Green Energy and Fuel Research

Review

Advancing Hydrogen Development from 2015 to 2024 and Mitigating No_x Emissions from Hydrogen-Enriched Combustion for a Cleaner Energy Future

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Abstract: This study explores hydrogen energy's transformative role in achieving net-zero greenhouse gas emissions, focusing on mitigating nitrogen oxides (NO_x), a byproduct of hydrogen-enriched fuel combustion. Driven by rapid growth in hydrogen research from 2015 to 2024, it highlights hydrogen's potential to address critical energy and environmental challenges. Hydrogen production is classified into thermolysis, biophotolysis, electrolysis, and photoelectrochemical processes, with distinct energy sources and outputs. Color codes denote hydrogen types: green (electrolysis using renewables), blue (carbon capture in natural gas reforming), gray (no carbon capture), pink (nuclear-powered), and turquoise (methane decomposition). By 2050, green hydrogen, aligned with decarbonization goals and declining costs, is expected to dominate the market, while blue hydrogen will act as a transitional source. The paper emphasizes the importance of hydrogen pricing, regional production cost disparities, and strategic investments to enhance low-emission hydrogen competitiveness. However, a major challenge is increased NO_x emissions from higher combustion temperatures. This study reviews key mitigation strategies, including hydrogen-natural gas blending, staged combustion, exhaust gas recirculation (EGR), and post-combustion measures such as Selective Catalytic Reduction (SCR). Among these, EGR effectively lowers peak combustion temperatures, while staged combustion optimizes fuel-air mixing to minimize NO_x formation. Additionally, SCR remains one of the most efficient post-combustion solutions, reducing NO_x emissions by over 80% in various applications. This study demonstrates how these strategies can maximize hydrogen's energy potential while minimizing environmental impacts.

Keywords: hydrogen; combustion challenges; sustainability; net zero; nitrogen oxides (NO_x)

1. Trends in Hydrogen Technology Research for Net Zero Emission

The significance of hydrogen energy research has surged over the past decade, as demonstrated by the marked escalation in the number of publications on the subject between 2015 and 2024. Hydrogen is progressively acknowledged as a cornerstone in the transition to a sustainable energy future, providing a clean, versatile, and adaptable energy vector for diverse applications. Data retrieved from the ScienceDirect platform using the keyword "hydrogen production" reveals an extraordinary increase in research and review articles, with the total number of publications surging from 32,224 in 2015 to 111,618 in 2024. This remarkable growth underscores the global emphasis on hydrogen as a fundamental pillar for addressing critical energy, environmental, and societal challenges. Hydrogen possesses immense potential to drive decarbonization across industrial processes, transportation, and energy storage, thereby catalyzing heightened interest among researchers, industry leaders, and policymakers globally. The sustained focus on hydrogen technology, as evidenced by the growth in both fundamental research and applied studies, underscores its pivotal role in fostering a cleaner, more resilient energy infrastructure. Future advancements are expected to drive groundbreaking innovations, solidifying hydrogen's position as an indispensable component of global energy strategies [1]. The data was most recently updated on 7 December 2024, with detailed results presented in Figure 1.

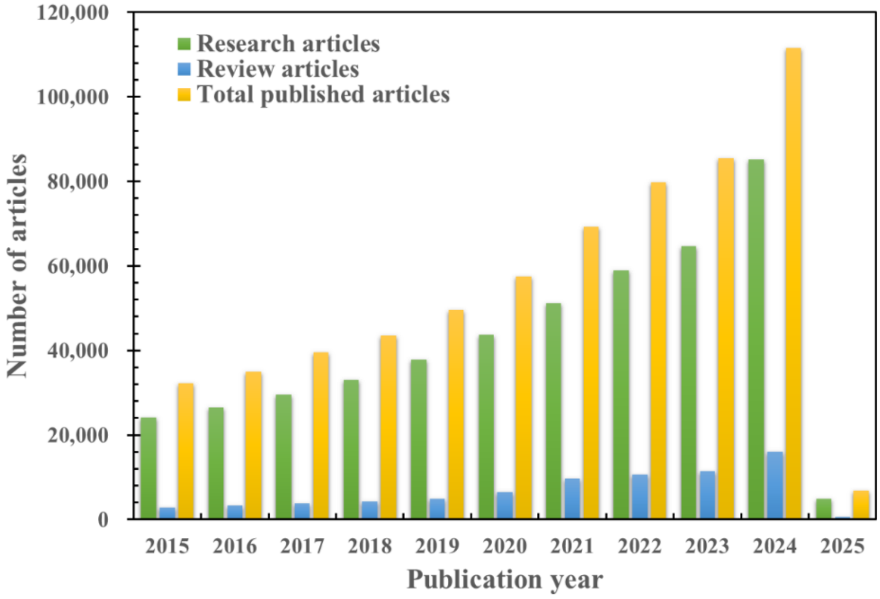

Figure 1. Number of articles published per year from 2015 to 2024 by December.

The network visualization illustrated in Figure 2 offers an in-depth and systematic overview of the interrelated topics and thematic areas within hydrogen energy research. These themes are derived from publications indexed in the Science Direct platform in 2024, with data retrieved on 7 December 2024. Leveraging keywords extracted from these publications, this analysis elucidates the complex interconnections among diverse topics pertaining to hydrogen production. The distinct colors in the figure denote discrete research clusters, emphasizing the interconnectedness and mutual influence across various domains. The varying sizes of lines and nodes signify the strength of these relationships, with larger nodes and thicker lines denoting stronger connections or greater influence within the research landscape. The red cluster encapsulates themes predominantly centered on the integration of hydrogen energy with renewable resources and the associated challenges of hydrogen storage. Prominent topics, including "solar power generation", "carbon dioxide", and "biomass", underscore significant research endeavors aimed at integrating solar energy and biomass for hydrogen production while addressing carbon dioxide emissions [2,3]. The node for "hydrogen storage" exemplifies sustained efforts to address challenges surrounding safe and efficient storage methods, which persist as a critical barrier to the widespread adoption of hydrogen as an energy carrier. Subtopics such as "gasification", "energy efficiency", and "economic analysis" indicate that researchers are increasingly focusing on the financial viability and energy yield of these processes. The green cluster, centered on "photocatalysis" and "photocatalytic activity", illustrates an increasing emphasis on utilizing light-driven processes for hydrogen production. Key terms such as "heterojunctions", "photocatalytic hydrogen", and "light absorption" underscore advancements in the understanding and optimization of photocatalytic materials aimed at enhancing the efficiency of hydrogen production by directly harnessing solar energy [4]. This area is closely tied to the increasing global interest in sustainable and environmentally friendly hydrogen production methods. The inclusion of terms such as "charge separation" and "active site" highlights the technical sophistication of this research, with substantial efforts dedicated to optimizing materials at the nanoscale to enhance their solar energy utilization efficiency. The blue cluster, featuring terms such as "catalyst activity", "density functional theory", and "oxidation", underscores a pronounced focus on the foundational aspects of catalyst development for hydrogen production. This cluster delves into the intricate mechanisms underpinning catalytic reactions, with significant efforts devoted to optimizing catalysts for enhanced efficiency in water splitting or processing hydrogen-enriched feedstocks. The prominence of "density functional theory" (DFT) underscores the critical role of computational approaches in predicting the properties of novel catalytic materials, enabling researchers to model and refine catalysts prior to experimental validation [5]. The yellow cluster, dominated by terms such as "electrolysis", "electrocatalysts", and "water splitting", highlights research efforts centered on hydrogen production through electrochemical methodologies. The node sizes within this cluster reflect their significant influence, underscoring the pivotal role of electrolysis as a foundational technology for hydrogen production.

The inclusion of terms such as "electrolyzers", "oxygen evolution reaction", and "water electrolysis" underscores the critical importance of enhancing electrolysis efficiency while minimizing associated costs.

Significant attention is directed toward the development of advanced electrocatalysts capable of reducing the energy requirements for water splitting, thereby enhancing the economic viability of the process [6]. The interconnectedness of these clusters is visually represented by numerous lines linking nodes across different colored regions, signifying an extensive degree of interdisciplinary research. For instance, the connection between "carbon dioxide" within the red cluster and "electrocatalysts" in the yellow cluster likely reflects efforts to convert carbon dioxide into value-added chemicals or to integrate carbon capture with hydrogen production processes. Likewise, the linkage between "photocatalysis" and "electrocatalysts" suggests the emergence of hybrid technologies that integrate photochemical and electrochemical processes, marking a promising trajectory for future research.

The keyword interaction analysis derived from this network visualization reveals the extensive scope and profound depth of hydrogen energy research. The interconnectedness of diverse themes, such as solar power generation, photocatalysis, electrolysis, and catalyst activity, underscores the inherently interdisciplinary nature of ongoing research efforts. Research initiatives are explicitly directed toward addressing the technical and economic challenges intrinsic to hydrogen production, encompassing efforts to enhance catalyst efficiency, integrate renewable energy sources, optimize storage solutions, and reduce production costs to bolster economic feasibility. Each cluster delineates a critical pathway for advancing hydrogen technology, while the robust interconnections among them underscore the indispensable collaborative approach required to surmount the multifaceted challenges of positioning hydrogen as a cornerstone of a sustainable energy future.

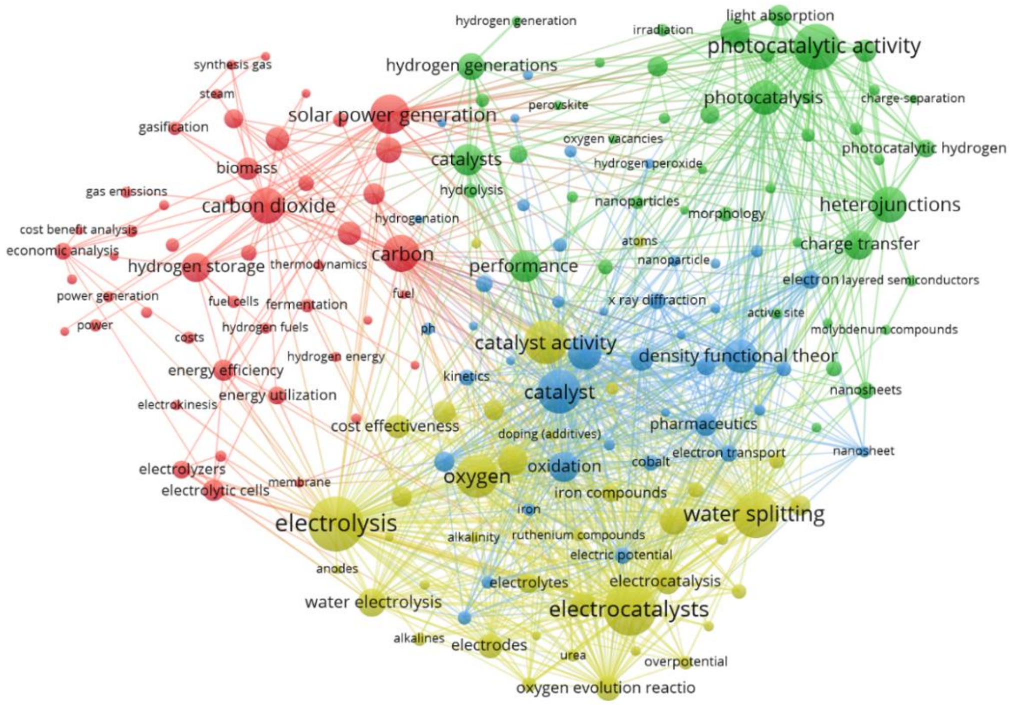

Figure 2. Keyword network of VOSviewer application papers (the frequency of words is not less than 50 times, and there are 172 keywords in total).

2. Hydrogen Production Through Four Technologies with Chemical Reactions

Figure 3 delineates four principal technologies for hydrogen production: thermolysis, biophotolysis, electrolysis, and photo-electrochemical processes [7]. Each of these technologies leverages a distinct energy source: thermal energy for thermolysis, microorganism metabolism for biophotolysis, electrical energy for electrolysis, and solar energy for photo-electrochemical processes.

Thermochemical processes encompass several well-established methodologies, including steam reforming, partial oxidation, autothermal reforming, gasification, and thermal decomposition. In the United States, approximately 95% of hydrogen production is achieved through steam methane reforming. This statistic clearly demonstrates the high level of technological maturity and commercial viability of SMR for hydrogen production [8]. These methodologies commonly produce hydrogen alongside carbon dioxide (CO_2) as a byproduct [9,10]. If this CO_2 is not subjected to carbon capture, utilization, and storage (CCUS) but is instead released directly into the atmosphere, the resulting hydrogen is classified as brown or gray hydrogen. Conversely, when CCUS is implemented, the hydrogen is categorized as blue hydrogen. Notably, the thermal decomposition of methane presents an alternative pathway, wherein methane is decomposed into solid carbon and hydrogen, yielding what is known as turquoise hydrogen. Biophotolysis processes include both photofermentative and dark fermentative methodologies [11]. Hydrogen generated through photofermentative processes is classified as green hydrogen owing to its environmentally sustainable nature. Conversely, dark fermentative processes yield methane, which can subsequently be decomposed to produce either blue or turquoise hydrogen, contingent upon whether CCUS is implemented or solid carbon is recovered.

Electrolysis processes comprise three primary methodologies: alkaline water electrolysis (AWE), proton exchange membrane electrolysis (PEME), and solid oxide electrolysis (SOE). When driven by renewable energy sources, the hydrogen generated via these methods is classified as green hydrogen [12]. Currently, there are two main types of electrolyzer technologies available: one is the alkaline electrolyzer, a simple system with a history spanning over a century, and the other is the proton exchange membrane (PEM) electrolyzer, a more complex system that requires significant amounts of precious metals such as iridium and titanium. Recently, Enapter has successfully developed an anion exchange membrane (AEM) electrolyzer, which converts renewable electricity and water into green hydrogen (H_2) for storage. The AEM electrolyzer combines the advantages of both the alkaline and PEM systems—offering convenience and robustness without the extensive use of precious metals—and its modular stackability makes it well-suited for large-scale production [13]. If nuclear power is utilized to produce the electricity required for electrolysis, the resulting hydrogen is designated as pink hydrogen. Although other hydrogen production techniques exist, this manuscript specifically concentrates on hydrogen production via chemical reaction processes.

To provide a clearer understanding of the feasibility and scalability of hydrogen production technologies, we summarize the Technology Readiness Level (TRL) and commercialization status for each method. Thermolysis, particularly Steam Methane Reforming (SMR), is the most mature technology, with a TRL of 9 (fully commercialized). SMR accounts for approximately 95% of global hydrogen production and is widely applied in industrial settings [14–16]. Biophotolysis, on the other hand, remains in the research and development phase, with a TRL of 4–5 (lab-scale to pilot-scale) [17]. While promising, it faces challenges in efficiency and scalability, limiting its current commercialization to pilot-scale demonstrations. For electrolysis, Alkaline Water Electrolysis (AWE) has a TRL of 8–9 (commercialized) and is well-established in industries requiring high-purity hydrogen [18]. Proton Exchange Membrane Electrolysis (PEME) has a TRL of 7–8 (demonstration to early commercialization) and is gaining traction, particularly in renewable energy integration, though high costs and material requirements hinder widespread adoption [19,20]. Solid Oxide Electrolysis (SOE), with a TRL of 6–7 (pilot to demonstration phase), shows potential for high efficiency but faces challenges related to durability and high operating temperatures [21]. Finally, photoelectrochemical processes are in the early stages of development, with a TRL of 3–4 (lab-scale to early prototype). This method requires significant advancements in material science and efficiency to achieve commercialization. These insights highlight the varying stages of technological maturity and the challenges that must be addressed to scale up hydrogen production methods for broader adoption [12].

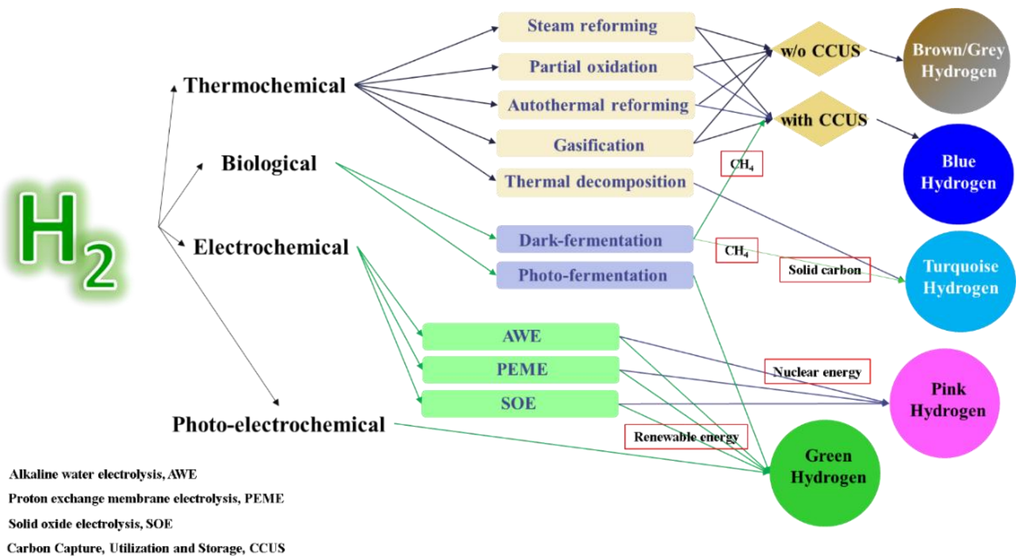

Figure 3. Four hydrogen production pathways.

3. 2050 Hydrogen Usage Projections by Color

The future utilization of hydrogen, categorized by its distinct color codes, is anticipated to undergo substantial evolution by 2050 and beyond as nations advance decarbonization and sustainable energy strategies. Hydrogen is classified into distinct types—green, blue, gray, and pink, and turquoise hydrogen—based on production methods and technologies involved [22]. Each type represents a unique approach to energy production, spanning renewable to fossil fuel-based sources, thereby shaping their projected roles in the future energy landscape. green hydrogen, produced through the electrolysis of water using renewable electricity, is projected to emerge as the predominant form of hydrogen by 2050 and beyond. This trend aligns with global initiatives aimed at reducing carbon footprints and attaining net-zero emissions. The rapid expansion of renewable energy sources, including wind and solar power, is expected to ensure the availability of clean electricity, thereby driving the large-scale adoption of green hydrogen, particularly in sectors such as heavy industry, transportation, and energy storage [23]. The scaling up of electrolyzer technologies, coupled with declining renewable energy costs, is anticipated to propel this growth, positioning green hydrogen as an indispensable pillar of a sustainable energy future. Blue hydrogen is produced via natural gas reforming integrated with CCUS to reduce carbon emissions. As illustrated in Figure 4, this process encompasses indicative hydrogen production pathways from natural gas, biomass, and electrolysis powered by renewable energy.

Blue hydrogen is anticipated to serve as a pivotal transitional energy source through 2050, bridging the gap between fossil fuel-derived hydrogen and fully renewable green hydrogen. Additionally, biomass-derived hydrogen integrated with CCUS technology is also categorized as blue hydrogen [24]. This approach offers a renewable carbon source while ensuring effective carbon capture and storage, thereby enhancing the overall sustainability of hydrogen production. The ease of obtaining biomass, sourced from agricultural waste, planned forestry, bamboo, or other fast-growing plants, is a key advantage of this approach. This method of hydrogen production can partially augment the hydrogen supply, positioning it as a sustainable alternative. Gray hydrogen, produced from fossil fuels without capturing associated CO_2 emissions, is projected to decline substantially by 2050 as global efforts to reduce greenhouse gas emissions intensify [25]. Currently dominating global hydrogen production, gray hydrogen is likely to become less economically viable in the coming decades due to stringent climate policies and carbon pricing mechanisms. Similarly, Pink hydrogen, derived from nuclear power, may find niche applications in regions where nuclear energy constitutes a significant portion of the energy mix. It could offer a stable, low-carbon alternative to renewable-powered electrolysis, particularly in regions with constrained access to renewable energy resources.

The utilization of hydrogen categorized by color codes in 2050 and beyond will mirror the global decarbonization trajectory, marking a decisive shift from fossil fuel-based hydrogen (gray and blue) to renewable-based green hydrogen [26]. This transition will be propelled by advancements in renewable energy technologies, economic incentives, and the growing demand for sustainable industrial processes. Blue hydrogen is expected to serve as an interim solution, whereas pink hydrogen may offer alternative, region-specific pathways to achieving decarbonization.

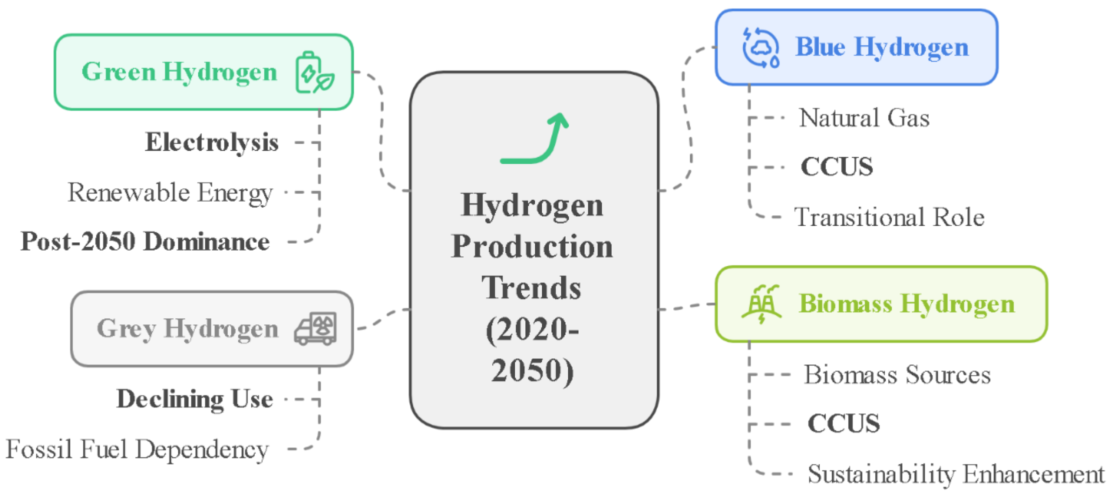

Figure 4. Hydrogen production trends and transition pathways (2020–2050).

4. The Impact of Hydrogen Costs on Its Adoption

Pricing is poised to play a critical role in shaping the future application and adoption of different types of hydrogen, particularly those projected to have greater market potential in the future: gray, blue, green, and biomass-derived (yellow) hydrogen. The *IEA Global Hydrogen Review 2024* provides a comprehensive cost outlook for each hydrogen production method, emphasizing the economic factors and regional disparities that define the competitiveness of various hydrogen types [27]. The report presents an in-depth analysis of hydrogen production costs, underscoring the pivotal roles of regional resources, policy incentives, and technological readiness in shaping hydrogen's economic landscape. The subsequent discussion delves into specific factors bearing on the costs of gray, blue, green, and yellow hydrogen across different regions of the world, as outlined in Table 1. The cost projections presented in Table 1 reflect estimated prices for hydrogen production by the year 2030, based on anticipated technological advancements and policy-driven cost reductions. These estimates account for declining renewable energy costs, scaling of electrolyzer technology, and the expansion of carbon capture utilization and storage (CCUS) infrastructure, which are expected to significantly impact hydrogen economics over the next decade.

The report highlights gray hydrogen, derived from unabated natural gas reforming, as one of the most economically viable production pathways. However, the cost of gray hydrogen is heavily influenced by natural gas prices, which exhibit significant regional variation. For instance, in the United States, where natural gas supplies are abundant, gray hydrogen production costs range from USD 0.8 to 1.5 per kg H_2. In contrast, in Europe, characterized by higher and more volatile natural gas prices, costs range between USD 1 and 5.7 per kg H_2. This pronounced regional variation renders gray hydrogen more economically viable in gas-rich regions but presents challenges in areas with elevated energy costs, thereby incentivizing these regions to explore lower-emission alternatives.

Blue hydrogen, produced via natural gas reforming integrated with CCUS, exhibits a cost structure that is highly sensitive to the efficiency and expense of CCUS infrastructure. In the Middle East, where natural gas is inexpensive and CCUS infrastructure is well-established, blue hydrogen production costs are among the lowest globally, estimated at USD 1.5 to 2 per kg H_2. In Europe and North America, where CCUS technology is advancing rapidly, blue hydrogen production costs range from USD 2 to 3 per kg H_2, supported by policy frameworks that actively incentivize carbon reduction efforts. These regions remain at the forefront of blue hydrogen development, propelled by intertwined economic and environmental objectives.

Green hydrogen, generated through water electrolysis powered by renewable energy, is projected to undergo significant cost reductions as technology matures and scales up by 2030. Regions endowed with abundant renewable energy resources, such as Latin America—particularly Chile and Argentina—are capable of achieving production costs below USD 2 per kg H_2, owing to optimal wind and solar conditions. In China, characterized by extensive renewable energy deployment and cost-efficient electrolyzer manufacturing, green hydrogen production costs are projected to decline to USD 2–3 per kg H_2 by 2030. In Europe, despite substantial policy support, green hydrogen costs are anticipated to remain slightly elevated, at approximately USD 3 per kg H_2, primarily due to higher renewable electricity prices, underscoring the influence of regional electricity costs on hydrogen production.

Biomass-derived hydrogen integrated with CCUS is emerging as a nascent yet expensive alternative. The report highlights that in the United States, characterized by optimal production conditions, biomass-derived hydrogen costs range from USD 1.2 to 2.4 per kg H_2, though average costs tend to be closer to USD 4.5 to 7 per kg H_2. In Europe, where biomass and regulatory costs are higher, production costs range between USD 3 and 7 per kg H_2. Similarly, Asia encounters comparable cost constraints stemming from elevated feedstock prices and limited domestic biomass availability. Despite these elevated costs, Japan and other Asian nations are actively investigating biomass-derived hydrogen as an integral component of their carbon-neutral strategies.

The IEA's analysis underscores the critical role of regional strategies and infrastructure investments in reducing hydrogen production costs and enhancing the competitiveness of low-emission hydrogen [28]. Countries endowed with abundant natural resources, such as the United States and the Middle East, are poised to lead in blue and green hydrogen production by leveraging competitive energy prices and advanced CCUS infrastructure. Conversely, regions with elevated energy costs, such as Europe, are intensifying investments in renewable energy and CCUS technologies to mitigate production expenses. The report concludes that as hydrogen production technologies advance and achieve widespread implementation, the costs of green and blue hydrogen are expected to converge, facilitating the development of a more balanced and economically sustainable global hydrogen market.

Table 1. projected hydrogen production costs by region and production type.

Hydrogen Production Type	Europe	United States	China	Middle East	Latin America
Gray hydrogen	USD 1–5.7 per kg H_2 (high variability due to gas prices)	USD 0.8–1.5 per kg H_2 (abundant natural gas)	USD 0.9–2 per kg H_2 (local gas prices)	Not a primary focus, low-cost gas favors blue hydrogen	Not widely produced
Blue hydrogen	USD 2–3 per kg H_2 (supportive CCUS investment)	Around USD 2 per kg H_2 (low natural gas and CCUS advantage)	Not a primary focus but potentially feasible	USD 1.5–2 per kg H_2 (low gas price + CCUS)	Potentially viable but not widely produced
Green hydrogen	USD 3 per kg H_2 by 2030 (higher renewable prices)	Not a primary focus but competitive in some regions	USD 2–3 per kg H_2 by 2030 (high renewable capacity)	Not a primary focus but may develop for export	Below USD 2 per kg H_2 (exceptional wind resources)
Biomass-derived hydrogen with CCUS	USD 3–7 per kg H_2 (higher biomass and regulatory costs)	USD 1.2–2.4 per kg H_2 (optimal); commonly USD 4.5–7	USD 4–6 per kg H_2 (limited biomass)	Not commonly used due to limited biomass resources	Limited use, costs depend on biomass availability

5. Technological Solutions for Reducing No_x Emissions in Hydrogen-Enriched Combustion

Since the Industrial Revolution, the dramatic surge in CO_2 emissions has exacerbated global climate change with dire environmental consequences. Free of the element of carbon, hydrogen emerges as a clean energy carrier and a transformative technology for energy conservation and carbon reduction, presently undergoing active international development. The integration of hydrogen into energy systems offers a pathway to partially mitigate greenhouse gas emissions, fostering the development of a hydrogen-based circular economy and reducing reliance on carbon-intensive fuels. The utilization of hydrogen spans both its production and application domains. Hydrogen production entails technologies focused on its generation, storage, and transportation. On the application front, hydrogen is employed in power generation and combustion technologies. In power generation, hydrogen serves as a fuel to generate electricity via fuel cell systems. Alternatively, hydrogen can be blended with fossil fuels in combustion processes to mitigate CO_2 emissions. While this entails the undesired byproducts of NO_x emissions, methods to address such a problem will be discussed in this section.

Figure 5 shows hydrogen blending in a conventional boiler, highlighting staged combustion, exhaust gas recirculation, and selective catalytic reduction for low NO_x emissions. In many hydrogen-enriched combustion processes, NO_x formation is strongly correlated with combustion temperature [29]. An increase in hydrogen content within the fuel typically elevates the combustion temperature, leading to a substantial rise in NO_x emission concentrations [30]. This phenomenon is attributable to hydrogen's higher calorific value and combustion rate, which typically result in combustion temperatures for hydrogen-enriched combustion surpassing those of pure hydrocarbon combustion [31]. Furthermore, hydrogen's wide flammability range and low ignition energy facilitate localized over-rich combustion within the combustion zone, further elevating combustion temperatures [32–35].

The primary mechanism for NO_x formation is thermal NO_x, generated through high-temperature reactions between nitrogen (N_2) and oxygen (O_2) at elevated temperatures. The production rate of thermal NO_x is highly sensitive to temperature, often rising exponentially [36]. As the hydrogen blending ratio increases, modifications in the combustion pattern induce localized high-temperature regions, elevating the local combustion temperature peak and triggering a nonlinear escalation in NO_x formation. Consequently, NO_x concentrations do not exhibit a linear correlation with the hydrogen blending ratio but instead rise exponentially. This phenomenon represents a significant technical barrier to the broader adoption of hydrogen-enriched combustion systems.

To mitigate these challenges, various technological solutions have been proposed and evaluated. Table 2 highlights innovative approaches to combustion control and emission reduction using advanced technologies, emphasizing the importance of integrating cutting-edge methodologies in hydrogen-enhanced systems. For instance, Glanville et al. [37] investigated the effects of hydrogen/natural gas blends on partially premixed combustion equipment. The study evaluated three scenarios: operation of standard and "ultra-low NO_x" burners from common heating equipment in simulated environments with hydrogen/methane blends of up to 30% by volume; testing of the same heating equipment; and field sampling of a broader range of equipment with 0–10% hydrogen/natural gas blends at a utility-owned training facility. The equipment demonstrated successful operation with hydrogen blends of up to 30%, with minimal visual changes to the flames. Key findings included: hydrogen blending from 0% to 30% led to an input rate reduction of up to 11%, frequently exceeding predictions based on the Wobbe Index; NO_x and CO emissions remained stable or decreased with increasing hydrogen blending; and efficiency changes were negligible, with standard water heaters showing a 1.2% efficiency decrease and ultra-low NO_x water heaters showing a 0.9% efficiency increase.

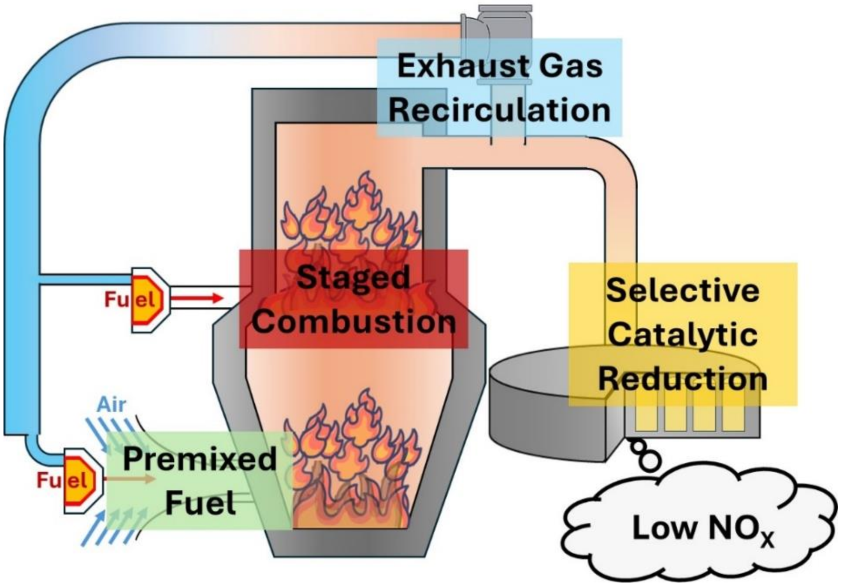

Figure 5. Shows hydrogen blending in a conventional boiler, highlighting staged combustion, exhaust gas recirculation, and selective catalytic reduction for low NO_x emissions.

Staged combustion entails a multi-step process of mixing fuel and air to regulate peak combustion temperatures, thereby mitigating NO_x formation. Mao et al. [38] investigated the influence of various conditions on NO_x emissions from the two-stage combustion of NH_3-H_2 mixtures. The study employed a chemical reactor network (CRN) model to simulate NO_x emissions under varying fuel pressures, inlet temperatures, primary air humidification fractions, total equivalence ratios, and primary equivalence ratios. Three distinct artificial neural network (ANN) models—back propagation (BP), radial basis function (RBF), and general regression (GRNN)—were developed and validated based on computational results derived from the CRN simulations. The BP model exhibited the highest accuracy, achieving an R^2 value of 0.99826, followed by the RBF model with an R^2 value of 0.99742. The study underscores the importance of maintaining a primary equivalence ratio between 1.1 and 1.3 for effective NO_x control, managing elevated pressures, precisely monitoring inlet temperatures, incorporating adaptive secondary airflow controls, and strategically introducing water vapor. Xu et al. [39] examined the NO reduction characteristics of CH_4/H_2 moderate or intense low-oxygen dilution (MILD) combustion across a broad range of hydrogen blending ratios. A serial perfectly stirred reactor (PSR) network model was employed to develop a performance prediction model for non-staged, air-staged, and fuel-staged MILD combustion. Results revealed that hydrogen addition induced a non-linear increase in NO emissions, with a maximum rise of 35.8% at 100% hydrogen blending. The study determined that air-staged MILD combustion exhibited the highest NO reduction efficiency, achieving a peak reduction of 67.4% at 100% hydrogen blending. Fuel-staged MILD combustion demonstrated a comparatively lower NO reduction efficiency, achieving a peak reduction of 52.4% at 0% hydrogen blending. The study concluded that air-staged MILD combustion is preferable for fuels with high hydrogen content, whereas fuel-staged MILD combustion is better suited for methane and its blends with low hydrogen content.

Exhaust gas recirculation (EGR) is a widely adopted technique that recirculates a portion of exhaust gases back into the combustion process, reducing oxygen concentration, lowering combustion temperature, and diluting the combustion zone to effectively mitigate NO_x formation. Sekar et al. [40] investigated the effects of EGR combined with hydrogen as an auxiliary fuel in diesel engines. The study utilized response surface methodology (RSM) and particle swarm optimization (PSO) to develop a performance prediction model for a methane-hydrogen non-premixed burner. Results indicated that the hydrogen mixing ratio significantly influenced NO and CO_2 emissions, reducing them by 64.6% and 83.5%, respectively. The equivalence ratio demonstrated no substantial effect on flue gas temperature, NO, or CO_2 emissions. Using PSO optimization, a Pareto set was derived, indicating NO and CO_2 emissions were reduced by 59.4% and 78.3%, respectively, while the peak temperature increased by 2.30%. The study revealed that EGR reduces the brake thermal efficiency (BTE) of the engine while significantly mitigating NO_x emissions. When EGR was combined with hydrogen, the BTE of the engine improved, leading to a substantial reduction in CO and CO_2 levels. However, HC emissions increased due to the reduced availability of oxygen atoms in the combustion chamber. Masoumi et al. [41] explored the feasibility of employing exhaust gas recirculation (EGR) in hydrogen/ammonia mixtures. The study experimentally evaluated the impact of artificial EGR on combustion pattern and unstretched laminar burning velocities, while flame stability and NO emissions were analyzed through numerical simulations based on established kinetic models. Experiments and numerical simulations were conducted across a range of equivalence ratios, initial temperatures, pressures, EGR rates, and compositions. The results demonstrated that exhaust gas recirculation enhances flame stability by mitigating hydrodynamic instabilities, although it adversely impacts laminar burning velocities. This adverse effect, which becomes more pronounced under non-stoichiometric conditions, reduces the flow rate of the gaseous products from combustion by 19% to 58%, depending on the flue gas content of the combustible mixture. Despite this reduction, exhaust gas recirculation significantly decreases the high NO emissions of hydrogen/ammonia/air mixtures. Notably, the addition of flue gases reduces maximum NO concentrations by up to 45% under near-stoichiometric conditions. The effects become even more pronounced in fuel-rich conditions, reducing NO emissions by up to 84% at an equivalence ratio of 1.3. Finally, these findings support the application of exhaust gas recirculation for utilizing hydrogen/ammonia blends as a clean fuel, while acknowledging the trade-off of reduced burning rates.

In the domain of post-combustion treatment and emission control, selective catalytic reduction (SCR) represents a pivotal technology for mitigating NO_x emissions. SCR employs catalysts, such as ammonia or urea, along with reductants to convert NO_x into nitrogen (N_2) and water (H_2O), thereby substantially reducing pollutant concentrations in exhaust gases. Kim et al. [42] analyzed NO_x emissions in relation to after-treatment devices, including SCR, lean NO_x trap—selective catalytic reduction (LNT-SCR), and diesel particulate filter coated SCR (SDPF), as well as control strategies employed in Euro-6 light-duty diesel vehicles. The study utilized a range of experimental techniques to develop a performance prediction model for NO_x emissions. The results demonstrated that the SCR system exhibited the highest NO_x reduction efficiency (exceeding 80%), followed by SDPF (ranging from 60% to 80%) and LNT (60% or less). The study revealed that the implementation of real-road emission regulations drove the widespread adoption of LNT-SCR hybrid devices in both domestic and imported vehicles. An analysis of NO_x emissions from certification and real drive emission tests under hot and cold start conditions indicated that NO_x emissions ranged from 0.01 to 0.08 g/km for domestic vehicles, with slightly lower values observed for imported vehicles. Li et al. [43] utilized a range of experimental techniques to develop a performance prediction model for magnetic γ-Fe_2O_3 catalysts modified with tungsten doping. The results demonstrated that the tungsten doping amount significantly influenced the crystallite size, pore structure, and redox properties of the catalysts. The optimal tungsten doping level was identified as 7.5 wt%, achieving the highest NH_3-SCR activity and the broadest reaction temperature window. The study revealed that tungsten doping enhanced the stability of γ-Fe_2O_3, reduced the particle size of iron oxide crystals, and decreased their crystallinity. H_2 temperature-programmed reduction (H_2-TPR) results indicated that tungsten doping modulated the redox properties of the catalysts, effectively suppressing the non-selective catalytic oxidation of NH_3. NH_3 temperature-programmed desorption (NH_3-TPD) results demonstrated that tungsten doping significantly increased the surface acidity of the catalysts, thereby enhancing NH_3 adsorption.

The integration of hydrogen-enhanced combustion with optimized burner designs and advanced exhaust gas treatment systems presents substantial potential for sustainable energy applications. This study reviews key mitigation strategies, including hydrogen-natural gas blending, staged combustion, exhaust gas recirculation (EGR), and post-combustion measures such as Selective Catalytic Reduction (SCR). Among these, EGR effectively lowers peak combustion temperatures, while staged combustion optimizes fuel-air mixing to minimize NO_x formation. Additionally, SCR remains one of the most efficient post-combustion solutions, reducing NO_x emissions by over 80% in various applications. By combining these strategies, high combustion efficiency can be achieved while effectively mitigating NO_x emissions, thereby paving the way for cleaner and more sustainable hydrogen combustion technologies.

Table 2. innovative approaches to combustion control and emission reduction with advanced technologies.

Technology Used	Technology Readiness Level	Category	Key Conditions	Performance Indicators	Commercialization scale	Authors	Ref.
Premixed fuel	7–8	Fuel control	Hydrogen/methane blends (0–30% by volume) in partially premixed equipment	NO_x and CO emissions stable or decreased, input rate reduced by 11%, minor efficiency changes	Early commercial trials	Glanville et al.	[37]
Staged combustion	6–8	Combustion control/ NH_3	Equivalence ratio (1.1–1.3), CRN and ANN models developed (BP, RBF, GRNN)	BP model accuracy (R = 0.99826); optimal NO_x reduction achieved at primary equivalence ratio 1.1–1.3	Modeling/pilot stage	Mao et al.	[38]
		Combustion control/ CH_4	Hydrogen blending ratios (0–100%), staged vs. non-staged combustion	Air-staged MILD combustion is optimal for high-hydrogen fuels, while fuel-staged is better for methane or low-hydrogen blends.	Demonstration	Xu et al.	[39]
Exhaust gas recirculation	7–9	Emission reduction/ Diesel	Diesel engine with EGR and hydrogen, optimized using PSO	NO reduced by 59.4%, CO_2 reduced by 78.3%, peak temp +2.30%	Commercial trials	Sekar et al.	[40]
		Emission reduction/ Ammonia	Hydrogen/ammonia blends, various EGR rates, equivalence ratios	NO emissions reduced up to 84%; exhaust flow rate decreased by 19–58%	Commercial trials	Masoumi et al.	[41]
Selective catalytic reduction	8–9	Post-combustion control	Euro-6 diesel vehicles, SCR, LNT + SCR, SDPF systems	SCR NO_x reduction >80%, SDPF 60–80%, LNT ≤60%	Fully commercialized	Kim et al.	[42]
		Catalyst optimization	Tungsten doping (7.5 wt%), NH_3-SCR reaction	Highest NH_3-SCR activity, improved stability and surface acidity	Fully commercialized	Li et al.	[43]

6. Potential Challenges and Perspectives

While the review highlights significant advancements in mitigating NO_x emissions from hydrogen-enriched combustion, several challenges remain that must be addressed to fully realize the potential of hydrogen as a clean energy carrier. One of the primary challenges is the inherent trade-off between achieving high combustion efficiency and minimizing NO_x emissions. The high temperature of hydrogen during combustion and its wide flammability range, while advantageous for energy conversion, exacerbate NO_x formation. This necessitates the development of more sophisticated combustion control strategies, such as advanced staged combustion and exhaust gas recirculation (EGR), which can effectively lower peak temperatures without compromising combustion efficiency. However, these technologies often require complex system integration and optimization, which can increase operational costs and complexity.

Another challenge lies in the scalability and economic viability of post-combustion NO_x reduction technologies, such as Selective Catalytic Reduction (SCR). While SCR has demonstrated high efficiency in reducing NO_x emissions (over 80% in many applications), the reliance on catalysts like ammonia or urea introduces additional costs and logistical challenges, particularly in large-scale industrial applications. Furthermore, the development of more durable and cost-effective catalysts, such as tungsten-doped γ-Fe_2O_3, remains an ongoing area of research. The integration of these catalysts into existing infrastructure will require significant investment and innovation.

From a broader perspective, the transition to hydrogen-based energy systems must also consider the entire value chain, from production to end-use. While green hydrogen, produced via renewable energy-powered electrolysis, is the most sustainable option, its current high production costs and reliance on intermittent renewable energy sources pose significant barriers to widespread adoption. Blue hydrogen, produced from natural gas with carbon capture, utilization, and storage (CCUS), offers a transitional solution but still faces challenges related to CCUS infrastructure and long-term carbon sequestration viability. Additionally, the development of robust hydrogen storage and transportation systems is critical to ensuring a reliable supply chain, particularly for industries and regions with high energy demands.

Looking ahead, advances in materials science, particularly in the development of more efficient catalysts and combustion technologies, will play a pivotal role in reducing NO_x emissions and improving the overall efficiency of hydrogen combustion systems.

7. Conclusions

Hydrogen energy has become a pivotal element in global efforts to achieve net-zero emissions and establish a sustainable energy future. The rapid expansion of hydrogen research highlights its immense potential to tackle pressing energy and environmental challenges. Diverse hydrogen production technologies—including thermolysis, biophotolysis, electrolysis, and photo-electrochemical processes—provide distinct pathways for hydrogen generation, each characterized by unique environmental impacts and economic considerations. While gray hydrogen remains the major product in supply today, blue hydrogen, which mitigates emissions from natural gas reforming with carbon capture and store technologies, is projected to act as a transitional energy source in the following decades before green hydrogen, which is extracted exclusively from renewable energy sources, moves to dominate the hydrogen market by 2050. The transition from gray to blue and eventually green hydrogen underscores a global commitment to reducing greenhouse gas emissions and advancing toward cleaner energy systems. The adoption of hydrogen is profoundly influenced by production costs, which vary widely from one region to another, as they are shaped by resource availability, technological capabilities, and policy incentives. Strategic investments in infrastructure and technology are crucial for enhancing the competitiveness of low-emission hydrogen and facilitating its widespread adoption.

Although the increased emissions of nitrogen oxides (NO_x) resulting from higher combustion temperatures poses significant barriers to the broader application of hydrogen combustion, advancements in combustion technologies—including hydrogen/natural gas blending, staged combustion, exhaust gas recirculation (EGR), and post-combustion treatments such as Selective Catalytic Reduction (SCR)—provide effective pathways for mitigating NO_x emissions. The integration of these technologies facilitates the effective utilization of hydrogen's energy potential while minimizing its environmental impacts. With the collaboration among researchers, industry stakeholders, and policymakers, the successful positioning of hydrogen as a cornerstone for substituting fossil fuels will pave the pathway towards a sustainable energy future by realizing global net-zero emissions.

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References

1. Lee, K.-T.; Cai, Y.-S.; Hou, Q.-Y.; et al. A Brief Overview of Green Hydrogen on Production, Regulations, and Commercialization. *Green Energy Fuel Res.* **2024**, *1*, 3–12.
2. Obiora, N.K.; Ujah, C.O.; Asadu, C.O.; et al. Production of hydrogen energy from biomass: Prospects and challenges. *Green Technol. Sustain.* **2024**, *2*, 100100.
3. Singh, S.K.; Tiwari, A.K. Solar-powered hydrogen production: Advancements, challenges, and the path to net-zero emissions. *Int. J. Hydrogen Energy* **2024**, *84*, 549–579.
4. Dharani, S.; Vadivel, S.; Gnanasekaran, L.; et al. S-scheme heterojunction photocatalysts for hydrogen production: Current progress and future prospects. *Fuel* **2023**, *349*, 128688.
5. Anekwe, I.M.S.; Akpasi, S.O.; Enemuo, E.M.; et al. Innovations in catalytic understanding: A journey through advanced characterization. *Mater. Today Catal.* **2024**, *7*, 100061.
6. Zhang, J.; Ma, C.; Jia, S.; et al. Electrocatalysts Design Guided by Active Intermediates of Hydrogen Evolution Reaction. *Adv. Energy Mater.* **2023**, *13*, 2302436.
7. Naqvi, S.R.; Kazmi, B.; Ammar Taqvi, S.A.; et al. Techno economic analysis for advanced methods of green hydrogen production. *Curr. Opin. Green Sustain. Chem.* **2024**, *48*, 100939.
8. Office of Fossil Energy. *Hydrogen Strategy, Enabling a Low Carbon Economy*; Office of Fossil Energy: Washington, DC, USA, 2020.
9. Karaca, A.E.; Qureshy, A.M.M.I.; Dincer, I. An overview and critical assessment of thermochemical hydrogen production methods. *J. Clean. Prod.* **2023**, *385*, 135706.
10. Chen, W.-H.; Biswas, P.P.; Ong, H.C.; et al. A critical and systematic review of sustainable hydrogen production from ethanol/bioethanol: Steam reforming, partial oxidation, and autothermal reforming. *Fuel* **2023**, *333*, 126526.
11. Ivanenko, A.A.; Laikova, A.A.; Zhuravleva, E.A.; et al. Biological production of hydrogen: From basic principles to the latest advances in process improvement. *Int. J. Hydrogen Energy* **2024**, *55*, 740–755.
12. 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.
13. Shiva Kumar, S.; Lim, H. An overview of water electrolysis technologies for green hydrogen production. *Energy Rep.* **2022**, *8*, 13793–13813.
14. Oni, A.O.; Anaya, K.; Giwa, T.; et al. Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions. *Energy Convers. Manag.* **2022**, *254*, 115245.
15. Dermühl, S.; Riedel, U. A comparison of the most promising low-carbon hydrogen production technologies. *Fuel* **2023**, *340*, 127478.
16. Bento, C.; Lopes, T.F.; Rodrigues, P.; et al. Biogas reforming as a sustainable solution for hydrogen production: Comparative environmental metrics with steam-methane reforming and water electrolysis in the Portuguese context. *Int. J. Hydrogen Energy* **2024**, *66*, 661–675.
17. Li, Y.; Lin, R.; O'Shea, R.; et al. A perspective on three sustainable hydrogen production technologies with a focus on technology readiness level, cost of production and life cycle environmental impacts. *Heliyon* **2024**, *10*, e26637.
18. Saravanan, P.; Khan, M.R.; Yee, C.S.; et al. 7—An overview of water electrolysis technologies for the production of hydrogen. In *New Dimensions in Production and Utilization of Hydrogen*; Nanda, S., Vo, D.-V.N., Nguyen-Tri, P., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 161–190.
19. *Green Hydrogen Cost Reduction*; International Renewable Energy Agency: Masdar City, Abu Dhabi, 2020.
20. Kumar, S.S.; Lim, H. Recent advances in hydrogen production through proton exchange membrane water electrolysis—A review. *Sustain. Energy Fuels* **2023**, *7*, 3560–3583. https://doi.org/10.1039/D3SE00336A.
21. Bianchi, F.R.; Bosio, B. Operating Principles, Performance and Technology Readiness Level of Reversible Solid Oxide Cells. *Sustainability* **2021**, *13*, 4777.
22. Incer-Valverde, J.; Korayem, A.; Tsatsaronis, G.; et al. "Colors" of hydrogen: Definitions and carbon intensity. *Energy*

Convers. Manag. **2023**, *291*, 117294.
23. Swadi, M.; Jasim Kadhim, D.; Salem, M.; et al. Investigating and predicting the role of photovoltaic, wind, and hydrogen energies in sustainable global energy evolution. *Glob. Energy Interconnect.* **2024**, *7*, 429–445.
24. AlHumaidan, F.S.; Absi Halabi, M.; Rana, M.S.; et al. Blue hydrogen: Current status and future technologies. *Energy Convers. Manag.* **2023**, *283*, 116840.
25. Xu, G.; Huang, Z.; Jiang, M.; et al. "Gray" Prediction of Carbon Neutral Pathways in the G7 Economies by 2050. *Appl. Energy* **2024**, *373*, 123924.
26. Pathak, P.K.; Yadav, A.K.; Padmanaban, S. Transition toward emission-free energy systems by 2050: Potential role of hydrogen. *Int. J. Hydrogen Energy* **2023**, *48*, 9921–9927.
27. *Global Hydrogen Review 2024*; International Energy Agency: Paris, France, 2024.
28. *Global Hydrogen Review 2022*; International Energy Agency: Paris, France, 2022.
29. Cao, D.N.; Hoang, A.T.; Luu, H.Q.; et al. Effects of injection pressure on the NO_x and PM emission control of diesel engine: A review under the aspect of PCCI combustion condition. *Energy Sources Part A: Recovery Util. Environ. Eff.* **2024**, *46*, 7414–7431.
30. Józsa, V. Mixture temperature-controlled combustion: A revolutionary concept for ultra-low NO_x emission. *Fuel* **2021**, *291*, 120200.
31. Stępień, Z. A comprehensive overview of hydrogen-fueled internal combustion engines: Achievements and future challenges. *Energies* **2021**, *14*, 6504.
32. Pitsch, H. The transition to sustainable combustion: Hydrogen-and carbon-based future fuels and methods for dealing with their challenges. *Proc. Combust. Inst.* **2024**, *40*, 105638.
33. Le, T.T.; Sharma, P.; Bora, B.J.; et al. Fueling the future: A comprehensive review of hydrogen energy systems and their challenges. *Int. J. Hydrogen Energy* **2024**, *54*, 791–816.
34. Strollo, J.; Peluso, S.; O'Connor, J. Effect of hydrogen on steady-state and transient combustion instability characteristics. *J. Eng. Gas Turbines Power* **2021**, *143*, 071023.
35. Taamallah, S.; Vogiatzaki, K.; Alzahrani, F.M.; et al. Fuel flexibility, stability and emissions in premixed hydrogen-rich gas turbine combustion: Technology, fundamentals, and numerical simulations. *Appl. Energy* **2015**, *154*, 1020–1047.
36. Wright, M.L.; Lewis, A.C. Emissions of NO_x from blending of hydrogen and natural gas in space heating boilers. *Elem. : Sci. Anthr.* **2022**, *10*, 00114. https://doi.org/10.1525/elementa.2021.00114.
37. Glanville, P.; Fridlyand, A.; Sutherland, B.; et al. Impact of hydrogen/natural gas blends on partially premixed combustion equipment: NO_x emission and operational performance. *Energies* **2022**, *15*, 1706.
38. Mao, G.; Shi, T.; Mao, C.; et al. Prediction of NO_x emission from two-stage combustion of NH3–H2 mixtures under various conditions using artificial neural networks. *Int. J. Hydrogen Energy* **2024**, *49*, 1414–1424.
39. Xu, S.; Chen, Y.; Tian, Z.; et al. NO emission reduction characteristics of CH4/H2 staged MILD combustion over a wide range of hydrogen-blending ratios. *Fuel* **2024**, *372*, 132239.
40. Sekar, M.; Selim, M.Y.E.; Saleh, H.E.; et al. Utilization of hydrogen and methane as energy carriers with exhaust gas recirculation for sustainable diesel engines. *Energy Convers. Manag. X* **2024**, *23*, 100618.
41. Masoumi, S.; Houshfar, E.; Ashjaee, M. Experimental and numerical analysis of ammonia/hydrogen combustion under artificial exhaust gas recirculation. *Fuel* **2024**, *357*, 130081.
42. Kim, H.J.; Jo, S.; Kwon, S.; et al. NO_x emission analysis according to after-treatment devices (SCR, LNT + SCR, SDPF), and control strategies in Euro-6 light-duty diesel vehicles. *Fuel* **2022**, *310*, 122297.
43. Li, C.; Xiong, Z.; Du, Y.; et al. Promotional effect of tungsten modification on magnetic iron oxide catalyst for selective catalytic reduction of NO with NH_3. *J. Energy Inst.* **2020**, *93*, 1809–1818.