hydrogen

MDPI

Article

Green Hydrogen and the Energy Transition: Hopes, Challenges, and Realistic Opportunities

Alessandro Franco

Department of Energy, Systems, Territory, and Constructions Engineering (DESTEC), University of Pisa, Largo Lucio Lazzarino, 56122 Pisa, Italy; alessandro.franco@ing.unipi.it

Abstract: This paper provides a system-level and dimensional analysis of green hydrogen, assessing its realistic deployment potential within broader energy transitions. While green hydrogen—produced via electrolysis using renewable electricity—is often promoted as a versatile decarbonization solution for industry, mobility, and civil applications, its practical implementation is constrained by high energy consumption, conversion inefficiencies, and complex supply chain requirements. This study highlights typical energy demands across key sectors and evaluates the scale of the renewable infrastructure needed to support them, offering quantitative insight into the feasibility of large-scale hydrogen integration. It also reflects current technological maturity, noting that many promising solutions remain far from industrial readiness. Finally, the paper underscores the importance of targeted policies and bankable investment models to foster the development of hydrogen ecosystems, emphasizing that its role should be framed within a selective, evidence-based strategy that focuses on high-impact applications. The analysis identifies key dimensional challenges, including the magnitude of renewable energy capacities required for sector-wide hydrogen integration and the scale of infrastructure investments needed to bridge current gaps.

Keywords: energy transition; decarbonization; climate neutrality; electrolysis; renewable energy; energy efficiency; blended combustion; industrial applications; process innovations

check for updates

Academic Editor: Rajender Boddula

Received: 3 March 2025
Revised: 15 April 2025
Accepted: 17 April 2025
Published: 19 April 2025

Citation: Franco, A. Green Hydrogen and the Energy Transition: Hopes, Challenges, and Realistic Opportunities. *Hydrogen* **2025**, *6*, 28. https://doi.org/10.3390/hydrogen6020028

1. Introduction

The concept of hydrogen as an energy vector dates to the 1970s energy crises when it was explored as an alternative fuel [1–3]. Interest declined due to production and transportation challenges but resurged in the 1990s with projects like Japan's WE-NET [4,5] and again in the early 2000s, driven by climate concerns and influential works like Rifkin's Hydrogen Economy [6]. Despite this renewed enthusiasm, hydrogen remained an "energy carrier" rather than a resource for many years [7]. The recent global focus on decarbonization, catalyzed by the European Green Deal [8] and the Fit for 55 packages [9], has revived attention on hydrogen—specifically green hydrogen. Unlike gray hydrogen (produced from natural gas) or blue hydrogen (produced with natural gas and carbon capture), green hydrogen is produced using renewable energy, positioning it as a key component of sustainable energy systems. The 2022 war in Ukraine highlighted the need for energy security, accelerating investments in green hydrogen alongside the rapid growth of renewable energy systems (RESs), which has expanded from marginal contributions of 200 at the beginning to over 3000 GW of installed capacity globally [10–13]. While RESs have expanded due to declining costs and supportive policies, their integration often requires costly incentive systems. These measures facilitate diffusion but support wind and PV solar, leading to the limited diffusion of technologies like concentrated solar and geothermal energy.

1.1. State of the Art: Green Hydrogen and Its Potential

The penetration of renewables has been transformative, with photovoltaic and wind power experiencing exponential growth. This progress has been supported by significant incentives, such as feed-in tariffs, tax breaks, and quota obligations, which offset the high upfront costs of renewable installations. However, renewable electricity still accounts for about 15% of global energy use, while thermal energy, representing nearly 50% of consumption, remains under-addressed. Green hydrogen offers a pathway to bridge this gap, but it presents several challenges. Although hydrogen has many advantages, such as its high energy density (calorific values of 120 and 144 MJ/kg), its drawbacks, such as storage issues and high production costs, cannot be ignored [14]. Its low density (0.08–0.09 kg/m^3 at atmospheric conditions) makes storage and transport difficult, requiring high pressures or low temperatures. Additionally, hydrogen is highly flammable and has a wide flammability range. Hydrogen is not an energy source but an energy carrier. This means it must be generated from primary sources, including both renewable and fossil fuels. Some production methods, such as Steam Methane Reforming (SMR) with carbon capture and storage (CCS), still pose environmental and efficiency challenges. Hydrogen production via electrolysis holds promise to reduce emissions, as it uses renewable electricity, but it remains energy-intensive and costly. Green hydrogen produced via water electrolysis and powered by renewables can contribute significantly to decarbonizing sectors that are difficult to electrify, such as heavy industry, high-temperature processes, and transportation. It also plays a key role in mitigating the intermittency of renewable energy by enabling large-scale storage and offering the potential for long-distance transport.

In recent years, numerous research streams on hydrogen have been active, reflecting an innovative dynamism and engagement in the sector. Research activities can be classified into five main research areas, each addressing key challenges along the hydrogen value chain. These areas include hydrogen production through electrolysis (focusing on improving efficiency, reducing costs, and scaling up technologies like alkaline, PEM, and solid oxide electrolysis); alternative hydrogen production methods (such as thermochemical, photochemical, and biological processes and low-carbon pathways like methane pyrolysis); innovations in storage and transportation (covering compression, liquefaction, and hydrogen carriers like ammonia and liquid organic hydrogen carriers); and end-use applications, particularly in industries like steelmaking, ammonia synthesis, and refinement, as well as emerging applications in mobility and power generation.

An additional area of importance involves activities that support the widespread deployment of hydrogen, such as the development of policy frameworks, infrastructure planning, market development, and system integration. Each of these areas includes 5-10 distinct research topics, demonstrating the breadth and complexity of ongoing efforts, as reported in Figure 1 [15]. Figure 1 provides a structured overview of the current research landscape in hydrogen technologies. The figure is organized as a matrix, with five main columns representing the following key thematic areas: (i) hydrogen production through electrolysis, (ii) alternative low-carbon production pathways, (iii) storage and transportation, (iv) end-use applications, and (v) cross-cutting activities. Each column is further divided into 4–7 specific research topics, which capture the most relevant and active lines of investigation within each area. This classification illustrates not only the diversity of technological approaches but also the systemic nature of the hydrogen challenge, where progress depends on advancements across multiple interconnected domains. While substantial progress has been made, a key challenge remains in aligning these technological advancements with practical implementation strategies to ensure that hydrogen effectively contributes to the decarbonization of the global energy system [15]. Many projects centered on hydrogen are currently active worldwide and across Europe, fostering collaboration among research institutions, academia, and industry. While costs continue to decline, green hydrogen remains expensive and less efficient than direct electrification, presenting ongoing challenges for large-scale adoption. Moreover, infrastructure for storage and transport is still underdeveloped, and rapid scaling risks unintended consequences, such as increased fossil fuel use in production [16,17].

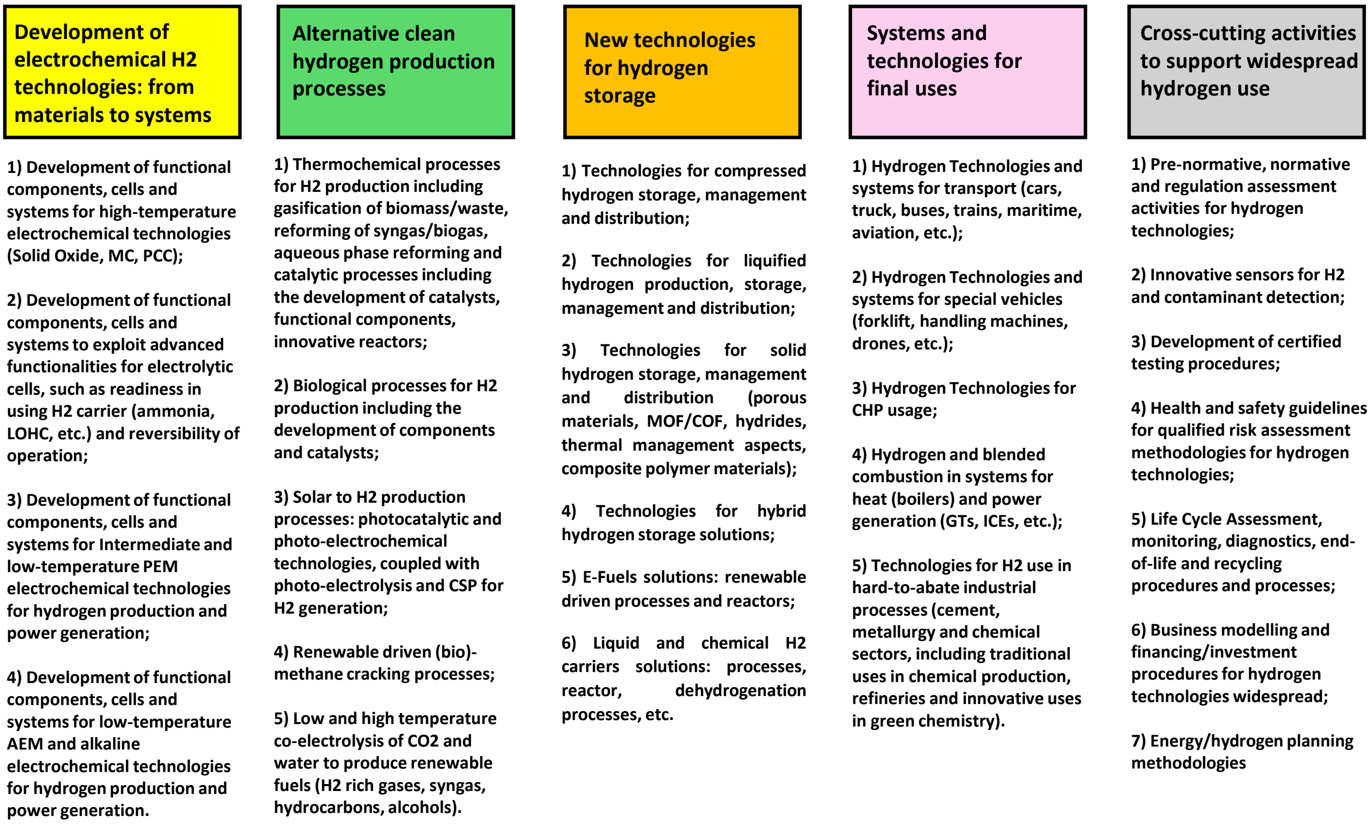

Figure 1. A matrix of various research activities in the field of green hydrogen.

While the hydrogen sector is experiencing significant growth in research and innovation, only a few technologies have advanced to high Technology Readiness Levels (TRLs), making them suitable for large-scale deployment. The TRL scale ranges from early-stage conceptual research (TRL 1) to fully operational and commercially viable technologies (TRL 9). This reveals that many promising hydrogen technologies are still in the early stages of development. While innovation potential is significant, considerable efforts are still needed to move from research to industrial-scale implementation.

The integration of hydrogen must be approached with caution to avoid rebound effects and inefficiencies. Ambitious hydrogen strategies have emerged under the European Green Deal, aiming to produce millions of tons of green hydrogen annually, though often lacking clarity on production sources and timelines. Green hydrogen can drive the energy transition, but only if used correctly. To unlock its full potential, it is crucial to consider the entire energy chain, including storage, transfer, and necessary infrastructure changes.

1.2. Contribution of This Paper

The author has analyzed the problem from different perspectives in recent papers [18–20]. What is often overlooked in the current hydrogen-related literature is the identification of coherent, scalable strategies that connect technological development with practical implementation in specific sectors. There is a lack of mid-level strategic thinking—between system-wide visions and component-level analyses—that can inform decisionmaking about hydrogen value chains to prioritize their use in the short-to-medium term. This paper critically examines the role of green hydrogen within energy transition, identifying the most promising strategies for its implementation. Special attention is given to the dimensional aspects of hydrogen deployment, such as plant scale, infrastructure compatibility, and the Technology Readiness Level (TRL) of specific technologies. It builds on recent technological advances, including lower renewable energy costs and improved electrolysis efficiency, to assess effective integration pathways. The objective is not only to assess technological progress but to critically distinguish between promising developments with near-term potential and other developments, the practical impact of which remains limited.

Beyond critical assessment, this work outlines a broader vision for hydrogen's role. While diversified research is essential, this paper argues for a more structured and prioritized approach to avoid fragmentation and maximize system-level benefits.

This work adopts an energy systems perspective, highlighting the need to balance hydrogen production with system-wide efficiency. By evaluating sector coupling, energy storage, and infrastructure development, this analysis aims to provide actionable insights. This article contributes to the literature by combining a system-level perspective with a critical synthesis of current research trends, thereby bridging the gap between techno-economic evaluations and deployment strategies. By grounding the discussion in historical lessons, recent data, and a critical review of ongoing initiatives, a more realistic roadmap for leveraging green hydrogen is provided while tempering excessive optimism to avoid disillusionment as challenges become clearer. Through targeted dimensional analyses, this work emphasizes the need to approach green hydrogen deployment from a systemic perspective, especially in its initial stages, avoiding a fragmented bottom-up approach and instead prioritizing coordinated, strategic interventions.

The paper is organized as follows. After an introduction covering the recent history of hydrogen, Section 2 critically examines its potential as a key element in reducing greenhouse gas emissions, particularly in hard-to-abate sectors, while also examining its diverse applications in industry, energy storage, and mobility. Section 3 analyzes the technical and economic challenges hindering widespread adoption, such as efficiency losses, storage difficulties, and high production costs, alongside potential strategies to overcome these barriers through innovation, policy support, and cross-sectoral integration. Section 4 offers a forward-looking assessment, outlining pathways that can strengthen the role of green hydrogen in the global energy transition by linking technological advancements with market scalability and system-level priorities. Finally, Section 5 presents the conclusions of the study.

2. From Hydrogen to Green Hydrogen: Technological Pathways and Emerging Developments

This section traces the evolution of hydrogen technologies, highlighting how past developments have laid the groundwork for today's focus on green hydrogen. While hydrogen has long been considered a promising energy carrier, only recent advancements, especially in electrolysis and renewable integration, have unlocked its decarbonization potential. Interest in hydrogen first surged during the 1970s oil crisis [21] and again in the 1990s, when projects such as Japan's WE-NET explored its role in thermodynamic cycles (e.g., STIG) and direct energy conversion via fuel cells [22,23]. These early efforts paved the way for modern green hydrogen technologies, which leverage renewable electricity and include innovative approaches like biological processes and photoelectrochemical conversion. In the early 2000s, the role of hydrogen was revisited with a stronger focus on environmental sustainability. It was seen as a tool to decarbonize energy systems, but its role as an energy carrier—not a primary energy source—posed challenges [24]. Recently, an effort has evolved to align hydrogen with the growing penetration of renewable energy from the perspective of decarbonization [25]. Table 1 outlines the differences in hydrogen use proposals over the years, highlighting the shifting priorities and challenges across these periods.

Table 1. The recent evolution of hydrogen uses proposals across various periods.

Period	Primary Proposal	Context	Challenges Identified
1970–2000	Fuel for transport and power generation via H_2-O_2 turbines and STIG cycles	Introduced to cut fossil fuel use in transport and improve efficiency in power generation	Lack of infrastructure, storage issues, high costs, and integration challenges in thermodynamic power cycles
2000–2020	Hydrogen for mitigating environmental impacts of energy use (the "Hydrogen Economy")	Connection to sustainability goals and reducing greenhouse gas emissions	Hydrogen as an energy carrier and among the most difficult carriers to manage and utilize effectively
Recent Years	Hydrogen linked to decarbonization, RES penetration, and its restored role as an energy carrier and storage agent	Promoted to balance renewable energy supply and demand, supporting decarbonization efforts	Energy losses in production chains, storage challenges, and economic competitiveness

Hydrogen is now being reconsidered for its potential to store excess RES production and facilitate grid balancing. Green hydrogen combustion produces no CO_2 emissions, and its versatility makes it suitable for applications ranging from mobility to high-temperature industrial processes. Over the past 30 years, renewable energy sources have significantly expanded in international energy systems, driven by technological advancements, economic incentives, and international regulations. In the last decade, the installed capacity of wind and solar has surpassed hydropower, which has historically been the dominant renewable source. As a result, renewables now account for at least 30% of electricity generation. However, electrification remains limited in the thermal and mobility sectors: these are areas where hydrogen can drive decarbonization. Green hydrogen leverages renewables to decarbonize hard-to-electrify sectors while enabling long-term energy storage to balance renewable intermittency. However, efficiency remains a key challenge. The hydrogen supply chain (Figure 2) involves multiple stages, including electricity generation, electrolysis, storage, transportation, and final use. Figure 2 outlines the full conceptual structure of the green hydrogen supply chain, starting from various renewable energy sources—such as solar, wind, and hydrogen—and extending to a wide range of end uses in sectors like industry, mobility, and the built environment. The diagram highlights the main steps required to convert renewable electricity into hydrogen via electrolysis, followed by storage, possible conversion processes (e.g., compression, liquefaction, or synthesis), transportation, and finally, utilization. While many theoretical pathways exist for integrating hydrogen into diverse energy systems, the figure illustrates that the overall chain is inherently complex and involves multiple technological layers. From a systemic perspective, such complexity often translates into higher energy losses, greater infrastructure demands, and increased costs. Each stage incurs losses, reducing overall efficiency to below 30%. Electrolyzers operate at 60–70% efficiency, while storage and transport introduce additional losses, making direct electrification a more efficient alternative. The economy adds another challenge. As is well recognized in energy system design, the longer and more articulated the supply chain is, the harder it becomes to achieve economic and operational competitiveness—especially when compared to more direct electrification pathways. Therefore, although green hydrogen offers strategic flexibility, its large-scale deployment will likely be feasible only in specific contexts where direct electrification is impractical or inefficient and where hydrogen can offer unique added value. Green hydrogen, produced via water electrolysis powered by renewables, currently costs between USD 4 and USD 6 per kilogram, which are values significantly higher than that of blue hydrogen, which is produced from natural gas with carbon capture and storage (CCS) at a cost of USD 1 to USD 2.5 per kilogram [26–29].

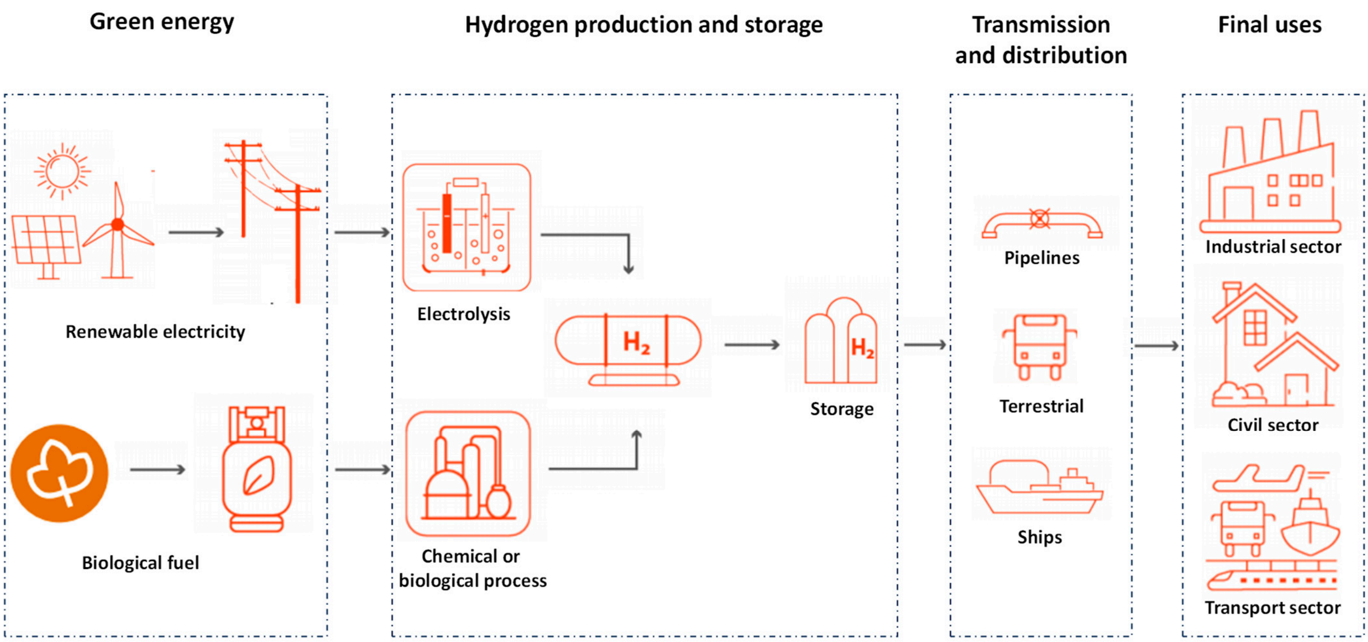

Figure 2. Green Hydrogen supply chain.

Hydrogen production is primarily dependent on fossil fuels, specifically, methane through the Steam Methane Reforming (SMR) process, which produces large amounts of CO_2. While CCS can theoretically capture up to 90% of emissions, technical limitations and high energy costs reduce actual capture rates. Additionally, methane leakage occurs along the natural gas supply chain, and methane is problematic due to its greenhouse gas, which surpasses that of CO_2. Although blue hydrogen offers some near-term advantages, its strong reliance on fossil fuel infrastructure raises concerns about prolonging carbon-intensive systems and shifting resources from fully renewable solutions. Moreover, the long-term viability of CCS is uncertain due to the risks of CO_2 leakage from geological storage sites and the economic challenges of scaling it effectively. In contrast, green hydrogen is the only fully sustainable alternative, though significant barriers remain. High costs, low efficiency, and dependence on renewable infrastructure require targeted strategies to enhance competitiveness and ensure effective deployment. The strategic emphasis on green hydrogen as a cornerstone of decarbonization reflects its role in decarbonizing sectors that cannot rely solely on electrification [30]. However, its large-scale adoption must align with technological and economic feasibility, prioritizing cases where its advantages justify its inefficiencies. The present section, based on the data rearranged by the author from refs. [27–29] explore these strategies, focusing on promising technologies, infrastructure needs, and policies to accelerate deployment while avoiding inefficient transitional approaches.

Despite growing policy momentum, hydrogen production expansion has been slow, with green hydrogen still representing a tiny fraction of global output. By the end of 2023, it made up just 0.1% of global hydrogen production, highlighting its marginal presence in the sector. Hydrogen demand has followed broader energy trends rather than direct political initiatives. Currently, more than 99.9% of demand is in traditional sectors like refining and chemical production, while under 0.1% is used in new applications in heavy industry, transport, or power generation. The adoption of low-emission hydrogen remains marginal, covering just 0.7% of demand. The annual growth rate of hydrogen production remains at 1–2%, which is far below what is needed to meet ambitious decarbonization targets. Table 2 and Figure 2 provide an overview of hydrogen production, highlighting key challenges and opportunities. Growth trends, particularly for green hydrogen, remain slow (1–2% per year). Table 3 and Figure 3 further emphasize the sluggish evolution of the sector. Figure 3 illustrates current hydrogen production shares, clearly showing the dominance of fossil-based sources. This reflects the maturity, lower cost, and existing infrastructure of conventional methods like Steam Methane Reforming (SMR), while the minimal share of green hydrogen (approximately 0.1%) highlights the ongoing challenges in cost, scalability, and renewable integration. Despite its central role in decarbonization narratives, recent data fail to indicate a definitive trend of robust growth. The key sectors for green hydrogen are refining, ammonia production, methanol production, and steel manufacturing. This underscores the need for a revised strategy to overcome technical, economic, and policy barriers for effective green hydrogen deployment (Table 4). A structured strategy could unfold in four key phases (Table 5). These include the initial phase with medium-scale production for major consumers, expansion with semi-centralized hubs for local markets, market maturation, and finally, the development of a cross-regional or intercontinental hydrogen market. Although this roadmap offers structure, numerous initiatives are progressing concurrently. The field of green hydrogen research and application is vibrant and rapidly evolving, as evidenced by the wide array of ongoing studies and initiatives.

Table 2. Current hydrogen production and recent trends.

Year	Hydrogen Production [Mton]
2021	94
2022	95
2023	97

Table 3. The main actual sectors of hydrogen use and share of its uses.

Sectors	Use Share [%]
Refining	43
Ammonia Production	35
Methanol Production	17
Steel Manufacturing	5

Table 4. Recent evolution of hydrogen and green hydrogen production.

Year/Period	Metric	Value	Source/Trend
2023	Global Hydrogen Production	~97 Mtons	Primarily fossil fuels (natural gas and coal)
2023	Share of Green Hydrogen in Global Production	~0.1%	Minimal growth despite renewable advancements

Table 4. *Cont.*

Year/Period	Metric	Value	Source/Trend
2020–2023	Annual Growth Rate of Green Hydrogen	~1–2%	Limited by high costs and infrastructure gaps
2023	Levelized Cost of Hydrogen (Green)	4–10 USD/kg	Higher than hydrogen from fossil fuels (~USD 1/kg)
2023	Hydrogen Electrolyzer Capacity Installed	~700 MW	Increasing, but far from required scaling levels

Table 5. Possible historical deployment pattern of hydrogen.

Sectors	Power Scale	Geographical Scale
On site	MW	Local-wide
Semi-centralized	Tens of MW	Nation-wide
Centralized	Hundreds of MW	Region-wide
Intercontinental	GW	Intercontinental-wide

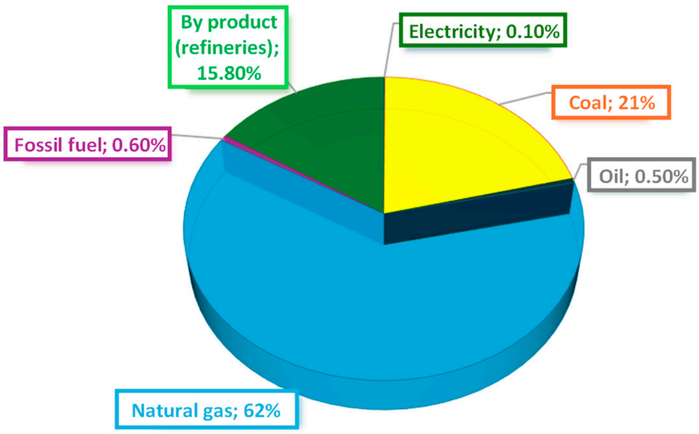

Figure 3. The marginal contribution of green hydrogen to global hydrogen production.

Despite the current achievements being relatively modest, substantial efforts are underway across various fronts, from production technologies to storage solutions and their integration into energy systems. However, many of these activities lack a cohesive and overarching strategic vision. The realization of green hydrogen's potential as a key driver of decarbonization will require progress on two interconnected levels: the optimization of individual technologies and the development of a more integrated and strategic framework.

2.1. Technologies for Green Hydrogen Production: Water Electrolysis

In a green hydrogen production chain, energy losses during production are a critical factor. Water electrolysis, the key method for green hydrogen generation, inherently requires more energy than the hydrogen it produces. Advanced electrolysis technologies are crucial for integrating renewable sources like solar and wind while mitigating fluctuations between demand and supply. Research focuses on improving both low-temperature (PEM, ALK, AEM) and high-temperature electrolyzers through multiscale modeling, material optimization, and prototype testing.

Figure 4 illustrates the three main water electrolysis technologies—Alkaline Electrolysis (ALK), Proton Exchange Membrane (PEM) Electrolysis, and Solid Oxide Electrolysis (SOE)—highlighting their key differences in terms of their electrolyte type, transported ions, and electrochemical reactions occurring at the cathode and anode. The goal is to enhance efficiency, durability, and scalability by refining materials and components, ultimately advancing fuel cells and electrolyzes for large-scale applications.

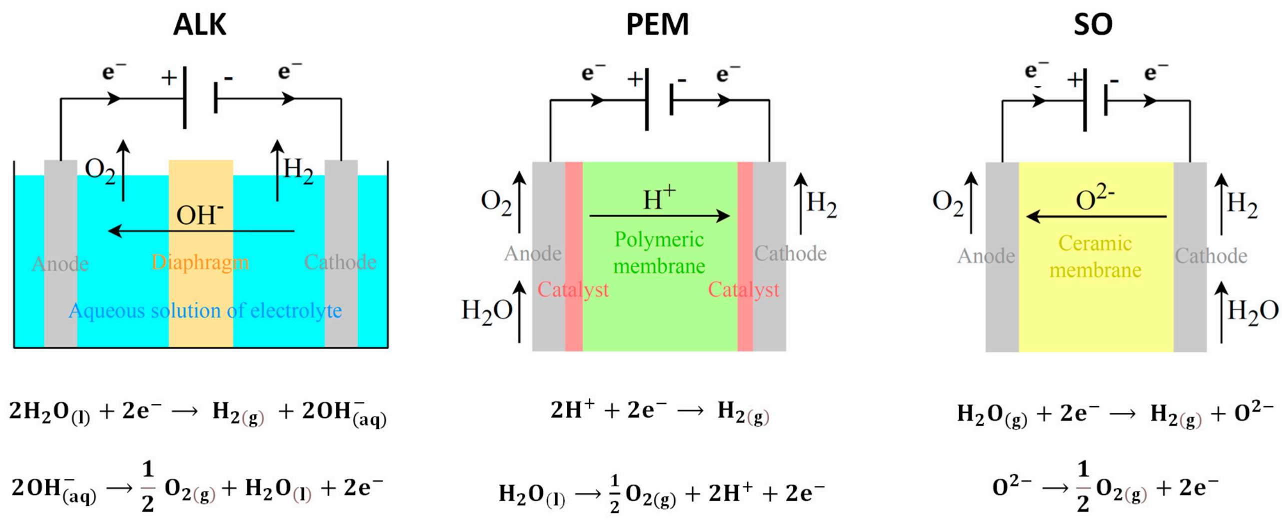

Figure 4. Simplified schematics of the distinct operational principles of water electrolysis.

Table 4 provides a summary of data that effectively frames the current state of technology. Several papers, like [31], critically examine recent innovations and prospects in electrolyzer design, focusing on improving efficiency and reducing costs. The great part about these contributions is the need for ongoing research to address bottlenecks such as material degradation, energy loss, and scalability. Enhancing electrolyzer performance is crucial to making green hydrogen competitive with hydrogen produced from fossil fuels, particularly in terms of cost and energy efficiency. Data from the literature and the market, summarized in Table 6, show that actual energy consumption for hydrogen production exceeds theoretical values.

Table 6. Main physical characteristics of electrolyzers reported in literature and available on the market [28].

Technology	Maximum Power [MW]	Activation Time [min]	SEC System [kWh/kgH_2]	Operating Pressure [bar]
ALK	1000	30–60	>50	1–30
PEM	100	5	>50	1–80
AEM	10	20	>57	1–35
SO	10	600	>45	1–10

Electrolyzers with nominal powers above 100 kW demonstrate specific electricity consumption (SEC) averaging at 55–60 kWh/kg for low-temperature systems and 48–50 kWh/kg for high-temperature systems (in this case, no market data are available). The state of the art suggests a value of 0.6 for the efficiency of the electrolysis process through the following synthetic equation, in which the water and energy requirements to obtain 1 kg of hydrogen, considering optimal available technologies, are outlined as follows:

$$8.8 \text{ kg } H_2O \xrightarrow{55 \text{ kWh}} 1 \text{ kg } H_2 + 7.8 \text{ kg } O_2 \quad (1)$$

These figures underscore efficiency losses and higher energy demands in practical hydrogen production. The current production capacity of electrolyzers is still relatively low and predominantly focused on low-temperature technologies. This reflects the early stage of development of high-temperature electrolysis technologies, which, although promising, have not yet matured for large-scale production. Figure 5 clearly illustrates how the majority of electrolyzer manufacturing capacity is still dedicated to low-temperature technologies, with limited growth in high-temperature technologies, which are expected to remain a niche in the coming years.

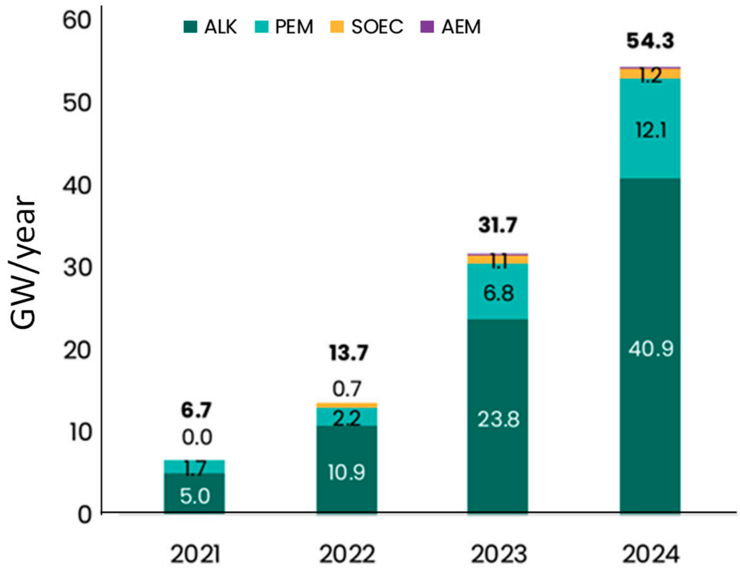

Figure 5. Global electrolyzer manufacturing capacity. Data from IEA 2024; Global Hydrogen Review 2024, https://www.iea.org/reports/global-hydrogen-review-2024 (accessed on 1 January 2025).

Electrochemical hydrogen technologies, including water electrolysis for green hydrogen and fuel cells for power generation, are under active investigation (Tables 6–8). Solid oxide electrolysis is the most promising technology conceptually, but its high operating temperatures add complexity. Research targets both low-temperature systems (PEM, ALK, and AEM) and high-temperature solutions (SO) through modeling, material optimization, and prototyping. Novel materials aim to enhance performance and durability. Water electrolysis has seen the most development, with available systems showing potential for decarbonization, though further evolution is needed.

Table 7. Main electrical characteristics of electrolyzers reported in literature and available on the market [28].

Technology	Current Density [A/cm^2]	Voltage [V]	Power Density [W/cm^2]
ALK	0.2–0.8	1.4–3.0	0.3–2.4
PEM	1.0–2.0	1.4–2.5	1.4–5.0
AEM	0.2–2.0	1.4–2.0	0.3–4.0
SO	0.3–1.0	1.0–1.5	0.3–1.5

Table 8. Main research activities on electrochemical hydrogen technologies.

Research Focus	Technologies/Systems	Main Research Activities
Hydrogen Production	Water electrolysis: Low-temperature systems (PEM, ALK, AEM) High-temperature systems (SO)	• Multiscale and multicomponent modeling. • Design and optimization of materials and system layouts; • Prototyping, testing, and validation.
Power Generation via Fuel Cells	Various types of fuel cells for efficient power generation	• Performance optimization; • System integration and efficiency testing.
Materials Development and Functionalization	Novel materials and commercial enhancements: synthesis of new materials; functionalization of existing materials to improve durability and overall performance	• Material synthesis; • Functionalization techniques; • Enhancing key properties (e.g., gas permeability and durability).
System Integration and Upscaling	Complete electrochemical systems Combining production and utilization technologies into scalable solutions	• Defining guidelines for manufacturing improvements; • Developing strategies for system upscaling; • Ensuring cost-effectiveness and the long-term reliability of integrated systems.

2.2. Green Hydrogen Production Beyond Electrolysis

A relevant research activity deals with the exploration and development of the most promising alternatives to the electrolytic route to produce clean hydrogen. Research is increasingly focused on alternative routes to electrolysis for producing clean hydrogen, aiming to ensure its availability even in urban and industrial areas, as well as in remote communities or in agriculture-based economies. Tailoring production technologies to local socio-economic contexts is crucial. The targets of the selected technologies will be the production of clean hydrogen from renewable feedstocks, such as bio-methane or biomass, direct bio-hydrogen production, photoelectrochemical systems and electrolytic production from carbon dioxide and water. While electrolysis remains the most discussed method for producing green hydrogen, other pathways—such as pyrolysis, biomass gasification, and microbial hydrogen production—offer renewable options (Figure 6). This technological diversity confirms that sustainable hydrogen production must follow multiple context-specific trajectories.

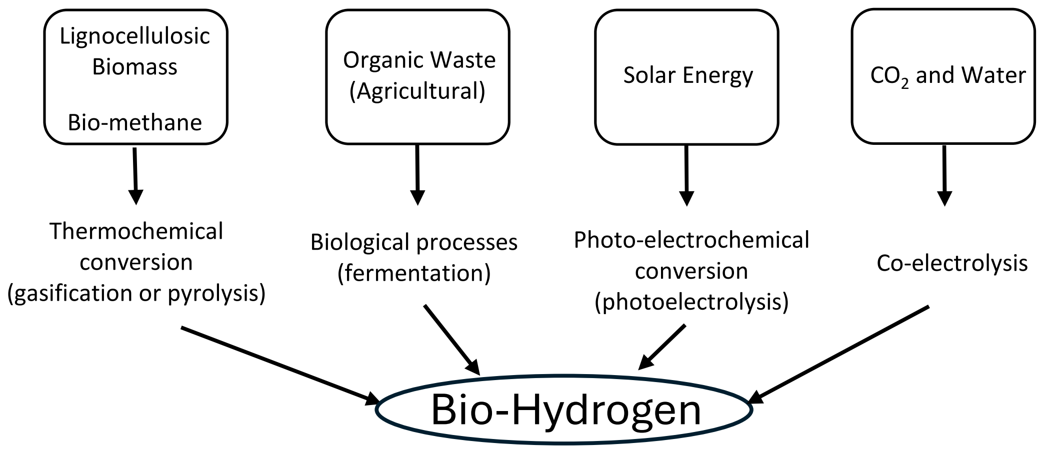

Figure 6. Alternative pathways for green hydrogen production from renewable sources.

These methods broaden hydrogen production possibilities across diverse socio-economic and geographic contexts. However, their long production chains and energy balance challenges raise efficiency and economic concerns. Still, they deserve attention, especially in niche applications. Considering the process, it is essential to account for its energy efficiency, defined as the ratio between the energy content of the produced hydrogen and total energy input, including feedstock and additional energy contributions. The proper analysis of hydrogen production from biomass should consider the ratio between the energy obtained and total energy used, including feedstock, vapor, and mechanical energy. Assuming the use of an efficiency parameter, this would be given by the ratio of the useful energy produced to the total energy used in the process, including the feedstock, mechanical energy, and electricity used.

$$\Psi = \frac{\dot{E}_{H_2}}{\dot{E}_{feed} + \dot{E}_{vap} + \dot{E}_{mech}} \tag{2}$$

2.2.1. Thermochemical Processes

Hydrogen can be produced from biomass or bio-methane through thermochemical conversion, utilizing organic waste and offering benefits like waste reduction, particularly in agricultural areas. Key feedstocks include energy crops, agricultural residues, and forestry waste. Among thermochemical processes, gasification is currently seen as one of the most promising technologies [30]. Gasification is a relatively long-chain process, as illustrated in the schematic flow of Figure 7. The energetic efficiency of a gasification process, generally known as cold-gas efficiency, CGE, can be determined as follows:

$$CGE = \frac{\dot{n}_{H2,out} \cdot \left(\widetilde{h}_{d,i}\right)}{\dot{m}_{fuel} \cdot LHV_{fuel} + \dot{m}_{vap} \cdot h_{vap} + \dot{m}_{O2} \cdot E_{O2}} \tag{3}$$

where LHV_{gas} and $LHV_{biomass}$ are the net heat values of combustion (with lower heating values) of hydrogen and biomass, respectively, and the energy required to produce oxygen and steam. Considering the chemical composition of biomass, shifting them towards hydrogen generation requires the use of accurate chemical pathways, balancing the input of feedstock, oxygen (air), and vapor, though they are inefficient from an energy perspective. In general, the biomass gasification reaction can be expressed as follows:

$$nC_xH_yO_z + mH_2O + wO_2 \rightarrow x_1CO + x_2H_2 + x_3CO_2 + x_4CH_4 + x_5H_2O + x_6O_2 \tag{4}$$

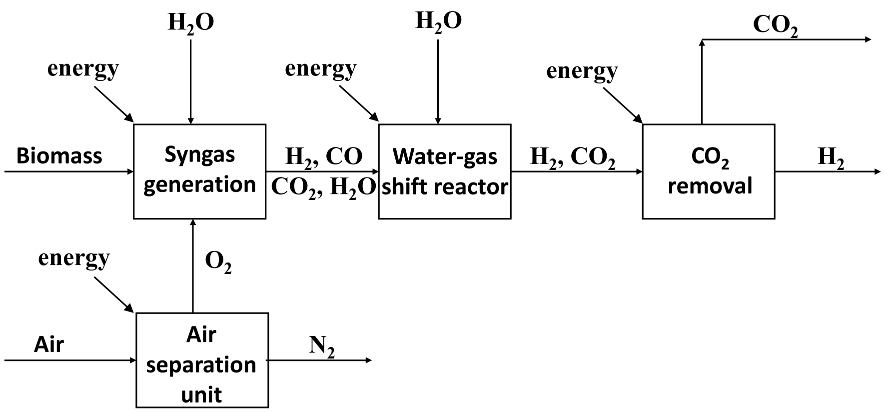

Figure 7. Process scheme for hydrogen production through biomass gasification.

If it is considered that the fractions of CO_2, O_2, and H_2O formed in gasification are mainly the products of combustion and are used to obtain the necessary energy to perform gasification and cover the energy losses included in the efficiency of the gasification reactor, where the production of CH_4 is negligible, and the reaction to obtain hydrogen from biomass can be reduced to the following:

$$nC_xH_yO_z + mH_2O \rightarrow x_1CO + x_2H_2 \quad (5)$$

This is followed by the shift reaction:

$$x_1CO + x_3H_2O \rightarrow x_4CO_2 + x_5H_2 \quad (6)$$

Despite extensive discussion, experimental data on gasification for hydrogen production is lacking. As a result, energy balance analyses are used for upper-bound estimates, which can appear overly optimistic. Biomass hydrogen production is limited by the feedstock's hydrogen content (5–8% of dry biomass), and theoretical yields often exceed 10%. However, factoring in all energy inputs, including those difficult to quantify, efficiency typically falls below 5%. Even in ideal conditions, purification further reduces overall efficiency. Referring to biomass, whose chemical composition is extrapolated from [32] and provided in Table 9, it is possible to estimate hydrogen production from biomass, such as that reported in Table 10.

Table 9. Chemical composition of biomass used as feedstock for gasification processes.

Biomass Type	C	H	N	O	Moisture	Ash	LHV (MJ/Kg)
Biomass 1	44.2	6.2	0.8	48.8	10.0	15.2	14.9
Biomass 2	52.2	5.5	1.6	40.6	12.3	0.8	17.8
Biomass 3	49.1	5.6	1.2	44.1	8.8	5.1	16.2

Table 10. Estimation of hydrogen production from biomass based on its chemical composition.

Biomass Type	H_2 Theoretical (g/kg Biomass)	Biomass to Hydrogen Efficiency
Biomass 1	59.3	0.47
Biomass 2	62.9	0.42
Biomass 3	58.8	0.43

2.2.2. Biological Processes

Similar raw materials considered for thermochemical conversion can be used for bio-hydrogen production through biological processes, as stated in refs [33,34]. Biological hydrogen production methods involve distinct processes based on the conversion of glucose and acetic acid. Biological hydrogen production processes are diverse and largely rely on solar radiation as the primary energy input, coupled with the catalytic action of various bacteria that convert substrates like glucose and acetic acid into hydrogen. Table 11 provides a general description of each process including the main chemical reactions and bacteria involved. Biological processes can also be combined, as represented in Figure 8, reprinted with permission by [34]. Table 12 provides a highly qualitative estimation of the energy yield expected from biological processes, given the current lack of consistent and conclusive experimental data.

Table 11. Overview of biological processes, including main chemical reactions and associated bacteria.

Process	General Reaction	Bacteria
Direct Biophotolysis	$2H_2O + light \rightarrow 2H_2 + O_2$	Microalgae
Photo-fermentation	$CH_3COOH + 2H_2O + light \rightarrow 4H_2 + 2CO_2$	Purple bacteria Microalgae
Indirect Biophotolysis	$6H_2O + 6CO_2 + light \rightarrow C_6H_{12}C_6 + 6O_2$ $C_6H_{12}O_6 + 2H_2O \rightarrow 4O_2 + CH_3COOH + 2CO_2$ $2CH_3COOH + 4H_2O + light \rightarrow 8H_2 + 4CO_2$	Microalgae Cyanobacteria
Thermophilic Fermentation	$C_6H_{12}O_6 + 2H_2O \rightarrow 4H_2 + 2CO_2 + 2CH_3COOH$	Fermentative bacteria; Methanogenic bacteria
Dark Fermentation	$C_6H_{12}O_6 + 6H_2O \rightarrow 12H_2 + 6CO_2$	Fermentative bacteria

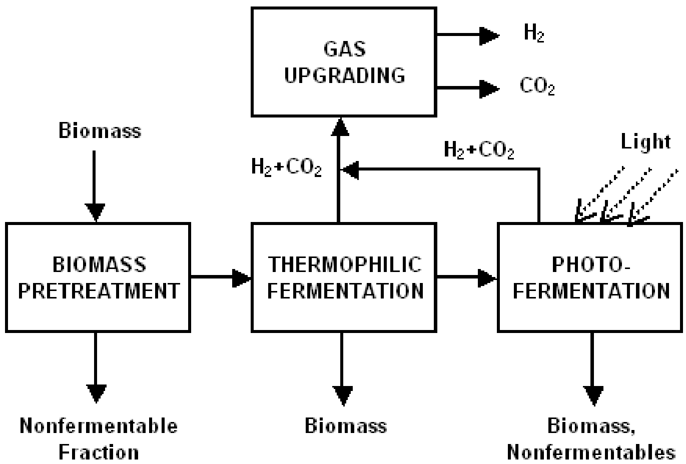

Figure 8. Schematic representation of a possible biological hydrogen production process driven by solar energy according to [34].

Table 12. Comparison of biological processes for hydrogen production.

Process	Description	Energy Yield
Direct Biophotolysis	Photosynthetic microorganisms split water using sunlight	Very low
Indirect Biophotolysis	Utilizes photosynthesis to produce organic matter, which is later broken down to release hydrogen	Low
Dark Fermentation	Anaerobic bacteria break down organic substrates to generate hydrogen	Moderate (but still low)
Photo-fermentation	Purple non-sulfur bacteria use organic acids and light to produce hydrogen	Low

2.2.3. Photoelectrochemical Systems

Photoelectrochemical (PEC) processes enable the conversion of solar energy into hydrogen via water splitting, relying on semiconductor materials to generate electron–hole pairs. The basics of this process can be found in [35], and appropriately designed semiconductors are irradiated in aqueous electrolytes. Depending on the type of semiconductor material and the solar intensity, this current density is 10–30 mA/cm^2. At these current densities, the voltage required for electrolysis is much lower, and therefore, the corresponding electrolysis efficiency is much higher. Laboratory devices currently report solar-to-hydrogen (STH) efficiencies of 10–20% and incident photon-to-current efficiency (IPCE), which is often 50–90% for specific wavelengths. Key challenges include the optimization of bandgap (1.6–2.2 eV), reducing charge recombination, and improving stability against photodegradation. Materials like TiO_2 offer durability but low efficiency, while perovskites and GaAs achieve higher performance but lack stability. Advances in catalysis, light absorption, and system design are crucial to achieving scalable, high-efficiency hydrogen production for renewable energy applications. The solar-to-hydrogen conversion efficiency (η_{STH}) is used as an indicator to evaluate the performance of PEC devices. The formula is as follows:

$$\eta_{STH} = \frac{\text{H2 energy output}}{\text{solar energy input}} = \frac{\Delta G \cdot Y_{H2}}{I_{sun} \cdot S} \tag{7}$$

where ΔG is the Gibbs free energy of water splitting in J/mol, Y_{H2} is the yield of hydrogen (mol s^{-1}), I_{sun} is the intensity of the incident light in W/m^2, and S is the irradiated area (in m^2). In a recent review [36], several laboratory-scale devices were cited, featuring diverse configurations and materials, such as GaInP/GaInAs, $MAPbI_3$, CuInGa, and $BiVO_4$, with hydrogen conversion efficiencies ranging from 1% to 16%. Interest in these systems has grown since they use solar energy to split water directly, integrating hydrogen production with renewable energy, though scalability and efficiency remain challenging [37,38]. Developing integrated photoelectrochemical systems that combine solar radiation and photovoltaic power can enhance overall efficiency by fully utilizing renewable energy resources. From a more practical perspective, the efficiency of a photoelectrochemical conversion system can be expressed as follows:

$$\eta_{PEC} = \frac{\dot{m}_{H2} \cdot LHV_{H2}}{I_{sun} \cdot A + \dot{W}_{el}} \tag{8}$$

where $\dot{W}_{el}$ is the electricity input applied to the reactor from a PV module, I_{sun} is the solar irradiance, and A is the illuminated electrode area. The PEC conversion system could become of significant interest if conversion efficiencies reach 20%. Although photoelectrochemical devices that convert sunlight into hydrogen are promising on a small scale, they appear to be quite far from achieving widespread scalability.

2.2.4. Electrolytic Production from CO_2 and Water

Co-electrolysis has gained significant interest as a dual-purpose technology for both hydrogen production and CO_2 reduction (Figure 9). This process converts CO_2 and water into hydrogen, leveraging electricity from renewable sources. At the anode, water oxidation generates oxygen, protons, and electrons, while CO_2 reduction at the cathode yields hydrogen and carbon monoxide (CO) or other compounds. This concept has been explored in different papers, like [39,40], and recent contributions are paying attention to the more recent advancements in catalyst optimization and system integration [41]. While still largely experimental and energy-intensive, co-electrolysis is increasingly seen as a key pathway in decarbonization efforts, as it offers a means with which to recycle CO_2 emissions into valuable products, contributing to a more circular and sustainable energy system. Current system efficiencies remain below 50% due to the high overpotentials required for CO_2 activation. Research is focused on improving catalyst selectivity, stability, and overall efficiency to enhance scalability and economic viability [42]. Each of these technologies has specific targets and applications, but they share the challenge of overcoming energy inefficiencies and high operational costs. Further advancements in materials and system design are necessary to lower these costs and enhance long-term economic feasibility.

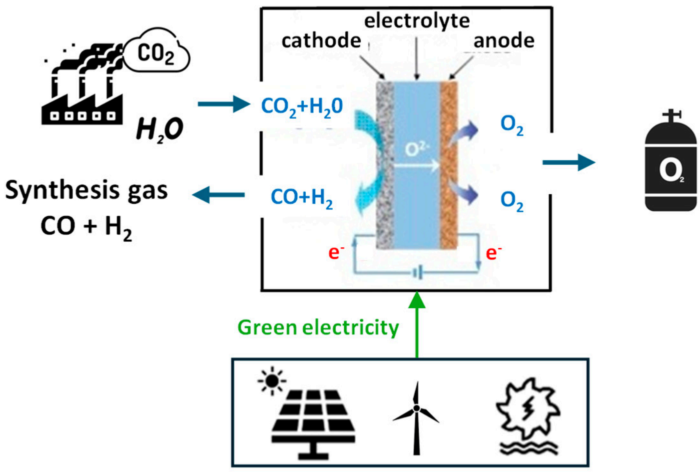

Figure 9. Conceptual representation of CO_2 and H_2O co-electrolysis.

2.2.5. Critical Analysis of the Routes for Hydrogen Production Beyond Electrolysis

Hydrogen production from renewables beyond electrolysis faces challenges, primarily due to the low energy density of biomass and the limited efficiency of conversion processes. Biomass-based methods, such as thermochemical or biological conversion, expand the range of renewable sources and could help address both waste management and hydrogen supply. However, their large-scale viability is limited by technical and economic constraints. Among alternative approaches, co-electrolysis—converting CO_2 and water into hydrogen and carbon monoxide—could integrate hydrogen production with industrial processes, particularly in "hard-to-abate" sectors. Despite its potential, co-electrolysis remains in its early development stages and requires significant advances in efficiency and cost reduction to become commercially viable. While these methods are unlikely to become widespread solutions, they remain relevant for research, particularly in localized hydrogen production (Table 13).

Table 13. Overview of key processes for green hydrogen production from renewable energy sources, highlighting their physical constraints and main limitations.

Production Method	Description	Key Advantages	Challenges/ Considerations	Maximum Efficiency	Potential Applications
Thermochemical processes using renewable feedstock	Hydrogen production from bio-methane or lignocellulosic biomass	Leverages organic waste materials; reduces waste; utilizes biomass	Long production chains; energy balance concerns; complex logistics.	30–40% (based on feedstock and processes)	Agricultural economies; biomass-rich regions.
Bio-hydrogen production	Hydrogen production using biological processes (fermentation or microbial electrolysis)	Aligns with circular economic principles; has potential for low-cost local production	Still in the early stages; low efficiency; scalability issues.	15–30%	Rural areas; agricultural economies.
Photoelectrochemical systems for solar hydrogen	Hydrogen production via solar energy to directly split water using photoelectrochemical systems (PEC)	Integrates hydrogen production with solar energy; offers promising sustainability	Scaling and efficiency challenges with high energy input requirements (early research).	10–20%	Remote communities; solar-rich areas.
Electrolytic production from CO_2 and water	Converting CO_2 and water into H_2 and other reduced products using electrolysis	Potential to address carbon emissions while producing hydrogen	High energy input required; experimental; energy inefficiency.	30–40% (depending on technology and energy sources)	Carbon capture and utilization; experimental setups.

In summary, while alternative hydrogen production methods from renewable fuels offer some strategic value, their low efficiency, high costs, and limited scalability make their widespread adoption unlikely—except in specific niche contexts. In this view, these technologies face challenges similar to those of biofuels, which, despite years of research and investment, still play a marginal role in the global energy mix.

3. Limitations of Green Hydrogen for Energy Transition: Technical and Economic Challenges

This section expands on the previous analysis of hydrogen production, shifting focus to the broader technical and economic challenges involved in developing a complete hydrogen supply chain from production to end-use. Key limitations, including energy losses in electrolysis, storage, and transportation, as well as high costs and underdeveloped infrastructure, reduce overall efficiency. While hydrogen is often presented as a universal solution, a more strategic approach—focused on high-impact sectors such as hard-to-abate industries and energy storage—may be essential for its effective integration. The substantial investments required raise questions about its economic viability. These issues are summarized in Table 14, which outlines the current challenges, and Table 15, which highlights potential solutions and prospects. The need for realistic expectations and targeted policies is critical to support hydrogen's role in the energy transition.

Table 14. Current prospects for hydrogen.

Aspect	Current Situation	Challenges
Production Methods	Primarily electrolysis; limited alternative methods	High energy costs; low efficiency; limited scalability
Sector Focus	General application in various sectors	Lack of sector-specific strategies and clear objectives
Storage and Transport	Storage at low pressure (~30 bar); costly transport	Energy loss; high costs; limited infrastructure
Technical Limitations	Early-stage technology; high energy consumption	High capital investment; technical scalability issues
Economic Feasibility	Hydrogen produced from renewable sources is still costly	High production; storage; and transport costs

Table 15. Future prospects for hydrogen.

Aspect	Future Potential	Opportunities
Target Sectors	Hard-to-abate industries; thermal energy generation	Decarbonizing industrial sectors; reducing reliance on natural gas
Energy Chain Integration	Hydrogen as both an energy carrier and chemical agent in processes	Support renewable energy integration; enhance energy storage systems
Technological Advances	Advanced electrolysis; bio-hydrogen; photoelectrochemical systems	Improved efficiency; lower costs; new production technologies

Table 15. *Cont.*

Aspect	Future Potential	Opportunities
Strategic Focus	Sector-specific strategies for targeted hydrogen application	Clear objectives; focused policy and regulatory framework
Economic Viability	Targeted applications in specific sectors; gradual scaling up	Economies of scale; improved cost-effectiveness over time

3.1. Hydrogen Storage and Infrastructure Challenges

An often-underestimated aspect of hydrogen utilization is the need for a comprehensive view of the entire energy chain. Beyond production, multiple critical steps—such as storage, transfer, and distribution—introduce significant technical and economic challenges, which are frequently overlooked in broad discussions about hydrogen's role in decarbonization. Several analyses indicate that upgrading existing infrastructure to accommodate hydrogen can raise capital costs by 20–30% compared to conventional systems, highlighting the complexity and financial burden of such modifications. One of the most pressing challenges is storage. Hydrogen produced by standard electrolyzers typically exists at relatively low pressures (around 30 bar), requiring additional compression—often exceeding 200 bar—to meet storage and pipeline specifications. This compression alone can demand an extra 10–15% of the total energy input, further reducing overall system efficiency. Studies on hydrogen compression technologies have extensively examined trade-offs between energy consumption, storage density, and economic feasibility, revealing current methods—whether based on mechanical, cryogenic, or adsorption-based storage—that still present significant limitations in large-scale applications. Additionally, research on hydrogen embrittlement and material degradation underscores the need for specialized infrastructure, as traditional pipelines and storage tanks may suffer from structural weakening over time when exposed to high-purity hydrogen. These findings reinforce the fact that fully realizing the potential of green hydrogen hinges not only on advancements in production but also on substantial improvements in storage technologies and infrastructure. There are numerous articles addressing the costs of hydrogen storage. However, to gain a comprehensive understanding, it is advisable to explore both energy-related challenges, as discussed in a recent study by the author [43], and the associated economic aspects [44].

3.2. Green Hydrogen and Blending with Natural Gas

Green hydrogen could progressively be integrated into blended combustion systems for both heat and power generation. Owing to its unique properties—such as higher diffusivity, increased flame speed, and elevated adiabatic flame temperatures—its use in burners and combustors may pose significant challenges that require innovative design solutions. Advanced experimental and modeling efforts can address these issues by optimizing flame structure, enhancing the stability of combustion (e.g., mitigating flashback and blowoff), and reducing NOx emissions. The topic of blended combustion has been extensively explored in the literature. Numerous studies have analyzed the technical, environmental, and economic implications of blending hydrogen with natural gas in existing infrastructure. For instance, ref. [45] examines the effects of hydrogen blending on combustion efficiency and pollutant emissions, while [46] focuses on the adaptability of current gas networks and safety considerations. Additionally, ref. [47] provides insights into the economic feasibility of large-scale hydrogen injections, and ref. [48] discusses policy and regulatory challenges. Blending hydrogen with conventional fuels like natural gas or biogas could be an emerging transitional strategy, offering improved performance while facilitating a smoother shift toward fully renewable energy systems. However, further research is required to address the scalability of these approaches, their integration into existing infrastructures, and their long-term economic sustainability.

3.3. Green Hydrogen and Final Uses in Energy Systems: Applications in Industrial Decarbonization

Recent advances in integrating green hydrogen into renewable energy systems have demonstrated its potential as a flexible energy carrier capable of balancing the intermittency of renewable sources and stabilizing energy grids through the storage of surplus wind or solar power. A growing body of research in the literature—including significant contributions from Italian research groups—has explored diverse aspects of this integration. For instance, techno-economic analyses have evaluated solid oxide fuel cell cogeneration systems for decarbonizing energy-intensive industries [49] and assessed the decarbonization potential via hydrogen integration in different sectors such as, for example, paper [50] and steel sectors [18,19,51]. Other studies have addressed energy modeling challenges to fully decarbonize hard-to-abate sectors [52] and investigate the viability of essential infrastructure elements such as hydrogen refueling stations [53,54] and liquid hydrogen supply chains for ship refueling [55]. Although these studies have generated significant interesting contributions and advanced our understanding, the transformative impacts expected from hydrogen integration are not yet fully realized. A balanced perspective that considers efficiency, infrastructure, and economic viability at multiple scales remains essential for unlocking hydrogen's full potential in energy transition.

3.4. Cross-Cutting Activities for Hydrogen Introduction in Energy Systems

Achieving widespread hydrogen adoption goes beyond the technical breakthroughs and demands that have coordinated progress in several cross-cutting areas. Alongside improving production technologies, ongoing research must focus on updating regulatory frameworks and developing normative standards that can streamline hydrogen's integration into energy systems. For instance, ref. [56] discusses the importance of harmonizing international regulations to facilitate cross-border hydrogen trade and implementation. Safety initiatives, such as the development of advanced sensors and comprehensive safety guidelines for industrial and commercial use, are essential to ensuring secure adoption at scale, as highlighted by [57]. Similarly, life cycle assessments (LCAs) and strategies for material recovery are critical to ensure environmental sustainability and circularity. Recent studies, such as ref. [58], emphasize the importance of evaluating the full environmental impact of hydrogen production, from cradle to grave, and integrating recycling strategies for key materials like catalysts and membranes. Finally, planning tools that support techno-economic analyses and strategic investment are needed to scale hydrogen projects. According to [59], the development of integrated modeling approaches can help align technical feasibility with economic viability, guiding long-term investments in the hydrogen sector. Together, these efforts provide a crucial roadmap for overcoming non-technical barriers and realizing hydrogen's full potential in the energy transition.

3.5. Economic Aspects Related to Green Hydrogen Development

This renewed interest in hydrogen reflects its foundational role as an energy carrier. However, persistent challenges—such as conversion inefficiencies, storage complexity, and high economic costs—remain at the core of current debates. As highlighted in Figure 10, hydrogen occupies a central position within a delicate balance of interdependent factors: technological readiness, economic viability, and political–strategic support. These dimensions are deeply interconnected and largely influenced by future technological breakthroughs.

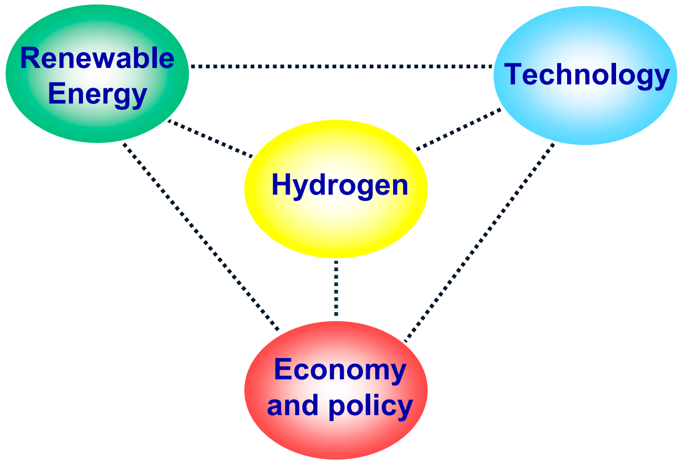

Figure 10. Hydrogen at the nexus of renewables, technology, economics, and regulation, with cost as a key challenge.

This figure underscores how green hydrogen's development is not solely a matter of technological maturity but also of strategic alignment between policies, market mechanisms, and infrastructure planning. Discussions on hydrogen often shift across perspectives—ranging from the integration of renewables to the configuration of the supply chain—without fully accounting for the systemic nature of its deployment. While green hydrogen holds the potential to become cost-competitive, its large-scale adoption in industrial sectors is still constrained by economic and systemic barriers. The future of hydrogen will depend not only on cost reduction but on how effectively we can coordinate innovation, policy, and investment within a coherent strategic framework. These challenges include financial, technological, social, and political aspects; more specifically, (i) the cost of green hydrogen is still quite high compared to other fuels; (ii) the demand for green hydrogen in the future is not guaranteed; (iii) the impacts of green hydrogen projects on water and land resources; (iv) the lack of international regulations and standards; and (v) the general public acceptance of hydrogen. One of the methods to estimate the hydrogen cost is the levelized cost of hydrogen.

Hydrogen is expected to become particularly significant in industrial sectors as a substitute for natural gas. Persistently, the low price of natural gas has posed a major challenge, complicating the economic case for such a transition. Additionally, the economic feasibility of hydrogen is influenced by fluctuating energy prices, evolving regulatory frameworks, and the need for significant infrastructure investments, including storage and transportation networks. Emerging technologies introduce uncertainties not only in terms of efficiency but also in terms of long-term cost reduction potential and scalability. These factors make the financial assessment of hydrogen projects particularly complex. The problem of analyzing the economic aspects related to hydrogen production appears to be quite difficult due to the uncertainty correlated with emerging technologies. The production cost analysis for various hydrogen technologies is based on a levelized cost approach, where all expenditures (both CAPEX and OPEX) are discounted using a discount rate reflecting the average risk of hydrogen production projects.

The levelized cost of hydrogen (LCOH) and levelized cost of energy (LCOE) appear to be a valuable tool for comparing energy technologies, like the use of hydrogen, more than traditional financial metrics like the net present value (NPV). While the NPV remains a useful indicator for project-specific investment decisions, LCOH provides a standardized metric for comparing different hydrogen production pathways, independent of short-term market fluctuations. This makes it highly relevant for policymakers and investors focusing on long-term energy planning. LCOH provides a standardized cost per unit of hydrogen produced, making comparisons across technologies straightforward. One key advantage of LCOH analysis is its independence from market prices, focusing solely on production costs. However, LCOH also has limitations: it does not fully account for external financial support mechanisms such as government subsidies, carbon pricing, or policy incentives, which can significantly influence the competitiveness of hydrogen technologies. Additionally, factors like geographic variability in energy prices and infrastructure development costs introduce complexities that cannot be captured by a single metric. This makes it highly useful for policymakers and investors assessing long-term energy strategies. Additionally, LCOH accounts for all costs over an asset's lifetime, including capital, operation, and maintenance, providing a clearer picture of economic feasibility. To improve the robustness of economic assessments, LCOH should be complemented by scenario analyses and sensitivity studies that consider market dynamics, policy developments, and technological advancements. This approach enables a more comprehensive evaluation of the risks and opportunities associated with hydrogen deployment. The levelized cost of hydrogen (LCOH) is typically calculated using the following formula (in EUR/kg H_2):

$$LCOH = \frac{\sum_k CAPEX_k + C_{proj} + \sum_{j=1}^{n} \frac{\sum_k OPEX_{k,j}}{(1+i)^j}}{\sum_{j=1}^{n} \frac{m_{H2,prod,j}}{(1+i)^j}} \quad (9)$$

where $m_{H2,prod,j}$ [kg] is the mass of hydrogen produced during the j-th year, n is the lifetime of the project, i is the investment rate set at 5%, $CAPEX_k$ is the investment cost of the k-th component [EUR], $OPEX_{k,j}$ represents the operation and maintenance costs for the k-th component during the j-th year, and C_{proj} represents the project costs estimated at 12.5% of $CAPEX$ excluding PV and batteries. Current estimates for green hydrogen vary widely.

The estimation of the levelized cost of green hydrogen (LCOH) remains highly speculative due to technological immaturity and uncertain assumptions, though it still provides a useful basis for the comparison of potential system configurations.

The European Hydrogen Observatory, ref. [60] estimates green hydrogen costs around 7 EUR/kg, with a range between 4.18 and 9.60 EUR/kg. BloombergNEF in ref. [61], on the other hand, reports a wider range of 4.5–12 USD/kg. While some optimistic forecasts suggest prices as low as 3 EUR/kg, actual projects in Central Europe indicate costs between 5 and 8 EUR/kg by 2030. These discrepancies—further exacerbated by additional expenses such as transport and storage—highlight the uncertainties that exist in achieving cost-competitive green hydrogen. Table 16 summarizes the reference values for the actual reference cost of green hydrogen in comparison to gray and blue hydrogen and with electricity and water.

Table 16. Economic model: the cost of hydrogen compared with electricity and water [61,62].

Vector	Type	Value
Hydrogen	Gray H_2	3 EUR/kg
	Blue H_2	4.5 EUR/kg
	Green H_2	8 EUR/kg
Electricity	-	0.07 EUR/kWh
Demineralized water	-	3.58 EUR/m^3

3.6. Policy and Market Considerations

Across these studies, a recurring theme is the importance of coordinated policy and market development to support green hydrogen. Governments and industry leaders alike are increasingly recognizing the strategic value of hydrogen in energy transition. For example, the European Union's REPowerEU plan sets ambitious targets for domestic green hydrogen production and imports, including the deployment of 10 million tons of green hydrogen by 2030. Similarly, the U.S. Inflation Reduction Act has introduced generous tax credits—such as the 45 V hydrogen production credit—creating strong financial incentives for green hydrogen projects. The authors emphasize the need to create favorable market conditions through subsidies, carbon pricing, and targeted incentives to accelerate adoption. However, it must be recognized that hydrogen's potential cannot rely solely on these incentives. While such measures play a key role in market activation, they are not sufficient to ensure long-term viability. For the hydrogen value chain to become truly sustaining, a critical focus must be placed on the bankability of investments. This means developing robust financial models and risk-mitigation strategies that attract private capital and ensure long-term project viability. Without addressing these challenges, capital will remain hesitant, and the sector may struggle to scale beyond early demonstrators. Notably, countries like Japan and South Korea have begun to couple ambitious hydrogen roadmaps with clear industrial strategies, focusing on infrastructure development and public–private partnerships to de-risk investment. At the same time, new hydrogen exchange platforms and long-term contracts—such as those piloted in Germany and Australia—signal growing interest in creating transparent and tradable markets for green hydrogen. Achieving such bankability is complex and, if not properly addressed, could emerge as another barrier to the widespread adoption of hydrogen technologies. Therefore, alongside policy support, concerted efforts are needed to secure the financial sustainability of the hydrogen sector, ensuring that investments are both attractive and resilient over time, paving the way for a complete shift in fully renewable solutions without overreliance on transitional technologies like blue hydrogen.

4. Solution for Green Hydrogen Promotion in Specific Sectors

In this section, we examine several promising concepts that demonstrate how hydrogen can be effectively integrated into broader energy systems, underscoring that technology, by itself, is not enough. To effectively foster the development of green hydrogen, it is essential to move beyond small-scale pilot projects and adopt strategies that enable its large-scale penetration. Since the overarching goal is to use hydrogen as a key enabler for the further expansion of renewable energy sources, it is worth highlighting some possible initiatives that could accelerate this transition. Hydrogen can act as a strategic link between renewable electricity generation and end-use sectors—such as industry, civil energy needs, and mobility—that require stable, high-energy inputs. In areas where grid capacity limits the further integration of renewables, converting surplus electricity into hydrogen offers an effective alternative to curtailment. This energy can then be redirected toward thermal use, transport, or stored for long durations—which is far beyond battery capabilities—supporting system resilience. To illustrate the dimensional implications, a simplified sizing example is proposed using a photovoltaic (PV) plant as a reference. While PV is chosen for clarity, similar logic applies to other renewable systems.

The energy production of a PV plant is dependent on the site of installations, but it can be estimated by means of the following equation:

$$E_{PV} = (\eta_{BOS} \cdot H_{SN}) \cdot P_{PV} \tag{10}$$

where H_{SN} is the typical insulation of the place expressed in kWh/kW installed for the observation period (one day, one month, one year), P_{PV} is the power of the plant, and η_{BOS} is the balance of system efficiency for the plant (typically 0.7–0.8).

The production of 1 kg of hydrogen requires a well-defined amount of energy production ($E_{el,H2}$). With current electrolysis technologies requiring around 55–60 kWh per kg of

H_2, even moderate-use scenarios imply significant energy demands and the relevant size of the plants. The size of the PV plant that is necessary to support the energy transition, producing a well-defined annual quantity of hydrogen, M_{H2}, can be evaluated based on annual energy production by means of the following equation:

$$P_{PV} = \frac{M_{H2} \cdot E_{el,H2}}{(\eta_{BOS} \cdot H_{SN})} \quad (11)$$

Vice versa, the annual mass of hydrogen produced by a well-defined plant with power, P_{PV}, can be roughly estimated using the following:

$$M_{H2} = \frac{(\eta_{BOS} \cdot H_{SN}) \cdot P_{PV}}{E_{el,H2}} \quad (12)$$

In Table 17, some data are provided to illustrate the amount of hydrogen that can be generated per installed kW peak, depending on the solar irradiation of the location. The values highlight how hydrogen production varies significantly based on solar availability, affecting the overall efficiency and yield of the system.

Table 17. Requirements for green hydrogen production with PV plants.

H_{SN} of the Site (Ideal) (kWh/kW_{peak})	Green Hydrogen Yearly Produced by PV Plants in Realistic Scenarios [kg/kW]	Min PV Surface for a kg of H_2 ($m^2/(kg_{H2}/y)$)
1230	17.89	0.27
1450	21.09	0.23
1500	21.82	0.22
1580	22.98	0.21
1860	27.05	0.18
1930	28.07	0.17
2060	29.96	0.16

4.1. Hydrogen Integration in Energy Districts

Hydrogen can also play a crucial role in energy district clusters of buildings or industrial areas with shared energy resources. In these districts, hydrogen can serve as an energy carrier that facilitates the integration of renewable energy, providing a flexible solution for both electricity and heat demand. Whether in the form of district heating or for industrial processes, hydrogen's ability to decarbonize thermal energy use is a key differentiator from other renewable solutions. Beyond these applications, a particularly promising strategy involves directing surplus renewable energy toward hydrogen production and its subsequent injection into the gas grid in regions where renewable generation exceeds grid capacity. This approach allows for an effective utilization of excess energy while maintaining the stability of the energy system. Of course, hydrogen injections must comply with existing constraints on gas network pressure and composition limits to ensure safe and efficient integration. Nevertheless, this method represents a viable pathway for enhancing the role of hydrogen in energy transition, particularly in areas facing grid saturation, as illustrated in Figure 11. Figure 11 illustrates how excess renewable energy in areas with surplus production can be converted primarily into hydrogen through electrolysis rather than being wasted by disconnecting plants. This hydrogen can then be injected into the gas grid in controlled amounts, providing a flexible means of utilizing surplus energy and enhancing grid stability.

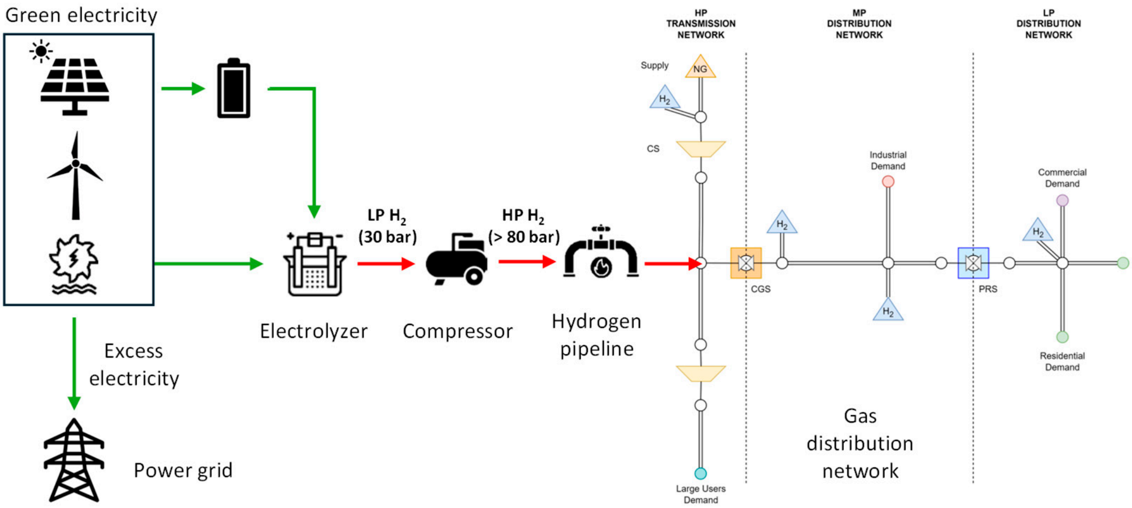

Figure 11. Hydrogen as a flexible energy carrier in district clusters, enabling renewable integration and the decarbonizing of heat, with gas–grid blending.

4.2. Supporting Industrial Decarbonization in "Hard-to-Abate" Sectors

One of the most challenging aspects of decarbonization is the industrial sector, particularly in "hard-to-abate" industries like steel, cement, and chemicals. Green hydrogen offers a direct path to decarbonize these industries, which are heavily reliant on fossil fuels for both electricity and thermal energy. In this context, the two primary pathways for integrating renewable energy into these sectors revolve around the electrification of industrial processes or the introduction of hydrogen as a key feedstock or energy carrier (Figure 12). Figure 12 illustrates a potential energy supply chain where renewable energy is directly used by an industrial user or converted into green hydrogen via electrolysis. Hydrogen can be used as a direct energy carrier, as a chemical feedstock, or for blended combustion. Importantly, only surplus electricity—which is not used by the industry or the electrolyzer—is fed into the grid. This model highlights the local, efficient use of renewable resources, aiming to maximize self-consumption and system sustainability. A particularly notable example is the steel industry, where Direct Reduced Iron (DRI) technology offers a realistic opportunity for full decarbonization, as highlighted in [20]. In this process, hydrogen can replace coal or natural gas as the reducing agent, enabling the production of steel with near-zero emissions. However, the sheer scale of hydrogen demand required for such a transformation must be carefully considered. Producing one ton of steel requires approximately 70 kg of hydrogen, meaning that a typical large-scale steel plant—often exceeding 1 million tons per year—would require hydrogen production capacities on the order of several gigawatts of dedicated renewable energy.

If hydrogen were to be used in a blended combustion approach—for instance, at levels below 20%—the overall energy demand could be slightly reduced, but it would still represent a major infrastructural and logistical challenge. Table 16 provides reference data on the renewable energy capacity required to support such an industrial transition, using photovoltaic power generation as a benchmark.

Beyond the steel sector, hydrogen remains a promising decarbonization vector due to its clean combustion and its potential to replace fossil fuels in high-temperature industrial processes. However, its adoption faces significant challenges: its high combustion velocity and lower heat transfer efficiency require careful process monitoring and adaptation, while safety concerns related to storage and handling add further complexity. Additionally, substantial modifications to existing equipment and materials are needed to mitigate issues like corrosion and material brittleness, and the intermittent nature of green hydrogen production must be addressed to ensure stable industrial operations.

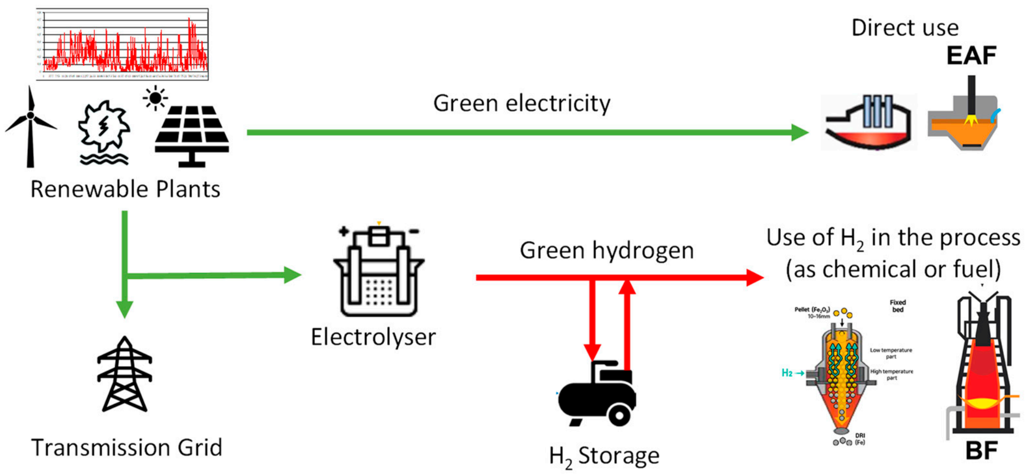

Figure 12. Hydrogen's role in supporting direct electrification for the decarbonization of hard-to-abate industrial sectors.

In general, the integration of renewable energy and hydrogen into hard-to-abate sectors is a promising avenue for decarbonization. However, it is crucial to understand the significant constraints these industries face. Large production facilities in sectors such as steel, cement, glass, and paper operate on a massive scale, with power demands often reaching several hundred MW. Table 18 provides the reference values for the energy required by some of the most energy-intensive industrial processes based on the final product. These values, derived from the literature, represent the average energy consumption figures for specific sectors. It is important to note that these values should be multiplied by the typical production volume of each facility, as energy demand can vary significantly depending on the scale and specific requirements of the production process. This approach helps contextualize the energy needs of different industries, allowing for more accurate assessments when planning for the integration of hydrogen in decarbonization strategies [20,63,64].

Table 18. Specific energy requirements for steel production processes.

Process	Specific Energy Consumption [GJ/Tons of Product]	Specific Energy Consumption [kWh/Tons of Product]
Steel BOF	18–25	5000–7000
Steel DRI–NG	13–17	3600–4700
Steel DRI–H_2	15–20	4100–5600
Cement	3–4	800–1200
Glass	4–8	1200–2400
Paper	6–8	1800–2400

The successful deployment of hydrogen in these industries will, therefore, require long-term planning, large-scale infrastructure investments, and relevant policy support.

Any effective decarbonization strategy must account for these high energy requirements and the substantial capacity of the equipment involved. A rough estimation of the scale of the necessary installations can be taken considering a photovoltaic plant as a reference. Table 17 provides a summary of the typical scale dimensions for these sectors. Understanding these dimensional benchmarks is essential for designing renewable energy and hydrogen systems that can effectively meet the large-scale energy demands of these industries.

As highlighted in the analysis of Table 19, the use of hydrogen for the decarbonization of hard-to-abate industrial sectors requires significant energy commitment due to the scale of consumption and the high power demand of production processes. To make a meaningful impact in these sectors, it is not realistic to rely on renewable energy plants dedicated to individual industries. Instead, a more systemic approach is necessary, involving integrated energy infrastructure and large-scale planning to ensure a stable and efficient hydrogen supply.

Table 19. Typical scale dimensions for hard-to-abate industrial sectors.

Industry Sector	Annual Production Capacity	Plant Power (MW)
Steel (DRI)	1 million tons/year	3000–3500 MW
Steel (Integrated)	5–10 million tons/year	3000–6000 MW
Steel (mini mills)	Several hundred thousand up to ~1 million tons/year	300–1000 MW
Cement	2–10 million tons/year	300–1500 MW
Glass	200,000–1,000,000 tons/year	100–300 MW
Paper	100,000–1,000,000 tons/year	50–350 MW

Given the substantial size of the energy requirements in these industries, the transition to green hydrogen cannot be left solely to individual industrial actors. It must be supported by appropriate strategic policies. This includes increasing the deployment of renewable energy plants in regions with significant industrial clusters, ensuring the availability and stability of the hydrogen supply, and facilitating the decarbonization of these high-demand sectors.

4.3. Hydrogen Integration with Mobility Systems

Hydrogen's potential in the mobility sector, particularly in heavy-duty transportation, is well-documented. From trucks to trains and even ships, hydrogen-powered vehicles offer a practical alternative to battery-electric solutions, especially for long-range or high-load applications. By developing a network of refueling stations and improving hydrogen fuel cell technology, we can accelerate the decarbonization of transport and reduce dependence on fossil fuels. Figure 13 schematically illustrates the potential applications of hydrogen in supporting a fleet of vehicles for specific use cases, highlighting key advantages and infrastructure requirements. The figure also outlines the integrated supply chain, beginning with renewable energy generation, followed by hydrogen production and storage, and culminating in the fueling of hydrogen-powered vehicles.

Achieving a significant impact in the transport sector requires substantial investment and a large volume of hydrogen, as demonstrated in the table below. Even under the optimistic assumption of using 2–3 kg of hydrogen per 100 km traveled, the required quantities remain considerable. Table 20 includes some dimensional parameters to help illustrate what minimal hydrogen penetration in the transport sector might entail. This analysis considers light-duty vehicles (assuming a consumption of 2 kg of hydrogen per 100 km) and heavy-duty vehicles (assuming a consumption rate that is double that of light vehicles).

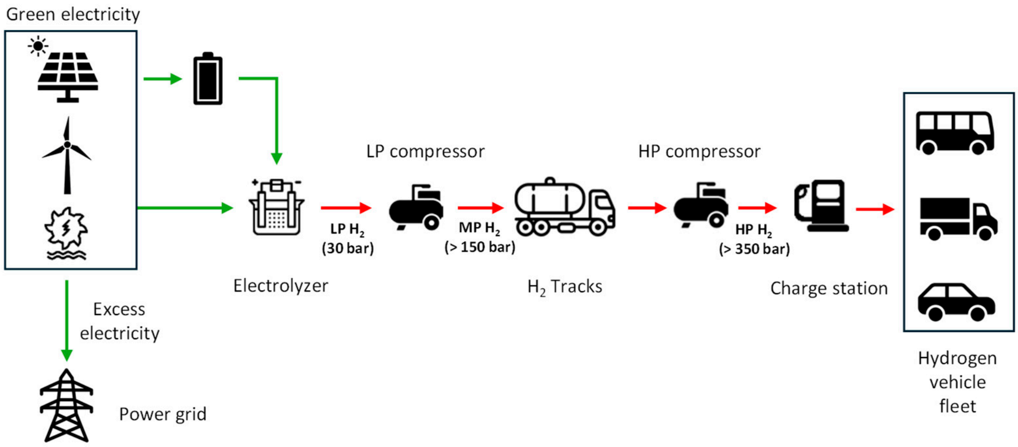

Figure 13. Hydrogen-powered vehicles for specialized applications, showcasing their role in decarbonizing heavy-duty transport with dedicated refueling infrastructure.

Table 20. Key dimensional aspects of hydrogen penetration in the private mobility sector.

Parameter	Description	Estimated Value
Vehicle annual consumption	Average hydrogen consumption per fuel cell vehicle (15,000 km/year at 2 kg/100 km)	~300 kg of H_2 per vehicle per year
Fleet requirement	Annual hydrogen requirement for a fleet of 1 million vehicles	~300,000 tons of H_2 per year
Heavy transport vehicle consumption	Average hydrogen consumption per truck (100,000 and 150,000 km/year at 3 kg/100 km)	~3000–4500 kg of H_2 per vehicle per year
Fleet requirements	Annual hydrogen requirement for a fleet of 100,000 vehicles	~400,000 tons of H_2 per year

4.4. Discussion About the Future Perspectives of Hydrogen for Decarbonizations

Although there are genuine opportunities to develop supply chains incorporating green hydrogen, it is crucial to consider the magnitude of the challenges involved. In typical scenarios, effective solutions require the deployment of high-capacity plants.

While all the approaches analyzed in the present section are conceptually interesting, assessing the actual impact and sustainability of these plant solutions requires a thorough evaluation of their producibility. It is also important to consider that before the final use, hydrogen needs to be stored (and, in general, compressed in a gaseous form). As shown in Figures 11–13, the supply chain includes a compression system capable of storing hydrogen at a pressure of at least 80 bars, ensuring compatibility with standard industrial storage and distribution requirements. The estimation of the energy required for compression can be derived by the following model, according to [18]. The minimum work needed for compression can be obtained in isothermal compression as follows:

$$l_{c,id} = R \cdot T_1 \cdot ln\left(\frac{p_2}{p_1}\right) \tag{13}$$

To obtain a realistic estimation of the work required, it will be necessary to consider the efficiency of the compression (which, according to the data available in the literature, can be estimated as 0.6) [18]. So that the specific work required can be estimated as follows:

$$l_{c,real} = \frac{l_{c,id}}{\eta_{comp}} \tag{14}$$

This is to ensure that the efficiency of the compressor phase can be estimated as 0.5–0.6 according to the main data discussed in [43]. In practical terms, such operations result in energy penalties that can reach 10–15% of the hydrogen's original energy content, depending on the pressure levels and the technologies adopted. These losses, though often underestimated, accumulate along the value chain, significantly affecting the overall system efficiency, and should be factored into any serious assessment of hydrogen's role in decarbonization strategies. As illustrated in Figure 14, due to losses occurring at various stages (production, conversion, and transportation), the energy that ultimately reaches end-use applications is significantly reduced compared to the original primary energy input. In most cases, these losses exceed 40%, meaning that only one part was effectively utilized. This limitation must be considered to avoid inefficiencies and ensure hydrogen is directed to appropriate applications. Similar considerations can be made for PV plants, wind, and hydroelectric plants, with the latter two typically operating for more hours. When evaluating the role of hydrogen, it is crucial to consider the entire energy chain. While hydrogen is increasingly regarded as a key option for decarbonizing hard-to-electrify sectors, many of the challenges that have hindered its adoption remain. Despite growing momentum driven by climate concerns and the expansion of renewable energy, hydrogen's physical and chemical properties continue to limit its scalability and economic feasibility in several applications [65].

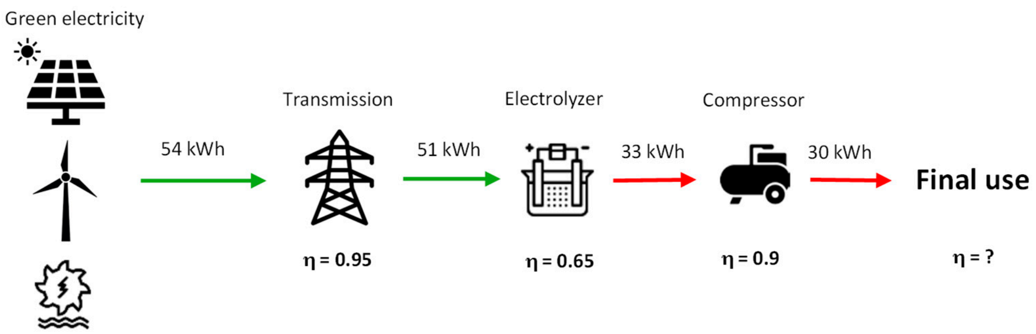

Figure 14. Energy losses across the hydrogen value chain from production to end-use applications.

Given the growing interest in hydrogen, it is essential to adopt a broader and more realistic perspective on its development. Not all hydrogen applications are equally beneficial or feasible in the short term, making it crucial to identify areas where its use can have the greatest impact. From the author's perspective, a strategic approach should focus on developing the hydrogen value chain, starting with sectors where it is already in use or where it can be a truly competitive option compared to existing alternatives. A pragmatic approach to hydrogen deployment should recognize four distinct categories of applications. The following classification outlines different hydrogen applications based on their effectiveness and feasibility according to the vision developed by the author.

Established Industrial Uses with Clear Benefits—The most effective and immediate way to reduce emissions with low-carbon hydrogen is to replace its current fossil-based production in industries where it is already essential. This includes sectors like oil refining, ammonia and methanol synthesis, and steelmaking, where hydrogen plays a fundamental role in existing processes.

Sectors with Potential but Significant Challenges—Industries, such as long-haul transport by air, sea, and heavy-duty road vehicles, could benefit from hydrogen-based solutions, but technical and cost barriers remain considerable, requiring further advancements before large-scale deployment becomes viable.

Specialized or Limited-Scale Applications—In certain contexts, hydrogen may be useful for specific energy-related purposes, such as balancing electricity grids or providing long-duration energy storage. However, its role in these areas is highly situational and dependent on technological progress and economic feasibility.

Uses with Weak Justification—Some proposed applications of hydrogen, such as its use in residential heating or passenger vehicles, appear inefficient compared to more practical and cost-effective alternatives like direct electrification through heat pumps and battery electric vehicles.

While hydrogen will undoubtedly play a role in the low-carbon transition, its deployment must be guided by realistic, evidence-based strategies focused on high-impact and cost-effective use cases. As with renewables, the early deployment of hydrogen requires strong incentives and public support to overcome current cost and infrastructure barriers. However, national approaches differ significantly, reflecting diverse industrial priorities and technological focuses. In this evolving policy landscape, more attention should be given to the economic sustainability of green hydrogen. Although current production costs range from USD 4–6/kg, significant reductions are expected due to the following:

- Electrolyzer improvements (e.g., CAPEX reduction from PEM and alkaline technologies);
- Cheaper renewable electricity (e.g., solar LCOE < USD 20/MWh);
- Scale-up effects, such as the mass manufacturing of electrolyzers and balance-of-plant systems.

At the same time, infrastructure challenges remain a major barrier. Quantitative analysis is essential to understand the energy losses from hydrogen compression or liquefaction, the cost of pipeline retrofits, and storage limitations. Without addressing these systemic issues, large-scale hydrogen deployment risks remain confined to niche applications. For an effective hydrogen policy, integration with broader energy systems goes together with clear financial roadmaps and infrastructure planning. The following references offer points of view concerning policies for green hydrogen promotion [66–68].

5. Conclusions

This study offers a dimensionally grounded overview of green hydrogen deployment, emphasizing the scale of energy demand, the infrastructure required, and the limitations of current technologies. It underlines how many proposed applications overlook the real-world constraints tied to plant sizes, conversion efficiencies, and systemic integration. Moreover, it highlights that while several innovative technologies are currently being explored in research—ranging from advanced storage methods to next-generation electrolysis systems—many of them are still far from being ready for practical, large-scale deployment. This gap between laboratory potential and industrial feasibility must be clearly acknowledged in both planning and policy design. The main contributions can be summarized as follows:

- Green hydrogen holds promise across sectors such as heavy industry, mobility, and heating, particularly where direct electrification is unfeasible.
- Current commercial technologies—like alkaline and PEM electrolysis—are available but have not yet been deployed at the scale required for systemic impact.
- The hydrogen value chain entails significant energy losses and logistical complexity, especially in storage and transport stages.

Application scenarios aiming to decarbonize energy-intensive sectors require multi-GW scale renewable inputs, which demand coordinated territorial and infrastructural planning. To move from experimental interest to real-world deployment, future work should prioritize the following points:

- Bridging the gap between promising lab-scale innovations and deployable industrial solutions.

- Improving the economic viability of green hydrogen through cost reductions in electrolyzers, improved system integration, and renewable energy pricing.
- Quantifying infrastructure trade-offs, including compression, pipeline adaptation, and energy loss across stages.
- Identifying high-impact use cases where hydrogen delivers the most value relative to alternatives.
- Strengthening policy and financial frameworks to support coherent, scalable hydrogen ecosystems—not isolated projects.

Ultimately, green hydrogen can become a key enabler of the energy transition, but only if pursued with realistic expectations, system-level thinking, and strategic prioritization.

Funding: This work was supported by the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3—Call for tender No. 1561 of 11.10.2022 of Ministero dell'Università e della Ricerca (MUR); and by the European Union—NextGenerationEU. Award Number: Project code PE0000021, Concession Decree No. 1561 of 11.10.2022 adopted by Ministero dell'Università e della Ricerca (MUR), CUP I53C22001450006, according to attachment E of Decree No. 1561/2022, Project title "Network 4 Energy Sustainable Transition—NEST".

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The author declares no conflicts of interest.

Symbols and Abbreviations

The following abbreviations are used in this manuscript:

A	Illuminated electrode area in Equation (8) [m^2]
ALK	Alkaline
BOF	Blast Oxygen Furnace
BOS	Balance of system
CAPEX	Capital expenditure [EUR]
C	Cost [EUR]
CCS	Carbon capture and storage
CGE	Cold gas efficiency
Comp	Compressor
DRI	Direct Reduction Iron
E	Energy generated [kWh]
$E_{el,H2}$	Electricity required for producing hydrogen by electrolysis [kWh/kg]
Feed	Feedstock
Fuel	Input fuel
H_2	Hydrogen
H_{SN}	Irradiance [kWh/(m^2 day)]
HP	High pressure
Hyd	Reference cost of hydrogen [EUR/kg]
I_{sun}	Specific solar power input [W/m^2]
ICE	Internal Combustion Engines
lc,id	Specific work for compression, ideal value [kJ/kg]
lc,real	Specific work for compression, real value [kJ/kg]
LCOE	Levelized cost of energy [EUR/kWh]
LCOH	Levelized cost of hydrogen [EUR/kg]
LHV	Lower heating value
LP	Low pressure
$\dot{m}$	Mass flow rate [kg/s]

M	Mass [kg]
Mech	Mechanical
N	Lifetime of the project [years]
NG	Natural gas
NPV	Net present value [EUR]
O&M	Operation and management
OPEX	Operational expenditure [EUR]
P_{PV}	Power of photovoltaic plants [W]
P	Pressure [bar]
PEC	Photo Electro Chemical
PEM	Polymer Electrolyte Membrane
Proj	Project
PV	Photovoltaic
R	Constant of the gas [J/kg K]
RES	Renewable energy systems
S	Surface [m^2]
SEC	Specific electricity consumption [kWh/mass]
SMR	Steam Methane Reforming
SO	Solid oxide
STH	Solar to Hydrogen
T	Temperature [K]
Vap	Vapor
Y_{H2}	Yield of hydrogen [mol/s]
ΔG	Gibbs free energy [J/mol]
Ψ	Generic efficiency parameter
η	Efficiency

References

1. Bockris, J.O.M. A hydrogen economy. *Science* **1972**, *176*, 1323. [CrossRef]
2. Marchetti, C. On hydrogen and energy systems. *Int. J. Hydrogen Energy* **1976**, *1*, 3–10. [CrossRef]
3. Winter, C.J.; Klaiβ, H.; Nitsch, J. Hydrogen as an energy carrier: What is known? What do we need to learn? A consideration of the parameters. *Int. J. Hydrogen Energy* **1990**, *15*, 79–91. [CrossRef]
4. Mitsugi, C.; Harumi, A.; Kenzo, F. WE-NET: Japanese hydrogen program. *Int. J. Hydrogen Energy* **1998**, *23*, 159–165. [CrossRef]
5. Veziroğlu, T.N. Quarter century of hydrogen movement 1974–2000. *Int. J. Hydrogen Energy* **2000**, *25*, 1143–1150. [CrossRef]
6. Rifkin, J. The Hydrogen Economy: The Creation of the Worldwide Energy Web and the Redistribution of Power on Earth. Jeremy, P., Ed.; Tarcher/Penguin: New York, NY, USA, 2003.
7. Andrews, J.; Shabani, B. Re-envisioning the role of hydrogen in a sustainable energy economy. *Int. J. Hydrogen Energy* **2012**, *37*, 1184–1203. [CrossRef]
8. European Commission. The European Green Deal, Striving to Be the First Climate-Neutral Continent. Available online: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (accessed on 30 January 2025).
9. European Council of the European Union. Fit for 55. Available online: https://www.consilium.europa.eu/en/policies/fit-for-55/ (accessed on 30 January 2025).
10. IEA. IEA World Energy Statistics & Balances, International Energy Agency. Available online: www.iea.org/data-andstatistics/data-product/world-energy-balances (accessed on 30 January 2025).
11. IRENA. Renewable Energy Statistics 2024, International Renewable Energy Agency, Abu Dhabi. Available online: www.irena.org/Publications/2024/Jul/Renewable-energy-statistics-2024 (accessed on 30 January 2025).
12. REN21. Renewables 2024 Global Status Report, Renewable Energy Policy Network for the 21st Century. Available online: www.ren21.net/gsr-2024/modules/global_overview (accessed on 30 January 2025).
13. Ritchie, H.; Rosado, P.; Roser, M. Energy. Published Online at OurWorldinData.org. Available online: https://ourworldindata.org/energy (accessed on 30 January 2025).
14. The Engineering ToolBox. Hydrogen-Density and Specific Weight vs. *Temperature and Pressure.* Available online: https://www.engineeringtoolbox.com/hydrogen-H2-density-specific-weight-temperature-pressure-d_2044.html (accessed on 3 February 2025).

15. NEST. Network for Energy Transitions, Spoke 4, Clean Hydrogen and Finale Uses. Available online: https://fondazionenest.it/spoke/clean-hydrogen-and-final-uses/ (accessed on 23 February 2025).
16. Burchardt, J.; Hegnsholt, E.; Holm, M.; Klose, F.; Ritter, D.; Schonberger, S. Turning the European Green Hydrogen Dream into Reality: A call to action—Without additional regulatory support, European green hydrogen may remain the fuel of the future. In *White Paper*; Boston Consulting Group: Sydney, Australia, 2023.
17. Aghakhani, A.; Haque, N.; Saccani, C.; Pellegrini, M.; Guzzini, A. Hydrogen transportation and distribution. In Towards Hydrogen Infrastructure. Elsevier: Amsterdam, The Netherlands; pp. 187–224.
18. Franco, A.; Giovannini, C. Routes for Hydrogen Introduction in the Industrial Hard-to-Abate Sectors for Promoting Energy Transition. *Energies* **2023**, *16*, 6098. [CrossRef]
19. Franco, A.; Rocca, M. Renewable electricity and green hydrogen integration for decarbonization of "hard-to-abate" industrial sectors. *Electricity* **2024**, *5*, 471–490. [CrossRef]
20. Franco, A.; Carcasci, C.; Ademollo, A.; Calabrese, M.; Giovannini, C. Integrated Plant Design for Green Hydrogen Production and Power Generation in Photovoltaic Systems: Balancing Electrolyzer Sizing and Storage. *Hydrogen* **2025**, *6*, 7. [CrossRef]
21. Jones, L.W. Liquid Hydrogen as a Fuel for the Future: Replacement of hydrocarbon fuel for transportation systems by liquid hydrogen is proposed and discussed. *Science* **1971**, *174*, 367–370. [CrossRef]
22. Dicks, A.L. Hydrogen generation from natural gas for the fuel cell systems of tomorrow. *J. Power Sources* **1996**, *61*, 113–124. [CrossRef]
23. Bannister, R.L.; Newby, R.A.; Yang, W.C. Final report on the development of a hydrogen-fueled combustion turbine cycle for power generation. *J. Eng. Gas Turb. Power* **1999**, *121*, 1. [CrossRef]
24. Turner, J.A. Sustainable hydrogen production. *Science* **2004**, *305*, 972–974. [CrossRef]
25. European Union Agency for the Cooperation of Energy Regulators. *European Hydrogen Observatory—The European Hydrogen Market Landscape—Report 01*; European Union Agency for the Cooperation of Energy Regulators: Ljubljana, Slovenia, 2024.
26. Posseme, B.; Paulin, F.; Boillet, C.; Gouret, M.; Mantulet, G.; Abbas, A. *Energy System Infrastructures and Investments in Hydrogen. European Parliament—Policy Department for Economic*; Scientific and Quality of Life Policies Directorate-General for Internal Policies: Brussels, Belgium, 2024; PE 754.207.
27. International Energy Agency (IEA). *Global Hydrogen Review*; International Energy Agency: Paris, France, 2023.
28. International Energy Agency. *Hydrogen Production and Infrastructure Projects Database*; International Energy Agency: Paris, France, 2023.
29. Hydrogen Europe. *Clean Hydrogen Production Pathways*; Hydrogen Europe: Brussels, Belgium, 2024.
30. Capurso, T.; Stefanizzi, M.; Torresi, M.; Camporeale, S.M. Perspective of the role of hydrogen in the 21st century energy transition. *Energy Convers. Manag.* **2022**, *251*, 114898. [CrossRef]
31. Franco, A.; Giovannini, C. Recent and future advances in water electrolysis for green hydrogen generation: Critical Analysis and Perspectives. *Sustainability* **2023**, *15*, 16917. [CrossRef]
32. Cárdenas, R.; Alfonso, D.; Peñalvo, E.; Perez-Navarro, A.; Perpiñá, C.; Vargas, C. Potential For Hydrogen Production From Biomass Residues in the Valencian Community. In Conference Proceedings, 2007; Volume 98. Available online: https://h2tools.org/bibcite/reference/4658 (accessed on 18 April 2025).
33. Xu, X.; Zhou, Q.; Yu, D. The future of hydrogen energy: Bio-hydrogen production technology. *Int. J. Hydrogen Energy* **2022**, *47*, 33677–33698. [CrossRef]
34. Modarresi, A.; Wukovits, W.; Friedl, A. Exergy analysis of biological hydrogen production. In *Computer Aided Chemical Engineering*; Elsevier: Amsterdam, The Netherlands, 2008; Volume 25, pp. 1137–1142.
35. Walter, M.G.; Warren, E.L.; McKone, J.R.; Boettcher, S.W.; Mi, Q.; Santori, E.A.; Lewis, N.S. Solar water splitting cells. *Chem. Rev.* **2010**, *110*, 6446–6473. [CrossRef] [PubMed]
36. Zhao, Y.; Niu, Z.; Zhao, J.; Xue, L.; Fu, X.; Long, J. Recent advancements in photoelectrochemical water splitting for hydrogen production. *Electrochem. Energy Rev.* **2023**, *6*, 14. [CrossRef]
37. Qureshi, F.; Tahir, M. Photoelectrochemical water splitting with engineering aspects for hydrogen production: Recent advances, strategies and challenges. *Int. J. Hydrogen Energy* **2024**, *69*, 760–776. [CrossRef]
38. Imran, S.; Hussain, M. Emerging trends in water splitting innovations for solar hydrogen production: Analysis, comparison, and economical insights. *Int. J. Hydrogen Energy* **2024**, *77*, 975–996. [CrossRef]
39. Zheng, Y.; Wang, J.; Yu, B.; Zhang, W.; Chen, J.; Qiao, J.; Zhang, J. A review of high temperature co-electrolysis of H_2O and CO_2 to produce sustainable fuels using solid oxide electrolysis cells (SOECs): Advanced materials and technology. *Chem. Soc. Rev.* **2017**, *46*, 1427–1463. [CrossRef] [PubMed]
40. Graves, C.; Ebbesen, S.D.; Mogensen, M.; Lackner, K.S. Sustainable hydrocarbon fuels by recycling CO_2 and H_2O with renewable or nuclear energy. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1–23. [CrossRef]

41. Zong, S.; Zhao, X.; Jewell, L.L.; Zhang, Y.; Liu, X. Advances and challenges with SOEC high temperature co-electrolysis of CO_2/H_2O: Materials development and technological design. *Carbon Capture Sci. Technol.* **2024**, *12*, 100234. [CrossRef]
42. Reichelt, E.; Herz, G.; Jahn, M. Co-electrolysis. In *Powerfuels*; Springer: Cham, Switzerland, 2025; pp. 539–564.
43. Franco, A.; Giovannini, C. Hydrogen gas compression for efficient storage: Balancing energy and increasing density. *Hydrogen* **2024**, *5*, 293–311. [CrossRef]
44. Khan, M.A.; Young, C.; Mackinnon, C.; Layzell, D.B. The techno-economics of hydrogen compression. *Transit. Accel. Tech. Briefs* **2021**, *1*, 1–36.
45. Ozturk, M.; Sorgulu, F.; Javani, N.; Dincer, I. An experimental study on the environmental impact of hydrogen and natural gas blend burning. *Chemosphere* **2023**, *329*, 138671. [CrossRef]
46. Wang, H.; Tong, Z.; Zhou, G.; Zhang, C.; Zhou, H.; Wang, Y.; Zheng, W. Research and demonstration on hydrogen compatibility of pipelines: A review of current status and challenges. *Int. J. Hydrogen Energy* **2022**, *47*, 28585–28604. [CrossRef]
47. Huang, H.; Sun, X.; Li, J.; Yu, B.; Wang, X.; Pu, M.; Ma, L. Economic analysis of blending hydrogen into natural gas pipelines: Supply chain and station modification. *Int. J. Hydrogen Energy* **2025**, *118*, 300–311. [CrossRef]
48. Erdener, B.C.; Sergi, B.; Guerra, O.J.; Chueca, A.L.; Pambour, K.; Brancucci, C.; Hodge, B.M. A review of technical and regulatory limits for hydrogen blending in natural gas pipelines. *Int. J. Hydrogen Energy* **2023**, *48*, 5595–5617. [CrossRef]
49. Ademollo, A.; Mati, A.; Pagliai, M.; Carcasci, C. Exploring the role of hydrogen in decarbonizing energy-intensive industries: A techno-economic analysis of a solid oxide fuel cell cogeneration system. *J. Clean. Prod.* **2024**, *469*, 143254. [CrossRef]
50. Mati, A.; Ademollo, A.; Carcasci, C. Assessment of paper industry decarbonization potential via hydrogen in a multi-energy system scenario: A case study. *Smart Energy* **2023**, *11*, 100114. [CrossRef]
51. Bonacina, C.N.; Romano, M.C.; Colbertaldo, P.; Milocco, A.; Valenti, G. Techno-economic study of chimneyless electric arc furnace plants for the coproduction of steel and of electricity, hydrogen, or methanol. *J. Clean. Prod.* **2024**, *468*, 143048. [CrossRef]
52. Groppi, D.; Pastore, L.M.; Nastasi, B.; Prina, M.G.; Garcia, D.A.; de Santoli, L. Energy modelling challenges for the full decarbonisation of hard-to-abate sectors. *Renew. Sustain. Energy Rev.* **2025**, *209*, 115103. [CrossRef]
53. Sgaramella, A.; Pastore, L.M.; Basso, G.L.; Mojtahed, A.; de Santoli, L. HCNG refuelling station to accelerate the transition towards a real hydrogen economy: A techno-economic analysis. *Int. J. Hydrogen Energy* **2024**, *69*, 1403–1416. [CrossRef]
54. Lanni, D.; Di Cicco, G.; Minutillo, M.; Cigolotti, V.; Perna, A. Techno-economic assessment of a green liquid hydrogen supply chain for ship refueling. *Int. J. Hydrogen Energy* **2025**, *97*, 104–116. [CrossRef]
55. Genovese, M.; Cigolotti, V.; Jannelli, E.; Fragiacomo, P. Current standards and configurations for the permitting and operation of hydrogen refueling stations. *Int. J. Hydrogen Energy* **2023**, *48*, 19357–19371. [CrossRef]
56. Abdin, Z. Empowering the hydrogen economy: The transformative potential of blockchain technology. *Renew. Sustain. Energy Rev.* **2024**, *200*, 114572. [CrossRef]
57. Ramaiyan, K.; Tsui, L.K.; Brosha, E.L.; Kreller, C.; Stetter, J.R.; Russ, T.; Du, W.; Peaslee, D.; Hunter, G.; Xu, J.; et al. Recent developments in sensor technologies for enabling the hydrogen economy. *ECS Sens. Plus* **2023**, *2*, 045601. [CrossRef]
58. Lotrič, A.; Sekavčnik, M.; Kuštrin, I.; Mori, M. Life-cycle assessment of hydrogen technologies with the focus on EU critical raw materials and end-of-life strategies. *Int. J. Hydrogen Energy* **2021**, *46*, 10143–10160. [CrossRef]
59. Harichandan, S.; Kar, S.K. Financing the hydrogen industry: Exploring demand and supply chain dynamics. *Environ. Sci. Pollut. Res.* **2023**, 1–18. [CrossRef]
60. Europen Hydrogen Observatory. The European Hydrogen Market Landscape. Available online: https://observatory.clean-hydrogen.europa.eu/sites/default/files/2024-11/The%20European%20hydrogen%20market%20landscape_November%202024.pdf (accessed on 18 April 2025).
61. BloombergNEF. Hydrogen Market Outlook. Available online: https://euhydrogenweek.eu/wp-content/uploads/2023/12/Adithya-Bhashyam-Associate-%E2%80%93-Hydrogen-BloombergNEF.pdf (accessed on 18 April 2025).
62. IEA. Levelised Cost of Hydrogen Maps. Available online: https://www.iea.org/data-and-statistics/data-tools/levelised-cost-of-hydrogen-maps (accessed on 10 April 2025).
63. Franco, A.; Miserocchi, L.; Testi, D. Energy indicators for enabling energy transition in industry. *Energies* **2023**, *16*, 581. [CrossRef]
64. Miserocchi, L.; Franco, A.; Testi, D. An integrated framework for energy performance improvement in manufacturing: From mapping to optimization. *J. Clean. Prod.* **2023**, *411*, 137387. [CrossRef]
65. Wakim, G.; Tovar, M. Hydrogen for Decarbonization A Realistic Assessment. Available online: https://www.catf.us/resource/hydrogen-decarbonization-realistic-assessment/ (accessed on 18 April 2025).
66. European Commission. *Hydrogen Roadmap for Europe.* Available online: https://energy.ec.europa.eu/system/files/2020-07/hydrogen_strategy_0.pdf (accessed on 4 April 2025).

67. IEA. The Future of Hydrogen: Seizing Today's Opportunities. Available online: https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf (accessed on 4 April 2025).
68. Islam, A.; Islam, T.; Mahmud, H.; Raihan, O.; Islam, M.S.; Marwani, H.M.; Rahman, M.M.; Asiri, A.M.; Hasan, M.; Hasan, N.; et al. Accelerating the green hydrogen revolution: A comprehensive analysis of technological advancements and policy interventions. *Int. J. Hydrogen Energy* **2024**, *67*, 458–486. [CrossRef]