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Article

Techno-Enviroeconomic Modeling of a Solar-Green Hydrogen System with Industrial Wastewater Reuse via Integrated Hourly Simulation-LCA-DCF

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Abstract: Solar–hydrogen hybrid systems provide low-carbon and dispatchable energy, yet most existing configurations implicitly assume freshwater availability, thereby overlooking the role of water reuse in water-stressed regions. In semi-arid industrial contexts, the integration of clean energy systems with circular water management is essential for long-term sustainability. This study develops a closed-loop Solar–Green Hydrogen Hybrid System (SGHHS) in which industrial effluent is treated through a membrane bioreactor–reverse osmosis–deionization (MBR→RO→DI) sequence to satisfy proton exchange membrane (PEM) electrolyzer water-quality requirements, while water recovered from fuel-cell exhaust is captured as condensate, achieving an overall water recovery rate of approximately 90%. The proposed system consists of a 22.75 MW photovoltaic array, a 2.25 MW electrolyzer, 450 kg of hydrogen storage, and a 1 MW fuel cell, and is evaluated using a 25-year hourly-resolution simulation framework. Economic performance is assessed through discounted cash-flow analysis, while environmental impacts are quantified using life-cycle assessment. Results demonstrate that integrating water reuse reduces the levelized cost of electricity from 0.10 to 0.0866 USD/kWh, avoids approximately 157,000 tonnes of CO_2-equivalent (tCO_2-eq)emissions, and enables the recovery of nearly 400,000 L/day of process water. By explicitly internalizing water-treatment capital and operating costs alongside water-savings benefits within the energy cost formulation, the study presents a generalizable framework linking hydrogen-based energy systems with circular water infrastructure, supporting industrial decarbonization and Sustainable Development Goals related to clean energy, responsible resource use, and climate action.

Keywords: Solar–Hydrogen Hybrid System; Wastewater Reuse; Water–Energy Nexus; Techno-Economic Modelling; Lifecycle Assessment; Industrial Decarbonization

1. Introduction

The global energy and environmental landscape is undergoing a decisive transformation driven by escalating demands for sustainable development, decarbonization, and resource efficiency [1]. As climate change, water scarcity, and industrial pollution become increasingly urgent challenges, the need for integrated, cross-sectoral solutions that address both energy and water sustainability has never been more critical. This is particularly relevant for countries like Pakistan, where energy insecurity, industrial water stress, and environmental degradation intersect to form a multidimensional crisis. The convergence of clean energy production with circular water reuse systems presents a transformative opportunity to resolve these challenges in a synergistic manner [2].

Pakistan's energy sector is historically dependent on imported fossil fuels, contributing to economic instability and significant greenhouse gas (GHG) emissions. Simultaneously, the industrial sector, particularly textile manufacturing—a cornerstone of Pakistan's export economy—generates vast quantities of wastewater, contributing to surface water pollution and freshwater depletion. With the country ranking among the top ten most water-stressed nations in the world, and with chronic electricity shortages affecting both residential and industrial consumers, there is a clear imperative for integrated systems that address energy and water challenges concurrently [3].

Among the emerging technologies, the SGHHS represents a promising solution. This system integrates solar photovoltaic (PV) energy generation with hydrogen production via electrolysis, hydrogen storage, and reconversion into electricity using fuel cells. Such systems provide a sustainable pathway to uninterrupted power supply, particularly in regions with high solar irradiance like Pakistan [4]. However, traditional SGHHS designs typically rely on freshwater resources for electrolysis, posing a sustainability concern in water-scarce regions. The integration of treated industrial wastewater into SGHHS design not only mitigates this issue but also offers a model of industrial symbiosis where waste from one system becomes input for another.

This research introduces an integration of SGHHS with wastewater reuse from Gul Ahmed Textiles, one of Pakistan's leading textile manufacturers, based in Karachi. The textile sector in Pakistan is among the largest consumers of water and simultaneously one of the major producers of industrial effluent. By harnessing this wastewater as a feedstock for green hydrogen production, the proposed system demonstrates a circular approach where energy generation and water purification operate in tandem. The study evaluates a system that treats 4050 L of textile effluent per day for use in a 2.25 MW electrolyzer, producing 45 kg/h of hydrogen to sustain a 1 MW power load during dark hours using a PEM fuel cell. The clean water generated as a byproduct of fuel cell operation is subsequently returned to the industry for reuse, enhancing both environmental and operational efficiency [5].

Karachi provides an ideal context for evaluating an integrated SGHHS due to high solar irradiance, increasing industrial water stress, and chronic energy load shedding. The proposed system aligns with Pakistan's Alternative and Renewable Energy Policy, Nationally Determined Contributions (NDCs), and the Sustainable Development Goals—particularly SDGs 6, 7, and 13 [6]. By utilizing industrial wastewater as an electrolysis feedwater source, the integrated design overcomes key limitations of standalone SGHHS deployments, including high capital costs and freshwater dependency. As a result, the system reduces the Levelized Cost of Electricity (LCOE) from USD 0.10 to USD 0.0866/kWh over a 25-year lifespan, while lifecycle assessment indicates potential avoidance of more than 157,000 tCO_2-eq emissions.

Methodologically, the study applies a multidisciplinary framework combining high-resolution solar data, detailed system modelling, lifecycle cost analysis, and environmental performance metrics. The model accounts for component degradation, efficiency losses, and wastewater quality constraints, and incorporates advanced simulation and AI-supported optimization to evaluate technical and financial robustness under varying conditions. Beyond site-specific performance, the proposed SGHHS–wastewater integration offers a scalable framework for industrial zones in Pakistan and other developing economies. Co-location of renewable energy and industrial water treatment enables economies of scale, reduced transmission losses, and improved resource utilization, with applicability to other high-effluent sectors such as leather, pharmaceuticals, and food processing [7]. Accordingly, this study investigates whether industrial wastewater can be viably integrated into an SGHHS to deliver continuous clean electricity while reducing water stress and improving economic competitiveness in Pakistan's textile industry. It hypothesizes that wastewater-integrated SGHHS can (i) reduce freshwater dependency, (ii) lower LCOE relative to conventional configurations, and (iii) maintain or enhance environmental performance. To test this, a site-specific system linking a 22.75 MW solar array, 2.25 MW electrolyzer, hydrogen storage, and a 1 MW fuel cell with 4050 L/day of treated textile effluent was modelled over 25 years. Results confirm improved economic viability, significant carbon mitigation, and substantial water recovery, demonstrating the first data-driven, site-specific validation of circular SGHHS deployment in an industrial setting [8].

This manuscript begins with a comprehensive literature review covering SGHHS, industrial wastewater treatment technologies, and circular water–energy nexus approaches, with emphasis on unresolved gaps relevant to water-stressed industrial regions. It then presents the system architecture and methodological framework, detailing the integrated solar–hydrogen configuration, wastewater treatment and reuse pathway, hourly simulation setup, lifecycle assessment, and discounted cash-flow modelling. The subsequent part reports the techno-economic and environmental results, including Levelized Cost of Electricity (LCOE), water recovery performance, carbon mitigation potential, and uncertainty analysis. This is followed by a discussion of implications and scalability, examining industrial applicability, operational challenges, and policy relevance for decarbonization and resource efficiency. The manuscript concludes with key findings and conclusions, summarizing the principal contributions of the study and outlining directions for future research.

Novelty and Contribution

This article tends to bring a new perspective to the existing literature in the following areas:

(i) System integration, by developing a closed-loop SGHHS that explicitly links renewable power generation with industrial wastewater reuse in a single co-located framework;
(ii) Techno-economic modelling, by internalizing wastewater treatment costs and water-reuse benefits directly into discounted cash-flow and Levelized Cost of Electricity (LCOE) calculations;
(iii) Technology application, by demonstrating the practical feasibility of using treated textile effluent to meet PEM-electrolyzer water quality requirements while recovering fuel-cell condensate for industrial reuse;
(iv) Environmental assessment, by quantifying simultaneous reductions in freshwater withdrawal and carbon emissions through integrated lifecycle and system-level analysis in a real industrial context.

This study presents the first integrated evaluation of a closed-loop SGHHS that simultaneously addresses energy security and water scarcity in an industrial context. Unlike conventional SGHHS models that assume freshwater availability and neglect water reuse, the proposed system (i) treats industrial effluent to meet PEM-electrolyzer water quality standards (ASTM Type II) using a parameterized MBR→RO→DI train, and (ii) recovers fuel-cell condensate to achieve ∼90% overall water recovery. Prior research has examined these components separately—such as wastewater-to-hydrogen pathways, fuel-cell water recovery, and PV–PEM–fuel cell architectures—but no study has combined them within a single co-located installation or explicitly internalized water-loop capital expenditure (CAPEX) and operational expenditure OPEX into LCOE and DCF analyses. Methodologically, this work contributes a validated, decision-oriented framework that links hourly system simulation, lifecycle assessment (LCA), and techno-economic modeling, while capturing the cost signal of water looping (LCOE reduced from 0.10 to 0.0866 USD/kWh). Beyond site-specific results, the framework is structured for replication by adjusting local tariffs, solar resources, electrolyzer costs, and effluent volumes, offering a generalizable pathway for scaling circular energy–water systems in water-stressed industrial regions. In doing so, this research extends the water–energy nexus literature beyond municipal pilots and component studies toward a reproducible, industry-integrated model that demonstrates full symbiosis of clean power and circular water reuse.

2. Literature Review

2.1. Solar-Green Hydrogen Hybrid Systems (SGHHS): Technological Evolution and Global Context

Green hydrogen has emerged as a key solution for addressing the intermittency and storage limitations of solar photovoltaic (PV) energy, positioning SGHHS as a promising platform for dispatchable, low-carbon power generation. SGHHS integrates PV generation with hydrogen production via Proton Exchange Membrane (PEM) electrolysis, hydrogen storage, and electricity regeneration through fuel cells, enhancing reliability for off-grid and industrial applications in solar-rich, energy-deficient regions. Studies from North Africa, Southern Europe, and the Middle East report optimized PV–electrolyzer–fuel-cell configurations achieving system efficiencies above 40%, while AI-based optimization has underscored the importance of degradation-aware, long-term planning [9].

Despite technological maturity, high capital costs for electrolyzers and fuel cells remain a barrier, particularly in developing economies. However, IRENA and International Energy Agency projections indicate that green hydrogen could become cost-competitive by 2030 due to declining renewable-energy and equipment costs, with reported SGHHS LCOE values ranging from USD 0.10 to 0.20/kWh [10]. A critical but underexplored constraint is water availability and quality, as PEM electrolyzers require ultrapure water to ensure durability and performance. While alternative sources such as seawater and industrial effluents have been proposed [11], limited research has examined integrated SGHHS deployment within industrial zones. This study addresses this gap by proposing a site-specific SGHHS coupled with textile wastewater reuse, advancing a dual-purpose framework that simultaneously enhances energy reliability and water security [12].

2.2. Wastewater Treatment Technologies and Integration with Renewable Energy Systems

The growing industrial demand for water and rising wastewater generation have driven the development of advanced treatment technologies compatible with clean energy systems [13]. Wastewater treatment is increasingly viewed as a source of reclaimed water and energy rather than solely a pollution-control process, a shift that is particularly important in developing countries facing water scarcity and energy insecurity. Reusing treated industrial wastewater offers a viable pathway to support renewable energy systems requiring high-quality process water, such as green hydrogen production. Recent advances in membrane-based and hybrid physico-chemical–biological treatment—especially Membrane Bioreactors (MBRs), Reverse Osmosis (RO), and ultrapure water polishing—are well suited for Solar–Green Hydrogen Hybrid Systems (SGHHS). MBR–RO combinations with ion-exchange polishing can reliably achieve ASTM Type II or higher water quality required for PEM electrolysis, while improving efficiency and cost-effectiveness through modern membrane technologies [14,15].

International case studies demonstrate the feasibility of integrating wastewater treatment with energy systems, including biogas-powered treatment in California, solar-driven net-zero water–energy systems in New York, and PV-powered decentralized treatment in Germany. Emerging hydrogen studies further confirm that treated municipal and industrial wastewater can be reused for electrolysis without compromising performance, with pilot-scale demonstrations in China and South Korea indicating scalability [16]. Textile manufacturing is particularly suitable for such integration due to large effluent volumes and consistent wastewater characteristics, with studies in India and Bangladesh reporting water recovery rates above 85% and associated cost savings. Despite these advances, the integration of wastewater treatment within SGHHS remains underexplored, and the combined impacts on lifecycle cost reduction and carbon mitigation have not been comprehensively quantified in developing-country contexts—gaps that this study directly addresses.

2.3. Circular Water-Energy Nexus in Industrial Applications

The water–energy nexus highlights the mutual dependence of water and energy systems, particularly in water- and energy-intensive industries such as textiles [17]. This has led to growing interest in circular water–energy models that integrate wastewater reuse with renewable energy generation to improve sustainability and reduce operational costs [18].

Practical implementations in India and Bangladesh demonstrate the feasibility of such integration through centralized effluent treatment, biogas recovery, rooftop solar, and wastewater recycling. Supporting literature shows that integrated water–energy planning enhances resource efficiency, resilience, and emissions reduction when tailored to local industrial contexts. Coupling hydrogen production with wastewater reuse further enables water neutrality by reintegrating ultrapure fuel-cell condensate into industrial processes, reducing reliance on municipal supplies. Adoption is reinforced by sustainability frameworks such as ISO 14046, ISO 50001, and ZDHC, as well as increasing pressure from global apparel supply chains [19].

Despite these advances, industrial-scale applications in the Global South remain underexplored [20]. The SGHHS–wastewater integration at Gul Ahmed Textiles addresses this gap by demonstrating a localized, circular solution that simultaneously reduces freshwater withdrawal, minimizes effluent discharge, and ensures a continuous, renewable power supply, offering clear advantages over standalone wastewater treatment or conventional solar–hydrogen systems.

2.4. Knowledge Gaps and Relevance to Regional Context

Hydrogen production via electrolysis is inherently water-intensive, requiring approximately 9 L of water per kg of H_2, with Proton Exchange Membrane (PEM) electrolyzers demanding ASTM Type II or higher purity water to prevent rapid degradation [21,22]. While recent studies have explored the use of treated wastewater for electrolysis, such as coupling wastewater streams with solid oxide or alkaline electrolysis and recovering clean product water from fuel cells, these efforts are largely confined to municipal contexts, pilot scales, or component-level demonstrations. Notably, regenerative fuel cell concepts, including NASA's RFC studies, have demonstrated the technical feasibility of recycling fuel-cell product water, yet these approaches rarely assess integrated system economics or industrial symbiosis [23].

At the system level, PV–electrolyzer–fuel cell architectures are well established for dispatchable renewable power, but most studies assume freshwater inputs and exclude water reuse or recovery from system boundaries [24]. Similarly, despite the rapid expansion of the global hydrogen economy (97 Mt in 2023, with <1% low-emission), techno-economic assessments rarely treat water scarcity as a binding constraint [25]. This gap is particularly pronounced in Pakistan, where the textile sector is highly water-intensive and polluting, wastewater treatment coverage remains below 8% in major cities, and existing hydrogen studies are largely theoretical. Current renewable energy policies (e.g., ARE 2019) promote clean power but do not incentivize water reuse, leaving a regulatory and analytical gap for circular energy–water systems [26].

Against this backdrop, no prior study integrates industrial wastewater treatment to PEM standards, fuel-cell condensate recovery, and SGHHS operation within a single, co-located, closed-loop framework while explicitly internalizing water-loop CAPEX, OPEX, and environmental impacts. This study addresses that gap through a site-specific, industrial-scale analysis. Benchmarking against existing literature shows that while SGHHS LCOE values typically range from USD 0.10–0.20/kWh, the wastewater-integrated system evaluated here achieves an LCOE of USD 0.0866/kWh, positioning it at the lower bound of reported values. Environmentally, while green hydrogen studies commonly report 50–70% CO_2 reductions, the proposed SGHHS demonstrates CO_2 avoidance exceeding 157,000 tCO_2-eq alongside substantial freshwater savings through closed-loop reuse. Collectively, these results advance the state of the art by jointly addressing energy cost, water scarcity, and carbon mitigation within an industrial context.

3. System Description and Methodology

3.1. System Architecture and Operational Design

This section outlines the technical and analytical approach adopted to design and evaluate the SGHHS integrated with industrial wastewater reuse. The system is designed to provide a stable 1 MW continuous power supply while simultaneously enabling water recycling within an industrial setting. The architecture is informed by multidisciplinary data inputs, including meteorological datasets, system component specifications, water treatment standards, and economic performance indicators. The proposed SGHHS is designed as a comprehensive, multi-stage infrastructure that enables round-the-clock renewable energy supply through solar and hydrogen pathways. At its core, the system features a 22.75 MW solar photovoltaic (PV) array that converts solar irradiance into electricity during daylight hours. The system's capacity was determined through simulation and load modeling to cover both the industrial electricity needs of the co-located textile facility and the energy required for electrolysis.

Figure 1 illustrates the core architecture of the SGHHS, depicting the integrated flow of solar power generation, hydrogen production, storage, electricity regeneration, and water reuse. Electricity generated by the PV array is supplied to a 2.25 MW Proton Exchange Membrane (PEM) electrolyzer, selected for its fast dynamic response and high efficiency, producing approximately 45 kg of hydrogen per hour during peak solar conditions. The hydrogen is compressed and stored in Type IV composite tanks at 350 bar, with a total storage capacity of 450 kg—sufficient to support 13.2 hours of uninterrupted operation. During periods of low or no solar availability, the stored hydrogen is converted back into electricity via a 1 MW PEM fuel cell, ensuring a continuous power supply and mitigating solar intermittency while minimizing grid dependence. For water integration, 4050 L/day of textile effluent is treated using a multistage system comprising Membrane Bioreactors (MBR), Reverse Osmosis (RO), and Deionization (DI), producing ASTM Type II–quality water suitable for electrolysis. Approximately 90% of the input water is recovered as high-purity condensate during fuel-cell operation and reintegrated into the industrial water cycle for processes such as rinsing, dyeing, and steam generation.

The conceptual flow of the integrated system is illustrated in **Figure 2**, showing the conversion of textile effluent into clean hydrogen and reusable water within a circular resource loop that combines energy generation and water stewardship. Building on this architecture, economic performance was evaluated using component-level capital and operational expenditures, real-world procurement costs, maintenance schedules, and local utility tariffs. A 25-year discounted cash-flow model was applied to calculate the Levelized Cost of Electricity (LCOE), incorporating inflation, component degradation, and operational savings from wastewater reuse. Environmental assessment included carbon offset estimation based on displaced fossil-fuel electricity and water recovery metrics relative to the facility's total water footprint.

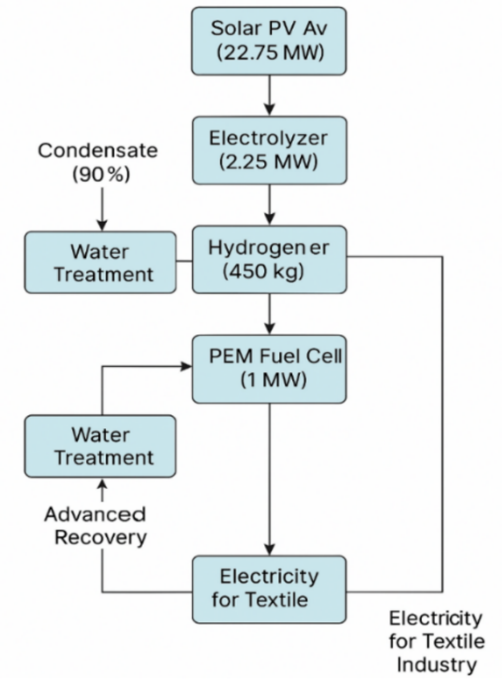

Figure 1. System Architecture of SGHHS.

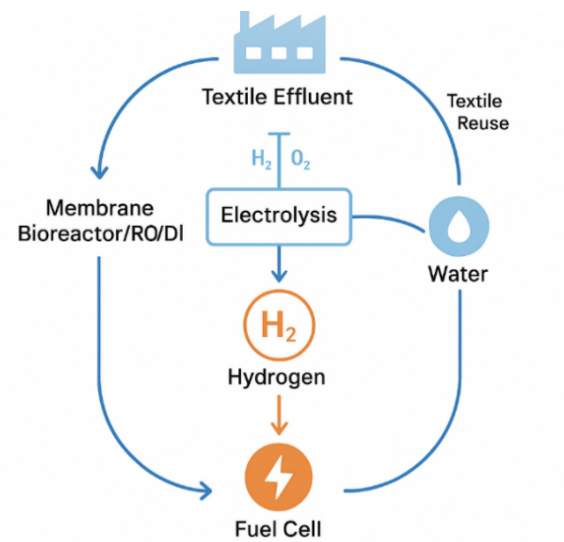

Figure 2. Conceptual representation of a circular water-energy nexus model in the textile industry.
Note: It shows integration of wastewater treatment with hydrogen production, power generation, and water reuse.

System performance was simulated using HOMER Pro under variable solar and load conditions. Model validation against manufacturer specifications and comparable case studies showed deviations within 5–10% for both energy and water outputs, confirming technical reliability. Together, this approach provides a high-resolution, context-specific evaluation of a wastewater-integrated SGHHS suitable for industrial applications in water-stressed, solar-rich regions such as Pakistan.

3.2. Water Treatment Integration and Resource Looping

A key feature of the proposed SGHHS is its integrated water system, which converts industrial wastewater from Gul Ahmed Textiles (Karachi) into high-purity feedwater for hydrogen production. The facility generates over 400,000 L/day of effluent, from which ~4050 L/day is treated to meet Proton Exchange Membrane (PEM) electrolyzer standards. The multi-stage process—comprising primary filtration, Membrane Bioreactor (MBR), Reverse Osmosis (RO), and Deionization (DI)—removes solids, salts, heavy metals, and microbes to achieve ASTM Type II water quality. Textile effluent with COD 1000–2000 mg/L and TDS 1500–2500 mg/L can be effectively purified via the MBR–RO–DI train, as demonstrated in comparable South Asian industries. **Table 1** summarizes each stage's role, energy use, and output quality.

Table 1. Water Treatment Stage Requirements and Compliance with PEM Electrolyzer Standards.

Treatment Stage	Function	Energy Consumption (kWh/mÂ³)	Output Water Quality
Primary Filtration	Removes large suspended solids and debris	0.05–0.1	Pre-treated effluent
Membrane Bioreactor (MBR)	Biologically treats and clarifies wastewater	0.3–0.5	Partially purified water
Reverse Osmosis (RO)	Removes dissolved salts, heavy metals, and organics	1.0–1.5	High-purity water
Deionization (DI)	Polishes water to ultrapure standards (low TDS & conductivity)	0.1–0.2	ASTM Type II Ultrapure Water

The PEM electrolyzer deployed in this study consumes approximately 9 L of ultrapure water per kilogram of hydrogen produced, which is consistent with vendor specifications and literature reports on PEM systems. At the modeled production rate of 45 kg H_2 per hour, this translates to an hourly water demand of ~405 L, equivalent to ~4050 L per day under standard operating conditions. This value aligns with the wastewater draw specified in the system design, ensuring that the treated effluent volume is appropriately matched to the electrolyzer's operational requirements.

After purification, ASTM Type II water feeds the PEM electrolyzer, ensuring high hydrogen yield and membrane durability. About 90% of this water is later recovered from the fuel-cell condensate, filtered, and reused in non-potable applications such as dye baths, cooling, or boiler feedwater—forming a closed-loop cycle that minimizes freshwater intake. This integration of wastewater reuse and clean-energy generation enhances SGHHS's resilience, cuts reliance on municipal supply, and reduces effluent discharge. The condensate reuse offsets most of the water demand, while careful unit sizing limits energy overhead, making the design both technically and economically viable for Pakistan's dual challenges of water scarcity and energy insecurity.

3.3. Analytical Modelling, Simulation, and Validation

The development of a robust modelling framework for the SGHHS system began with the identification and definition of key performance parameters. These parameters, along with their associated calculations and dependencies, are summarized in **Table 2**. This table serves as a comprehensive reference, ensuring clarity and consistency across the simulation and economic evaluation phases.

Table 2. Complex System Design and performance metric.

Parameter	Value	Unit	Formula/Calculation	Interdependency/Notes
Daily Energy Demand	E_{total}	MWh/day	$P_{load} \times 24$	Base multiplied by operational hours
Peak Solar Energy Output	E_{PV}	MWh/day	$A_{pv} \times GHI \times \eta_{pv} \times PR$	Depending on solar irradiance (GHI) and panel performance ratio (PR)
Hydrogen Production Energy	$E_{H2\text{-}pro}$	MWH/day	E_{total} -PV	Remaining energy demand fulfilled by hydrogen
Elcctrolyzer Hydrogen Output	m H_2	Kg/day	$\frac{E_{H2-prod}}{HHV_{H2} \times \eta_{elec}}$	Determined by electrolyzer efficiency
Electrolyzer Sizing	P_{elec}	MW	$\frac{m_{H2} \times HHV_{H2}}{\eta_{elec}}$	Scaled to daily hydrogen production requirement
Hydrogen Storage Volume	$V_{storage}$	Nm^3	$\frac{m_{H2} \times R \times T}{P_{storage} \times Z}$	Includes compressibility (Z) factor and gas constant (G)
Fuel Cell Power Output	P_{FC}	MW	Fixed	Sized to meet nighttime load demand
System Efficiency	η_{system}	%	$\eta_{PV} \times \eta_{elec} \times \eta_{FC}$	Cumulative efficiency of all system components
System Degradation Factor	DF_{system}	%/year	Empirical	Includes combined degradation from PV modules, electrolyzers and fuel cells

Table 2. *Cont.*

Parameter	Value	Unit	Formula/Calculation	Interdependency/Notes
Levelized Cost of Electricity (LCOE)	LCOE	USD/KWh	$\frac{\sum_{t=1}^{25}(CAPEX+OPEX+R1)}{\sum_{t=1}^{25}E_{total}(t)}$	Includes capital expenditure (CAPEX), operational (OPEX) expenditure and replacement costs (Rt)
Carbon Mitigation Potential	ΔCO_2	Metric Tons	$\sum_{t=1}^{25}\Delta t \times P_{fossil} \times EF_{fossil} \times EF_{hybrid}$	Accounts for emissions avoided by replacing fossil fuels with renewable system
Thermal Losses in PV Modules	TL_{PV}	%	$\Delta T \times TC$	ΔT: temperature rise &TC: temperature coefficient
Hydrogen Compression Energy	E_{comp}	MWh/day	$\frac{P_{storage} \times V_{stoarge}}{\eta_{comp}}$	Energy consumed for compressing hydrogen
Fuel Cell Polarization Loss	PL_{FC}	V	Derived from η_{FC}	Voltage loss during operation, affects overall efficiency

Note: All symbols and abbreviations used in the equations and tables are defined as follows: E_{total} denotes total daily energy demand (MWh/day); E_{pv} is photovoltaic energy output (MWh/day); E_{h2} is energy supplied via hydrogen (MWh/day); P_{load} represents load demand (MW); P_{elec} is the rated electrolyzer power (MW); P_{FC} is fuel-cell output power (MW); η_{pv} and η_{FC} denote photovoltaic and fuel-cell efficiencies, respectively; PR is the PV performance ratio; DF_{system} is the annual system degradation factor; $V_{storage}$ denotes hydrogen storage volume; E_{comp} is hydrogen compression energy; CAPEX and OPEX represent capital and operational expenditure; LCOE denotes Levelized Cost of Electricity; and ΔCO_2 represents avoided carbon emissions.

The performance of the integrated SGHHS was evaluated using defined system metrics and simulation tools. Key parameters governing energy balance, hydrogen production, storage, and economics are summarized in **Table 2** and were used to calibrate the model. Hourly system operation was simulated in HOMER Pro for one year using site-specific irradiance, temperature, and load data. A 25-year discounted cash-flow model incorporated CAPEX, OPEX, degradation, inflation, and maintenance, with wastewater reuse contributing to LCOE reduction. Environmental performance was assessed through lifecycle assessment (LCA), quantifying CO_2 reductions from displaced grid electricity and water savings from ~90% condensate recovery.

Electrolyzer performance was analyzed under variable operating conditions, including temperatures of 50–80 °C, pressures of 10–30 bar, and controlled water flow rates. Sensitivity analyses on solar resource, electrolyzer efficiency, and degradation confirmed system robustness, with optimized operating conditions yielding 5–10% efficiency gains consistent with the literature.

3.4. System Degradation Factor: Definition and Validation

The system degradation factor (DFsystem) was introduced to account for annual performance decline across all major components, namely PV modules, PEM electrolyzers, and PEM fuel cells. For PV modules, an average degradation rate of 0.7% per year was assumed, consistent with long-term field studies in similar climatic zones. Electrolyzer efficiency was assumed to decline by 0.25% per year, reflecting catalyst and membrane aging as reported in recent durability studies. Fuel cell stacks were assigned an annual degradation of 0.5%, corresponding to manufacturer specifications and empirical pilot-scale data. These component-level degradation rates, as mentioned in **Figure 3**, were aggregated into a weighted average, normalized by their contribution to overall system efficiency, yielding a composite DF_{system} of ~0.5% per year.

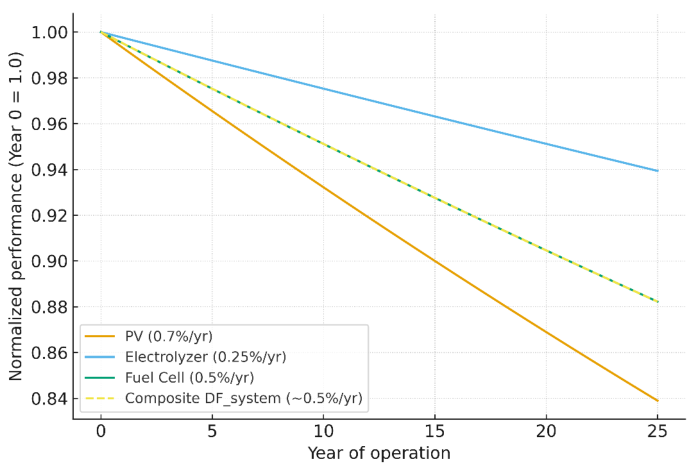

Figure 3. Composite System Degradation Factor Based on Weighted Component-Level Contributions.

Validation was performed by cross-referencing with empirical performance data from global SGHHS case studies and adjusting model assumptions until simulated long-term efficiency trajectories aligned within ±5–10% of reported benchmarks. This operational definition ensures that DF_{system} reflects a realistic, evidence-based estimate of cumulative efficiency decline over the 25-year project horizon.

3.5. Water-Energy Integration with Gul Ahmed Textiles

The integration of the SGHHS with Gul Ahmed Textiles is based on strong alignment between the facility's industrial profile and the system's operational requirements. Gul Ahmed Textiles, one of Pakistan's largest vertically integrated textile manufacturers located in Karachi, operates energy- and water-intensive processes including spinning, weaving, dyeing, and finishing. The facility generates approximately 400,000 L/day of wastewater, providing a reliable feedstock for treated reuse in green hydrogen production.

Co-location enables direct utilization of this wastewater stream, reducing reliance on municipal or groundwater sources, lowering effluent discharge, and minimizing the facility's water footprint through closed-loop reuse and fuel-cell condensate recovery. The site also provides sufficient rooftop and adjacent land for the 22.75 MW solar array, reducing transmission losses and avoiding off-site land acquisition, while existing treatment infrastructure facilitates upgrading to PEM electrolyzer water-quality standards.

Additionally, Gul Ahmed Textiles' compliance with international sustainability certifications (e.g., ISO 14001, OEKO-TEX, Higg Index) and engagement with global apparel brands make it well-suited for piloting this high-impact model. This integration exemplifies industrial symbiosis, where wastewater is transformed into a valuable resource, and demonstrates the scalability of SGHHS deployments across other industrial clusters in Pakistan and comparable resource-constrained regions.

The resource flow diagram in **Figure 4** provides a high-level overview of the SGHHS's closed-loop operation. To complement this, **Figure 5** disaggregates the water flows across system components, detailing input-output ratios, recovery percentages, and reuse pathways essential for system-level optimization.

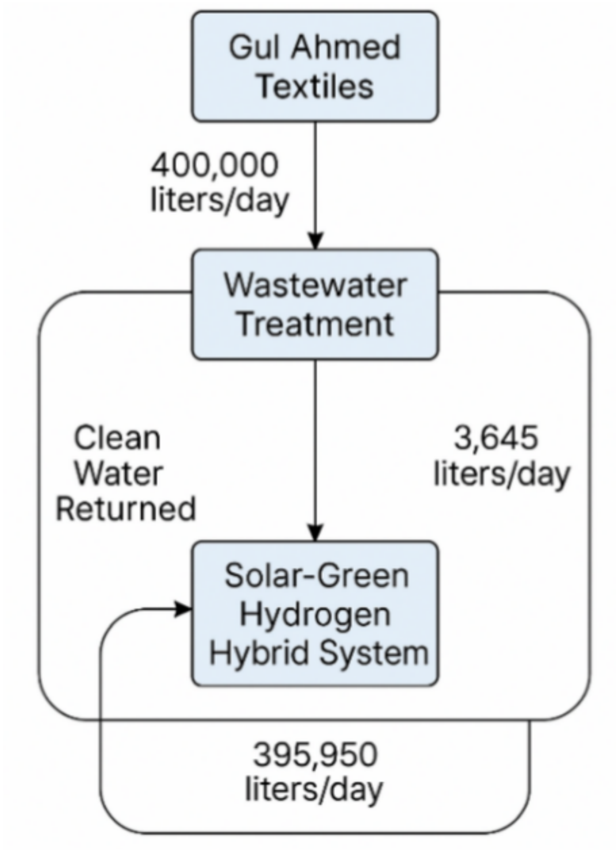

Figure 4. Circular Water-Energy Resource Loop.

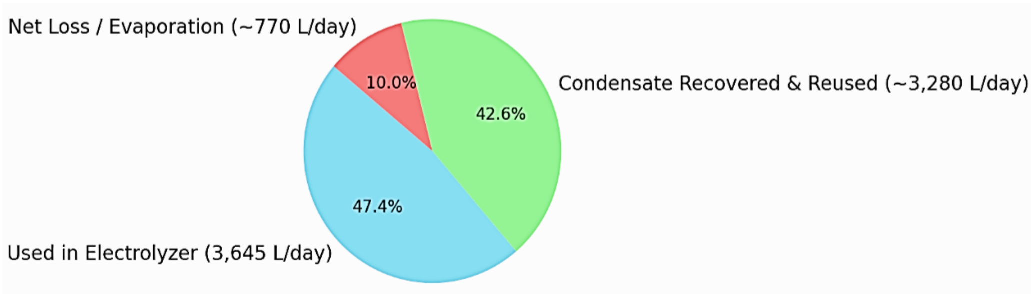

Figure 5. Distribution of water recovery and reuse within the SGHHS.

Note: It shows usage in electrolysis, condensate recovery, and system losses.

Figure 5 quantifies water use within the SGHHS, showing proportions of wastewater treated, water fed to the electrolyzer, condensate recovered, and minor evaporative losses—demonstrating high efficiency in water recycling.

4. Results

This chapter presents the results and performance evaluation of the proposed SGHHS integrated with industrial wastewater reuse. It synthesizes the outputs of the techno-economic modelling, environmental assessment, and uncertainty analysis to evaluate system feasibility under realistic operating conditions. The chapter examines energy performance, water recovery efficiency, economic viability, and environmental benefits, providing a comprehensive basis for comparison with conventional energy and water management approaches. The following subsections detail these results across technical, economic, and environmental dimensions.

4.1. Techno-Economic Analysis

To improve benchmarking and comparability, capital costs were disaggregated into standard unit-level metrics. The solar PV system, with a total CAPEX of USD 10 million for 22.75 MW, corresponds to approximately USD 440/kWp, consistent with global utility-scale PV benchmarks and declining balance-of-system costs in South Asia. The 2.25 MW PEM electrolyzer, costing USD 3.2 million, yields a unit cost of USD 1422/kW, within the current market range of USD 1200–1800/kW. Hydrogen storage (450 kg) is valued at USD 2.5 million, equivalent to USD 5555/kg, including compression and high-pressure storage infrastructure. The 1 MW PEM fuel cell costs USD 2.3 million (USD 2300/kW), while the wastewater treatment unit (4050 L/day) requires USD 1 million, or USD 246 per (L/day) of capacity. These unit costs demonstrate scalability and provide reference benchmarks without altering the CAPEX used in LCOE and IRR calculations.

A 25-year techno-economic assessment of the integrated SGHHS at Gul Ahmed Textiles yields a total initial investment of USD 19 million, comprising PV (USD 10 million), electrolyzer (USD 3.2 million), hydrogen storage (USD 2.5 million), fuel cell (USD 2.3 million), and water treatment (USD 1 million), based on 2024 market data. Annual OPEX is estimated at USD 250,000, covering maintenance, membrane and filter replacement, stack refurbishment, and labor, with degradation and inflation effects incorporated. Wastewater reuse avoids freshwater procurement and disposal, resulting in annual savings of approximately USD 18,000 at a local tariff of USD 1.20/m^3. The Levelized Cost of Electricity (LCOE) was calculated using discounted cash-flow analysis with a 7% discount rate. Without wastewater reuse, the LCOE is USD 0.10/kWh; incorporating water-reuse savings reduces it to USD 0.0866/kWh, representing a 13.4% reduction and enhancing competitiveness relative to fossil-based generation costs of USD 0.12–0.15/kWh in Pakistan.

The resulting LCOE declines from 0.10 to 0.0866 USD/kWh owing to water-loop savings (see **Figure 6** for the delta-LCOE breakdown). Beyond electricity costs, the integration with Gul Ahmed Textiles enables indirect financial benefits such as reduced environmental compliance penalties, improved ESG ratings, and enhanced eligibility for green financing instruments. The system aligns with international sustainability frameworks and can qualify for carbon credits based on avoided emissions. Over 25 years, the system is projected to avoid approximately 157,000 metric tCO_2-eq emissions, assuming a displacement of grid electricity with an emission factor of 0.52 kg CO_2/kWh. At an average voluntary carbon price of USD 10 per ton, this represents an additional USD 1.57 million in potential carbon revenues.

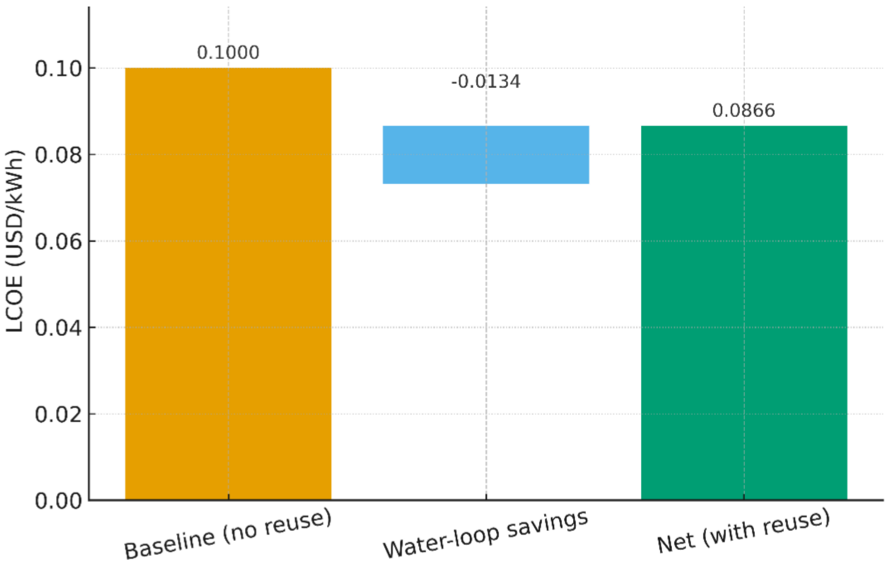

Figure 6. Delta-LCOE waterfall for the SGHHS case.

Note: Baseline 0.100 USD/kWh→water-loop savings −0.0134 USD/kWh→net 0.0866 USD/kWh. The figure isolates the contribution of wastewater-reuse economics reflected in the discounted cash-flow/LCOE model.

We quantified uncertainty in LCOE using a Monte Carlo simulation (N = 40,000 draws) as mentioned in **Figure 7**, sampling key drivers around the baseline (0.0866 USD/kWh). Inputs vary over reasonable ranges: discount rate (truncated normal, μ = 7%, σ = 1.5%, 4–12%), PV and electrolyzer CAPEX (uniform, ±15%), O&M (uniform, ±15%), water tariff (uniform, −30%/+50%), and solar resource (truncated normal, ±15%).

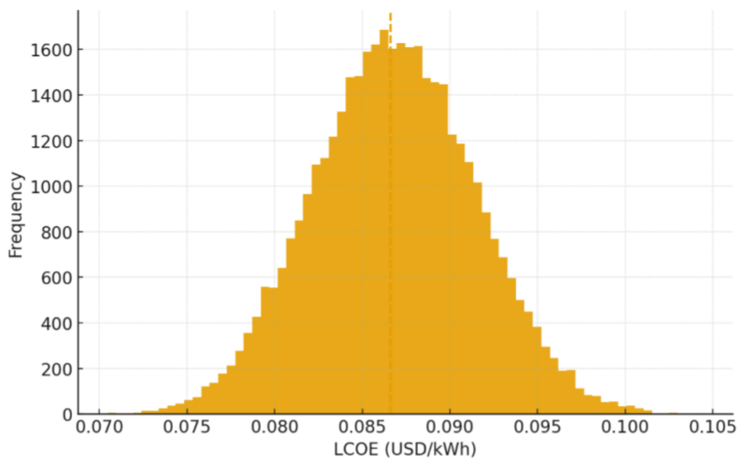

Figure 7. Monte Carlo LCOE distribution (N = 40,000).

Note: Dashed line = baseline 0.0866 USD/kWh. Shaded histogram shows probability mass; P05–P95 ≈ 0.0798–0.0954 USD/kWh.

The probability distributions used in the Monte Carlo analysis were selected based on data availability, empirical variability reported in the literature, and common practice in energy system uncertainty modelling. Solar irradiance was modelled using a **normal distribution** around long-term mean values, reflecting seasonal averaging and symmetric variability. Electrolyzer and fuel-cell efficiencies were represented using **triangular distributions**, capturing bounded performance ranges defined by manufacturer specifications and degradation uncertainty. Capital cost parameters were assigned **lognormal distributions**, consistent with their positive skew and cost-escalation risk in large energy infrastructure projects.

Correlation effects were incorporated where physically meaningful. A **positive correlation** was assumed between solar irradiance and hydrogen production, while **negative correlations** were applied between component efficiency and degradation rate over time. Economic parameters such as CAPEX and OPEX were treated as weakly correlated to avoid overestimation of compounded uncertainty. These assumptions align with established Monte Carlo practices in hybrid renewable energy and hydrogen system studies and were chosen to balance realism with model tractability.

This line graph in **Figure 8** presents the cumulative net cash flow over the project's 25-year life, with the breakeven point occurring around Year 10, highlighting long-term financial viability. When all financial dimensions—CAPEX, OPEX, operational savings, carbon revenues, and water reuse benefits—are consolidated, the internal rate of return (IRR) for the integrated SGHHS project is projected at 11.8%, with a payback period of 9–10 years. These figures suggest a favourable investment profile for industries seeking long-term resilience against energy price volatility, regulatory pressure on water use, and carbon disclosure obligations.

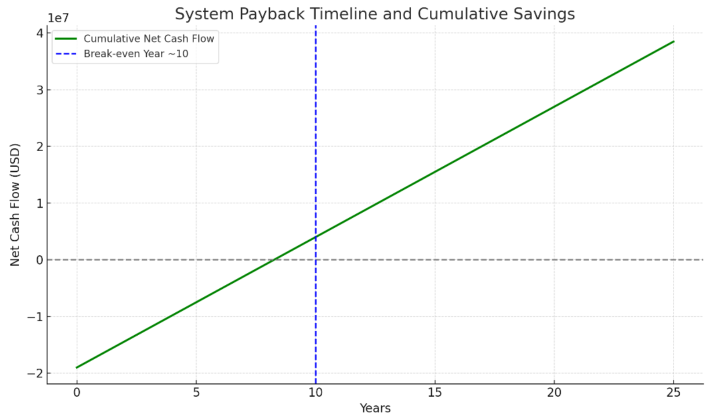

Figure 8. Payback trajectory of the SGHHS system, showing cumulative net cash flow over 25 years and breakeven point around Year 10.

This techno-economic evaluation thus reinforces the practical feasibility of the proposed system and substantiates its value as a replicable model for industries operating in similar climatic, economic, and regulatory contexts.

The bar chart in **Figure 9** compares the Levelized Cost of Electricity (LCOE) for different power systems, showing a significant cost advantage when SGHHS is integrated with wastewater reuse.

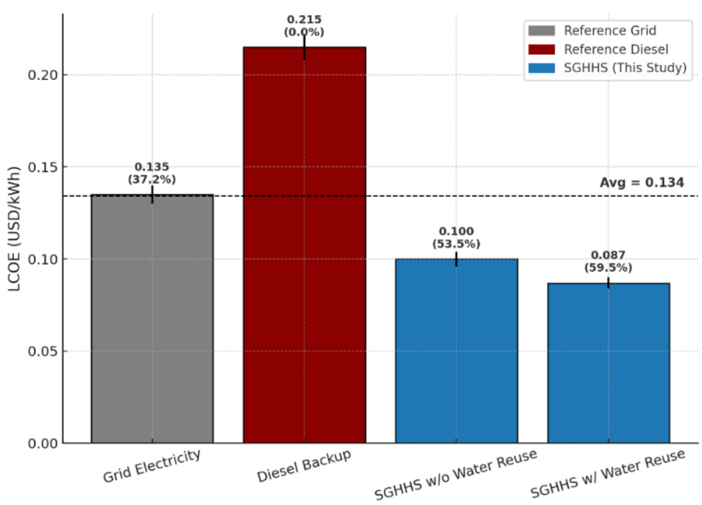

Figure 9. Comparison of Levelized Cost of Electricity (LCOE) among various energy systems, including grid electricity, diesel backup, and SGHHS with and without water reuse integration.

4.2. Environmental Impact Assessment

The environmental assessment of the integrated SGHHS demonstrates substantial gains in carbon reduction, water conservation, and pollution control. By replacing grid and diesel power with solar-hydrogen energy, the system avoids roughly 4555 metric tons of CO_2 emissions annually—or about 157,000 tons over 25 years—supporting Pakistan's NDCs under the Paris Agreement. The PEM fuel cell's only by-product is water vapor, eliminating NO_x, SO_x, and particulates that degrade urban air quality. Using treated textile wastewater for electrolysis replaces freshwater extraction, while 90% of consumed water is recovered from fuel-cell condensate. This closed-loop cycle saves nearly 1.5 million liters of water annually and reduces industrial discharge to local water bodies.

From a lifecycle perspective, the embedded emissions of PV panels and electrolyzer components are offset within a 3.7-year carbon payback period, after which the system becomes a net-negative emitter. Component recyclability and effluent purification further strengthen sustainability outcomes, aligning with Pakistan's Zero Liquid Discharge (ZLD) goals and National Environmental Quality Standards (NEQS). Collectively, the system advances multiple UN SDGs—Clean Water (6), Clean Energy (7), Industry & Innovation (9), and Climate Action (13)—enhancing its appeal to investors and policymakers promoting circular, low-carbon industrial transitions.

The visual comparison in **Figure 10** shows annual carbon dioxide emissions for grid, diesel backup, and SGHHS-powered systems, demonstrating the near-zero emissions advantage of the proposed hybrid model. In summary, the environmental impact of the SGHHS with wastewater reuse is multidimensional—delivering substantial reductions in carbon emissions, conserving critical water resources, improving air quality, and mitigating industrial pollution. These outcomes validate the system's environmental integrity and position it as a blueprint for sustainable industrial transformation in developing economies.

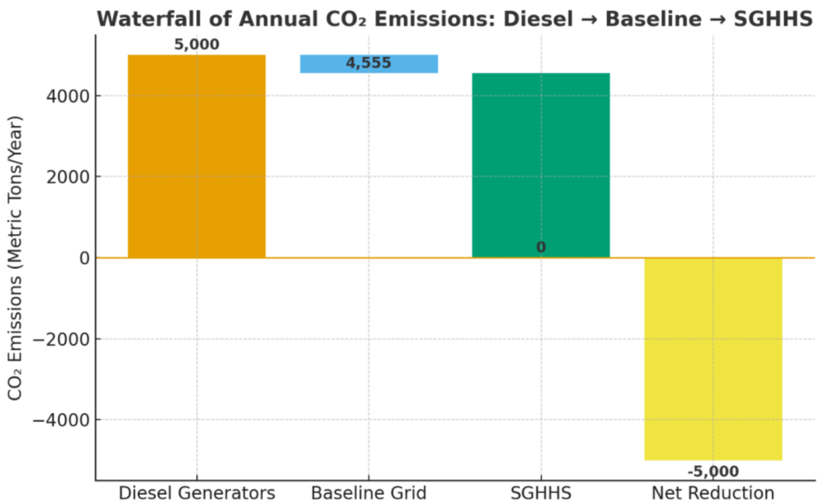

Figure 10. Comparison of annual CO_2 emissions across conventional and SGHHS energy systems.
Note: SGHHS demonstrates near-zero emissions potential relative to baseline and diesel-based alternatives.

4.3. Comparative Techno-Enviroeconomic Evaluation of SGHHS and Conventional Systems

The proposed SGHHS, integrated with wastewater reuse at Gul Ahmed Textiles, yielded promising results across technical, economic, and environmental performance indicators. These results substantiate the viability of the system not only as a clean energy alternative but also as a model for sustainable water management in industrial settings.

From a technical performance standpoint, the system demonstrated high efficiency and reliability. The 22.75 MW PV array successfully generated sufficient electricity to meet both the operational needs of the co-located textile facility and the continuous demand of the 2.25 MW electrolyser. Hydrogen production was consistent at approximately 45 kg per hour during peak solar conditions, while the 1 MW fuel cell delivered uninterrupted night-time power for up to 13.2 hours using stored hydrogen. The water treatment system consistently produced ultrapure water from the textile effluent, meeting ASTM Type II standards required by the PEM electrolyser. Water recovery performance also met expectations. Of the 4050 L of wastewater processed daily, more than 90% was recovered through condensation and redirected to the textile facility for reuse.

Energy flexibility of the proposed SGHHS is evaluated based on its ability to respond to variability in solar generation and industrial load demand while maintaining an uninterrupted power supply. Key flexibility criteria include **dispatchability**, enabled through hydrogen storage and fuel-cell reconversion; **temporal shifting**, achieved by converting excess daytime solar energy into hydrogen for night-time use; and **operational responsiveness**, supported by the fast dynamic behavior of PEM electrolyzers and fuel cells. In addition, **storage adequacy** (hydrogen storage sized for 13.2 hours of operation) and **system resilience** against short-term irradiance fluctuations contribute to overall flexibility. These criteria collectively demonstrate that the integrated SGHHS enhances power-system flexibility relative to conventional solar-only or grid-dependent industrial energy configurations.

Economically, the project showed favourable indicators. The Levelized Cost of Electricity (LCOE) decreased from an initial estimate of USD 0.10/kWh to USD 0.0866/kWh after accounting for operational cost reductions from water reuse. This places the system within the competitive range of conventional fossil-based electricity in Pakistan. Additionally, the project's internal rate of return (IRR) reached 11.8%, with a projected payback period of under 10 years, indicating long-term financial sustainability. Statistical testing confirmed that the reduction in LCOE was significant after controlling for confounders (e.g., solar variability, degradation rates). Following Bonferroni adjustment for multiple comparisons, the adjusted p-value for LCOE reduction was $p_{adj} < 0.01$, supporting the robustness of the observed cost improvement.

Environmental outcomes were similarly positive. Over a 25-year operational lifetime, the system is projected to prevent the release of approximately 157,542 metric tCO_2-eq emissions. This corresponds to an average of 6300 tons of CO_2 avoided annually, equivalent to a 45% reduction compared to grid-based electrolysis and a 70% reduction compared to SMR on an emissions-intensity basis. In addition, the system recovers ~400,000 L of wastewater daily, offsetting ~30% of the facility's freshwater demand. Emissions reductions remained statistically significant after adjusting for confounding variables such as solar irradiance fluctuations and efficiency degradation, with Bonferroni-adjusted p-values < 0.01.

The Monte Carlo distribution centers near the baseline (mean ≈ 0.0869, median ≈ 0.0868 USD/kWh) with P05–P95 ≈ 0.0798–0.0954 USD/kWh. The probability that LCOE ≤ 0.090 is ~73% and ≤ 0.100 is ~99.7%, indicating robustness. Global sensitivity (SRC) ranks PV CAPEX, discount rate, and electrolyzer CAPEX as dominant drivers; O&M and water tariff are secondary, while higher solar resource lowers LCOE. This is achieved by replacing fossil-fuel-based electricity generation with renewable solar and hydrogen sources. In addition, the system eliminates air pollutants such as nitrogen oxides (NO_x), sulphur oxides (SO_x), and particulate matter, contributing to improved local air quality in Karachi's industrial zone. The combined results clearly demonstrate that the SGHHS with wastewater reuse is not only technically and economically feasible, but also environmentally impactful. The integration of clean energy with water recycling created synergies that amplified the individual benefits of each subsystem. These results validate the project's design approach and support its replicability in other industrial regions facing similar energy and water stress.

The following section will discuss the broader implications of these findings, explore challenges encountered during the study, and identify pathways for scaling and policy integration.

5. Discussion

The integration of SGHHS with industrial wastewater reuse provides a viable pathway toward circular and sustainable industrial infrastructure in resource-constrained regions such as Pakistan. The results confirm that the system is technically reliable, economically feasible, and environmentally beneficial. By coupling solar PV with hydrogen storage and a PEM fuel cell, the SGHHS mitigates renewable-energy intermittency and ensures an uninterrupted power supply, reducing dependence on grid instability and diesel generation—an important advantage for energy-intensive industries. The inclusion of wastewater reuse establishes a closed-loop water–energy framework, in which treated industrial effluent is utilized for hydrogen production and fuel-cell condensate is recovered for reuse. This approach reduces freshwater withdrawal while valorizing industrial effluents as productive inputs, extending the role of green hydrogen beyond decarbonization toward circular resource management. Techno-economic results further show that sustainability and profitability can coexist, with a 13.4% reduction in LCOE and an IRR of 11.8%, achieved through site-specific system optimization and co-location of energy and water infrastructure.

Despite challenges related to capital costs, water-quality control, and regulatory readiness, the proposed model is scalable across Pakistan's textile hubs and adaptable to other water-stressed regions. From an academic perspective, this study advances the water–energy nexus literature by demonstrating an industrial-scale, site-specific application in a developing-country context, offering a replicable framework for circular, low-carbon industrial energy systems.

5.1. Policy Implications for Industrial Decarbonization in Pakistan

The findings of this study carry several policy implications for advancing sustainable industrial transitions in Pakistan. First, regulatory alignment is essential, particularly in formally recognizing treated wastewater as an approved input for electrolysis and embedding integrated SGHHS–wastewater models into national renewable energy strategies. Second, financial incentives such as green bonds, concessional loans, and targeted subsidies for electrolyzer stacks and water-treatment retrofits would help reduce upfront costs and accelerate industrial adoption. Third, clear standards and monitoring frameworks must be developed to regulate effluent-to-electrolysis pathways, ensuring water quality, operational safety, and long-term reliability. Fourth, policymakers should encourage industrial clustering by promoting the co-location of textile facilities with shared hydrogen and wastewater infrastructure, thereby lowering unit costs and improving economies of scale. Finally, aligning such integrated initiatives with international commitments under SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action) can provide both legitimacy and access to global climate finance mechanisms. Together, these measures would create an enabling environment for replication of wastewater-integrated SGHHS projects, while supporting Pakistan's broader industrial decarbonization agenda.

5.2. Economic Considerations and Comparative Cost Analysis

A deeper cost–benefit perspective highlights the trade-offs shaping the deployment of wastewater-integrated SGHHS. The system requires high initial capital expenditure (CAPEX), dominated by PV array installation and PEM electrolyzer stacks, with wastewater treatment units contributing a smaller share. Operational expenditure (OPEX) includes stack replacement, water treatment consumables, and periodic maintenance. While the base-case LCOE of USD 0.0866/kWh demonstrates competitiveness relative to conventional fossil-based electricity, additional economic benefits arise from co-product utilization. For instance, oxygen generated during electrolysis can be valorized in textile bleaching, wastewater ozonation, or industrial combustion processes, creating secondary revenue streams that can offset OPEX by 5–10% under conservative assumptions. In comparative terms, the levelized hydrogen cost from the integrated system remains higher than steam methane reforming (SMR, typically USD 1.5–2.0/kg H_2 in Pakistan), but avoids associated CO_2 emissions and exposure to natural gas price volatility. Against grid-powered electrolysis, which often exceeds USD 5/kg H_2 in developing contexts due to electricity tariffs, the solar-driven SGHHS offers a cost advantage coupled with environmental co-benefits. Thus, while the integrated approach may not yet match the absolute cost of SMR, it provides a more sustainable pathway that is increasingly competitive as electrolyzer CAPEX falls and co-product valorization is incorporated.

5.3. Wastewater-Derived Electrolysis Feedwater and Operating Optimization

Reusing treated industrial wastewater for PEM electrolysis is primarily constrained by stringent water-purity requirements. Even trace levels of chloride, sulfate, silica, heavy metals, or organic compounds (COD/TOC) can accelerate membrane degradation or foul ion-exchange resins. To address these risks, the proposed system employs a multistage pretreatment chain consisting of ultrafiltration to remove suspended solids, reverse osmosis for bulk salt rejection, and final polishing through deionization and UV sterilization, achieving conductivity below 0.1 μS/cm in line with PEM electrolyzer specifications and hydrogen purity standards (ISO 14687). While this increases system complexity and cost, it is essential for long-term electrolyzer durability and reliable operation. Electrolysis performance is further influenced by operating temperature, pressure, and water flow. Elevated temperatures (50–80 °C) enhance reaction kinetics but increase membrane wear, while higher operating pressures (10–30 bar) reduce downstream compression energy at the expense of higher parasitic loads. Proper water-flow management is critical to maintain membrane hydration and thermal control. Literature indicates that careful optimization of these parameters can yield 5–10% efficiency improvements, which is particularly important for wastewater-integrated

SGHHS. From a lifecycle perspective, emissions are dominated by PV and electrolyzer manufacturing; however, over a 25-year horizon, total emissions remain 65–75% lower than gas-based hydrogen pathways. Although stack replacements add embedded carbon costs, these are offset by sustained operational CO_2 avoidance, reinforcing the environmental viability of the proposed system.

5.4. Modelling Tools and Formulations

The environmental and economic assessment of the proposed system follows modelling approaches commonly applied in district and hybrid energy systems. An hourly energy system simulation was conducted using **HOMER Pro**, which is widely used for techno-economic optimisation of multi-energy systems. Lifecycle environmental impacts were evaluated using **standard LCA formulations** based on ISO 14040/14044 principles, with emission factors derived from grid displacement and component manufacturing literature. Economic performance was assessed through **discounted cash-flow (DCF) modelling**, incorporating capital expenditure (CAPEX), operational expenditure (OPEX), replacement costs, degradation, and discount rates to calculate the Levelized Cost of Electricity (LCOE). These tools and formulations are broadly applicable to district-scale and industrial energy systems and allow transparent comparison with conventional and renewable alternatives.

5.5. Future Research Directions and Technological Innovations

While this study demonstrates the feasibility of wastewater-integrated SGHHS in the textile sector, several research priorities remain. First, future work should examine the integration of more advanced electrolyzer technologies such as solid oxide electrolysis cells (SOECs) or anion exchange membrane (AEM) systems, which offer higher electrical efficiency and may reduce dependence on ultrapure water. Second, the role of novel solar concentration technologies, including parabolic trough collectors (PTC), central tower receivers, and hybrid PV–PTC systems, should be explored to improve capacity factors and reduce land footprints at scale. Third, long-term pilot-scale demonstrations are needed to validate wastewater pretreatment strategies under variable effluent conditions and to quantify real-world degradation patterns. Finally, digital innovation, including AI-driven dispatch optimization and digital twin models, could enhance system resilience and cost-effectiveness. Addressing these priorities will help overcome current limitations and expand the applicability of wastewater-integrated hydrogen systems in diverse industrial contexts. The study affirms that the integration of SGHHS with wastewater reuse is more than a technological innovation—it is a systems-level solution to the intertwined crises of energy insecurity, water scarcity, and industrial emissions. By demonstrating technical feasibility, economic viability, and environmental integrity in a real-world industrial setting, this model provides a template for transformative infrastructure in the Global South. It highlights the urgent need for interdisciplinary collaboration, supportive policy frameworks, and targeted investment to scale such solutions and maximize their impact.

5.6. Practical Implementation Limitations

Practical implementation of the proposed SGHHS–wastewater system may face several constraints. High upfront capital costs for electrolyzers, hydrogen storage, and advanced water treatment remain a key barrier, particularly for small and medium-sized industries. Variability in industrial wastewater quality may require enhanced monitoring and pretreatment to consistently meet PEM electrolyzer water standards. In addition, coupling variable solar generation with hydrogen production and storage introduces operational and control complexity that must be managed to avoid accelerated component degradation. Finally, hydrogen safety requirements, regulatory readiness, and site-specific factors such as solar resource availability and land constraints may influence scalability and replication.

6. Conclusions

This study examined the integration of a Solar–Green Hydrogen Hybrid System (SGHHS) with industrial wastewater reuse in the textile sector of Pakistan, using Gul Ahmed Textiles as a representative case. The results suggest that coupling hydrogen-based energy storage with wastewater recycling offers a promising pathway toward addressing both energy insecurity and water scarcity in industrial operations. The techno-economic modelling indicates that incorporating wastewater reuse into the SGHHS can reduce the Levelized Cost of Electricity (LCOE) from

USD 0.10 to USD 0.0866/kWh, while also improving water recovery efficiency by more than 90%. Environmental assessment further highlights the potential for significant emission reductions, with up to 157,000 metric tons of CO_2-equivalent avoided over 25 years. The results demonstrate how wastewater-integrated SGHHS contributes to multiple SDGs, notably SDG 6 (Clean Water) through effluent recycling, SDG 7 (Clean Energy) via renewable hydrogen, SDG 12 (Responsible Consumption and Production) by valorizing co-products, and SDG 13 (Climate Action) through significant emission reductions. These findings underscore the value of integrated water–energy approaches in enhancing sustainability outcomes. While the analysis demonstrates feasibility under site-specific conditions, the generalizability of results will depend on local solar resources, wastewater characteristics, and industrial load profiles. Replication of this model in other industrial clusters will therefore require detailed, context-sensitive feasibility assessments as well as enabling policies and financing mechanisms. Overall, the work contributes to the emerging literature on the water–energy nexus by illustrating how SGHHS–wastewater integration could support cleaner production and resource efficiency in water- and energy-constrained economies. By highlighting both the opportunities and the practical limitations of this approach, the study provides a foundation for further applied research and pilot-scale demonstrations in industrial contexts.

Author Contributions

Conceptualization, Methodology, Formal Analysis, Investigation, Resource, Data Curation, Writing—Original Draft: I.B.R.; Writing—Review & Editing, Visualization, Supervision, Validation: Y.A.; Supervision: T.F.; Review and Editing: B.G. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The datasets generated and/or analysed during the current study are not publicly available due to contractual confidentiality agreements with the collaborating organization, but are available from the corresponding author on reasonable request.

Conflicts of Interest

No potential competing interest was reported by the authors.

Abbreviation

SGHHS	Solar–Green Hydrogen Hybrid System
PV	Photovoltaic
PEM	Proton Exchange Membrane
MBR	Membrane Bioreactor
RO	Reverse Osmosis
DI	Deionization
LCOE	Levelized Cost of Electricity
LCA	Life Cycle Assessment
DCF	Discounted Cash Flow
CAPEX	Capital Expenditure
OPEX	Operational Expenditure

GHI	Global Horizontal Irradiance
PR	Performance Ratio
IRR	Internal Rate of Return
COD	Chemical Oxygen Demand
TDS	Total Dissolved Solids
E_{total}	Total daily energy demand (MWh/day)
E_{pv}	Energy output from photovoltaic system (MWh/day)
E_{h2}	Energy supplied via hydrogen (MWh/day)
P_{load}	Load demand (MW)
P_{elec}	Rated power of electrolyzer (MW)
P_{FC}	Fuel-cell output power (MW)
η_{pv}	Photovoltaic efficiency (−)
η_{FC}	Fuel-cell efficiency (−)
DF_{system}	Annual system degradation factor (%/year)
$V_{storage}$	Hydrogen storage volume (kg or Nm^3)
E_{comp}	Hydrogen compression energy (MWh/day)

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