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(REVIEW ARTICLE)

Hybrid renewable-hydrogen systems for industrial decarbonization

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Abstract

Hard-to-abate industrial sectors like steel, cement, chemicals, and petroleum refining sectors account for 30% of CO_2 emissions worldwide, thereby challenging climate ambitions. This review paper critically assesses the contribution of hybrid renewable-hydrogen systems and technology architectures integrating renewable energy sources such as solar, wind, hydro, geothermal energy systems, coulpled with hydrogen generation and storage, in facilitating deep decarbonization of these industries. Evidence from flagship projects like Shell's 10 MW Refhyne project and Sweden's H2 Green Steel illustrates emission reductions of 95% using integrated wind-solar-electrolyzer systems. Modelled research indicates that hybrid systems can be cost-competitive with a levelized cost of hydrogen (LCOH) under $2/kg by 2030, rendering green hydrogen economically viable. The review synthesizes more than 10 case studies and 15 techno-economic models with a focus on system architectures, energy flows, electrolyzer utilization, and sectoral applications. Challenges such as high capital intensity, intermittency, and regulatory gaps are also discussed, with strategic suggestions for scaling deployment through hydrogen hubs, AI-driven control systems, and next-generation electrolyzer technologies. Hybrid renewable-hydrogen systems overall, offer a promising solution to minimize emissions, increase industrial resilience, and meet energy transition goals concurrently.

Keywords: Green Hydrogen; Hybrid Renewable Energy; Industrial Decarbonization; Electrolyzer Integration; Levelized Cost of Hydrogen (LCOH)

1. Introduction

The global energy landscape is undergoing a pivotal transformation driven by the urgent need to combat climate change and reduce the environmental footprint of industrial activities. Among the most challenging contributors to global greenhouse gas (GHG) emissions are energy-intensive industries such as steelmaking, cement production, chemical manufacturing, and petroleum refining. These sectors are responsible for approximately 30% of global CO_2 emissions and are often referred to as “hard-to-abate” due to their dependence on high-temperature heat and fossil-based feedstocks [1]. Traditional decarbonization pathways, such as direct electrification, are often insufficient or impractical for these applications due to process-specific energy demands, operational constraints, and infrastructure limitations. In this context, hydrogen has emerged as a clean and flexible energy carrier capable of decarbonizing industrial processes. When produced from fossil fuels (grey hydrogen), hydrogen contributes to emissions [2]. However, green hydrogen, derived from water electrolysis powered by renewable energy sources, offers a carbon-free solution. Green hydrogen can serve as both a combustion fuel for high-temperature heat and as a chemical feedstock for industrial

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synthesis, enabling the replacement of conventional fossil-based methods in a variety of applications. Moreover, hydrogen can be stored and transported across time and space, making it a valuable energy vector for managing the intermittency associated with renewable power generation [3]. While green hydrogen has significant promise, the full realization of its potential is contingent on the integration of renewable energy systems that can supply the necessary electricity for electrolyzers at a sufficient scale and reliability. This has led to the emergence of hybrid renewable-hydrogen systems technological configurations that combine renewable energy (solar, wind, hydropower, or geothermal) with hydrogen production, storage, and utilization. These hybrid systems offer the ability to generate and store clean energy, decouple supply from demand, and supply multiple energy services (electricity, heat, and fuels) with a low carbon footprint. Recent flagship projects demonstrate the viability of such systems [4]. For instance, Shell's Refhyne project in Germany employs a 10 MW PEM electrolyzer powered by renewables to supply hydrogen for refinery operations [5]. Similarly, the H2 Green Steel project in Sweden is deploying integrated wind-powered electrolyzers for decarbonized steel production [6]. These examples illustrate how the integration of renewables and hydrogen can support the transition of industrial operations toward net-zero emissions. Furthermore, declining costs of renewable power and electrolyzers are making these systems increasingly competitive, with projected levelized costs of hydrogen (LCOH) falling below $2/kg by 2030 in favorable regions [7]. This review paper aims to provide a comprehensive assessment of hybrid renewable-hydrogen energy systems for industrial decarbonization. The core objectives include: Examining the role of hydrogen in industrial transformation; Reviewing renewable sources compatible with hydrogen production; Analyzing hybrid system architectures, energy flows, and storage dynamics; Highlighting sector-specific applications and real-world case studies; Identifying key technical, economic, and policy challenges; and Proposing future directions for research, deployment, and scalability. By bridging insights from energy engineering, industrial ecology, and sustainability science, this review seeks to inform stakeholders and accelerate the development of innovative pathways for low-carbon industrial growth.

2. Overview of Hydrogen as a Clean Energy Vector

Hydrogen is the most abundant element in the universe, yet it does not exist freely in nature and must be extracted from compounds such as water or hydrocarbons. Due to its high energy content (120 MJ/kg) and zero-emission combustion, hydrogen has gained prominence as a strategic energy carrier in the global transition to sustainable energy systems. Its application spans power generation, transportation, heating, and most critically, industrial processes that require high-temperature energy or serve as feedstock pathways [8].

2.1. Classification of Hydrogen Based on Production

Hydrogen is categorized based on its production source and associated carbon emissions: Grey Hydrogen: Produced from fossil fuels, primarily via steam methane reforming (SMR). It accounts for over 95% of today's hydrogen supply and emits around 9–12 kg of CO_2 per kg of H_2 [9]. Blue Hydrogen: Produced similarly to grey hydrogen but coupled with carbon capture, utilization, and storage (CCUS). Emissions are lower but still non-zero, and life-cycle sustainability depends heavily on capture rates and methane leakage [10]. Green Hydrogen: Generated through electrolysis of water using electricity from renewable sources such as solar, wind, or hydro. This is considered truly carbon-free hydrogen, though currently less than 1% of global hydrogen is produced this way [11]. Turquoise, Pink, and White Hydrogen: Emerging variants include turquoise hydrogen (methane pyrolysis without CO_2), pink hydrogen (nuclear-powered electrolysis), and white hydrogen (naturally occurring geological hydrogen). The production pathway influences both the carbon intensity and the economic viability of hydrogen use in industrial systems [12].

2.2. Key Properties of Hydrogen for Industrial Use

Hydrogen is uniquely suited to decarbonize industrial applications due to the following attributes: High gravimetric energy density, enabling use in energy-intensive applications like steelmaking and chemical synthesis.Combustion at high flame temperatures (over 2000°C), essential for industries such as glass, ceramics, and cement manufacturing. Feedstock compatibility, especially in sectors like ammonia production and petroleum refining. Molecular compatibility with emerging energy carriers such as ammonia and synthetic fuels. Storage and transport flexibility, although challenges remain regarding volumetric density, compression energy, and material compatibility. Despite these advantages, hydrogen faces significant hurdles ; Storage and transport require specialized infrastructure (e.g., high-pressure tanks, pipelines, cryogenic vessels). Energy inefficiency: Electrolysis has conversion losses (~60–70% efficiency), and further losses occur in compression, storage, and end-use.Safety concerns, particularly related to flammability and embrittlement effects on materials [13, 14, 15].

2.3. Hydrogen in Industrial Applications

Today, hydrogen is primarily used in: Oil refining (hydrotreating, hydrocracking), Fertilizer production (ammonia via the Haber-Bosch process), Methanol and synthetic chemical production, Semiconductor and electronics manufacturing. In a decarbonized future, green hydrogen will enable: Hydrogen-based steelmaking (Direct Reduced Iron or DRI), Hydrogen-fueled high-temperature kilns in cement and ceramics, Chemical recycling of plastics and synthetic fuel production, Grid balancing and seasonal energy storage via hydrogen energy storage systems (HESS). The integration of renewables with hydrogen production creates a pathway to provide both clean fuel and process feedstock, enabling deep decarbonization across the industrial sector [16, 15, 17].

3. Renewable Energy Sources for Hydrogen Production

The global shift toward a carbon-neutral future necessitates the development of low-emission hydrogen production technologies. Among the most sustainable methods is electrolysis, where water is split into hydrogen and oxygen using electricity. The carbon intensity of this process depends entirely on the source of electricity. When powered by renewable energy, electrolysis yields green hydrogen, a crucial element in industrial decarbonization. This section discusses the primary renewable energy sources; solar, wind, hydropower, geothermal, and biomass, that can be harnessed for hydrogen production. Each source offers unique advantages and limitations with respect to efficiency, intermittency, geographic suitability, and cost-effectiveness [18].

3.1. Solar Energy

Solar energy, particularly in the form of photovoltaic (PV) and concentrated solar power (CSP) technologies, is a widely available and scalable source for producing green hydrogen.

3.1.1. Photovoltaic Systems

Solar PV systems convert sunlight directly into electricity using semiconductor materials. This electricity can then power electrolyzers (such as proton exchange membrane (PEM) or alkaline electrolyzers) to produce hydrogen. PV systems are relatively simple to deploy, scalable from kilowatt to gigawatt levels, and increasingly cost-competitive. The International Renewable Energy Agency (IRENA) estimates that global solar PV costs have dropped by over 85% between 2010 and 2020. In regions with high solar irradiance, such as the Middle East, Africa, Australia, and parts of South America, PV-powered hydrogen production offers significant potential. For instance, the NEOM green hydrogen project in Saudi Arabia will utilize 4 GW of solar and wind power to produce 650 tons of hydrogen per day by 2026. However, the intermittency of solar energy (day-night cycles, weather variability) necessitates the use of hydrogen storage, battery buffering, or hybrid systems combining multiple energy inputs for stable operation [19, 20].

3.1.2. Concentrated Solar Power (CSP)

Unlike PV, CSP systems use mirrors or lenses to focus sunlight onto a central receiver, generating high-temperature heat (400–1000°C). This heat can be converted into electricity via steam turbines or used directly in high-temperature electrolysis or thermochemical water splitting. CSP is especially relevant for industrial applications requiring process heat, and it allows for thermal energy storage using molten salts or phase change materials, improving dispatchability. Pilot projects in Spain and Morocco have demonstrated the feasibility of CSP-driven hydrogen production, though CSP remains more capital-intensive than PV [21, 22].

3.2. Wind Energy

Wind energy is another abundant and mature renewable source used in hydrogen production. Onshore and offshore wind farms generate electricity that can be directly fed into electrolyzers. Unlike solar, wind energy can be available during night hours or cloudy conditions, complementing PV production. The cost of wind power has also declined sharply in the last decade, with onshore wind reaching global average LCOE (Levelized Cost of Electricity) of around $0.03–$0.06/kWh and offshore wind approaching $0.08–$0.13/kWh, depending on location and technology maturity. One notable example is the H2 Green Steel project in Sweden, which plans to integrate onshore wind power with electrolyzers to supply green hydrogen for steel production via the direct reduced iron (DRI) route. Additionally, countries with strong wind resources such as Germany, Denmark, and the UK are investing heavily in offshore wind-to-hydrogen conversion systems, where electrolyzers may be placed on floating platforms or near coastal substations. Wind's primary limitation is its variability and geographic dependency. Remote wind farms may require long-distance transmission or power-to-gas (P2G) conversion to transport energy as hydrogen [23, 20].

3.3. Hydropower

Hydropower provides stable and dispatchable electricity, making it an ideal power source for electrolyzers, especially in countries with mature hydropower infrastructure like Norway, Canada, Brazil, and China. Hydrogen production using hydroelectricity avoids the intermittency challenges faced by solar and wind, enabling continuous operation of electrolysis units and improving capacity factors. In Norway, for example, abundant hydropower allows for cost-effective green hydrogen production, which is being used in maritime applications, such as hydrogen-powered ferries. However, hydropower expansion is geographically constrained by topography and water availability, and large-scale projects may face environmental and social challenges (e.g., land submersion, biodiversity loss, and community displacement). Additionally, climate change-induced water variability may affect hydropower reliability in the future, which could in turn impact hydrogen production capacity in water-scarce regions [24, 25].

3.4. Geothermal Energy

Geothermal energy harnesses the Earth's internal heat to generate electricity or supply direct heat. It is highly reliable, operating at capacity factors above 85%, and provides a continuous, base-load renewable energy source. In hydrogen production, geothermal electricity can power conventional electrolysis, while geothermal heat can support high-temperature steam electrolysis (HTSE), which is more energy-efficient than low-temperature electrolysis. For example, solid oxide electrolyzer cells (SOECs) operating at 600–1000°C can achieve higher conversion efficiencies above 80% when driven by geothermal heat. Iceland has experimented with geothermal-powered electrolysis using its abundant volcanic energy to produce hydrogen for fuel cell vehicles and potential export. The integration of geothermal energy and hydrogen production is particularly promising in volcanic regions such as East Africa, Indonesia, and parts of Latin America. Challenges include high initial drilling costs and site-specific feasibility, though co-production from existing oil and gas wells (e.g., in California and Oman) is being explored to reduce exploration risks and leverage existing infrastructure [24, 26].

3.5. Biomass and Biogas

Biomass-derived energy offers another pathway to renewable hydrogen. Methods such as: Thermochemical conversion (gasification), Biological conversion (anaerobic digestion), Biomass reforming, can yield hydrogen with potentially negative carbon intensity when coupled with carbon capture and storage (CCS) referred to as biohydrogen. While not used in electrolysis, biomass-based systems serve as complementary hybrid partners to renewables, especially in off-grid or rural settings. For instance, hybrid solar-biomass electrolyzer systems can supply decentralized hydrogen in agricultural zones. Limitations include land use competition, feedstock logistics, and lower energy conversion efficiency compared to wind or solar. However, waste-to-hydrogen systems using agricultural residues or municipal waste hold significant potential for circular economy integration [27, 28].

3.6. Hybrid Renewable Configurations

To overcome the limitations of individual sources, hybrid systems that combine solar, wind, hydro, or geothermal inputs offer enhanced flexibility, reliability, and cost efficiency. Examples include: Solar + Wind: Complementary generation profiles help maintain electrolyzer utilization. Solar + Geothermal: CSP and geothermal heat can feed HTSE for round-the-clock hydrogen production. Hydro + PV: Used in Latin America to balance seasonal water flow with solar peaks.Wind + Battery + Hydrogen Storage: Used to buffer short-term and long-term fluctuations in remote grids. Such systems are already being deployed in pilot projects, and advanced modeling tools are helping optimize their configuration based on local resource availability, electrolyzer sizing, and hydrogen demand profiles.

3.7. Key Considerations in Source Selection

Resource availability: Site-specific solar insolation, wind speeds, geothermal gradients, and water resources determine feasibility. Energy price and LCOE: Cost-effective electricity is essential to reduce LCOH. Infrastructure readiness: Grid access, land availability, and electrolyzer compatibility influence deployment speed. Environmental impact: Land use, water consumption, and ecological disruption should be minimized. Renewable energy sources offer the backbone of green hydrogen production, with each contributing unique advantages and technical constraints. Solar and wind dominate early deployments due to cost competitiveness, while geothermal and hydro offer valuable stability. The future lies in hybridized systems that leverage multiple renewable sources to optimize electrolyzer operation and minimize intermittency. As costs continue to decline and technologies mature, renewable-powered hydrogen will become a scalable and essential pillar of global industrial decarbonization.

4. Hybrid Renewable-Hydrogen System Configurations

The successful deployment of green hydrogen for industrial decarbonization hinges not only on the availability of renewable energy but also on how well that energy is integrated into the hydrogen value chain. Single-source systems, those powered solely by solar, wind, hydro, or geothermal face inherent limitations, particularly due to the intermittency and variability of renewable sources. To overcome these constraints and enhance system performance, researchers and engineers are increasingly developing hybrid renewable-hydrogen system configurations that synergize multiple energy inputs, storage methods, and energy services. This section provides a comprehensive examination of the design architectures, integration strategies, and operational considerations for hybrid renewable-hydrogen energy systems. It also discusses their roles in supplying continuous power, supporting hydrogen production, and delivering heat and fuel to industrial sectors.

4.1. Concept and Components of Hybrid Systems

A hybrid renewable-hydrogen system typically combines two or more renewable energy sources such as solar photovoltaic (PV), wind turbines, concentrated solar power (CSP), hydropower, or geothermal energy to generate electricity. This electricity is used in: Electrolyzers (e.g., PEM, alkaline, or solid oxide) to produce hydrogen; Battery energy storage systems (BESS) or thermal storage to balance supply and demand; Industrial loads that consume electricity, hydrogen, or heat. Key components of a typical hybrid system include: Renewable generation units (PV panels, wind turbines, etc.); Electrolyzer units (to produce H_2 from water); Hydrogen storage (compressed, liquefied, or in solid carriers); Power conditioning systems (inverters, converters, control systems); Energy management systems (EMS) for optimizing dispatch, storage, and demand matching; Industrial process integration modules (heating systems, furnaces, fuel cells, etc.). The goal is to maximize the utilization of renewable electricity, minimize curtailment, ensure stable hydrogen production, and deliver reliable energy for industrial use.

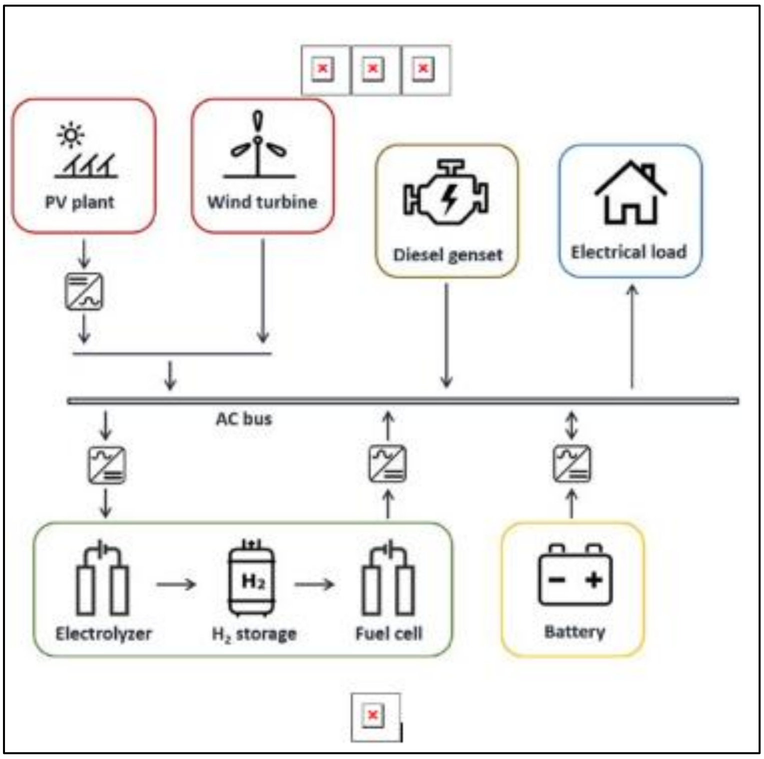

Figure 1 Generic Illustration of hybrid renewable energy system [60]

4.2. System Architecture Variants

Hybrid systems vary widely depending on their application and local resource conditions. Common architectures include:

4.2.1. Solar-Wind-Hydrogen Systems

In many regions, solar and wind resources exhibit complementary generation patterns, solar peaks during the day and summer, while wind is stronger at night and during cooler seasons. Combining these inputs enables higher electrolyzer utilization rates. Case Study: The H2RES project in Denmark uses offshore wind and onshore solar PV to power a 1.25 MW PEM electrolyzer. The hybrid system produces hydrogen for buses and fuel cell vehicles while balancing the local grid [29].

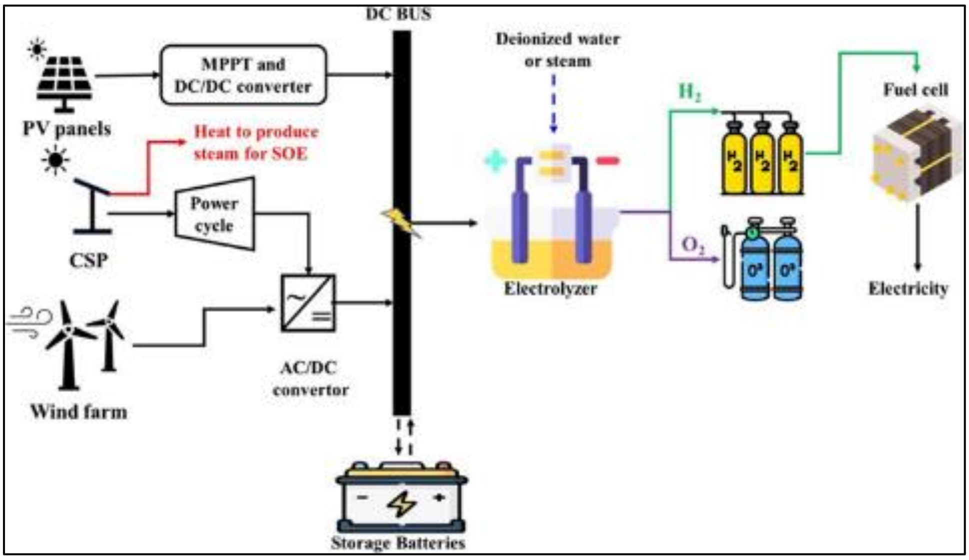

Figure 2 Schematic of solar-wind hydrogen production system [61]

4.2.2. Solar-Geothermal-Hydrogen Systems

This configuration leverages solar thermal or PV for peak-time electricity and geothermal heat for base-load hydrogen production via high-temperature steam electrolysis (HTSE). Geothermal can also provide backup during low solar availability. Case Study: A model by [30] demonstrated a solar-boosted geothermal flash cycle for combined electricity, desalinated water, and hydrogen production, achieving an exergetic efficiency of 21.9% and a payback period of 4.74 years.

4.2.3. Hydro-Solar Hybrid Systems

Hydropower provides stable generation while solar compensates during dry or high-demand periods. These systems are particularly effective in countries with abundant rivers and sunlight. Case Study: In Brazil, hydro-solar integration is being tested to power large-scale electrolyzers, reducing reliance on fossil-fired peaker plants [31].

4.2.4. Hybrid Systems with Energy Storage

Battery storage or thermal storage is often incorporated to buffer intermittent sources, smooth load profiles, and maintain stable electrolyzer operation. Design Consideration: Electrolyzers are capital-intensive and operate best under steady power supply. Fluctuations from renewables can reduce efficiency and lifespan, hence storage smoothens the power input curve [32].

4.2.5. Multi-Vector Hybrid Systems

These combine hydrogen production, electricity generation, process heat, and by-product services like desalinated water or cooling. Often called polygeneration systems, they maximize energy efficiency and economic return. Example: Dong et al. (2023) proposed a heat recovery-based thermal design for a solar thermal-driven multigeneration scheme, generating 1.2 MW of electricity, 460 kW of cooling, 33 kg/s of desalinated water, and 9.7 kg/h of hydrogen [33].

4.3. Integration Strategies and Control Systems

The performance of hybrid systems depends heavily on energy management strategies and real-time control. Key elements include: Load forecasting: Predicting renewable output and hydrogen demand enables preemptive dispatch decisions. Peak shaving and load shifting: Hydrogen storage and BESS help shift energy use to low-cost periods. Smart controls: AI-optimized controllers or fuzzy logic systems adjust power flow dynamically to balance inputs and outputs. Dynamic sizing: Modular electrolyzers and scalable storage allow systems to grow with demand or integrate seasonal strategies. Advanced control systems help maximize electrolyzer efficiency, prevent overload, and ensure seamless integration with industrial processes.

Table 1 Key Research Insights on Hybrid Renewable-Hydrogen Energy Systems for Industrial Decarbonization

Paper Reference	Objectives	Results	Findings	Practical Implications
[34]	Establish HYRES framework for industrial utility systems. Discuss renewable energy technologies and their integration.	Establishes the HYRES framework for industrial utility systems. Highlights need for better control and localized integration.	Establishes HYRES framework for renewable energy integration. Highlights need for improved control and reliability approaches.	Need for better control and reliability approaches. Focus on localized integration of renewable energy.
[35]	Develop a renewable-based hydrogen and power supply facility (HPSF). Optimize configuration for industrial hydrogen and electrical loads.	Hybrid storage improves sustainability-weighted ROI by 4%/yr. Single-battery system offers 0.7%/yr higher ROI.	Hybrid storage improves sustainability-weighted ROI by 4%/yr. Single-battery system offers 0.7%/yr higher ROI.	Enhances sustainability and reliability of renewable energy supplies. Provides insights for integrating hydrogen production in industrial symbiosis.
[36]	Determine optimal technical characteristics of SMR/H2 system. Estimate potential environmental benefits and CO2 emission reductions.	Achieves LCOE between EUR 0.046/kWh and EUR 0.052/kWh. Reduces carbon emissions by over 5 million tons annually.	Techno-economic feasibility of SMR and hydrogen production system. Potential CO2 emissions reduction over 5 million tons annually.	Establishes a hydrogen economy on Crete through SMR systems. Reduces CO2 emissions by over 5 million tons annually.
[37]	Review hydrogen production methods and energy management strategies. Examine control strategy for hydrogen-based hybrid microgrid integration.	The results provide a roadmap for developing HHMG systems with HSS. The parameters of the HHMG are represented in Appendix A.	Analyzed hydrogen production and storage methods in hybrid microgrids. Developed control strategy for integrating renewable energy sources effectively.	Technology for hydrogen and fuel cells has advanced significantly in the past 15 years. Policymakers recognize the potential of hydrogen and fuel cells for sustainable development.
[38]	Evaluate solar energy for industrial heating decarbonization. Optimize configurations for cost and emissions reductions.	The optimized compact parabolic trough system reduced CO2 emissions by 45% compared to the base gas-only system. The photovoltaic solution resulted in higher cost than the	Optimized solar heat reduces CO2 emissions by 45%. Photovoltaics have higher costs than solar heat solutions.	Reduces CO2 emissions in industrial heating using solar energy. Decreases dependence on gas transmission networks.

		compact parabolic trough solution.		
[39]	Develop a techno-economic model for hydrogen storage systems. Minimise costs and emissions under economic uncertainties.	Total cost minimised for three energy configurations evaluated. Levelised cost of energy ranges from 0.0702 to 0.1125 $/kWh.	Hydrogen from renewables offers clean mobility and backup storage. Robust optimisation minimizes costs and carbon emissions effectively.	Affordable hydrogen and electricity prices achieved. Minimisation of carbon emissions and excess energy export.
[40]	Determine cost-effective green hydrogen production strategies. Analyze various scenarios and technologies for feasibility.	Minimum cost of $3.01 per kg of green hydrogen. Internal rate of return (IRR) of 5.04%.	Hybrid system yields $3.01/kg green hydrogen cost. Solar thermal with ORC shows future potential for waste heat recovery.	Cost-effective green hydrogen production supports sustainable energy transition. Hybrid systems can minimize production costs significantly.
[41]	Electrify endothermic processes for hydrogen recovery from ammonia. Integrate renewable power with manufacturing for decarbonization.	Demonstrated technical feasibility of electrified ammonia decomposition reactors. Enabled hydrogen storage and transportation while decarbonizing production.	Electrified reactors enable renewable integration for ammonia decomposition. Decarbonizes hydrogen production while maintaining process integrity.	Enables decarbonized hydrogen production from ammonia decomposition. Integrates renewable energy with manufacturing processes efficiently.
[42]	Analyze hydrogen generation from solar and wind energy sources. Assess challenges and opportunities for commercial-scale deployment.	Hydrogen production from solar and wind energy sources Potential applications and barriers to commercial development	Hydrogen production from solar and wind is promising. Identified challenges and opportunities for commercial-scale deployment.	Green hydrogen production can address energy crises and environmental issues. Solar-wind-based hydrogen production systems have potential for commercial development.
[43]	Examine state of green hydrogen research and production technologies. Analyze integration of GH2 into renewable energy systems.	GH2 can decarbonize energy systems and industries. Economic analyses predict cost parity with fossil fuels by 2030.	Green hydrogen can decarbonize energy systems effectively. Challenges include high costs and infrastructure limitations.	GH2 can decarbonize energy-intensive sectors effectively. Addressing challenges accelerates transition to carbon-neutral systems.

Table 2 Summary of Case Studies Demonstrating Successful Hybrid Renewable-Hydrogen and EOR Applications

Case Study / Project	Technology Type	Key Achievements / Results	Region	Paper Reference
GlassPoint Miraah Project (Oman)	Solar thermal EOR using parabolic troughs	Generated over 1,000 MW^g steam; reduced natural gas consumption; up to 80% CO_2 emissions cut during peak solar periods	Oman	[44]
San Joaquin Valley (California)	Geothermal EOR using co-produced fluids	Lowered emissions and operational costs in mature fields; direct heat from geothermal fluids used in CSS	USA	[45]
Solar-boosted Geothermal Flash Cycle (Model Study)	Hybrid solar-geothermal EOR + desalination	Achieved 28.46 kg/s desalinated water, 21.9% exergetic efficiency, 4.74-year payback	China	[46]
Steel Plant Green Hydrogen Integration (H2GreenSteel)	Solar + wind + PEM electrolyzer	Projected to produce 5 million tons of CO_2-free steel; reduces emissions by >90% compared to blast furnace	Sweden	[47]
Hybrid Solar-Hydrogen System Optimization Study	Solar PV + Electrolysis + Fick's Law optimization	CO_2 reduced to 0.147 gCO_2eq/kWh; achieved 80% renewable integration; optimized cost: $57,539.85/year	Algeria	[48]
EGS with Intermittent Thermal Extraction (ITE)	Enhanced geothermal system (EGS)	Extended lifespan by 17.7 years; 13.1% increase in clean power generation vs continuous methods	China	[49]
Multigeneration Solar-Thermal System	Solar thermal + ORC + hydrogen + desalination	Generated 1.2 MW electricity, 460 kW cooling, 33 kg/s water, 9.7 kg/h hydrogen; cut CO_2 by 254 kg/h	UAE	[50]

4.4. Benefits of Hybrid Configurations

Hybrid renewable-hydrogen systems offer several key advantages: Higher system reliability and resilience: Redundant energy sources reduce risk of outages or production dips. Increased electrolyzer utilization: Continuous power availability improves asset returns. Cost savings: Optimized dispatch and reduced curtailment lower operational costs. Emission reduction: Integrated systems can approach near-zero CO_2 emissions, especially when waste heat is recovered. Energy security: Systems can operate off-grid or reduce dependence on imported fossil fuels. In industrial contexts, these benefits translate to process continuity, lower fuel costs, and compliance with emission regulations or carbon pricing mechanisms.

4.5. Challenges and Technical Barriers

Despite their promise, hybrid renewable-hydrogen systems face significant hurdles: Capital intensity: High upfront costs for electrolyzers, renewable infrastructure, and storage make projects economically challenging without subsidies or long-term contracts. System complexity: Coordinating multiple inputs, outputs, and storage units requires advanced modeling and monitoring capabilities. Interoperability: Integration into existing industrial processes demands compatibility in pressure, purity, and energy form (gas, heat, electricity). Location constraints: Optimal resource sites may not align with industrial demand centers, raising transport and conversion issues. Regulatory uncertainty: Lack of clear incentives, hydrogen standards, and permitting processes can delay deployment.

4.6. Optimization and Techno-Economic Modeling

System designers increasingly rely on multi-objective optimization models to assess configuration trade-offs. These models consider: Levelized Cost of Hydrogen (LCOH); Electrolyzer efficiency and degradation rates; Energy storage and dispatch schedules; System lifetime and maintenance requirements; Carbon savings vs. fossil-based baselines. Software tools like HOMER, TRNSYS, MATLAB-Simulink, and Aspen Plus are used for simulation and optimization. Recent studies using Fick's law-based algorithms have demonstrated optimal system sizing to reduce annualized cost and CO_2 emissions, such as Messini et al. (2024) achieving an LCOH below $2/kg with 80% renewable integration.

4.7. Industrial Case Applications

Hybrid renewable-hydrogen systems are being applied across sectors: Refineries: Green hydrogen replaces grey hydrogen for hydrocracking (e.g., Shell's Refhyne). Steel production: Integrated DRI systems use wind-solar hydrogen for iron reduction (e.g., H2 Green Steel). Desalination plants: Solar-hydrogen systems power water treatment with minimal emissions. Remote mining: Solar-geothermal-hydrogen systems ensure 24/7 power and fuel supply off-grid. These cases illustrate the scalability and adaptability of hybrid configurations across energy-intensive industries. Hybrid renewable-hydrogen systems represent a vital evolution in clean energy integration for industrial decarbonization. By combining the strengths of diverse renewable sources and coupling them with flexible hydrogen production and storage, these systems address intermittency, optimize efficiency, and provide continuous energy services for complex industrial demands. While technical and economic barriers remain, continued innovation, supportive policy frameworks, and falling renewable and electrolyzer costs are expected to accelerate the uptake of hybrid systems in global industry.

5. Applications of Hybrid Renewable-Hydrogen Systems in Industry

Hybrid renewable-hydrogen systems have the transformative potential to decarbonize multiple sectors of industry, particularly those classified as hard-to-abate, where direct electrification is difficult due to high-temperature processes, reliance on carbon-based feedstocks, or inflexible legacy infrastructure. These systems integrate renewable energy sources with hydrogen production, storage, and delivery to provide clean fuel, heat, and feedstocks essential for industrial operations. This section explores key industrial sectors where hybrid renewable-hydrogen systems are being applied or studied, highlighting technical integration strategies, performance outcomes, and sector-specific benefits. It also presents real-world case studies and identifies opportunities for broader deployment.

5.1. Oil and Gas Industry

The oil and gas sector both produces and consumes hydrogen extensively, particularly for refining operations such as hydrotreating, hydrocracking, and desulfurization. Traditionally, these processes rely on grey hydrogen derived from steam methane reforming (SMR), resulting in significant carbon emissions, approximately 9–12 kg CO_2 per kg of H_2 produced. Hybrid renewable-hydrogen systems can decarbonize this sector by: Replacing grey hydrogen with green hydrogen produced using solar, wind, or geothermal energy; Supplying steam or process heat via solar thermal or geothermal systems; Powering off-grid or remote field operations with hybrid microgrids.

5.2. Case Example

Shell's Refhyne Project in Germany: A 10 MW PEM electrolyzer powered by wind and solar generates green hydrogen for the Rheinland refinery, reducing emissions by ~10,000 tonnes/year [51].

GlassPoint Solar in Oman: Uses enclosed parabolic troughs to supply 1,021 MW^g of solar steam for enhanced oil recovery (EOR), reducing natural gas use and cutting GHG emissions by up to 80% during solar peak hours [52].

The integration of hydrogen into enhanced oil recovery (EOR) through solar and geothermal-powered steam generation is gaining traction. Abandoned wells in geothermal zones are being repurposed for co-producing geothermal heat, reducing costs and emissions in heavy oil fields.

5.3. Steel Manufacturing

Steel production is one of the largest industrial emitters of CO_2, accounting for approximately 7% of global emissions. The conventional blast furnace–basic oxygen furnace (BF-BOF) route relies heavily on coke (a carbon-rich fuel), resulting in high emissions. Green hydrogen can replace coke in the direct reduced iron (DRI) process, enabling nearly zero-emission steelmaking when powered by renewables. Hybrid systems that combine wind and solar can supply both electricity for electrolyzers and heat for DRI furnaces.

5.3.1. Case Example

H2 Green Steel (Sweden): Integrating 800 MW of wind and solar capacity to produce hydrogen for a DRI steel plant targeting 95% lower CO_2 emissions than conventional steel [53].

SALCOS Project (Germany): Salzgitter AG is developing hydrogen-based steel production powered by hybrid renewable energy systems to achieve full decarbonization by 2033 [54]. This transition also supports energy system balancing, as electrolyzers can modulate operations based on grid needs, providing demand-side flexibility.

5.4. Cement and Lime Industries

Cement production contributes approximately 8% of global CO_2 emissions, primarily from calcination of limestone and combustion of fossil fuels in kilns operating at temperatures >1,400°C. Electrification is not practical at such high temperatures, making hydrogen combustion a viable alternative. Hybrid systems using solar PV and wind generate hydrogen, which is stored and used to fuel cement kilns. In some designs, solar thermal collectors provide preheating of feedstocks, reducing fuel demand.

5.4.1. Research Example

Pilot studies in Germany and Switzerland have demonstrated the feasibility of retrofitting cement plants with hydrogen-capable burners. In parallel, CEMEX and Cemvita are exploring biological and hydrogen-based routes to process CO_2 emitted from kilns, integrating with hybrid energy systems. However, high hydrogen flame temperatures and NO_x formation risks require material upgrades and burner redesigns [55].

5.5. Chemical and Fertilizer Industry

The production of ammonia, methanol, and other chemicals is highly hydrogen-intensive. Ammonia synthesis via the Haber-Bosch process, for instance, accounts for roughly 1.8% of global CO_2 emissions, with most emissions tied to SMR-based hydrogen. Hybrid renewable-hydrogen systems can: Replace grey hydrogen with green hydrogen for ammonia and methanol production; Integrate on-site renewable generation with electrolyzers to stabilize costs; Provide oxygen byproduct from electrolysis for use in chemical processes.

5.5.1. Case Example

Yara's Green Ammonia Plant (Norway): Integrates hydropower and solar with electrolyzers to produce green hydrogen for ammonia synthesis, aiming to reduce emissions by 41,000 tonnes/year [56].

NEOM Project (Saudi Arabia): One of the world's largest planned green hydrogen-ammonia projects, 4 GW of solar and wind to produce 1.2 million tons of green ammonia annually. The chemical industry benefits from hybrid systems not only for sustainability but also resilience against volatile fossil feedstock prices [57].

5.6. Glass, Ceramics, and High-Temperature Manufacturing

Industries like glass and ceramics require uniform high-temperature heat, which is traditionally supplied by natural gas or oil. Direct electrification is often ineffective due to heat distribution challenges, making hydrogen combustion a cleaner substitute. Hybrid systems use solar thermal arrays with hydrogen back-up to provide stable thermal input. Research has shown that hydrogen-combustion furnaces can be modified to meet the performance requirements of these industries, though material compatibility (e.g., hydrogen embrittlement) remains a challenge. Demonstration: The HyGlass Project in the EU explores hydrogen retrofitting for flat-glass furnaces with solar-wind electrolyzer integration. Initial results suggest a 40% emission reduction potential with partial hydrogen substitution.

5.7. Desalination and Water Treatment

Desalination is energy-intensive and increasingly necessary in arid regions where industrial hydrogen demand may emerge. Hybrid systems are being explored to co-produce hydrogen and desalinated water, improving energy efficiency and resource synergy. Case Example: Solar-Geothermal Polygeneration in China [58]: A solar-boosted geothermal system achieved 28.46 kg/s desalinated water production and green hydrogen generation, with a 4.74-year payback period and exergetic efficiency of 21.9%. Such integration is especially beneficial for off-grid coastal regions, industrial zones in desert climates, and island economies.

5.8. Mining and Off-Grid Industrial Applications

Mining operations are often located in remote, off-grid areas, where diesel generators dominate energy supply. Hybrid renewable-hydrogen systems can provide clean, continuous power while producing hydrogen for heavy-duty vehicles or equipment. Solar-wind hybrid microgrids can supply electrolyzers to generate fuel for hydrogen trucks, drills, and mobile plants. Hydrogen storage supports 24/7 operation, reducing dependency on costly and polluting diesel logistics. Case Study: Anglo American's Mogalakwena Mine (South Africa) is deploying a 3.5 MW solar electrolyzer to fuel hydrogen haul trucks, aiming to cut diesel use and emissions by over 80% per vehicle. These applications represent a convergence of energy autonomy, environmental stewardship, and cost optimization [59].

5.9. Maritime and Aviation

Although still early-stage, hybrid systems are being explored to produce hydrogen-based fuels (ammonia, synthetic kerosene) for shipping and aviation. Integration with hydro-solar hybrid farms enables production of green hydrogen derivatives near ports and airports. Notable examples include:Green ammonia bunkering in Norway and Singapore; Power-to-liquid (PtL) fuel synthesis in Germany using wind-solar hydrogen. Such efforts support the decarbonization of transport-related industrial supply chains. Hybrid renewable-hydrogen systems are proving vital across a wide array of industrial sectors, offering tailored solutions for fuel switching, process heat, and feedstock decarbonization. These systems are not only advancing emissions reduction goals but also enhancing energy security, operational resilience, and long-term cost control. As technology matures and costs fall, broader implementation of these systems is expected, especially where policy incentives, carbon pricing, or sustainability mandates support clean industrial transitions.

6. Barriers and Challenges to Implementation

Despite the considerable promise of hybrid renewable-hydrogen systems for industrial decarbonization, widespread deployment is hindered by a complex array of technical, economic, infrastructural, regulatory, and social barriers. These challenges must be systematically addressed to ensure scalable, cost-effective, and sustainable integration of such systems into existing and emerging industrial operations. This section explores the multifaceted obstacles to implementation, drawing on real-world case studies, modeling insights, and policy evaluations to illuminate the constraints slowing down adoption. Understanding these challenges is critical to developing effective strategies, research directions, and enabling policies that will support the commercial maturity of hybrid renewable-hydrogen systems.

6.1. Technical Challenges

6.1.1. Intermittency and Variability of Renewable Sources

Solar and wind energy, often the primary inputs for hybrid hydrogen systems are inherently variable. Cloud cover, seasonal variation, and wind speed fluctuations affect electrolyzer performance and hydrogen output consistency. Operating electrolyzers under highly variable conditions reduces their efficiency and can accelerate degradation, particularly for Proton Exchange Membrane (PEM) and Solid Oxide Electrolyzers (SOE). Mitigation Strategy: Incorporating geothermal or hydropower for base-load capacity, as well as deploying battery energy storage systems (BESS) or hydrogen buffer storage, can smooth input variations. However, this adds cost and complexity.

6.1.2. Low Electrolyzer Utilization Rates

In many hybrid systems, electrolyzers operate below their rated capacity due to mismatches between renewable generation and industrial load profiles. This underutilization drives up the levelized cost of hydrogen (LCOH). For example, studies have shown that a system with <40% electrolyzer utilization may produce hydrogen at >$5/kg, economically uncompetitive compared to grey hydrogen (typically $1.5–$2/kg). Mitigation Strategy: System optimization, dynamic dispatch algorithms, and combining diverse energy sources can improve utilization. Emerging high-temperature electrolysis technologies (e.g., SOE) may also offer better integration efficiencies.

6.2. Economic and Financial Barriers

6.2.1. High Capital Costs

Electrolyzers, hydrogen storage infrastructure, renewable power plants, and control systems together form a capital-intensive configuration. The upfront investment required to deploy even a medium-sized hybrid system can be prohibitive for most industries. The International Renewable Energy Agency (IRENA, 2022) estimates capital costs of $900–$1,500/kW for PEM electrolyzers and $1,200–$2,500/kW for alkaline systems, excluding the cost of renewable energy supply.

6.2.2. Long Payback Periods

Industrial players require short-to-medium payback windows to justify investments. However, hybrid hydrogen systems often take 7–12 years to achieve economic break-even under current market conditions, unless carbon pricing, incentives, or power purchase agreements (PPAs) are available.

6.2.3. Uncertain Hydrogen Demand and Price Volatility

The future price trajectory of hydrogen is unclear, making long-term return-on-investment projections difficult. Additionally, industries are hesitant to switch from reliable fossil energy sources to relatively immature hydrogen markets, especially in absence of government-backed demand signals.

Mitigation Strategy: Policy mechanisms such as carbon credits, feed-in tariffs, green hydrogen subsidies, and contracts for difference (CfDs) can bridge the cost gap. Public-private partnerships and blended finance models are also being used to de-risk early investments.

6.3. Infrastructure and Logistics Constraints

6.3.1. Limited Hydrogen Storage and Distribution Infrastructure

Most regions lack adequate hydrogen pipelines, refueling stations, liquefaction plants, and storage terminals. Without these, industries must rely on high-cost on-site hydrogen production and storage, reducing scalability and increasing logistical complexity. Hydrogen's low volumetric energy density and flammability pose technical and regulatory hurdles in transport and storage, whether compressed, liquefied, or carried in ammonia/formic acid.

6.3.2. Geographic Disparity Between Supply and Demand

Optimal renewable energy generation sites (e.g., deserts for solar, coasts for wind) often do not align with industrial zones, creating a mismatch between hydrogen production centers and consumption hubs. Mitigation Strategy: Co-location strategies (e.g., producing hydrogen near industrial clusters), or transporting hydrogen via carriers like ammonia or methanol, are being explored. However, these introduce energy losses and cost premiums.

6.4. Regulatory and Policy Gaps

6.4.1. Lack of Hydrogen-Specific Regulations and Standards

In many countries, there is no unified framework governing hydrogen purity standards, safety protocols, storage codes, or emission accounting methodologies. This leads to market uncertainty, inhibits investment, and creates technical incompatibilities across regions and equipment types.

6.4.2. Insufficient Carbon Pricing or Incentive Mechanisms

Without robust carbon taxes or emission trading systems, green hydrogen remains uncompetitive with fossil-based alternatives. According to the Hydrogen Council (2023), only 18% of global hydrogen demand is exposed to carbon pricing or incentives strong enough to drive green hydrogen adoption.

6.4.3. Permitting and Bureaucracy

The process for securing permits for electrolyzers, solar fields, geothermal drilling, or hydrogen storage tanks can be slow, fragmented, and inconsistent, delaying project timelines and increasing costs. Mitigation Strategy: Clear and consistent national strategies, permitting frameworks, and bankable hydrogen roadmaps, such as the EU Hydrogen Strategy or Japan’s Basic Hydrogen Strategy are critical to facilitate deployment.

6.5. Social and Workforce Challenges

6.5.1. Public Acceptance and Safety Concerns

Hydrogen is flammable and often associated with safety incidents. Public resistance to infrastructure, especially pipelines or storage near residential areas, can derail project implementation. In addition, concerns over land use for solar fields or geothermal wells can trigger community opposition.

6.5.2. Workforce and Skill Gaps

The hydrogen sector requires specialized technical skills in process engineering, high-pressure systems, electrochemistry, control systems, and safety. Most industrial regions lack the trained workforce necessary to operate, maintain, and scale hybrid systems. Mitigation Strategy: Government-supported hydrogen training programs, certification schemes, and community engagement efforts are being developed to enhance public trust and workforce readiness.

6.6. Integration with Industrial Processes

6.6.1. Process Compatibility and Retrofitting Costs

Industrial systems are tightly optimized around fossil fuels. Replacing natural gas burners with hydrogen combustion systems, or redesigning process heat loops for solar-thermal integration, requires significant retrofitting. This introduces technical risk and often necessitates production downtime.

6.6.2. Hydrogen Quality and Pressure Requirements

Certain industrial applications require ultra-pure hydrogen at specific pressures. Variability in electrolyzer output or inconsistent renewable energy supply may compromise the quality and reliability of hydrogen delivered. Mitigation Strategy: Modularity in electrolyzer design, hybrid operation modes, and pressure-balancing equipment are being tested to ensure process compatibility. The deployment of hybrid renewable-hydrogen systems is not constrained by technological impossibility, but rather by a convergence of interrelated economic, regulatory, and practical barriers. These systems offer clear environmental and operational benefits, but the challenges outlined—especially cost, infrastructure, and policy alignment must be addressed with urgency. For hybrid systems to scale, governments must provide targeted support, industries must commit to long-term decarbonization goals, and researchers must continue to improve efficiency, affordability, and integration strategies. With coordinated action, the barriers can be transformed into catalysts for innovation and sustainable industrial transformation.

7. Future Outlook and Recommendations

The global energy transition is entering a decisive decade where clean technologies must scale rapidly to achieve climate targets. Hybrid renewable-hydrogen systems stand at the forefront of this transformation, offering a viable pathway for decarbonizing industrial sectors that have long resisted low-carbon alternatives due to their high energy demands and reliance on fossil feedstocks. As countries, corporations, and communities commit to net-zero goals, the convergence of renewable energy and hydrogen technologies will become increasingly central. However, the pace, scope, and efficiency of deployment will be determined by how effectively stakeholders address current limitations while leveraging opportunities. This section presents a forward-looking analysis of expected developments and offers strategic recommendations for accelerating adoption and maximizing the impact of hybrid renewable-hydrogen systems in industrial decarbonization.

7.1. Emerging Technological Trends

7.1.1. Advanced Electrolyzer Technologies

While conventional alkaline and PEM electrolyzers are commercially available, newer technologies promise improved performance and cost-efficiency: Solid Oxide Electrolyzers (SOE): Operate at high temperatures (~700–900°C) and achieve higher electrical efficiency by utilizing waste heat from industrial processes. When coupled with geothermal or solar-thermal systems, SOEs can achieve >80% efficiency. Anion Exchange Membrane (AEM) Electrolyzers: Combine the low cost of alkaline with the compactness of PEM systems and operate under mild conditions. Emerging studies show potential for scalable, low-cost green hydrogen. The commercialization of these next-generation systems will reduce the levelized cost of hydrogen (LCOH) and increase compatibility with industrial environments.

7.1.2. Artificial Intelligence and Energy System Optimization

AI-driven modeling and control systems will enhance the performance of hybrid systems by: Predicting energy supply variability; Optimizing electrolyzer load management; Forecasting industrial demand curves; Managing storage cycles to minimize energy loss. By enabling real-time operational intelligence, AI can reduce downtime, maximize electrolyzer utilization, and enhance the return on investment.

7.2. Policy and Market Projections

7.2.1. Hydrogen Hubs and Industrial Clusters

The International Energy Agency (IEA) projects over 30 major hydrogen hubs to emerge globally by 2030, with an emphasis on co-locating renewable generation, electrolyzers, storage, and industrial end-users. These hubs aim to: Aggregate demand across sectors (e.g., refining, steel, chemicals); Share infrastructure (pipelines, terminals); Benefit from economies of scale and coordinated permitting. Examples include: EU Hydrogen Backbone Initiative connecting regional hydrogen networks; U.S. Department of Energy's Regional Clean Hydrogen Hubs (H2Hubs) funded under the Infrastructure Investment and Jobs Act; Japan and South Korea's integrated industrial ports supporting green ammonia, methanol, and hydrogen bunkering. These hubs will accelerate the commercialization of hybrid systems and reduce marginal costs through shared assets.

7.2.2. Green Hydrogen Certification and Trade

Several countries and organizations are developing certification schemes to verify the carbon footprint of hydrogen and facilitate international trade. The EU's CertifHy, Australia's Guarantee of Origin, and similar platforms in Chile, UAE, and Canada are paving the way for a global hydrogen market. A clear definition of "green hydrogen" and harmonized standards will: Enable emissions-based subsidies and carbon trading; Promote cross-border investments; Foster demand from sustainability-conscious industries.

7.3. Research Priorities and Innovation Gaps

To realize the full potential of hybrid renewable-hydrogen systems, targeted research is needed in the following areas:

7.3.1. Integrated Thermal and Electrical Storage

Efficient energy storage systems are essential to bridge the gap between variable renewable supply and constant industrial demand. Innovations in: High-temperature thermal energy storage (HTTES); Hydrogen-based seasonal energy storage (HSES); Coupled battery-hydrogen systems are critical for round-the-clock operations. Research should focus on materials with high thermal conductivity and durability under cyclical loads to improve system resilience.

7.3.2. Material Compatibility and Hydrogen Embrittlement

Industrial retrofitting must address hydrogen-induced degradation in pipelines, valves, and heat exchangers. Future R&D should explore: Hydrogen-compatible alloys and composites; Corrosion-resistant coatings;Additive manufacturing for custom retrofits. This will improve safety, reduce maintenance, and prolong equipment lifespan.

c) Hydrogen Co-products and Circular Economy Integration

The byproducts of electrolysis (e.g., oxygen) and solar-thermal systems (e.g., waste heat) can be harnessed in co-located processes: Use of oxygen in steel and wastewater treatment; Use of low-grade heat in desalination or drying processes. Integration of hybrid systems into circular industrial ecosystems enhances economic viability and environmental performance.s

7.4. Industrial Strategy Recommendations

7.4.1. Phased Deployment Roadmaps

Industries should develop technology-neutral, phased decarbonization roadmaps, prioritizing: Low-hanging opportunities (e.g., hydrogen fuel switching in boilers); Medium-term retrofits (e.g., DRI-based steel furnaces); Long-term investments (e.g., synthetic fuel production or full green hydrogen conversion). Each phase should align with available policy instruments and projected technology maturity timelines.

7.4.2. Cross-Sector Collaboration

Industrial firms, utilities, electrolyzer manufacturers, and governments must form multi-stakeholder alliances. These collaborations should facilitate: Shared risk through joint ventures; Data sharing for optimization models; Aggregated procurement to reduce electrolyzer costs. Public-private consortia like HyDeploy, H2GreenSteel, and H2Future have demonstrated the success of such partnerships.

7.5. Policy Recommendations

To enable a supportive policy ecosystem, governments should: Implement carbon pricing or emissions caps that reflect the externalities of fossil energy; Offer investment tax credits, capital grants, and production-based subsidies for electrolyzers and renewables; Streamline permitting and regulatory approvals for integrated hybrid systems; Support hydrogen training and certification programs to build a qualified workforce; Establish national hydrogen strategies aligned with industrial decarbonization goals. These policies will create a predictable investment climate and reduce the barriers to first movers.

7.6. Socioeconomic Outlook

Beyond emissions reduction, hybrid systems offer: Job creation in engineering, construction, and operation of hydrogen infrastructure; Resilience to fossil fuel price shocks, increasing industrial competitiveness; Clean energy access in remote and developing regions, especially when integrated with microgrids and desalination systems; Sustainable export opportunities, positioning hydrogen-rich nations (e.g., Australia, Chile, Namibia) as global clean energy suppliers. Realizing this potential requires aligning climate goals with economic development and energy justice frameworks, ensuring inclusive growth. The outlook for hybrid renewable-hydrogen energy systems in industrial decarbonization is both promising and imperative. Technological advancements, falling renewable costs, and growing political will converge to make this decade the tipping point for clean industrial energy. However, strategic action is needed through policy, finance, innovation, and collaboration to unlock the full value of these systems. If adopted widely, hybrid systems will not only cut emissions but also reshape industrial ecosystems around sustainability, resilience, and circularity sdefining the future of industry in a net-zero world.

8. Conclusion

Hybrid renewable-hydrogen energy systems have emerged as a pivotal solution in the global effort to decarbonize industry especially sectors like oil and gas, steel, chemicals, cement, and high-temperature manufacturing where electrification is insufficient or impractical. These systems harness the complementary strengths of renewable energy (solar, wind, geothermal) and green hydrogen to deliver clean electricity, process heat, and chemical feedstocks, replacing conventional fossil-based inputs and significantly reducing greenhouse gas emissions. This review has comprehensively examined the technical foundations, industrial applications, current challenges, and future potential of integrating hybrid renewable-hydrogen technologies into industrial operations: Fundamentals and Systems: The combination of solar PV, solar thermal, wind, and geothermal energy with electrolyzers enables the generation of low-carbon hydrogen and high-temperature heat. Integration designs vary by geography, load profile, and process requirements, offering flexibility across industries. Applications: Real-world deployments and pilot studies ranging from GlassPoint's solar-steam EOR in Oman to green steel initiatives in Sweden and Germany illustrate how hybrid systems can reduce emissions by up to 80–95% compared to traditional practices. Hybrid setups also support ancillary processes like desalination, thermal storage, and off-grid power generation. Challenges: Despite the promise, hybrid systems face several barriers including high capital costs, intermittency of renewable resources, infrastructure limitations, safety concerns, and regulatory gaps. These challenges inhibit scale and require targeted interventions to overcome. Outlook and Recommendations: The pathway to large-scale adoption lies in advancing electrolyzer efficiency, reducing costs through economies of scale, fostering supportive regulatory frameworks, and encouraging public-private partnerships. The emergence of hydrogen hubs, certification schemes, and integrated industrial clusters marks an encouraging trend. Ultimately, the integration of hybrid renewable-hydrogen systems into industry offers not just environmental benefits, but also economic resilience, energy independence, and innovation leadership. As countries and corporations race toward net-zero targets, these systems will form the backbone of clean industrial transformation thereby enabling a sustainable and inclusive energy future.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclsoed.

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