particular region of Rawalpindi, Pakistan. The approach manifested in Fig 1 considers detailed data acquisition, comprehensive economic analysis, and thorough environmental assessment of the region vis-à-vis cost effectiveness. Accurate and high-resolution data are paramount for simulating the performance of renewable energy systems [33].

This study employed both satellite-derived and ground-based datasets to ensure precision in solar irradiance and climate parameters. Data were sourced primarily from the National Renewable Energy Laboratory's (NREL) National Solar Radiation Database (NSRDB) with hourly temporal resolution and 4 km² spatial granularity. Ground station measurements were used for cross-validation.

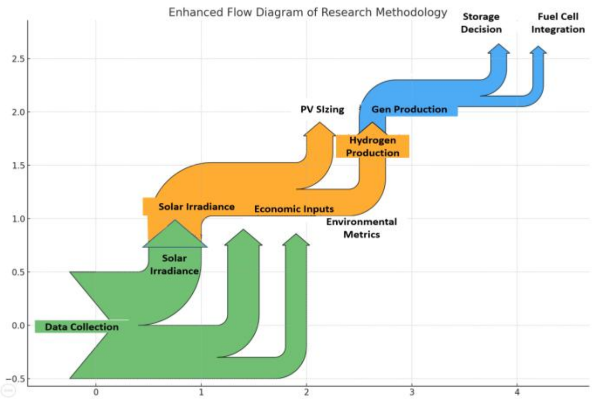

**Fig 1**. Python generated Sankey Diagram of Methodological Process

Fig 1 represents Python generated Flow Diagram of Research methodology necessitated by timeline manifested workflow. This study employed a combination of satellite-derived data and ground-based measurements ensuring precision and accuracy in solar irradiance and climatic parameters. Solar irradiance data derived from satellite has been obtained from the National Renewable Energy Laboratory's (NREL) National Solar Radiation Database (NSRDB). This database provides elaborated historical data on Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), and Diffuse Horizontal Irradiance (DHI) with high temporal (hourly) and spatial (4 km²) resolution [34]. These measurements were essential to account for micro level variations in climate and to validate the satellite data through cross - comparison [35]. This made sure that the input data for subsequent calculations were reliable and representative of actual conditions. Figure 2 represents a methodological process in pursuit of meaningful results.

To determine the optimal sizing of system components for a continuous 1 Mega Watt (MW) SGHHS in Rawalpindi, key climatic data—including solar irradiance, ambient temperature, and average peak sun hours—were used. The PV array capacity was calculated based on total daily energy demand and performance losses due to temperature, soiling, and inverters. Hydrogen requirements for nighttime load were derived from energy calculations involving electrolyzer efficiency and hydrogen's heating value.

In this study, a **Proton Exchange Membrane (PEM) electrolyzer** was selected for hydrogen production. PEM electrolyzers were chosen due to their high efficiency (75%), rapid dynamic response, and compatibility with variable solar photovoltaic input. Unlike alkaline electrolyzers, PEM systems operate effectively under fluctuating power conditions, making them suitable for renewable energy integration. The sizing of 2.25 MW was determined to ensure sufficient hydrogen generation during peak solar hours to sustain the 1 MW nocturnal load requirement.

The electrolyzer and storage systems were sized to meet daily hydrogen production targets, factoring in storage pressure and temperature using the ideal gas law. Fuel cell capacity was designed to meet night-time demand at 50% efficiency. AI-enhanced simulations in HOMER Pro were used to model dynamic system behavior, integrating real-time adjustments and seasonal variations. Overall system efficiency was calculated as the product of all component efficiencies, identifying loss areas for optimization.

After analyzing the efficiency at each stage, areas with significant losses were identified, allowing for focussed improvements in system design and operation.

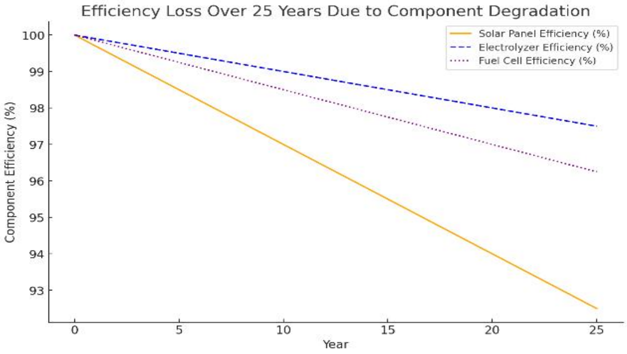

**Fig 2**. Efficiency loss due to component degradation

Fig 2 shows the efficiency loss over 25 years for the solar panels, electrolyzer, and fuel cells. Each component incurres degradation, which resultantly reduces overall system performance and impacts long-term efficiency. The economic feasibility of the system was evaluated using detailed calculations of capital expenditure (CAPEX), operational expenditure (OPEX), and the levelized cost of electricity (LCOE).

The economic analysis of the Solar-Green Hydrogen Hybrid System (SGHHS) includes capital expenditure (CAPEX) covering all major components including PV modules, electrolyzers, hydrogen storage units, and fuel cells, while operational expenditure (OPEX) accounts for maintenance, replacements, labor, and inflation over a 25-year lifespan. The LCOE was calculated using discounted cash flow to assess long-term cost-effectiveness, with an 8% discount rate. Environmentally, a LCA was conducted to quantify carbon emissions, considering the full lifecycle of system components. Compared to a conventional oil-fired power plant, SGHHS showed negligible operational emissions and significant overall $CO_2$ reduction, confirming its environmental superiority and sustainability benefits.

## 4 Data Validation and Verification

In order to confirm the accuracy of the proposed SGHHS, an elaborate validation process was undertaken during the course of research. Cross validation of the solar panel capacity was carried out using HOMER Pro software, taking into account solar irradiance data and net system loses [36]. The results deviations received from HOMER Pro as well as principle methods demonstrated mere 5% which confirmed the reliability of capacity estimates. The storage and production of hydrogen was compared with specifications given by the manufacturer which showed specifications given by the manufacturer showed consistency in production rates, cost estimates and efficiencies.

The LCOE calculations made through research was validated through simulations run with HOMER Pro and sensitivity analysis [37]. The results came out be in alignment with regional benchmarks and deviation of <10% were observed. The emission savings were also validated using IPCC factors of emissions and benchmarks taken from Jamshoro power Plant which is fossil fuel run power plant. A total reduction of 157,542 metric tons over 25 years was validated.

The research methodology and assumptions taken up in the study were validated by subject experts after reviews. This is done to validate the approach and calculations. Feedback from subject experts led to subsequent refinements in SGHHS design and sensitivity analysis for LCOE projections. Sensitivity Analysis were performed to ascertain the effect of key variables on the LCOE and the economic viability in order to assess how reductions in PV modules prices, electrolyzers cost, and fuel cell expenses could affect the LCOE. These analyses helped to create validations and verifications against documented system and its results. In addition, the methodology has been validated through published research. The approach for solar PV performance modeling and degradation rates follows the empirical degradation benchmarks established by various researchers [38]. The validation of hydrogen production efficiency and electrolyzer performance aligns with the findings of Kumar and Himabindu [39], which analyze proton exchange membrane (PEM) electrolyzer efficiencies under real-world conditions. The Levelized Cost of Electricity (LCOE) methodology and sensitivity analysis adhere to industry-standard frameworks outlined by Lagorse et al. [40] and Sengupta et al. [41], ensuring financial projections are based on established benchmarks. Furthermore, environmental impact assessments, particularly $CO_2$-equivalent emissions mitigation, were validated using Intergovernmental Panel on Climate Change (IPCC) emissions factors [42], aligning with internationally recognized carbon accounting methodologies. Operational and Maintenance (O&M) costs were validated using manufacturer data & industry benchmarks. It used manufacturer data and industry benchmarks to ensure that the estimates are for 25-year project

Fig 4 represents the comprehensive methodology outlined, which ensures that the study's findings are vigorous, reliable, and applicable to actual real-world problems and conditions. By integrating detailed economic and environmental analyses, the research extends a firm base for evaluation of proposed solar-hydrogen hybrid system's feasibility in Rawalpindi and offers insights that can be extended to similar context [43].

## 5 Results

This research intends to manifest a wholesome multi-disciplinary evaluation of the proposed solar-hydrogen hybrid system for Rawalpindi region, integrating technical optimization, economic viability, and wholesome environmental sustainability. Below is an expanded and comprehensive results section with all relevant graphs embedded to enhance clarity.

The system tends to integrate photovoltaic (PV) power generation, hydrogen production via electrolysis, compressed hydrogen storage, and electricity regeneration via fuel cells. The design ensures a seamless energy supply while accounting for diurnal and seasonal variations, degradation over a 25-year lifespan, and operational tests.

The PV array, sized at 22.75 MW DC, was optimized to meet both immediate electrical loads and ancillary energy requirements for hydrogen production. A performance ratio (PR) of 0.75 was calculated, reflecting losses due to temperature coefficients (-0.38%/°C), soiling, inverter inefficiencies, and system mismatches. The nominal module efficiency of 20% ensures reliable operation under Rawalpindi's climatic conditions.

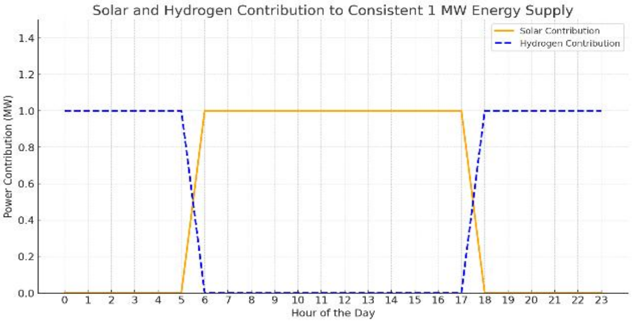

**Fig 3**. Energy Supply Over a 24-Hour Period

Fig 3 highlights the energy supply dynamics, showing solar power meeting energy demands from 6 AM to 6 PM, while hydrogen takes over during nighttime hours. This hybrid approach compensates for solar intermittency. The calculation within the study incorporates the variation in daylight and dark hours and the graph varies for different parts of the year, however, this graph represents a generalization of energy consumption for better understanding of results.

A Proton Exchange Membrane (PEM) electrolyzer, with an efficiency of 75%, was selected for hydrogen production. It requires 2.25 MW of power to produce 45 kg/hour of hydrogen, achieving a daily production of 396 kg over a 10-hour operational window. This hydrogen sustains the 1 MW nocturnal load, which spans approximately 13.2 hours.

The hydrogen storage system was designed to accommodate 450 kg of hydrogen, incorporating a safety margin of 13.6%. Type IV high-pressure composite vessels, rated at 350 bar, were used. Adjusted for compressibility factors, the total storage volume required is approximately 5,600 Nm³.

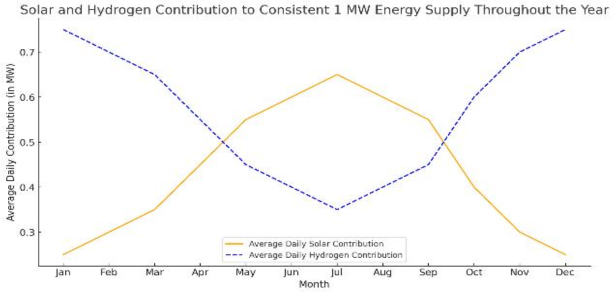

**Fig 4**. Seasonal Energy Contributions of Solar and Hydrogen

Fig 4 illustrates the seasonal variation in energy sources. During summer, longer daylight hours reduce hydrogen demand as solar provides a larger share of the energy. Conversely, in winter, shorter days increase reliance on stored hydrogen to maintain the 1 MW load.

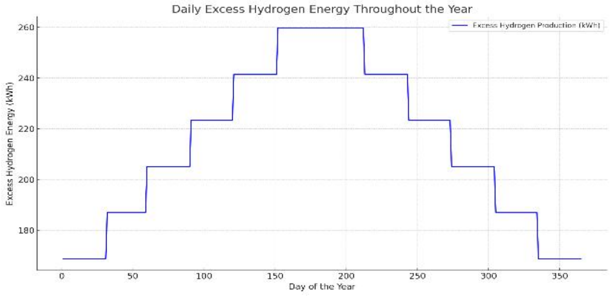

**Fig 5**. Daily Excess Hydrogen Production Over the Year

Fig 5 shows that excess hydrogen production peaks in summer months (May to August) due to higher solar generation, while winter months (December to February) exhibit reduced excess due to lower solar availability. This emphasizes upon the system's dependency on solar energy for efficient hydrogen storage. The fuel cell array, rated at 1 MW, was designed to regenerate electricity from stored hydrogen at an initial efficiency of 50%. Over 25 years, an annual degradation rate of 1% results in a cumulative efficiency loss of 22%. Performance modeling incorporated polarization curves and accounted for degradation due to catalyst sintering and membrane thinning.

The capital expenditure (CAPEX) for the integrated system totals approximately USD 19 million, distributed as follows:

- PV Array: USD 12.5 million (inclusive of modules inverters, and installation).
- Electrolyzer: USD 1.5 million.
- Hydrogen Storage: USD 0.6 million.
- Fuel Cell Assembly: USD 4.5 million.

The operational expenditure (OPEX) over 25 years is projected at USD 12.5 million, covering maintenance, staffing, component replacements, and consumables like deionized water. The Levelized Cost of Electricity (LCOE), calculated at an 8% real discount rate, is approximately USD 0.10/kWh. Sensitivity analyses reveal:

- A 6% discount rate reduces the LCOE to USD 0.087/kWh.
- A 10% cost reduction in PV modules or electrolyzer systems lowers the LCOE by 3-5%.

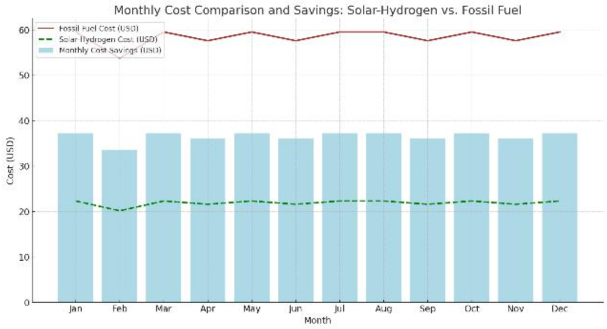

**Fig 6.** Monthly Cost Comparison Between Solar-Hydrogen and Fossil Fuel Systems

Fig 6 compares monthly costs, showing that the solar-hydrogen system consistently achieves significant savings, especially in high-demand months.

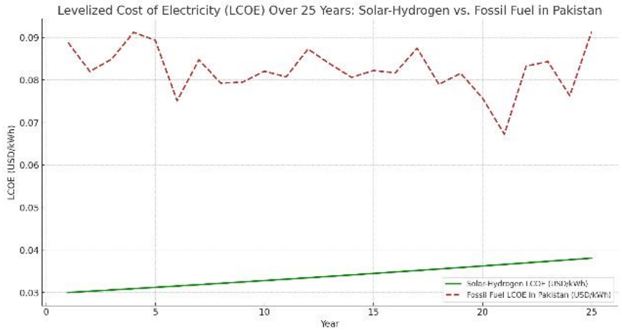

**Fig 7.** LCOE Comparison Over 25 Years

Fig 7 compares the solar-hydrogen system's LCOE with fossil fuel systems. The solar-hydrogen LCOE rises gradually due to system degradation but remains lower than the fluctuating LCOE of fossil fuels. The system avoids approximately 157,542 metric tons of $CO_2$-equivalent emissions over 25 years compared to an equivalent oil-fired power plant operating at 35% efficiency. This includes 5,000 metric tons of $CO_2$-equivalent emissions from the manufacturing and transportation of system components. Pakistan's Nationally Determined Contributions (NDCs) under the Paris Agreement reflect its commitment to reducing greenhouse gas (GHG) emissions and enhancing climate resilience. The country aims to cut emissions by 50% by 2030, with 15% through domestic efforts and 35% conditional on international support in the form of climate finance, technology transfer, and capacity building. Pakistan plans to increase renewable energy's share to 60%, achieve 30% electric vehicle adoption, and halt new coal power projects (except those under construction). Additionally, initiatives like the **10** Billion Tree Tsunami, climate-smart agriculture, and enhanced disaster risk management are central to adaptation strategies [44]. Pakistan seeks $101 billion in funding for climate action by 2030 while ensuring a just transition to a low-carbon economy [45]. These commitments align with the country's Vision 2025, Sustainable

Development Goals (SDGs), and national climate policies, reinforcing its role in global climate action [46].

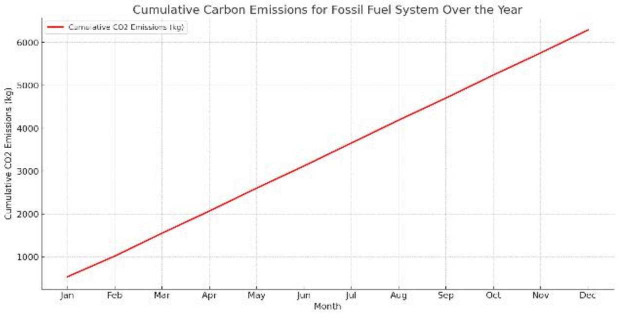

**Fig 8.** Cumulative Carbon Emissions - 25 Years

Fig 8 highlights the environmental benefits, demonstrating how the solar-hydrogen system significantly reduces carbon emissions compared to a fossil fuel-based system. The fossil fuel-based system projects significant carbon emissions while for the Solar-hydrogen hybrid solution, the carbon emissions are effectively zero. One may opine that manufacturing of Renewable infrastructure causes carbon emission from the very beginning but that stands true for Fossil Fuel run power plants as well, resultantly, difference between the two compared sources of energy as same as depicted in the graph [47].

The system achieves an overall energy efficiency of 12%, calculated as the product of:

- PV Module Efficiency: 20%.
- Electrolyzer Efficiency: 75%.
- Fuel Cell Efficiency: 50%.
- Performance Ratio (PR): 75%.

Degradation Analysis:

- PV Modules retain 88.6% efficiency after 25 years, with a degradation rate of 0.5% per year.
- Fuel Cells experience a 1% annual efficiency loss, totaling 22% over 25 years.

The results set forth the technical feasibility, economic viability, and significant environmental benefits of the solar-hydrogen hybrid system in Rawalpindi. Continued innovation and optimization of system components will further enhance its applicability in similar climatic and economic contexts.

## 6 Discussion

This study tends to submit a detailed analysis of a SGHHS which is designed specifically for Rawalpindi, showcasing its technical, economic, & environmental potential. The system combines photovoltaic (PV) power generation, hydrogen production and storage, and electricity regeneration through fuel cells, offering an innovative solution for sustainable energy needs. The hybrid system intends to address the issues of intermittency of solar energy by incorporating its components seamlessly. With a 22.75 MW DC PV array, it not only fulfills immediate energy requirements but also aims to support hydrogen production simultaneously. The performance ratio (PR) of 3/4 reflects realistic losses, such as temperature impacts, soiling, and inefficiencies in inverters.

From an economic perspective, the solar-hydrogen hybrid system requires a significant initial investment, with a CAPEX of around USD 19 million and an OPEX of approximately USD 12.5 million over 25 years. However, the Levelized Cost of Electricity (LCOE) of USD 0.10/kWh is competitive and less than Pakistan's national average electricity tariff. Sensitivity analyses show that a 10% decrease in PV module or electrolyzer costs could reduce the LCOE by 3-5%, indicating opportunities for further cost reductions. Given that the SGHHS proves cost-competitive in the long run, the next step is to ensure favorable policy interventions that can further enhance its viability. Strategic measures, such as tax exemptions on electrolyzers and subsidies for hydrogen infrastructure, could accelerate widespread adoption.

These findings suggest that solar-hydrogen hybrid systems can be viable alternatives to conventional fossil-fuel-based power generation, particularly in regions with high solar irradiance like Pakistan. Given that hydrogen storage mitigates intermittency issues associated with PV systems, this technology could be a sustainable solution for off-grid areas and industrial energy applications. Additionally, integrating hydrogen into Pakistan's National Renewable Energy Plan could enhance energy security and reduce dependence on imported fossil fuels. To support this transition, policymakers should consider incentives such as reduced import duties on electrolyzers and tax credits for green hydrogen production.

To enhance financial viability and encourage widespread adoption, strong policy interventions are necessary. Pakistan's National Hydrogen Policy (in progress) aims to establish a framework for hydrogen production and utilization, creating incentives for green hydrogen projects. Additionally, integrating carbon credit mechanisms within the country's renewable energy policies can improve the financial attractiveness of the system. Carbon credits allow industries to offset their emissions by investing in green energy projects, thereby reducing the effective cost of implementing solar-hydrogen hybrid systems.

Pakistan's State Bank Green Financing Schemes also provide concessional financing for renewable energy projects, including solar and hydrogen-based systems. The inclusion of tax incentives, subsidies for hydrogen infrastructure, and feed-in tariffs for excess hydrogen-generated electricity would further accelerate the adoption of SGHHS. Lessons from international policies, such as the EU Hydrogen Strategy and Japan's Hydrogen Roadmap, could help shape Pakistan's policy direction for large-scale green hydrogen deployment.

Although the initial CAPEX (USD 19M) remains a financial hurdle, the long-term economic benefits outweigh the upfront investment. Unlike fossil fuel plants, SGHHS eliminates volatile fuel costs, making it a predictable and stable energy source. Additionally, technological advancements and economies of scale are expected to drive further cost reductions, strengthening its financial case for policymakers and investors. Additionally, since there are no fluctuating fuel costs, the hybrid system provides stability and predictability, making it a more reliable energy source for the region given the huge solar potential in the region which is effectively never ending.

The environmental benefits of the solar-hydrogen hybrid system are particularly noteworthy and long lasting. Over the expected life span of 25 years, the system prevents 157,542 metric tons of $CO_2$ emissions over 25 years, aligning with Pakistan's Paris Agreement targets. This underscores the potential of solar-hydrogen systems as scalable, low-carbon alternatives to fossil fuels. The results also highlight the system's minimal carbon footprint during the manufacturing and transportation of components. Although these processes do contribute to carbon emissions, however, their impact is significantly negligible compared to the lifecycle emissions of fossil fuel-based energy systems. The study highlights the importance of considering the full lifecycle emissions of energy systems to provide a fair and accurate comparison. Moreover, the graphs depicting cumulative carbon emissions avoided and seasonal energy contributions underline the system's effectiveness in reducing overall dependence on fossil fuels. During summer, longer daylight hours enable the PV array to provide a larger share of the energy, reducing overall operational reliance on hydrogen storage, but will eventually lead to surplus hydrogen. Surplus hydrogen has numerous utilities from automobile to industrial domain. Inversely, the incremental use of stored hydrogen in winter demonstrates the system's adaptableness to seasonal variations, ensuring a consistent energy supply throughout the year.

This reduction of $CO_2$ as discussed aligns with Pakistan's climate goals under the Paris Agreement. If hydrogen policies include carbon credits and subsidies for green hydrogen adoption, the economic feasibility of such projects could be further enhanced. Additionally, creating a regulatory framework for hydrogen storage and transportation will be essential for large-scale deployment. Countries with strong hydrogen policies, such as Germany and Japan, have demonstrated how financial incentives can accelerate renewable hydrogen adoption. Pakistan could follow similar models by establishing feed-in tariffs for green hydrogen and integrating it into national energy transition plans.

In spite of its advantages, the solar-hydrogen hybrid system has many challenges before execution of the same commercial level. The degradation of system components, such as PV modules and fuel cells, manifests a long-term operational challenge. This research addresses this issue by integrating rates of degradation into performance modeling, ensuring realistic projections of system efficiency and output over a life time.

The initial efficiency of 12% for the overall system highlights the inherent energy losses associated with the conversion processes. While this is a limitation of current technology, ongoing progressive innovations in PV module efficiency, electrolyzer technology, and fuel cell design hold promise for improving overall system efficiency. For instance, advancements in catalyst materials and membrane durability could enhance the performance and longevity of fuel cells, reducing degradation rates and maintenance costs.

To contextualize our results, a relevant study in Niger reported an LCOE of about 0.13 USD/kWh for an off-grid SGHHS system. In contrast Austrian project integrating PV, wind, and underground hydrogen storage achieved a significantly lower LCOE of ~0.05 USD/kWh primarily due to presence of larger and better infrastructure. It was shown to be owing to dual-source input and mature infrastructure. Above given comparative studies projects that the proposed SGHHES for diverse region of Pakistan is economically viable, particularly in zones with higher irradiance such as Quetta and Bahawalpur. Moreover, this study extends beyond conventional techno-economic assessments by employing a comprehensive, multi-disciplinary integrative approach, combining techno-economic modeling and environmental life cycle assessment. As elaborated throughout this paper, the proposed system is not only designed for cost competitiveness but also demonstrates substantial carbon reduction benefits, with approximately 157,542 metric tons of $CO_2$-equivalent emissions avoided over a 25-year lifespan. These insights underline the system's capacity to address Pakistan's energy security and decarbonization goals, contributing to global sustainable development targets.

The study also identifies opportunities for further optimization. For example, the integration of advanced energy management systems could enhance the coordination between PV generation, hydrogen production, and electricity regeneration, minimizing energy losses and maximizing system efficiency. Similarly, the incorporation of predictive maintenance technologies could reduce OPEX by preemptively addressing potential issues before they lead to system failures. The applications of the research can be extrapolated beyond selected region, which will potentially offer valuable insights for deployment of SGHHS. The proposed system tends to address the key challenges which are linked with fossil fuel powered power plants. The continuous maintenance, ever rising carbon emissions will ultimately be contained as a result of application of this system make SGHHS a valuable alternative for alike regions across the globe.

In conclusion, this study demonstrates that solar-hydrogen hybrid systems are not only technically feasible but also economically and environmentally sustainable. While initial costs remain a challenge, ongoing innovations in electrolyzer technology and fuel cell efficiency, combined with favorable policy interventions, could drive large-scale adoption. As Pakistan and other nations transition towards net-zero emissions, SGHHS could play a significant role towards global sustainability.

## 6.1 Limitations

The adoption of hydrogen as an energy carrier presents challenges related to infrastructure development, regulatory frameworks, and public perception. In Pakistan, hydrogen infrastructure is still in its early stages, requiring significant investment in physical assets, regulatory harmonization, and safety protocols. Public acceptance remains a concern due to perceived safety risks, which can be mitigated through education, stringent safety standards, and demonstrable safety records. The scalability and replicability of the proposed system depend on regional climatic conditions, land availability, and grid integration capabilities. While Rawalpindi offers favorable solar resources, other regions may face geographic, environmental, or regulatory constraints. The intermittency of solar energy and challenges in integrating large-scale renewables into existing grids necessitate advanced grid management strategies, demand-side response mechanisms, and microgrid configurations. Policy interventions, including feed-in tariffs, tax credits, subsidies, and carbon pricing, can significantly improve the financial viability of solar-hydrogen hybrid systems. Additionally, streamlined permitting processes, standardized hydrogen safety codes, and support for research and development will be essential in overcoming regulatory and economic barriers, facilitating widespread adoption of this sustainable energy solution.

## 7 Conclusion

This study establishes a technically, economically, and environmentally viable framework for implementing solar-hydrogen hybrid systems in regions with high solar potential. The results provide a blueprint for policymakers, energy planners, and researchers to further develop sustainable, low-carbon energy solutions tailored to regional needs. As renewable energy technologies evolve and green hydrogen production scales up, such hybrid systems will play an integral role in the global transition toward a cleaner more resilient energy future.

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