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Review

Hydrogen in Burners: Economic and Environmental Implications

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Abstract: For centuries, fossil fuels have been the primary energy source, but their unchecked use has led to significant environmental and economic challenges that now shape the global energy landscape. The combustion of these fuels releases greenhouse gases, which are critical contributors to the acceleration of climate change, resulting in severe consequences for both the environment and human health. Therefore, this article examines the potential of hydrogen as a sustainable alternative energy source capable of mitigating these climate impacts. It explores the properties of hydrogen, with particular emphasis on its application in industrial burners and furnaces, underscoring its clean combustion and high energy density in comparison to fossil fuels, and also examines hydrogen production through thermochemical and electrochemical methods, covering green, gray, blue, and turquoise pathways. It discusses storage and transportation challenges, highlighting methods like compression, liquefaction, chemical carriers (e.g., ammonia), and transport via pipelines and vehicles. Hydrogen combustion mechanisms and optimized burner and furnace designs are explored, along with the environmental benefits of lower emissions, contrasted with economic concerns like production and infrastructure costs. Additionally, industrial and energy applications, safety concerns, and the challenges of large-scale adoption are addressed, presenting hydrogen as a promising yet complex alternative to fossil fuels.

Keywords: hydrogen combustion; energy generation; industrial burners; economic aspect; environmental impact

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1. Introduction

The rapid population growth and economic development on a global scale are generating a considerable increase in energy demand. Historically dependent on fossil fuels such as coal and oil, which account for over 60% of global electricity generation, this sector now confronts an urgent need to align with the sustainability goals of the 21st century. However, despite being a crucial element for any nation, energy generation is also a significant contributor to greenhouse gas emissions, responsible for approximately 26.2% of the global total [1,2].

Among all human activities, burning fossil fuels for energy production is the largest contributor to the increase in global greenhouse gas emissions, especially carbon dioxide (CO_2). These emissions have reached unprecedented levels, posing a significant threat to humanity as global warming continues to rise. In light of this, many countries have agreed on the necessity of reducing carbon emissions to mitigate the harmful effects of climate change. These effects include the destruction of coral reefs, heatwaves, wildfires, frequent flooding, droughts, and rising sea levels. To tackle these urgent challenges, the international community has recognized the need for coordinated efforts [3,4].

The Paris Agreement, adopted during COP21 in 2015, mobilized international actions to limit the increase in the average global temperature to 1.5 °C above pre-industrial levels and to enhance the global response to the threat of climate change. The agreement acknowledged that climate change is an irreversible danger to the planet, requiring all countries to engage in broad cooperation to achieve substantial outcomes in terms of reducing carbon and greenhouse gas emissions, and solutions for a sustainable future have been discussed, such as the transition to renewable energy sources [5,6].

Considering this, the energy transition refers to the shift in the global system of energy production and consumption from fossil fuels, such as oil, natural gas, and coal, to renewable energy sources, including wind, solar, hydro, biomass, geothermal, and ocean energy, as well as alternative energy sources such as nuclear, biofuels, and lithium-ion batteries, along with technologies based on renewable hydrogen. Hydrogen (H_2) is considered a key player in the transition to a low-carbon global economy aimed at achieving net-zero greenhouse gas emissions, as it has the potential to replace fossil fuels in a variety of combustion applications, such as power generation, industrial/residential heating, and transportation. It is estimated that hydrogen will supply 6–8% of total energy demand in the net-zero scenario for 2050. Several countries have recently announced plans to expand the production and consumption of clean hydrogen, and it is projected that USD 500 billion will be invested in developing hydrogen technologies worldwide by 2030 [6–9].

As a result of these initiatives, the production and demand for hydrogen are projected to grow rapidly in the future. It is estimated that the production of clean hydrogen will increase from 0.8 Mt/a today to 154 Mt/a by 2030, reaching 614 Mt/a by 2050. This growth will necessitate substantial investments, amounting to hundreds of billions of dollars annually. These investments must be allocated effectively to enable the economic production of hydrogen, thereby contributing to sustainable transformation. In this context, anticipating the optimal technologies, locations, and production parameters becomes essential [10].

Hydrogen is traditionally produced from fossil fuels like coal and natural gas; however, its real potential for a sustainable energy transition lies in production from renewable sources. Renewable hydrogen helps reduce dependence on fossil fuels, decreases greenhouse gas emissions, and supports a low-carbon energy system. There are various production methods available. Biological approaches are less energy-intensive and more sustainable, although they yield lower amounts of hydrogen. In contrast, thermochemical processes, such as biomass gasification, are faster and more efficient. Currently, electrolyzers are the most promising and widely adopted methods for hydrogen production. They work by splitting water into hydrogen and oxygen using electricity. There are three main types of electrolyzers: alkaline, proton exchange membrane (PEM), and solid oxide (SOEC). Each type differs in terms of cost, application, and level of technological maturity [11–13].

Hydrogen is a colorless gas; however, there are various color codes to identify the different types. These colors refer to the processes used to produce hydrogen, the evaluation of the production method, the resources consumed to generate the necessary energy, and the amount of pollutant emissions generated. Hydrogen deemed "green", which is often referred to as "clean hydrogen", "renewable hydrogen", or "low-carbon hydrogen", can be defined as hydrogen produced through renewable sources; the most common is the electrolysis of water using electricity sourced from renewable energy. By utilizing renewable energy, the production of green hydrogen does not emit carbon dioxide (CO_2) at any stage. This type of hydrogen is particularly relevant in the energy transition towards a more sustainable energy and transportation system. Besides serving as a fuel, hydrogen is valued as a commodity, as well as for its applications in the production of chemical feedstock. Based on the concept of sector coupling or sector integration, hydrogen has significant potential for connecting various energy carriers and consumption sectors, while simultaneously enhancing overall energy system security, reliability, and resilience. As part of decarbonization strategies, the deployment of energy technologies for gas and the establishment of hydrogen refueling stations have been promoted to reduce dependence on fossil fuels in the energy and transportation sectors [14–16].

Therefore, the combination of hydrogen with existing fuels can represent an effective transition strategy for the gradual migration to a hydrogen-based energy system. This approach allows for the utilization of current infrastructure while simultaneously reducing dependence on fossil fuels. A viable method for integrating hydrogen into these sectors is to use it as a fuel. An interesting approach is the application of hydrogen in mixed combustion processes, such as in burners, boilers, and furnaces. The combustion of hydrogen is highly exothermic and carbon-free, with water (H_2O) as its sole product. Compared to fossil fuels, the use of H_2 in internal combustion engines can increase thermal efficiency and reduce carbon emissions. The addition of hydrogen modifies the combustion dynamics and offers several advantages, including a high heating value, increasing flame speed, the production of more compact and turbulent flames, a higher diffusion rate, and more rapid oxidation characteristics. Combining renewable hydrogen with traditional fuels supports the integration of renewable sources into the energy mix, promoting energy security and sustainability [17,18].

In diesel engines, the supplementation of hydrogen can improve performance while also reducing greenhouse gas emissions and smoke production. Hydrogen-rich energy contains negligible ash, sulfur, and alkaline metals compared to coal, which can not only mitigate pollutant emissions such as sulfur oxides but also reduce the impacts associated with blast furnace operations and the environmental effects caused by carbon emissions. Recent investigations into hydrogen combustion have primarily focused on addressing these challenges through alternative combustion regimes, fuel additives, and advanced combustion technologies that enhance efficiency and reduce emissions, including the use of lean burn techniques, flame stabilization methods, and integrated system designs that optimize the use of hydrogen in various industrial applications. The effects of blending with hydrogen vary depending on the type of fuel, performance metrics, and fraction of total fuel. Thus, hydrogen-rich energy is considered one of the most promising energy sources and is expected to play a significant role in the global energy landscape in the future. Adapting existing combustion systems is crucial, especially in burner and furnace design [19–21].

Burners and furnaces are crucial components in combustion systems, playing essential roles in energy efficiency and emission minimization. Traditionally, these devices have been designed to operate with fossil fuels, such as natural gas, diesel oil, and coal, where combustion efficiency is optimized to maximize heat transfer and reduce pollutants. However, with the increasing pressure to decarbonize the energy matrix, hydrogen has emerged as a promising alternative, particularly in industrial sectors such as metallurgy, chemicals, and power generation. Implementing burners that utilize hydrogen presents significant technical challenges, including the need to redesign systems to accommodate the high flame temperature and the diffusion rate of hydrogen. Nevertheless, their use can lead to drastically reduced greenhouse gas emissions, contributing to the transition toward a low-carbon economy. Furthermore, adapting existing burners for alternative fuels can be a viable solution for industries seeking to comply with increasingly stringent environmental regulations [22,23].

In this perspective, the ongoing energy transition represents a crucial juncture for achieving sustainable development and mitigating climate change impacts. As hydrogen emerges as a pivotal solution, its integration into existing combustion systems holds the potential to revolutionize energy production and consumption across various sectors. By enabling the transition from fossil fuels to cleaner alternatives, hydrogen not only addresses the urgent need for reduced greenhouse gas emissions but also enhances the resilience and reliability of energy systems. The challenges inherent in adapting combustion technologies for hydrogen use highlight the importance of innovation and investment in research and development. Ultimately, the successful implementation of hydrogen as an energy carrier can play a transformative role in shaping a sustainable, low-carbon future, aligning with global commitments to combatting climate change and fostering economic growth.

Previous Studies and Research Gaps

Previous studies and research gaps in the hydrogen area are described in Table 1.

Table 1. Previous studies and research.

Main Focus of the Study	Research Gaps	Key Findings	Ref.
Focuses on the comparative analysis of heavy trucks powered by different types of fuels (diesel, LNG, electric, hydrogen, and methanol) in relation to costs, efficiency, and environmental impact.	Lack of detailed analysis on hydrogen's energy properties, infrastructure and production challenges, and specific environmental impact compared to other fuels.	• Hydrogen-powered trucks (HHTs) have the highest life cycle costs among the options analyzed. Methanol-powered trucks (MHT) rank second, followed by diesel-powered (DHT), electric-powered (EHT), and liquefied natural gas (LNGHT) models; • Currently, the economic viability of hydrogen trucks is limited by their high acquisition and fuel costs; • Trucks powered by liquefied natural gas (LNGHTs) have the lowest transportation cost per 100 km, making them the most economically viable option in the short term; • Electric trucks (EHTs) face significant challenges in cold climates, where energy consumption tends to increase; • Methanol-fueled trucks (MHTs) have considerable growth potential in China, driven by abundant coal resources.	Hu et al. [24]
The crucial role of green hydrogen in reducing CO_2 emissions, highlighting its production from renewable sources and the economic and technological challenges associated with its implementation. It promotes the idea of a hydrogen-based economy as a pathway to achieving climate neutrality.	Need for in-depth analysis of hydrogen's industrial applications, logistical and infrastructure challenges for large-scale production, comparison of production routes (gray, blue, turquoise), and detailed safety considerations.	• Green hydrogen is highlighted as crucial to mitigating CO_2 emissions and replacing fossil fuels; • Biomass gasification and pyrolysis are identified as promising processes to generate energy-rich hydrogen aligned with low-carbon energy goals; • The transition to green hydrogen implies systemic changes in infrastructure, requiring innovation and economic support.	Dorel et al. [25]

Table 1. *Cont.*

Main Focus of the Study	Research Gaps	Key Findings	Ref.
Focuses on describing the thermodynamic and transport properties of hydrogen mixed with other gases, which is fundamental for geological storage and safe and efficient transportation.	Practical insights on hydrogen in industrial combustion, plus analysis of its economic, social, and safety impacts for large-scale use, are needed to understand its role in the energy transition.	• Provides extensive analysis of the properties of mixtures of hydrogen and other gases, such as methane and CO_2, using sophisticated models to predict behavior under various temperature and pressure conditions; • It uses and validates the GERG-2008 model to predict physical and thermophysical properties, proving to be accurate for gas mixtures, which is crucial for practical application in the energy industry; • Discusses the storage capacity of hydrogen in geological reservoirs and the importance of gas mixtures for efficient and safe storage.	Hassanpouryouzband et al. [26]
Hydrogen as a promising alternative fuel for diesel engines in the automotive sector, highlighting its potential to increase engine efficiency and reduce emissions, thus contributing to more sustainable transport solutions.	Limited focus on hydrogen uses in automotive diesel engines, and lacks broader industrial applications, economic impacts, infrastructure challenges, and environmental benefits beyond transportation.	• Adding hydrogen improves engine efficiency by 5.3% at certain loads; • Significantly reduces CO_2, NO_X, and particulate emissions compared to conventional diesel. • The use of hydrogen–diesel blends for better environmental performance, although with some trade-offs in combustion variability.	Cernat et al. [27]
Explores the feasibility and benefits of hydrogen co-combustion in dual fuel compression ignition engines, emphasizing improvements in performance and emissions.	Lacks comprehensive economic assessment of hydrogen vs. traditional fuels, detailed exploration of long-term environmental impacts, and discussion on infrastructure and integration with other renewables beyond dual-fuel applications.	• Hydrogen co-combustion increases engine efficiency, with biodiesel showing greater efficiency gains compared to diesel; • Co-combustion reduces CO and CO_2 emissions, with biodiesel blends achieving a more significant reduction; • Hydrogen reduces ignition delay and combustion time, improving engine stability at specific hydrogen concentrations.	Tutak et al. [28]

2. Fuels

Fuels are substances that react chemically with an oxidant (normally oxygen) when receiving heat, resulting in the release of energy. The application of a fuel is dictated by the cost, availability, and ease of handling, and its use must be in accordance with environmental regulations. Some of the main physical properties are relative density, molecular mass, vapor pressure, viscosity, flash point, flammability range, enthalpy, specific heat capacity, and latent heat. Most fuels used in combustion systems are derived from non-renewable fossil sources [12,18].

Fossil fuels (petroleum, natural gas, and coal) are formed by organic matter from animal and plant remains that accumulated in underground reservoirs and entered decomposition millions of years ago under high pressure and temperature. This matter underwent a set of maturation processes that transformed it into organic sediment within the Earth's crust, which is employed as a source of energy. The use of fossil fuels aggravates the effects of global warming due to the CO_2 emissions resulting from the burning of fuel hydrocarbons, such as paraffin, olefins, naphthenes, and other aromatics [29,30].

Fuels are normally composed of hydrocarbons, other non-hydrogenated organic compounds, carbon monoxide (CO), ethanol, methanol, and biofuels. Although not considered fuels, other materials, such as sulfide minerals, release heat when oxidized and provide significant energy to the reaction. It is common to classify fuels based on their physical state, i.e., as solid, gaseous, or liquid fuels [31].

2.1. Solid Fuels

Solid fuels play a crucial role in the global energy landscape, with each class offering distinct characteristics and applications. Biomass, for instance, is a renewable resource derived from organic materials, such as wood, agricultural residues, and certain types of waste. This category is gaining popularity in modern energy systems due to its carbon-neutral potential, as plants absorb CO_2 during growth, offsetting emissions during combustion. Various technologies, such as gasification and pyrolysis, are being developed to convert biomass into cleaner forms of energy, further enhancing its sustainability and efficiency. Despite these advancements, the energy density of biomass remains low compared to fossil fuels, requiring larger quantities for the same energy output [32–34].

Coal, on the other hand, is a non-renewable fossil fuel with a high energy density and has historically been a cornerstone of industrialization. It is classified into different types based on carbon content and energy value, such as anthracite (86–97%), bituminous (45–86%), and lignite (25–35%), with anthracite being the highest grade. While coal remains a key energy source for electricity generation, its environmental impact, particularly concerning CO_2 emissions, has prompted a decline in its use in many regions. Advances in clean coal technologies, like carbon capture and storage (CCS), are being explored to mitigate these emissions. However, the extraction and burning of coal still contribute significantly to air pollution and environmental degradation, making the shift to cleaner energy sources increasingly critical [35,36].

Mixed municipal solid waste (MMSW) offers a more diverse and complex category of solid fuels, including waste from urban environments, which may contain materials like paper, plastic, food scraps, and even hazardous items like hospital and chemical waste. This form of waste is processed in waste-to-energy plants, which burn the waste to generate electricity and heat. While MMSW presents an opportunity to reduce landfill use and recover energy from non-recyclable materials, the combustion process requires advanced filtration and pollution control technologies to manage the release of harmful pollutants such as dioxins, heavy metals, and particulate matter. The integration of waste management with energy recovery through MMSW is a growing field, providing a solution to both waste disposal challenges and energy generation [37,38].

2.2. Liquid Fuels

Liquid fuels are widely used in industry due to the ease of storage, operation, and transport. Most liquid fuels are derived from oil, although some were produced from coal tar, a thick, black liquid byproduct derived in the past from coke production [31]. Petroleum derivatives (gasoline, diesel oil, kerosene, and fuel oil) (PNE 2030) and biofuels, such as biodiesel and ethanol, are examples of liquid fuels. The literature reports the basic properties of liquid fuels, such as the fire point (°C), kinematic viscosity (cSt), density (kg/m^3), fluidity point (°C), and ash content [18,29,31].

Gasoline is a product obtained from the refining of crude oil, whose composition depends on its use in aviation (high performance, mixture of hydrocarbons with 5 to 10 carbon atoms) or the automotive industry (refinery fuel for automobiles and military vehicles, mixture of hydrocarbons with 4 to 12 carbon atoms), its origin, and the oil refining process [39,40].

Diesel oil is a fuel composed mainly of hydrocarbons with chains of 8 to 16 carbon atoms, the different types of which are classified based on the maximum sulfur content: S-10, S-500, and S-1800. S-10 is used in the transportation of cargo and passengers, industry, energy generation, and machines; S-500 is suitable for vehicles such as buses and trucks and was manufactured prior to 2012; while S-1800 is used in energy generation, railroad transportation, and open pit mining. Marine diesel oil is used for boats and ships. Diesel oil may also contain added biodiesel within the legal limits [39,40].

Jet-A1 aviation kerosene is an oil derivative obtained by direct distillation in a temperature range of 150 to 300 °C, with a predominance of paraffin hydrocarbons with 9 to 15 carbon atoms, which is used in aeronautic turbines. Fuel oil or "bunker" fuel, often used for the generation of thermal energy in industrial applications and for marine transportation, is classified as heavy fuel oil, light fuel oil, or types A1/A2 or B1/B2, depending on the viscosity, sulfur content, and fluidity point [40].

2.3. Gaseous Fuels

Gaseous fuels may be natural or manufactured, the latter of which are generally obtained from petroleum (liquified petroleum gas [LPG]), coal, or biomass, and are used more for the supply of the plant itself. Both types vary considerably in chemical composition and physical characteristics. The most widely used gaseous fuel is natural gas, which is generally found compressed in porous rock, is mainly made up of methane (CH_4), and whose composition depends on the reservoir and degree of treatment to which it is subjected. However, the recent reduction in the supply has raised interest in other types of oil-derived fuels and alternative fuels, such as H_2 [18,29,31].

2.4. Biofuels

Biofuels, which are derived from renewable sources, are attractive alternatives to fossil fuels, with intense research and development underway to reduce CO_2 emissions. A biofuel is any type of solid, liquid, or gaseous fuel derived from biomass, i.e., renewable organic matter of a plant, animal, or microbial origin. The different types of biofuels include vegetable oil, biodiesel, bioalcohol, biogas, solid biofuels (wood, coal, etc.), and synthesis gas (syngas) [29].

Although pure vegetable oil can be used in some diesel motors, it is typically first converted into biodiesel, a liquid fuel obtained from oils and fats through a process called transesterification. Compared to traditional diesel, biodiesel can substantially reduce the emissions of unburned hydrocarbons, CO, sulfates, and particulate matter, with the exception of nitrogen oxides (NO_x) [41,42].

Bioalcohols, such as ethanol, propanol, and butanol, are produced through microbial fermentation of sugars, starch, or cellulose. Bioethanol, a type of bioalcohol, is primarily derived from corn in the United States and sugarcane in Brazil. Together, these two countries account for 84% of global bioethanol production. In the United States, ethanol is commonly blended with regular gasoline at a concentration of about 5% by volume to enhance efficiency and reduce emissions [29,43].

Biogas, mainly composed of CH_4, is generated by the anaerobic digestion of organic matter, such as urban waste (landfills) and animal waste. If this gas is collected and used for the generation of energy, greenhouse gases will be directly and indirectly reduced, lowering the amount of CH_4 released into the atmosphere and replacing the use of non-renewable fuels [29].

Syngas is a mixture of fuel gases produced by the gasification of a fuel containing carbon, such as coal or urban waste, through the steam reforming of natural gas. The production of syngas, normally consisting of a mixture of CO, CO_2, and H_2, has the advantage of converting a solid raw material into a gaseous form that can easily be used for energy generation [29].

3. Hydrogen

Hydrogen is a gas with a high calorific value that can be obtained from various raw materials and used in different energy and non-energy applications. The growing interest in this fuel throughout the world is due to its use as a form of energy that contributes to the reduction in greenhouse gases when produced from renewable energy sources [44].

In addition to its substantial energy content, hydrogen is distinguished by its adaptability, possessing the capability to facilitate a wide array of sectors, extending from industrial manufacturing to energy storage and transportation. In contrast to numerous other energy carriers, hydrogen can be synthesized from a variety of feedstocks, encompassing fossil fuels, biomass, and water, which provides considerable flexibility regarding production methodologies. When employed in fuel cells or combustion engines, hydrogen produces solely water as a byproduct, rendering it an attractive option for a carbon-neutral energy transition. Nevertheless, it persists as an energy carrier rather than a primary energy source, necessitating energy-intensive processes for its synthesis, thereby emphasizing the significance of optimizing production techniques to enhance both efficiency and environmental advantages [45].

3.1. Hydrogen Properties

Hydrogen is arguably the gaseous substance that most closely approximates the characteristics of an ideal fuel, attributable to its elevated flame velocity, extensive combustion limits, facile ignition, and the complete absence of particulate matter during its oxidation process. Among all fuels currently obtainable, hydrogen (H_2) showcases superior energy density per unit mass, exhibiting a calorific value that is three times that of traditional petroleum fuels; additionally, in its liquefied condition, it manifests the most notable cooling characteristics. Conversely, its predominant limitations include an exceedingly low density and a minimal boiling point, necessitating advanced storage methodologies, as well as elevated production costs [46,47].

From a physicochemical viewpoint, hydrogen (H_2) is acknowledged as the least massive element in the periodic arrangement, distinguished by a molar mass of just 2.016 g/mol, which makes it roughly fourteen times less dense than the surrounding atmospheric air. This property correlates with its low density of 0.0899 kg/m^3 at standard conditions of 0 °C and 1 atm. By comparison, diesel is about 830 kg/m^3, and gasoline would be somewhat lighter, at close to perhaps 720 kg/m^3. Although this reduced density enhances its potential energy efficiency per mass, it presents considerable challenges concerning storage and transportation, which necessitate either high-pressure compression or liquefaction at extremely low temperatures, that is, −253 °C [48,49].

In the context of combustion, hydrogen reveals extraordinary attributes that underscore its viability as a fuel source. Hydrogen exhibits an adiabatic flame velocity of around 2.65 m/s, significantly outpacing that of gasoline (~0.37 m/s) and diesel (~0.30 m/s). This phenomenon facilitates rapid and efficient combustion, thereby allowing for complete oxidation without the concomitant production of soot. Furthermore, hydrogen possesses broad flammability limits in atmospheric conditions, ranging from 4% to 75% by volume, which renders it highly reactive and readily ignitable. Nevertheless, this heightened reactivity necessitates stringent control measures to mitigate risks, particularly in industrial settings [50].

Notwithstanding these benefits, the volumetric energy density of hydrogen constitutes a pivotal concern. Although it boasts a heating value (PCS) of 142 MJ/kg, considerably greater than that of gasoline (~46 MJ/kg) and diesel (~45 MJ/kg), its low volumetric energy density (12.8 MJ/m^3 in the gaseous phase) necessitates significantly larger storage volumes to equate to the energy capacity of liquid fossil fuels. In contrast, diesel and gasoline provide approximately 35 to 38 MJ/L, rendering them more practical alternatives for storage and transportation in volumetric contexts [45–49].

One of the other uniquely valuable traits that hydrogen has is its combustion characteristic, namely, it burns clean. Unlike diesel and gasoline, which emit gases such as carbon dioxide (CO_2), hydrogen releases only water vapor on combustion, which means no smoke or other emissions derived from burning carbon compounds. Nevertheless, under conditions of elevated combustion temperature, the precursors for nitrogen oxides (NOx) are still present, so NOx emission-reducing measures will have to be taken in industrial and transportation-related applications [51].

3.2. Hydrogen Routes

Hydrogen is not a primary fuel but rather a secondary energy carrier, as it is typically bound to other elements in nature. Its molecular form (H_2) is rarely found in natural reservoirs (referred to as "white hydrogen"). To be utilized as an energy source, hydrogen must be extracted from various compounds, which invariably requires an external energy input. The methods for producing hydrogen are diverse, ranging from processes that rely on fossil fuels to those that employ renewable resources. Industrial-scale hydrogen is most economically produced from fossil fuels, through methods like coal pyrolysis, oil refining, and steam methane reforming (SMR) from natural gas. However, it can also be generated via renewable pathways, such as thermochemical or biological conversion of biomass, or the electrolysis of water powered by renewable energy sources [18].

The classification of hydrogen into different colors is directly linked to the method of production, with each color representing a specific production pathway. For example, "green hydrogen" refers to hydrogen produced via water electrolysis using electricity derived from renewable sources. This color-based nomenclature provides a framework for understanding the environmental impact and energy source associated with each hydrogen production method. The various colors—such as gray, blue, and turquoise—serve to distinguish hydrogen based on its carbon footprint and the sustainability of its production process [52,53].

3.2.1. Green Hydrogen

Green hydrogen is produced from renewable energy sources (such as wind, solar, and hydroelectric power), with water electrolysis being the predominant method of production. In this process, water (H_2O) is split into oxygen (O_2) and hydrogen (H_2) using electricity generated from renewable sources like solar, wind, or hydroelectric power [52]. The electrochemical reaction occurring during electrolysis can be represented by the following Equation (1):

$$2H_2O(l) + 118.6\frac{kJ}{mol}(\text{eletricity}) + \text{heat} \rightarrow 2H_2(g) + O_2(g) \quad (1)$$

The value of 118.6 kJ/mol represents the minimum energy required to perform the electrolysis of water. "Heat" was also added to the reaction to represent a scenario where there is a contribution of energy from external renewable sources or from some particularity of the system. The efficiency of the electrolysis process can vary significantly depending on several factors, including the technology used, the purity of the water, operational temperature and pressure, as well as the electricity source. Green hydrogen, produced from renewable energy sources, can reduce CO_2 emissions by 21.74 kg for every kg replaced by gray hydrogen. Electrolysis technologies include alkaline electrolysis (AE), proton exchange membrane electrolysis (PEM), and solid oxide electrolysis (SOE). AE is one of the most established and widely used technologies. In this method, an alkaline solution, typically sodium hydroxide (NaOH), is used as an electrolyte. The typical efficiency of alkaline electrolysis ranges from 60% to 80%. The simplicity of the design and the relatively low operating costs make this technology a viable option for large-scale production; however, its low power density limits its ability to respond rapidly to fluctuations in energy demand [52–55].

PEM electrolysis, on the other hand, employs a proton exchange membrane that allows for the passage of hydrogen ions while preventing the flow of gases such as oxygen. This technology offers a higher power density and a quicker response to fluctuations in electrical load, making it ideal for integration with intermittent renewable sources. However, the high cost of materials and the complexity of the system limit its widespread adoption. The efficiency of PEM electrolysis typically exceeds 70% and can reach up to 85% under optimal conditions [56,57].

SOE is an emerging technology for producing green hydrogen, operating at high temperatures (700 °C to 1000 °C) and achieving efficiencies exceeding 90%, especially when integrating waste heat from industrial processes and nuclear reactors. While it offers significant advantages in terms of efficiency and potential cost reduction due to its use of heat, SOE faces challenges related to system complexity and the need for materials that can withstand high temperatures. Compared to AE and PEM electrolysis, SOE excels in efficiency but may be less flexible in applications requiring rapid response, where PEM technology shines [58,59].

Emerging electrolysis technologies, such as concentrated solar power (CSP) electrolysis and anion exchange membrane (AEM) electrolysis, show promising efficiencies for green hydrogen production but still face significant challenges that limit their scalability. CSP electrolysis harnesses heat generated from concentrated solar sources; however, it relies on advanced infrastructure and integration with energy storage systems, which can increase costs and complexity for large-scale implementation. On the other hand, AEM electrolysis, which is less dependent on expensive materials like precious metals, is still in the early stages of development and faces challenges related to material durability and process efficiency under variable operating conditions [53,60,61].

3.2.2. Pink Hydrogen

Pink hydrogen is a form of hydrogen produced through the electrolysis of water, utilizing nuclear energy as the source of electricity. This approach integrates hydrogen generation with energy derived from nuclear power plants, providing a low-carbon alternative and contributing to the transition towards a more sustainable energy system. Nuclear power plants generate electricity through nuclear fission, releasing a substantial amount of energy without the direct emission of greenhouse gases. The electricity generated is then employed to perform the electrolysis of water, in which water is dissociated into gaseous hydrogen and gaseous oxygen through the passage of an electric current [62,63]. The reaction can be represented according to Equation (2):

$$2H_2O \xrightarrow{\text{eletricity}} 2H_2(g) + O_2(g) \tag{2}$$

The efficiency of electrolysis typically ranges from 60% to 80%, depending on the technology employed, and is combined with the energy generation efficiency of nuclear power plants, which typically ranges from 33% to 37%. Thus, the production of pink hydrogen can offer a competitive alternative for reducing carbon emissions, particularly in regions where nuclear energy is an abundant resource. Studies indicate that by employing advanced electrolysis technologies, such as PEM electrolysis, the overall efficiency of the process can be optimized, resulting in hydrogen production with reduced environmental impacts [15,64,65].

However, the adoption of pink hydrogen faces several challenges. Public acceptance of nuclear energy is a critical issue, as many citizens continue to have concerns regarding safety, waste management, and the environmental impact of nuclear power plants. Additionally, the high initial infrastructure costs for both nuclear facilities and electrolysis systems may limit the economic competitiveness of pink hydrogen compared to alternatives such as green hydrogen. Effective management of nuclear waste, which remains a persistent concern, must also be addressed to ensure the long-term viability of this technology [62,66].

3.2.3. Gray Hydrogen

Gray hydrogen is primarily produced through the steam methane reforming (SMR) process, a thermochemical method that converts methane (CH_4) into hydrogen and carbon dioxide (CO_2). This method is the most widely used globally due to its economic viability and the abundance of natural gas as a raw material source. The steam reforming process, which is the predominant technique, occurs in two main stages [53]. First, methane is mixed with steam at high temperatures (700–1000 °C) in the presence of a nickel catalyst, resulting in the production of carbon monoxide and hydrogen, as illustrated in Equation (3):

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (3)$$

Subsequently, the generated carbon monoxide undergoes an additional reaction (shift) with water vapor, which maximizes hydrogen production and the release of CO_2, as shown in Equation (4):

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (4)$$

Although this method is economically viable due to the abundance of natural gas and existing infrastructure, it generates large amounts of carbon dioxide, significantly contributing to greenhouse gas emissions. The production of one kilogram of gray hydrogen can result in up to 12 kg of CO_2 emissions, raising ethical and environmental concerns about its continued use. While gray hydrogen represents a short-term solution to meet industrial demand, its reliance on fossil fuels and contribution to global warming makes its sustainability questionable. In response to these challenges, cleaner alternatives, such as blue hydrogen—which incorporates CCS technologies—are being developed [67–69].

3.2.4. Blue Hydrogen

Blue hydrogen is also produced through the steam reforming process. The key distinction between blue hydrogen and gray hydrogen lies in the implementation of CCS technologies, which capture CO_2 before it is released into the atmosphere, safely transporting and storing it in deep geological reservoirs such as aquifers, depleted oil and gas fields, or even unminable coal beds. Moreover, blue hydrogen generates only 1 kg of CO_2 per kg of H_2 produced, approximately 83% less than gray hydrogen. This approach not only significantly reduces the carbon footprint associated with hydrogen production but also contributes to climate change mitigation, positioning blue hydrogen as a viable intermediate solution in the transition towards a low-carbon energy matrix [53,70].

However, while blue hydrogen offers advantages in reducing greenhouse gas emissions, its reliance on fossil fuels raises concerns about its long-term sustainability. The economic and technical feasibility of the infrastructure required for the capture, transport, and safe storage of CO_2 presents a significant challenge. The effectiveness of CCS technologies is critical, as insufficient CO_2 capture could undermine the environmental benefits of blue hydrogen. Additionally, the availability of suitable geological storage sites for CO_2 must be considered to ensure the safety and efficacy of the process. Despite these limitations, blue hydrogen is often recognized as an essential component in the decarbonization pathway, serving as a bridge between fossil-based hydrogen sources and more sustainable production methods, such as green hydrogen [15,70,71].

3.2.5. Turquoise Hydrogen

Turquoise hydrogen is gaining increasing attention due to its potential to offer a more sustainable alternative compared to gray and blue hydrogen. The production of turquoise hydrogen involves methane pyrolysis, a thermochemical process that occurs at high temperatures (typically above 1000 °C) and results in the decomposition of methane into H_2 and solid carbon (C), instead of CO_2 as a byproduct [53,72], as shown in Equation (5):

$$CH_4 \xrightarrow{\text{High Temperatures}} C(s) + 2H_2(g) \tag{5}$$

This approach not only generates hydrogen but also produces solid carbon, which can be used in various industrial applications, such as the manufacturing of electrodes, composite materials, and carbon capture and storage. This method has garnered interest due to its efficiency and potential to reduce the carbon footprint associated with hydrogen production. Methane pyrolysis can be carried out in fixed-bed, rotating-bed, or fluidized-bed reactors, the latter of which has shown promise due to improved heat transfer and uniform material distribution, resulting in higher process efficiency. In terms of efficiency, methane pyrolysis offers significant advantages, not only because it can utilize thermal energy from renewable sources but also because conversion efficiencies of up to 85% to 95% can be achieved, depending on operational conditions and reactor design [72–74].

3.2.6. Biological Route

Biological hydrogen production represents a promising approach to sustainable and renewable energy, leveraging microorganisms to convert organic matter into hydrogen. This process utilizes natural biochemical reactions conducted by bacteria, algae, or other organisms, often using energy sources such as sunlight or organic waste. A key advantage of this pathway is the potential to use agricultural and industrial residues, promoting a circular economy. Additionally, low emissions of polluting gases and potential cost reductions are significant benefits of this technology, especially compared to conventional hydrogen production methods such as natural gas reforming or electrolysis. Although promising, biological production still faces technological and economic challenges, including low conversion efficiency and the need for optimization of microorganism cultivation systems [75].

Photosynthesis is a process in which phototrophic microorganisms, such as microalgae and photosynthetic bacteria, harness solar energy to produce biological hydrogen. These organisms have the ability to capture sunlight and perform water photolysis, releasing oxygen (O_2) and protons (H^+), which, through the action of the enzyme hydrogenase, are converted into molecular hydrogen (H_2) [76], as shown in Equations (6) and (7).

$$2H_2O \xrightarrow{\text{sunlight}} 4H^+ + 4^{e-} + O_2 \tag{6}$$

$$4H^+ + 4e^- \xrightarrow{\text{hydrogenase}} 2H_2 \tag{7}$$

Microalgae, for example, contain an enzyme called hydrogenase, which catalyzes hydrogen production under anaerobic conditions. Photosynthetic bacteria, on the other hand, can carry out this conversion in light-rich, oxygen-poor environments by using simple organic substrates. Despite its great potential, the efficiency of this process remains low, primarily due to the inhibition of hydrogen production by the oxygen generated during photosynthesis. Consequently, current research is focused on advancing the metabolic engineering of these organisms and developing technologies to optimize hydrogen yield [77,78].

Fermentation is another biological pathway for hydrogen production, involving the conversion of organic matter by microorganisms in anaerobic environments. Agricultural residues such as straw and manure, and industrial byproducts like vinasse, are rich in organic matter. Key hydrogen-producing bacteria include *Clostridium*, *Enterobacter*, and *Klebsiella*. During this process, fermentative bacteria break down carbohydrates such as glucose, generating byproducts like organic acids, carbon dioxide (CO_2), and molecular hydrogen (H_2) [75,79]. The overall reaction for glucose fermentation to produce hydrogen can be represented by Equation (8).

$$C_6H_{12}O_6 + 2H_2O \xrightarrow{\text{fermentation}} 2CH_3COOH + 2CO_2 + 4H_2 \tag{8}$$

Although relatively simple and accessible, fermentation yields less hydrogen compared to other methods due to competition with other byproducts. Current research is focused on enhancing efficiency and yield by optimizing key process parameters, such as temperature, pH, substrate concentration, and hydraulic retention time. Additionally, efforts are directed toward selecting bacterial strains like *Clostridium butyricum* and *Clostridium acetobutylicum*, known for their high hydrogen production capacity and efficiency in utilizing diverse substrates [80].

3.2.7. Solar-Driven Route

Solar-powered hydrogen production is a sustainable alternative that aims to harness abundant solar radiation to generate clean hydrogen. This pathway encompasses various technologies that convert solar energy into chemical energy, stored as molecular hydrogen. Key technologies include solar-mediated water photolysis, photovoltaic cells coupled with electrolysis, and concentrated solar power (CSP) systems. Using solar energy for hydrogen production offers the advantage of a renewable, low-emission source. However, it still faces challenges, such as the need to optimize energy conversion efficiency and reduce the costs associated with required infrastructure [81–83].

Photolysis is the process of decomposing water into oxygen and hydrogen using direct sunlight. In this method, solar energy is absorbed by semiconductors or photosensitive catalysts that facilitate the splitting of water molecules into protons, electrons, and oxygen. These electrons and protons are subsequently used to form molecular hydrogen. This process is analogous to photosynthesis but without microbial involvement in solar capture. The main challenge with photolysis is its low efficiency in converting solar energy into hydrogen, which has driven the development of more efficient photocatalytic materials, such as doped semiconductors and metal oxide nanoparticles. Despite its environmentally advantageous potential, direct photolysis remains experimental, with current efforts focused on improving process efficiency and material durability [84,85].

Photovoltaic (PV) solar cells produce hydrogen indirectly by converting solar energy into electricity, which then powers an electrolyzer to generate hydrogen—acting as the energy source for electrolysis. Various types of PV cells, such as monocrystalline, polycrystalline, and thin film, each have distinct characteristics in terms of efficiency and cost. The basic principle of these cells is the conversion of photons into an electric current via semiconductor materials like silicon. When sunlight strikes the material, it excites electrons, creating an electric current. This current can power electrolyzers and may also be stored in batteries or used directly to supply electricity to homes, industries, and electric vehicles [86,87].

CSP is an innovative technology designed to maximize solar energy capture by using mirrors or lenses to focus sunlight on a specific point. This concentration generates high temperatures that can be utilized for both electricity generation and hydrogen production through thermal processes. CSP systems include various configurations, such as parabolic dishes, solar towers, and parabolic trough collectors, each with distinct characteristics and applications. In a typical electricity generation process, concentrated sunlight heats a fluid—such as water, thermal oil, or molten salt—to temperatures ranging from 200 °C to 600 °C. The heated fluid is then used to generate steam, which drives turbines connected to electrical generators [88,89].

The thermal energy generated can be directly applied in electrolysis processes, contributing to the decarbonization of industrial and transportation sectors. One of the main advantages of CSP is its capacity for thermal storage, allowing energy collected during the day to be utilized at night or during cloudy periods, thereby enhancing its viability as a renewable energy solution and for sustainable hydrogen production. The average efficiency of CSP systems varies by type: Parabolic dish reflectors exhibit the highest efficiency (up to 35%), followed by central receiver collectors (17–21%), linear Fresnel reflectors (LFRs) (11–19%), and parabolic trough collectors (PTCs) (13–14%). Their application is most viable in regions with high solar incidence, which may limit their geographical expansion. Current research focuses on improving the materials used and the overall efficiency of the systems, aiming to maximize sustainable hydrogen production [88–91].

3.3. Storage and Transportation

The transportation and storage of hydrogen are critical issues for the viability of its use as an energy carrier, especially as the demand for sustainable and low-carbon solutions grows. Hydrogen, being a low-density gas, presents unique challenges when it comes to compression, liquefaction, and large-scale handling. The ability to store and transport hydrogen efficiently is essential for its integration into various sectors, including transportation, chemical industries, and power generation. Ensuring effective infrastructure and technology for these processes is key to realizing hydrogen's potential as a versatile energy vector [45].

One of the primary methods for hydrogen transport is compression into cylinders or tanks at high pressures (CGH2), typically ranging from 350 to 700 bar. This technique allows for hydrogen storage in its gaseous state, but it poses challenges in terms of cost and safety, as compression requires significant energy, and the tanks must be designed to withstand high pressures. Alternatively, hydrogen can be liquefied (LH2) in cryogenic tanks at extremely low temperatures, which allows for a much higher energy density. However, the liquefaction process is energy-intensive and may compromise the overall efficiency of the system. In response to these limitations, emerging technologies are being explored where hydrogen is stored in the form of metal hydrides. These materials can absorb and release hydrogen safely, but they still lack large-scale development for commercial applications. Other structures, such as metal–organic frameworks (MOFs) and nanomaterials, show potential for high-density storage but require further research to optimize their performance for practical use [45,92].

The transportation of hydrogen has expanded to include the use of existing pipeline infrastructure, which can provide a cost-effective and efficient solution. Pipeline transport can be employed to transfer hydrogen from production sites to consumption centers, such as industries and power plants, over long distances. However, existing infrastructure is often inadequate for transporting pure hydrogen due to its high diffusivity and tendency to cause hydrogen embrittlement (HE) in materials. To overcome these challenges, high-strength alloys and specialized coatings are being implemented, and blending hydrogen with natural gas in pipelines has been adopted as a strategy to ease the transition [92,93].

Transporting hydrogen in chemical forms such as ammonia (NH_3) or methanol (CH_3OH) is emerging as a viable option, as these compounds can be easily handled and transported using existing fuel transportation infrastructure. For instance, converting hydrogen into ammonia allows for higher energy density and safer transport, although the conversion processes must be optimized in terms of efficiency and cost. Integrating carbon capture technologies and implementing policies that encourage investment in research and development are essential to ensure that transportation and storage methods are not only efficient but also economically viable. These strategies are critical for scaling up hydrogen infrastructure to support the broader adoption of hydrogen as a clean energy carrier [94,95].

3.4. Energy and Industrial Applications of Hydrogen

Hydrogen, with its versatility, enables its use in a wide range of energy and industrial applications, replacing traditional fossil fuels in sectors where electrification is difficult or impractical. Hydrogen applications can be classified into two major categories: established applications and emerging applications, each with its respective challenges and potential [96].

3.4.1. Conventional Energy Applications

One of the most traditional uses of hydrogen is as a feedstock in the petrochemical industry, primarily in petroleum refining processes and ammonia production. In the refining industry, hydrogen is utilized in hydrotreating processes, which remove sulfur from petroleum derivatives, and in hydrocracking, where heavy fractions of oil are converted into lighter, more valuable fuels. The demand for hydrogen in these processes is intrinsically linked to global oil consumption, which poses a limitation from the perspective of the energy transition, as these industries remain heavily dependent on fossil fuels [97–99].

In ammonia production, hydrogen is essential for the Haber–Bosch process, in which atmospheric nitrogen is combined with hydrogen to produce ammonia (NH_3), a crucial input in fertilizer manufacturing. While this process is one of the largest consumers of hydrogen globally, most of the hydrogen used is produced from natural gas, resulting in significant volumes of carbon dioxide as a byproduct. Transitioning to green hydrogen in these sectors is viewed as a promising solution to reduce the greenhouse gas emissions associated with fertilizer production [98–100].

One increasingly sought-after application of hydrogen is in stationary energy generation, where it is utilized in fuel cells to produce electricity with high efficiency (50–60%) and zero local pollutant emissions. In remote areas or as backup power systems, hydrogen presents a promising alternative to diesel generators, ensuring a continuous supply of electricity, particularly in locations with limitations on the use of traditional power grids. Fuel cells are also being integrated into microgrid systems, where hydrogen is combined with renewable energy sources such as solar and wind power. In this context, hydrogen serves as an energy storage medium, effectively smoothing out the intermittency associated with renewable sources [101,102].

In the mobility sector, hydrogen has gained prominence in transportation applications, particularly for heavy vehicles such as trucks, trains, and buses. Hydrogen fuel cells offer advantages over electric batteries in terms of energy density and refueling time. Lightweight hydrogen-powered vehicles are also under development, with automakers investing in fuel cell technologies that compete with battery electric vehicles (BEVs). However, the hydrogen refueling infrastructure remains a significant challenge, limiting large-scale adoption, especially in areas with lower population density [103–106].

3.4.2. Emerging and Promising Applications

In addition to established applications, hydrogen is emerging as a solution in sectors facing challenges in decarbonization. A notable example is the steel industry, which accounts for approximately 7% of global CO_2 emissions. Currently, the traditional steel manufacturing process relies on coal as a reducing agent to convert iron ore into metallic iron, releasing significant amounts of carbon dioxide in the process. Substituting coal with hydrogen in processes such as Hylsa and MIDREX for direct reduced iron (DRI) production presents a significant opportunity to eliminate CO_2 emissions, with water as the sole byproduct. Hydrogen-based direct reduction (HyDR) is gaining traction as a sustainable alternative, with studies indicating its potential to substantially reduce global CO_2 emissions from the steel industry. This represents one of the most significant opportunities for the large-scale use of hydrogen in industrial applications [107–109].

Another emerging sector benefiting from hydrogen is aviation, which faces significant challenges in electrification, particularly on long-distance routes. Hydrogen can be utilized directly in modified combustion engines or in fuel cells to power electric propulsion systems. Aerospace companies are investing in hydrogen-powered aircraft, both in its liquid form and in combination with biofuels, to drastically reduce carbon emissions. However, this technology still encounters technical challenges related to the safe storage of liquid hydrogen on aircraft and its comparatively low energy density compared to aviation kerosene [110–112].

Additionally, hydrogen is being considered as a decarbonization solution for high-temperature industrial sectors, such as cement and glass production, where the electrification of furnaces is not feasible due to the requirement for extremely high temperatures. Replacing fossil fuels with hydrogen in these processes could significantly reduce CO_2 emissions; however, technical challenges such as adapting furnaces and the high cost of hydrogen still need to be addressed [113,114].

A promising yet less explored application of hydrogen lies in large-scale energy storage. In systems with increasing integration of intermittent renewable sources, such as solar and wind, hydrogen provides a solution for storing excess energy generated during periods of low demand. This stored hydrogen can be converted back into electricity during times of high demand or used directly as fuel. Technologies like power-to-gas (P2G) are being developed to convert renewable electricity into hydrogen, which can be injected directly into natural gas networks or stored for future use, creating an efficient energy utilization cycle [115–117].

3.5. Challenges and Safety in Hydrogen Utilization

The use of hydrogen as an energy and industrial vector, while promising in terms of decarbonization and energy efficiency, is accompanied by a series of technical, economic, and safety challenges that must be addressed for this technology to be viable on a large scale. The specific nature of hydrogen, both in its chemical and physical properties, necessitates rigorous and sophisticated measures to ensure its safe handling and efficient use. In this context, the challenges span from production, transportation, and storage to end-use operations, all requiring technological innovations and stringent regulations to mitigate the associated risks [118,119].

3.5.1. Technical and Economic Challenges

The first and perhaps most critical challenge in the utilization of hydrogen is its sustainable, large-scale production in a clean manner and at competitive costs. Although hydrogen can be produced from various sources, representing a low-carbon solution, it still faces significant challenges regarding cost. Electrolysis, for example, is an energy-intensive process, and the efficiency of current technologies such as PEM and AEM still requires optimization to reduce the final cost of the produced hydrogen. The economic viability of green hydrogen heavily depends on the availability of cheap and abundant renewable energy sources, which is not yet a reality in many regions around the world. Currently, the cost of producing hydrogen is much higher than that of traditional fossil fuels, limiting its competitiveness in industrial sectors [15,120,121].

Brazil has characteristics that place it in a privileged position as a competitor in the chain of sustainable hydrogen. The country has a diversity of renewable energy resources, such as wind, solar, ethanol, and hydroelectric power, which can be used in the production of H_2 through electrolysis or natural gas steam reforming. The production of H_2 also provides a way to store the energy generated from sources that are normally limited in terms of availability due to seasonality (i.e., solar and wind power). Moreover, the geographic position and vast territory of Brazil expand opportunities for the exploration of H_2 in the domestic market (industry and transportation) and external market through exportation, especially to Europe [29].

Another significant challenge lies in the storage and transportation of hydrogen, particularly due to its low volumetric density, which necessitates large volumes to store relatively small amounts of energy. For long-distance transport or use in industrial and energy applications, hydrogen must be compressed at extremely high pressures or liquefied at cryogenic temperatures, with both processes requiring advanced technologies and, consequently, entailing high costs. Additionally, the construction of a dedicated hydrogen transportation infrastructure, such as pipelines or transportation systems via trucks and vessels, faces both economic and logistical barriers. Although it is possible to inject hydrogen into existing natural gas networks, the compatibility of pipeline materials and the efficient blending of hydrogen and natural gas remain subjects of ongoing research [45,92,120,122].

In addition to the challenges of production and infrastructure, the integration of hydrogen with existing energy technologies poses another complex obstacle to its large-scale utilization. Transitioning to hydrogen requires significant adaptations in sectors such as electricity generation, transportation, and energy-intensive industries that currently rely on fossil fuels. The main challenges revolve around efficiency and operational stability, as well as issues related to monitoring and control systems, in addition to the current lack of scalable hydrogen production. In the transportation sector, for instance, although hydrogen fuel cells present a promising solution, the infrastructure for refueling and the development of compatible vehicles remain in the early stages compared to battery-powered electric vehicles. The absence of a comprehensive and accessible infrastructure limits the widespread adoption of hydrogen-powered vehicles, which require appropriate and secure locations for refueling. Furthermore, the gradual replacement of internal combustion engines with hydrogen fuel cells necessitates the establishment of extensive and secure distribution networks, along with international standards, to ensure the compatibility of refueling systems [25,123–125].

In industry, the conversion of existing technologies for hydrogen uses faces both technical and economic challenges. Industrial processes such as steel and cement production, which are highly carbon-intensive, need to be adapted to utilize hydrogen as an energy source or as a chemical reductant. However, this adaptation is not trivial, as hydrogen operates under thermal conditions and pressures different from those of fossil fuels, which may require a complete overhaul of industrial plants. Furthermore, the retro compatibility with natural gas networks, which in some cases may blend a certain percentage of hydrogen, faces technical limitations related to material embrittlement and the need for the reconfiguration of combustion equipment. Thus, the transition to hydrogen utilization demands substantial investments in research and development, not only to enhance emerging technologies but also to adapt existing infrastructures and systems, ensuring that this transition is efficient, safe, and economically viable [93,107,113,114].

3.5.2. Safety in the Use of Hydrogen

Hydrogen, due to its chemical nature, presents complex safety challenges that are considerably different than those associated with fossil fuels. It is highly flammable and possesses a wide range of flammability, meaning it can ignite over a broad spectrum of concentrations in air. Additionally, hydrogen has a relatively low ignition point, and the energy required to initiate combustion is significantly lower than that of fuels such as methane or gasoline. These characteristics render hydrogen particularly hazardous in the event of leaks, especially in confined spaces. Even small amounts of hydrogen that escape into the atmosphere can rapidly form explosive mixtures, underscoring the urgent need for advanced monitoring systems to detect and mitigate leaks before they result in accidents [126–128].

Another risk factor associated with hydrogen is its rapid dispersion and odorless nature. Being the smallest element on the periodic table, hydrogen molecules can penetrate many materials, leading to issues such as the hardening and embrittlement of metals. This can compromise the integrity of storage containers, pipelines, and valves, posing a critical challenge in constructing safe and durable systems for handling the gas. Computational fluid dynamics (CFD) modeling is increasingly employed to predict hydrogen dispersion and inform safety assessments. Identifying materials resistant to these effects and developing suitable coatings or metal alloys are areas of intense research [129–131].

Additionally, while hydrogen is non-toxic, its low density and high diffusivity can result in leaks that are undetectable by conventional means, as the gas is colorless, odorless, and tasteless. This necessitates the development and implementation of highly sensitive and effective sensors capable of detecting small concentrations of hydrogen in the air to prevent potential explosions. Several sensors are currently being researched and developed to address this issue, including eye-readable reversible sensors (ERSs), 3ω sensors, HPNN sensors, and optical and acoustic sensors. In high-safety-demand areas such as industrial plants and hydrogen refueling stations for fuel cell vehicles, these monitoring systems must be highly robust and incorporate redundancies to ensure continuous protection [45,89–92,127].

3.5.3. Advances and Risk Mitigation

To address these challenges, the scientific and industrial communities have been actively seeking innovative technological solutions and enhancing regulations to ensure the safe and efficient use of hydrogen. Implementing stringent safety standards throughout the hydrogen life cycle, from production to end use, has become a priority to ensure that infrastructures are designed according to the highest safety standards. Moreover, advancements in fuel cell technology and the design of safer storage tanks using materials capable of resisting hydrogen embrittlement have significantly improved safety and reliability in the use of hydrogen across various sectors [129,132–138].

Another important area of development lies in real-time monitoring systems that utilize hydrogen sensors to detect hazardous concentrations and leaks, automatically triggering containment mechanisms. These systems are crucial for large-scale operations, such as the transportation and storage of liquid or compressed hydrogen, where the risks of failure must be minimized [131,139–141].

Initiatives and innovations in the H_2 industry are being driven by the current technological, economic, and political context. Decarbonization goals set out in the Paris Agreement and strengthened at COP26 underscore the need for technological options to reduce emissions in fossil fuel-dependent sectors of the economy, such as transportation and energy-intensive industries. Additional drivers have also emerged, such as the Net Zero Bank Alliance (NZBA) led by the United Nations (UN), which establishes guidelines for the availability of credits based on the commitment of investors to resolving the climate issue and the carbon emissions of each project funded [44].

4. Combustion

Combustion is an exothermal oxidative reaction in which fuel reacts quickly with the oxidant (generally air or O_2), producing energy in the form of heat as the reactants are consumed and transformed into products. This process plays a fundamental role in the use of fuels for residential and industrial heating, steam generation for industrial processes and electricity production, incineration of solid waste, and propulsion of internal combustion engines, gas turbines, and rockets. The fuel can be solid, liquid, or gaseous, and petrochemical, biological, or alternative. A source of heat/ignition is needed to start the reaction, providing the activation energy necessary for the fuel to overcome its fire point. The air-to-fuel ratio must be within the appropriate range so that combustion can occur. Once initiated, the energy generated in the form of heat anchors the reaction until the occurrence of a thermal balance between the products and reagents [45,46].

The combustion reaction may be complete or incomplete. With complete or stoichiometric combustion, all the fuel is burned until the end, while with incomplete combustion, part of the unburned fuel is found in the products. In the standard combustion of hydrocarbons with oxygen, the oxidation reaction is given by Equation (9), which represents the complete combustion reaction of a hydrocarbon:

$$C_xH_y + zO_2 \rightarrow xCO_2 + \frac{y}{2}H_2O + \text{energy} \quad (9)$$

in which x, y, and z = x + y/4 are stoichiometric coefficients.

The minimum amount of air necessary for the complete combustion of a fuel is denominated stoichiometric air or theoretical air. When a fuel is burned completely with theoretical air, no uncombined oxygen is present in the flue gases [30,45]. Complete combustion requires adequate (a) supply of atmospheric air or oxygen, (b) fuel-to-air ratio, (c) temperature in the combustion chamber for fuel ignition, and (d) residence time in the combustion chamber. Complete combustion typically produces a light blue and stable flame, indicating the presence of an optimal fuel-to-oxygen mixture. This flame is less visible but exhibits higher temperatures and cleaner burning characteristics. The complete reaction generally reaches elevated temperatures, as all the energy from the fuel is converted into heat [30,142,143].

In complete combustion, the reaction between fuel and oxygen occurs under optimal conditions, resulting in the total conversion of the fuel into stable products, predominantly carbon dioxide (CO_2) and water (H_2O). This process maximizes energy release, as the complete oxidation of hydrocarbons generates the highest possible amount of usable energy. Furthermore, despite the production of CO_2, it releases a lower quantity of harmful pollutants into the atmosphere, as the reaction products are more stable and less reactive [144].

Since insufficient airflow leads to incomplete combustion, excess theoretical air is normally used in actual combustion processes to increase the chance of complete combustion or control the temperature in the combustion chamber, even if this causes fuel waste and unburned residues, and increases the energy lost by the system [9,11,21]. Incomplete combustion can produce either carbon monoxide or soot. These general reactions of standard incomplete hydrocarbon combustion are given by Equations (10) and (11):

$$C_xH_y + zO_2 \rightarrow xCO + \frac{y}{2}H_2O + \text{energy} \tag{10}$$

$$C_xH_y + zO_2 \rightarrow xC + \frac{y}{2}H_2O + \text{energy} \tag{11}$$

in which x, y, and z are stoichiometric coefficients.

Incomplete combustion is often accompanied by a yellow or orange flame, resulting from the incandescence of unburned carbon particles. This type of flame is more unstable and produces a higher amount of soot, reflecting the inefficiency of the combustion process. Insufficient oxygen leads to the formation of intermediate products, such as carbon monoxide (CO), elemental carbon (C, in the form of soot), and, in some cases, volatile organic compounds (VOCs) such as aldehydes, ketones, and BTEX compounds. Consequently, the energy released during incomplete combustion is significantly lower, indicating reduced efficiency compared to complete combustion. The emission of CO is particularly concerning, as it is a toxic gas that can cause serious health issues, such as poisoning, and contributes to the formation of smog, which is the accumulation of air pollution in the atmosphere of cities in the form of haze. Soot particles, which can accumulate in the lungs and atmosphere, also have direct implications for air quality and public health, increasing the risk of respiratory and cardiovascular diseases [145–147].

The differences between complete and incomplete combustion have significant practical implications that directly impact energy efficiency, environmental sustainability, and public health. Combustion efficiency is a crucial factor in heating systems and power generation, where maximizing energy production and minimizing resource waste are primary objectives, especially considering the increasing demand for energy and the urgent need to reduce greenhouse gas emissions. In this context, efficiency becomes particularly evident in high-efficiency burners used in industrial furnaces, boilers, and heating systems. These burners are designed to optimize the fuel–air mixture, ensuring complete combustion. Advanced technologies such as oxygen sensors are now incorporated to optimize fuel–air ratios in automotive applications, enhancing combustion efficiency and reducing emissions through continuous monitoring and adjustment of operational conditions [148–151].

The combustion behavior of fossil fuels such as coal, oil, and natural gas is significantly influenced by their chemical composition and physical properties. The characteristics of each type of combustion not only affect energy efficiency and pollutant emissions but also have direct implications for the selection of fuels in various industrial and consumer contexts. Firstly, the nature of fossil fuels such as coal, oil, and natural gas is a determining factor in how they behave during combustion [152,153].

Natural gas, predominantly composed of methane (CH_4), is often selected for its high combustion efficiency and its ability to produce significantly fewer undesirable byproducts compared to other fossil fuels. The complete combustion of methane results in low emissions of carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter, making it widely used in residential and industrial applications where energy efficiency and emissions reduction are priorities. The combustion of natural gas in power plants and natural gas vehicles (NGVs) leads to significantly lower CO_2 emissions and improved engine efficiency, although NOx emissions may increase. Furthermore, the existing infrastructure for natural gas distribution and its ease of use in heating processes and electricity generation further enhance its viability [154–156].

The chemical and mineralogical composition of coal plays a crucial role in its combustion behavior, particularly influencing the ash melting temperatures and the characteristics of ash-related issues such as slagging and fouling. Coal combustion is often less efficient and more polluting due to incomplete combustion, especially under inadequate oxygen conditions, resulting in the formation of CO and soot, and significant emissions of sulfur oxides (SOx) and NOx. These pollutants are harmful to health, contributing to respiratory and cardiovascular issues, as well as climate impacts such as ozone formation and acid rain. While coal remains economically viable in regions with favorable infrastructure, its environmental implications necessitate emission control technologies such as carbon capture and storage (CCS) to mitigate its effects [127–135,157–159].

Liquid fuels such as gasoline and diesel exhibit relatively efficient combustion, achieving nearly complete combustion under optimized conditions, which results in lower emissions of pollutants such as carbon monoxide and particulate matter compared to coal. This efficiency is further enhanced using advanced combustion techniques such as moderate and intensely diluted combustion (MILD), which improves the homogeneity of the fuel–air mixture and reduces pollutant formation. Additionally, the employment of optimized fuel formulations and specific additives can further enhance performance and reduce emissions. Gas-to-liquid (GTL) fuels, produced from natural gas via Fischer–Tropsch synthesis, have a high cetane number, resulting in more efficient combustion with lower emissions of pollutants such as SOx and particulate matter compared to conventional fossil fuels [160–162].

In addition to their ease of transportation and storage, liquid fuels' ability to mix with air, their chemical composition, their atomization capacity, and their generation of fewer solid residues when burned are distinguishing characteristics. These features make them attractive options for applications where emission control is critical, such as in automobile engines and power generators. In urban environments, where air quality is a constant concern, the combustion efficiency of liquid fuels can help meet environmental regulations and public health standards [161–163].

Combustion occurs in various forms, not all of which are accompanied by flames or luminescence. The most important combustion mechanisms are deflagration and detonation. Deflagration is subsonic combustion characterized by a flame that propagates normally by thermal conductivity from the mixture of water and unburned vapor, resulting in accentuated temperature gradients and concentrations of species and accompanied by luminescence. Detonation consists of shock waves propelled by the release of energy in a chemical reaction zone, the speed of which is much higher than that of sound, often reaching Mach 5, as in the case of a mixture of hydrogen fuel and air [18,164,165].

Experiments have shown that a flame can only propagate within a range of mixture concentrations between the upper and lower limits of flammability. If small quantities of fuel gas or fuel vapor are gradually added to the air, the mixture becomes flammable at a certain point. The percentage of fuel at this point, called the lower limit of flammability, corresponds to the poorest mixture that allows stable flame propagation. If more fuel is added, another point will eventually be reached at which the mixture no longer burns. The percentage of fuel at this point is denominated the upper limit of flammability, which corresponds to a richer mixture [18,166].

In combustion processes, the energy released generally produces a flame that can propagate through space at a subsonic speed and with a wave frequency that depends on the degree of atom excitation and the purity of fuel to be oxidized. Combustion involves not only the field of physics that studies mass and energy transport, thermodynamics, and momentum transport in systems with a flow of reagents, but also the study of reactions, levels of emissions, and the release of heat and radiation. Most fundamental studies on flame combustion are conducted using gaseous or pre-vaporized fuels. Under a continuous flow of the air–fuel mixture, flames are divided into two main classes: premixed flames and diffusion flames, depending on whether the fuel and air are mixed prior to ignition or initially mixed by diffusion in the flame zone, respectively. Based on the predominant flow regimes, both types of flame can also be classified as laminar or turbulent [18,30].

Combustion efficiency is a measure of how much a mixture is burned, with a value of approximately 90% being considered a successful combustion event. Calculations of combustion efficiency presuppose complete fuel combustion and are based on three factors, namely, chemistry of fuel, liquid temperature of exhaust gases, and percentage of oxygen or CO_2 per unit volume after combustion. Failure to reach high combustion efficiency is generally considered unacceptable, in part because it implies a waste of fuel but mainly because it results in the emission of pollutants, such as unburned hydrocarbons and CO [29].

Combustion efficiency increases with increased temperature of reactants, contact time, vapor pressure, surface area, and stored chemical energy. The specific heat of combustion indicates the quantity of energy that can theoretically be extracted from a completely burned hydrocarbon. In practical combustion systems, the maximum heat release rate under any operating condition is governed by evaporation, mixture, or chemical reaction but rarely by all three at the same time [18,30].

4.1. Hydrogen Combustion

The use of hydrogen as a fuel is increasingly recognized as a fundamental element in the transition to a sustainable energy matrix, primarily due to its favorable physicochemical properties and high energy density. Hydrogen acts as a clean energy carrier, offering significant advantages over traditional fossil fuels, including reduced greenhouse gas emissions and enhanced energy efficiency. The primary benefit of utilizing hydrogen as a fuel compared to fossil fuels lies in its potential to drastically reduce emissions of greenhouse gases and atmospheric pollutants. When hydrogen is employed in combustion processes or fuel cells, the only byproduct generated is water vapor (H_2O), which is in stark contrast to the combustion of fossil fuels [167].

While the combustion of fossil fuels such as coal, oil, and natural gas is directly linked to the release of CO_2—the primary target for global organizations aiming to mitigate climate disasters—hydrogen presents a pathway for decarbonizing sectors that would otherwise be challenging to electrify. Blending hydrogen into the existing fuel mix represents a significant opportunity for decarbonization. Recent data indicate that the energy sector accounts for approximately 75% of global greenhouse gas emissions, with fossil fuels being the main contributors; furthermore, renewable energy technologies have the potential to eliminate carbon emissions from 90% of electricity generation by 2050 [9,121].

The combustion of hydrogen is an exothermic chemical reaction in which hydrogen (H_2) reacts with oxygen (O_2), resulting in the production of a significant amount of energy and water vapor molecules as the primary byproduct. This process has garnered special attention in scientific research and the development of clean energy technologies, as, unlike fossil fuels, hydrogen combustion does not produce direct greenhouse gas emissions [168]. The complete reaction of this gas is expressed in Equation (12):

$$2H_2 + O_2 \rightarrow 2H_2O + \text{Energy} \quad (12)$$

Incomplete combustion of hydrogen is a less common phenomenon compared to the incomplete combustion of fossil fuels, but it can occur under very specific conditions, particularly when there is an oxygen deficiency in the combustion process or in high-temperature and -pressure scenarios where the dissociation of water molecules may take place. Incomplete combustion leads to the formation of undesirable secondary products, such as hydrogen peroxide (H_2O_2) or traces of unburned hydrogen, instead of solely producing water vapor (H_2O) [9,168]. Equation (13) illustrates the incomplete reaction of hydrogen when there is a deficiency in oxygen supply during the reaction.

$$2H_2 + O_2 \rightarrow 2H_2O + \text{Unreacted } H_2 \quad (13)$$

If the available oxygen is insufficient, the reaction cannot proceed to the complete formation of water vapor, leading to the generation of byproducts such as hydrogen peroxide (H_2O_2) or even the persistence of unburned hydrogen (H_2) in the system. The blending of hydrogen with hydrocarbons can enhance the stability of combustion; however, an excess of hydrogen can disrupt the combustion process, resulting in incomplete reactions. This residual hydrogen released into the environment without undergoing a complete reaction poses a critical problem in terms of both energy efficiency and safety. From an efficiency standpoint, unburned hydrogen fails to release its energy potential, resulting in suboptimal fuel utilization—essentially, energy that could have been harnessed is wasted [9].

Moreover, because hydrogen is a highly flammable gas with a low ignition energy and a wide flammability range, even small quantities of residual hydrogen upon contact with an ignition source can lead to explosions or fires. In combustion systems or industrial facilities where hydrogen is used as a fuel, the uncontrolled release of this gas can result in extremely hazardous conditions, particularly in confined or poorly ventilated areas. Furthermore, due to its status as the lightest molecule, hydrogen can easily escape containment and accumulate in hard-to-detect areas, increasing the risk of accidents [169–171].

In situations of excessively high temperatures, the water vapor molecule produced by hydrogen combustion can undergo thermal dissociation, breaking down into its constituents, H_2 and O_2, or even generating reactive species such as free radicals (OH•, O•, H•), which can compromise the combustion process. This can result in the reintroduction of molecular hydrogen into the combustion environment as a byproduct, thereby characterizing incomplete combustion. Consequently, instead of releasing the full energy potential of hydrogen during the initial combustion, part of it is re-emitted as H_2, failing to contribute fully to heat or mechanical energy generation, resulting in lower overall efficiency and greater fuel consumption [172]. The thermal dissociation of water is described by Equation (14):

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \quad (14)$$

Dissociation occurs when the reaction temperature exceeds the threshold at which the chemical bonds in water molecules break, typically above 2000 °C. In systems where temperature control is inadequate, this effect can impair combustion efficiency; however, when managed efficiently, it can enhance efficiency by providing additional hydrogen molecules in the system to participate in parallel reactions. This scenario is more common in combustion systems that operate under extreme conditions, such as gas turbines, rocket engines, or hydrogen combustion systems under pressurized conditions. The presence of unburned H_2 can increase the risk of explosions or uncontrolled combustions, posing a safety threat [171,172].

Very high pressures can also alter the dynamics of hydrogen combustion. Under high-pressure conditions, the gas flow can become unstable, resulting in areas where the concentration of oxygen is insufficient to sustain complete combustion. These imbalances can create zones of incomplete combustion, where residual H_2 or byproducts such as H_2O_2 are formed. These byproducts are chemically unstable and can decompose violently, releasing additional heat and oxygen. Such decomposition is undesirable in combustion systems, as it can generate unexpected pressures and explosion hazards [172].

To prevent the incomplete combustion of hydrogen, modern combustion systems employ a range of techniques and technologies, such as precise control of the fuel-to-air ratio, oxygen sensors, and automatic regulators that adjust the amount of oxygen in real time. This ensures complete and efficient combustion while avoiding local concentrations of hydrogen that could potentially lead to explosions in extreme cases. In internal combustion engines, for example, incomplete combustion can be mitigated through advanced fuel injection systems and thermal management strategies, which ensure that hydrogen is burned with the appropriate amount of oxygen [173].

Future Perspectives of Hydrogen in Combustion Engines

Throughout this article, it is emphasized that the combustion of hydrogen has emerged as a promising alternative for internal combustion engines, particularly in the context of an energy transition towards carbon neutrality. Its primary advantage lies in its high energy density per unit mass, which significantly surpasses that of traditional fossil fuels such as gasoline and diesel. However, it also presents a major drawback due to its extremely low volumetric density, complicating storage solutions. The development and implementation of hydrogen combustion engines face significant technical challenges, including the management of hydrogen's flammability and explosiveness, as well as the need for enhancements in combustion control systems [50,167].

The emission of nitrogen oxides during the combustion of hydrogen at elevated temperatures is a significant consideration in engine combustion. As hydrogen combustion reaches high temperatures rapidly, the formation of NOx occurs due to the high reactivity of nitrogen present in atmospheric air when subjected to elevated combustion temperatures (1600–2300 K). Strategies are being developed to control these emissions, either through selective catalytic reduction (SCR) applications or by implementing exhaust gas recirculation (EGR) systems, water injection (WI), compression ratio (CR) reduction, or changes in fuel composition to form blends with fossil fuels, and the use of lean burn combustion has also emerged as a promising approach to mitigate NOx formation without compromising engine efficiency [174–177].

Recent research has focused on optimizing hydrogen engines to maximize thermal efficiency while minimizing the formation of undesirable byproducts. One of the most promising areas for enabling the use of hydrogen in internal combustion engines (H_2-ICEs) is the development of direct injection (DI) systems. These systems address issues such as backfire and allow for precise control of the hydrogen–air mixture, optimizing efficiency and reducing emissions. Hydrogen is considered a promising fuel for decarbonizing the maritime and aviation sectors, and technologies are being developed for its effective use in fuel cells and internal combustion engines [178].

The development of new materials and methods to address the challenging properties of hydrogen is also at the forefront of research. Emerging technologies, such as combustion chambers capable of withstanding high pressures and temperatures, along with direct hydrogen injection systems, are being explored to optimize combustion and mitigate risks associated with uncontrolled burning. However, one of the main bottlenecks for the large-scale adoption of hydrogen engines remains the distribution infrastructure. For hydrogen to become competitive, it is crucial to establish an efficient supply chain, encompassing large-scale green hydrogen production, as well as secure transportation and storage networks. Countries like Japan and Germany are leading efforts in this field, investing in hydrogen plants and refueling infrastructure, with the vision that hydrogen will become a central component of the global energy mix by 2050 [179,180].

However, the future success of hydrogen in internal combustion engines within these sectors will depend not only on technological advancements but also on favorable public policies and economic incentives. The recent introduction of policies promoting green hydrogen production in European Union countries, along with decarbonization initiatives such as the "Fit for 55" program, place hydrogen at the core of climate strategies. Government support for research and the development of hydrogen engines, as well as subsidies for infrastructure development, will be critical factors in accelerating the adoption of this technology. Consequently, the global adoption of hydrogen engines is intrinsically tied to the commitment of governments and industries to invest in sustainable energy solutions for the future [181,182].

5. Burners

A burner is one of the main pieces of equipment that composes a combustion line, whose basic function is to convert chemical energy through the burning of a fuel (solid, liquid, or gaseous) into thermal energy. Burners are traditionally fed with a variety of fuels, the most common of which are natural gas, petrochemical fuels, oil, and coal [183], as shown in Figure 1.

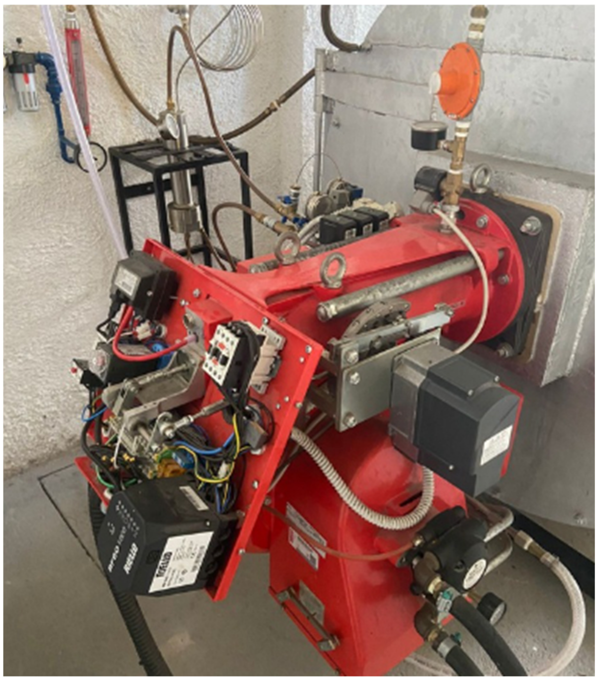

Figure 1. Hydrogen burner at the Advanced Institute of Technology and Innovation, Recife, Brazil.

Various factors are involved in the design of a burner, such as heat transfer and pollutant emissions. Significant changes have recently been made to traditional burner designs due mainly to the growing interest in reducing pollutant emissions. In the past, the main focus of burner design was the achievement of efficient fuel combustion and energy transfer for high thermal output. However, increasingly rigorous environmental regulations have required the consideration of pollutant emissions. In many cases, reducing emissions and maximizing combustion efficiency can be achieved simultaneously [184]

The main requirements of a good burner are high thermal efficiency, low emissions of harmful gases and soot, adequate turn-down ratio, flame stability, and the capacity to operate with different types of fuel [185]. The functioning principle of a burner varies in accordance with its design parameters.

5.1. Classification of Burners

The most common of the many ways of classifying burners is discussed in this subsection.

5.1.1. Classification of Burners Based on Air–Fuel Mixture

Burners based on air–fuel mixture can be classified as diffusive, premixed, partially premixed, or staged burners depending on the mixture phenomenon of the fuel and oxidant, with the latter being mainly stoichiometric atmospheric air $\left(O_2 + \frac{79}{21}N_2\right)$. In real applications, however, this air may contain more (oxy–fuel combustion) or fewer moles of O_2 [29,185].

- Diffusion burners

The fuel and oxidant are supplied separately to the combustion chamber or burner so as to create a concentration gradient in the combustion zone. Both pass through a diffuser or spinner, which is a specially designed component for this type of burner, providing the mechanical energy necessary to ensure that the fuel and air are completely mixed prior to combustion [184]. When the mixture reaches the flammability range, it is ignited by a spark or pilot light that triggers the combustion reaction, resulting in a theoretically stable flame. Diffusion burners normally have longer flames than premixed burners, a hot point that is not very high, and generally a more even distribution of temperature and heat flow. These burners, known for their high heat production and efficiency, are designed to ensure the complete combustion of the fuel oil, thus reducing emissions [184].

- Premixed burners

Premixed burners mix the fuel and air before passing through the nozzle and entering the combustion zone. Fuel and air are generally delivered by separate channels and then mixed in a mixer–combustion chamber prior to being flamed in the furnace. In addition to usually producing shorter and more intense flames compared to diffusion burners, they allow the adjustment of the mixture ratio to achieve the desired combustion characteristics in terms of flame shape, temperature, and stability [185,186]. Premixed burners are commonly used in industrial applications such as heating, fusion, and drying processes, in which high efficiency and low emissions are required, as well as in gas turbine motors for energy generation and aircraft propulsion, where the capacity to operate at high altitudes and under extreme conditions is important. This type of burner accepts a broad range of fuels, such as natural gas, propane, diesel, and hydrogen, making it versatile and adaptable to different applications. Thermal radiation burners and radiant wall burners are examples of premixed burners [184].

- Partially premixed burners

Using partially premixed burners, the fuel and air are partially premixed in a two-stage process, generally due to stability and safety reasons, to assist in anchoring the flame and to reduce the chance of flashbacks. This type of burner often has a flame length, temperature distribution, and heat flow between those of fully premixed and diffusion burners [184]. The mixture is performed in two stages. The fuel is injected into the combustion chamber in the former stage and mixed with a portion of the air, creating a fuel-rich mixture, which is ignited and burned in the primary combustion zone. Additional air is injected into the combustion chamber in the latter stage to create a fuel-poor mixture, which burns in the secondary combustion zone. This process assists in enhancing combustion efficiency and reducing pollutant emissions [187].

- Stage burners

Other mixture-based burners are known as stage burners, with an air stage and a fuel stage, with the difference being the injection of additional air or fuel after ignition. With this type of burner, secondary and, at times, tertiary injectors are used to inject a portion of the fuel and/or oxidant into the flame downstream from the flame base. This system is often used to control heat transfer, produce longer flames, and reduce pollutant emissions. The flames resulting from the stage generally have a lower peak temperature and more even heat flow distribution than premixed flames. However, multiple long flames can interact with each other with unpredictable consequences compared to a single short flame [184].

5.1.2. Classification of Burners Based on Fuel

- Gas burners

Gas burners are devices that produce a flame under conditions controlled by the combination of a fuel gas (e.g., acetylene, natural gas, or propane) and an oxidant (e.g., oxygen or ambient air), which are mainly used for welding, soldering, and brazing and whose main components are the mixer, burner nozzle, and stabilizing device. Their fundamental operating principle is known as the Venturi effect; the air–fuel mixture is conducted through a tube-like structure that increases, reduces, and then increases again in diameter, fluctuating the pressure and flow velocity. Gas burners, which are widely used in domestic and commercial networks [188,189], are classified according to the pressure, ranging from 5 kN/m^2 to more than 300 kN/m^2, or as diffusion gas burners, injection gas burners, and gas turbine burners.

Diffusion gas burners mix gaseous fuel and air in the combustion chamber to create an even temperature along the combustion front and are commonly used in industrial furnaces and boilers that require precise temperature control. Open hearth furnaces and glass fabrication furnaces are examples of diffusion gas burners that play a crucial role [188,189].

Injection burners "inject" the air for combustion using the gas flow energy, which is then mixed within the burner housing. When the fuel gas pressure is very low, air is used to inject the gas into the system. For gas burners operating at average pressure that require a complete mixture, a short combustion front is formed, enabling combustion to occur in a minimal volume of the furnace. In gas burners with partial mixture injection, only the necessary quantity of air (40–60%, called primary air) is provided and mixed with the fuel, whereas the remainder (secondary air) is provided to the combustion front by the atmosphere through the injection of gas–air currents and rarefaction in the furnace [188,189]

Gas turbine burners operate with the mixture of fuel and air in the combustion chamber, with the flame generating hot gases that fluctuate across the turbine blades, transforming the gas kinetic energy into mechanical energy that drives the turbine and, consequently, promotes electricity generation. Although the combustion process is similar to that of diffusion burners, the temperatures and pressures are exponentially higher. Fuel and air are commonly mixed in a combustion chamber or tubular burner designed to enable effective, constant combustion at high temperatures. The fuel may be natural gas, propane, diesel, or other liquid or gaseous fuels [188,189].

Combustion in a gas turbine burner is meticulously controlled so that the gases generated do not exceed the maximum temperature limits of the turbine components. This is achieved by control of the air–fuel proportion, flame stabilization, and cooling of combustion chamber walls. These burners are used in power generation applications, as they are capable of driving large generators to produce electricity, but they can also be used with industrial equipment, such as compressors, pumps, and any other equipment that requires mechanical energy. High efficiency, reliability and low emissions are some of their qualities [188,189].

Gas injection burners with infrared radiation, also known as flameless burners or radiant burners, have been gaining ground. They operate in such a way that the largest part of the heat generated by combustion is transferred through radiation. The gas burns in a thin radiant surface layer, making the combustion front imperceptible [31,32]. Unlike traditional burners that produce a visible flame, flameless burners function following the principle of surface combustion, by which fuel and air mixtures are burned on a porous ceramic or metal surface, creating a thin, flameless combustion layer. This type of burner is widely used for heating buildings with considerable air circulation, such as sports stadiums, greenhouses, and commercial buildings; for thawing frozen soil and loose materials; and for drying recently dyed surfaces, such as fabric or paper [188,189].

- Liquid fuel burners

Liquid fuel burners are used in some limited applications but are more common in certain regions of the world, such as South America. Although the most commonly used liquid fuels are oils [26], residual liquid fuels can also be used in incineration processes. One of the specific challenges of using oil is vaporizing the liquid into droplets small enough to burn it completely. There are three common types of oil burners: gun-type (spray), pot-type (vaporization), and rotary burners [188,189].

Oil burners use a controlled mixture of oil and air to generate energy. The most widely used are spray oil burners, in which the fuel oil is delivered from a storage tank by a pump or by gravity and passes through a filter to remove any impurities that could adversely affect performance. The oil is pressurized and sprayed by a high-pressure nozzle. By forming a fog, the oil droplets mix with air supplied by a blower or fan, generating a fuel mixture that, upon ignition, produces a flame, which can be achieved using an electrical spark or pilot light. The flow of the fuel oil and quantity of air furnished to the burner can be adjusted to control the flame size and intensity, depending on the application [188–190].

Modern oil burners are equipped with electronic controls to monitor, regulate, and optimize burner operation, which include sensors for measuring temperature, pressure, and air–fuel ratio, and with safety devices to switch the burner off in case of a problem, such as a lack of ignition. Adequate operation and maintenance of an oil burner are essential to ensuring safe, efficient operation and avoiding problems such as CO poisoning, risk of fire, and damage to the heating system. Regular maintenance, including burner cleaning and adjustments, can assist in ensuring reliable operation and extending the useful life of the heating system [188,189].

- Solid fuel burners

Solid fuel burners are not as widely used in industry as liquid and gas fuel ones. Such burners are commonly used in the lumber and paper industry or in regions where solid fuels, mainly coal, wood, and biomass, are more readily available and cheaper than liquid and gas fuels [188,189].

One of the main advantages of industrial solid fuel burners is the high thermal efficiency, as solid fuels, having high energy density, release a large quantity of heat per unit mass, thus reducing fuel costs and improving the overall efficiency of the heating system. However, in addition to requiring frequent periodic maintenance, solid fuels contain impurities, such as nitrogen, sulfur, and sometimes even hazardous chemicals, which can significantly increase polluting emissions [188,189].

- Dual fuel burners

As the name suggests, dual fuel burners can burn two different types of fuel, normally gas and oil. Their main advantages are the flexibility in fuel choice and the possibility for the operator to alternate between two fuel types based on availability, cost, and other factors. Other advantages include low maintenance, high efficiency, and low emissions. Dual fuel burners are used in refineries, petrochemical plants, and energy generation facilities [189].

Dual fuel burners normally function by mixing the fuel (gas and oil) with air and subsequently burning the mixture, with the quantity of fuel controlled by adjusting the fuel and air flowrates. They can operate with different air/fuel ratios and are versatile and adaptable to different operating conditions. There are two types of dual fuel burners, namely, monoblock and duoblock burners [189].

Monoblock burners combine both gas and oil burners in a single unit, simplifying the installation process, and are commonly used in small to medium-sized heating applications, such as boilers, ovens, and driers. The design generally consists of a combustion head that houses the gas and oil burners, a fan to provide combustion air, and a control panel to monitor and control the burner operation. Such burners offer high efficiency and low emissions and are normally capable of burning a broad gamut of fuels, such as natural gas, propane, and light and heavy fuel oil [189–191]. In duoblock burners, the gas and oil burners are separate and generally connected by a flexible duct, with each part controlled individually. The gas block generally had a gas valve, collector, and burner, whereas the oil block contains an oil fuel pump, nozzle, and burner. The blocks are designed to work in conjunction, with the gas and oil burners controlled independently to enable precise control of the combustion process. Duoblock burners are also capable of burning a large variety of fuels [189–191].

Monoblock burners are easier to install and require less space compared to duoblock burners, which have separate blocks that need to be placed on opposite sides of the boiler or oven. In terms of fuel flexibility, duoblock burners are more versatile and can be easily configured to burn different types of fuel, whereas monoblock burners are precisely designed to burn a previously defined, specific type of fuel. Duoblock burners offer more precise control of the combustion process, as the blocks are controlled independently, whereas monoblock burners generally have a single control panel to monitor and control the operation [189–191].

Besides the classifications addressed above, the literature describes other forms of classification, as shown in Table 2:

Table 2. Classifications of burners.

Basis of Classification	Types of Burners
Combustion process	Atmospheric burners Power burners High-speed burners Stage combustion burners
Orientation	Horizontal Vertical With flame directed upwards With flame directed downwards
Applicability	For industrial heating For industrial drying For industrial metal casting Incineration For heating boilers For heating ovens For heating furnaces
Capacity	Small scale Medium scale Large scale
Design	Single-stage burners Multiple-stage burners Swirl burners Premixed burners Surface combustion burners Flame retention burners
Control system	Manual Automatic Modulating
Emissions	Low NO_x burners Ultralow NO_x burners Burners with ultralow emissions Burners with high emissions

6. Furnaces

Furnaces are closed structures, generally rectangular, constructed with materials that can withstand intense heating processes at temperatures ranging from 100 °C to more than 2000 °C, as shown in Figure 2. This equipment is used in fabrication processes that involve materials such as metals, chemical products, glass, cement, etc. The main purpose of a furnace is to reach a higher processing temperature than can be achieved in open air. Although some processes can be performed in open air, doing so would be much less efficient, with a greater consumption of fuel, and process control would be much more difficult [31].

The literature describes different types of furnaces depending on the energy source (coal, gas, oil, electricity, or chemical energy), temperature and operation (drying, calcination, cooking, reheating, plasma arc, etc.), format (vertical, horizontal, rotary, fluidized bed, hearth, etc.), heat transfer (conduction, convection, or radiation), location of the heating system (top burn, bottom burn, direct, or indirect burn), and working atmosphere (reducing, oxidizing, or inert). The basic components are the internal chamber of the oven, which is lined with resistant materials such as refractory materials and steel plates, an energy-generating source (such as a burner), an exhaust system (chimney or fans), and an energy recovery system [192].

Figure 2. Hydrogen furnace at the Advanced Institute of Technology and Innovation, Recife, Brazil.

Furnace operation and control require numerous instruments and indicators for various functions. Temperature, pressure, and flow are major variables that require adequate measurement tools and display on the control panel. Furnace temperature is regulated through a thermocouple placed in the body of the furnace or, more rarely, through portable optical and infrared pyrometers. While pressure is measured in relation to atmospheric pressure through gauges, the flow rate of the fluids (combustion gases and cooling water) is regulated using flow meters based on differential pressure, velocity, positive displacement, and fluid mass [192].

As pneumatic systems are obsolete, all new furnaces and other innovative tools use programmable logic controllers (PLCs) for individual control or a control system distributed throughout the plant [31]. The process control system must meet one or more of the following objectives: (a) maximize the production capacity of the furnace, (b) ensure satisfactory quality of the product, (c) minimize fuel consumption and emissions, (d) control furnace heating, or (e) enable the smooth transition between different products, which can be achieved by controlling one or more of the following variables: (i) fuel flow rate or entrance of heat into the furnace; (ii) air flow rate or air–fuel ratio; (iii) temperature of the furnace, combustion air, product, and flue gases; (iv) composition of the flue gases; and (v) flow rate and physicochemical composition of the feed raw material [193].

With technological advances, it has become possible to perform modeling and prediction of variables using engineering software. Being chemical processes involving high temperatures and a reactive system, measurements are not always viable, which makes the analysis of the results of processes under real operating conditions quite a challenge. To overcome these difficulties, engineers and researchers have been using the Aspen HYSYS® environment, which is a chemical process simulator used for mathematical modeling of chemical processes, from unit operations to complete plants and refineries, as well as optimizing conceptual projects and operations [194,195].

7. Emissions

Hydrocarbons are released into the environment due to their broad use as fuels and chemical products as well as through leaks and accidental spills during exploration, production, refining, and transport. Anthropogenic contamination of soil and atmosphere by hydrocarbons is a serious global problem due to the persistence of these contaminants and their negative impact on human health [166]. Primary pollutants are those emitted directly into the atmosphere, while secondary pollutants are formed by chemical or photochemical reactions of primary pollutants after being released into the atmosphere and exposed to sunlight. Unburned hydrocarbons, nitrogen monoxide (NO), particulate matter, and sulfur oxides are examples of primary pollutants, whereas peroxyacyl nitrates (PANs) and ozone (O_3) are examples of secondary pollutants [31,166].

The gases emitted by the combustion of hydrocarbons are CO, CO_2, water vapor, unburned hydrocarbons, particulate matter (mainly carbon), NOx, and excess atmospheric oxygen and nitrogen. Carbon monoxide, which is highly toxic, is the result of incomplete combustion. Generally formed as the first step in the oxidation of coal and as one of the primary products of the pyrolysis of fuel during the rapid heating of solid and liquid fuels, CO is normally oxidized to CO_2 through a gas-phase reaction with atmospheric oxygen [31]. Some residual CO always remains in furnace combustion gases because mixing processes are not perfect and the reaction between CO and oxygen to produce CO_2 is reversible.

Precise control of combustion conditions is essential for achieving efficiency and reducing emissions. Modern technologies, such as advanced electronic injection systems, continuously adjust the fuel-to-air ratio to ensure an optimal mixture, enhancing combustion efficiency and minimizing pollutant formation. Additionally, air and temperature controls, along with the use of computational fluid dynamics (CFD) modeling for visualizing and optimizing airflow and fuel distribution within the combustion chamber, have been developed to maximize combustion efficiency. Recent studies indicate that engines equipped with gasoline direct injection (GDI) can significantly reduce emissions of carbon monoxide and unburned hydrocarbons, even under challenging operating conditions [196,197].

Emission control technologies are essential for capturing and treating pollutants generated during combustion. In systems utilizing solid or liquid fuels, particle filters and soot capture technologies have proven effective in removing particulate matter (PM) and other emissions. Selective catalytic reduction (SCR) systems are employed to reduce nitrogen oxide (NOx) emissions in internal combustion engines. This technology involves injecting a reducing agent, typically urea, that reacts with nitrogen oxides to form harmless nitrogen and water. Studies indicate that the implementation of SCR technology in heavy-duty vehicles and power plants has been highly effective in reducing NOx emissions [198–200].

In recent years, political decisions and legislation worldwide have intensified, with the aim of minimizing greenhouse gas emissions and other pollutants associated with the combustion of fossil fuels. These initiatives reflect a growing concern for climate change and public health, as well as compliance with the requirements of international agreements. The United Nations Conference of the Parties (COP) on Climate Change has served as a crucial platform for discussing and implementing global commitments related to emission reductions. Additionally, the latest update of the Nationally Determined Contributions (NDCs), presented during COP26 in Glasgow, revealed the intention of several countries to increase their emission reduction targets by 2030, underscoring the urgency of climate action [201,202].

The European Union and the United States have introduced stringent legislation aimed at reducing emissions, reflecting their climate ambitions and international commitments. In 2021, the European Commission announced a legislative package called Fit for 55, which includes measures to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. This proposal establishes stricter limits on CO_2 emissions from new vehicles, facilitating a transition to electric and hybrid cars, as well as revising the European Union Emissions Trading System (EU ETS). Under the Biden administration, the U.S. government implemented the Inflation Reduction Act (IRA) in 2022, which allocates significant investments to clean energy technologies, such as solar, wind, and hydrogen. This legislation aims to reduce emissions by at least 40% by 2030 compared to 2005 levels and includes tax incentives to promote the adoption of electric vehicles and energy efficiency [203,204].

Local policies and state incentives are also being implemented in regions such as California, New York, and London to minimize greenhouse gas emissions. The California Air Resources Board (CARB) has enacted stringent regulations for light and heavy-duty vehicles, mandating a significant reduction in greenhouse gas emissions. In 2020, California announced a goal for all new vehicles sold in the state to be electric or hybrid by 2035. New York and London have established low emission zones (LEZs) and congestion charging zones (CCZs) to reduce the traffic of polluting vehicles and improve air quality. These initiatives have proven effective in decreasing emissions of NOx and particulate matter while promoting the use of public transportation and sustainable mobility alternatives [205–208].

Recent political decisions and legislation aimed at reducing emissions reflect an increasing commitment to sustainability and public health. The interconnection between global commitments, national legislation, local policies, and emission standards is essential for addressing the complex issues of climate change and air quality. The successful implementation of these initiatives requires a collaborative effort among governments, industries, and civil society to create a more sustainable and healthier future [209].

8. Economic Issues

Energy is an integral part of our daily lives and is necessary for a large part of human activities. Fossil fuels such as oil, natural gas, and coal furnish more than 80% of all energy consumed globally, but they are not infinite resources, and an energy crisis is approaching if rigorous attitudes are not adopted. The excessive dependence on fossil fuels constitutes a crucial global challenge in the current economy, as reserves are depleting rapidly. This not only generates an increase in energy consumption but is also a threat to energy and economic security on a global scale. Moreover, these fuels are not environmentally friendly and release greenhouse gases and other pollutants that significantly contribute to global warming. Humanity is entering a phase in which life on the Earth can become unsustainable if serious measures are not adopted to mitigate the current energy challenge. Most scientists and engineers agree that the search for environmentally clean, accessible, sustainable energy sources capable of effectively replacing the current fossil fuel system can offer concrete solutions to this problem [209].

In 2022, governments allocated nearly USD 44 billion to energy research and development, with more than 80% directed to the field of clean energy. This marks a significant increase in comparison to the approximately USD 30 billion allocated in 2015, when 70% of funding was earmarked for clean energy projects. A large portion of this increase in investment in energy-related research and development occurred in China, which currently stands out as the main investor in the field [210].

8.1. Hydrogen Economy

Due to its exceptional qualities, hydrogen emerges as a promising ideal vehicle of sustainable energy for the future. The hydrogen economy is a proposed system in which H_2 is produced and used extensively as the main means of energy transport. The successful development of the hydrogen economy offers numerous advantages for the environment, economy, and end users. Low-carbon H_2 is expected to play a crucial role in energy systems and global energy transitions by the year 2040. In the context of energy transition, H_2 not only sustains the efforts of nations to achieve the goals of the Paris Agreement but also contributes to the diversification and security of their energy portfolios [67,209].

The relative economy will mainly depend on the resources available in a region or the option of importing at low cost when the local supply cannot meet the internal demand.

The cost of low-carbon H_2 production varies from region to region as well as with advances in new technologies over time [67,211].

The main focus of the H_2 market is crude oil refining, the production of ammonia fertilizers, and metal processing. The global H_2 generation market was valued at USD 155.35 billion in 2022, with an expected compound annual growth rate (CAGR) of 9.3% from 2023 to 2030. Moreover, the global carbon-free H_2 market was valued at USD 4.47 billion in 2022 and is expected to exceed USD 134.38 billion by 2032, with a predicted CAGR of 40.6% from 2023 to 2032. A substantial reduction in the cost of low-carbon H_2 by 2050 is also predicted [212].

Based on ongoing projects and those under construction, expenditures on electrolyzers reached a new record in 2022, totaling USD 0.6 billion globally, which is twice the amount recorded for 2021. Reaching USD 41 billion in expenditures on electrolyzers by 2030, as predicted for the scenario of achieving net zero emissions (NZE) by 2050, would require an annual investment growth of 70% for the rest of this decade [213].

Two of the largest current projects involving the production of green H_2 are in development in the Middle East. Through the NEOM Green Hydrogen Company (NGHC), Saudi Arabia is designing the largest green H_2 production station for obtaining green ammonia, with a capacity for 600 tons of green H_2 per day. In Oman, the ACME Group expects the production of 1.2 million tons per year. Both projects are expected to begin operations in 2026 [214,215].

In China, more specifically in Xinjiang, a pilot H_2 generation project by the Sinopec Group involving proton-exchange membrane electrolysis with solar and wind power began operations in July of 2023. The project is expected to produce 200,000 tons of green H_2 per year and fuel approximately 50,000 H_2 cars by the year 2025 [216].

The Shell Company is investing in the construction of Holland Hydrogen I, which will be the largest renewable H_2 factory in Europe and will be operational in 2025. A 200-MW electrolyzer will be built on the Tweede Maasvlakte at the Port of Rotterdam, with the capacity to produce up to 60,000 kg of renewable H_2 per day [217].

The United States and Canada are concentrating efforts on the production of H_2 through carbon capture, utilization, and storage and estimate the capture of more than 90% of CO_2 by 2025. India established an ambitious goal of producing 5 million tons of green H_2 per year by 2030, with operations scheduled for the end of the second semester of 2023 [213,218].

In the first semester of 2023, the European Union (EU) announced that it would invest EUR 2 billion in the Brazilian H_2 industry within the scope of the EU Global Gateway Initiative, which is part of a broad package of EUR 10 billion for investments in clean energy in Latin America and the Caribbean. The president of the European Commission, Ursula Von der Leyen, highlighted the "unlimited potential" of Brazil for renewable energy and, specifically, green H_2 [219].

The "H_2 Brazil" project conceived and executed by the Deutsche Gesellschaft für Internationale Zusammenarbeit to promote the corporative development of H_2 through Brazilian–German partnership demonstrates a notable interest in the production of green H_2 in the country. At the moment, approximately 42 projects in various stages of development have been identified in different regions of Brazil, with a striking concentration in the northeast, which stands out for its abundant solar capacity. Additionally, the project highlights the identification of more than 800 companies and institutions distributed among 12 different sectors of the green H_2 value chain in 5 regions of the country [220].

Brazil has established two significant partnerships, the first of which was at the beginning of this year with Germany during the Brazil–Germany Economic Meeting. In this agreement, approximately BRL 21 million (Brazilian currency) were allocated to green H_2, with a focus on initiatives of small and medium-sized companies, including startups, as well as research and technology institutions. Moreover, a cooperation agreement was formalized among Brazilian associations denominated the Brazilian Pact for Renewable

Hydrogen, one of the main goals of which is the definition of a regulatory framework and a market development fostering initiative for the application of green H_2 [220–222].

The state of Ceará is a pioneer in adherence to this pact as well as a precursor in the production of renewable H_2 in the country. The current pilot project in development at the Pecém Thermoelectrical Complex seeks the large-scale production of this biofuel, consolidating the commitment of the state to sustainable innovation. The strategic location of ports in Northeast Brazil combined with the presence of industrial consumers gives the country a significant advantage in the race for green H_2. Moreover, the favorable climatic and geographic conditions offer a solid base for the large-scale production of clean energy [220,221].

Chile, Colombia, and Uruguay are actively integrating the production of green H_2 in their energy policies as part of efforts to reduce greenhouse gas emissions, contributing to a notable boost in the H_2 market since 2022. According to the Hydrogen Index of Latin America and the Caribbean, Chile and Colombia are consolidating the initial development stages of projects that seek to diminish the dependence on fossil fuels, adopting investment strategies and public policies aligned with a low-carbon economy. Moreover, Peru, Colombia, and Argentina have presented bills related to H_2, with a focus on incentives for the production and development of this market [223].

Among the methods of obtaining green H_2, the production route involving solar thermal energy is free of carbon emissions and has enormous technical and financial potential to be one of the main methods of producing hydrogen in the upcoming decades. With a cost that is currently around USD 2.25–7.27/kg, it is becoming a less expensive method compared to other production processes, such as photovoltaic cells and electrolyzers, which still have high production costs. However, a substantial reduction in these costs has occurred in the past ten years due to technological advances and the growing demand for clean energy. Studies have shown that obtaining H_2 through wind turbines may also be economically attractive depending on the strength of wind in the region and the power of the electrolyzer, despite the high investment cost. Some authors estimate that the cost of H_2 production could range from USD 0.35/kg to USD 6.64/kg. Estimates reveal that the generation of electricity from renewable sources will grow from 30% in 2022 to nearly 60% in 2030 in the NZE scenario. Moreover, the combination of photovoltaic solar power and wind power could increase from 12 to 40% in the same period [210,224–227].

Geothermal power could also participate in the production of H_2 in the future. However, a set of factors still hinders its development and greater exploration, such as the high cost of perforating the ground, the high temperatures to ensure adequate efficiency of the chemical reaction, and the formation of possible contaminants and harmful gases depending on the origin of the water. With regards to energy obtained from biomass, gasification is the most widely used method to obtain H_2, with an estimated production cost of USD 52.3/kg by the year 2040. However, it can lead to the release of hydroxides and halogens, depending on the source of the biomass used. The quantity of pretreatments that biomass requires also makes this route costly, besides the fact that this method is not abundantly accessible to all countries [227,228].

8.2. Economic Challenges of Hydrogen Storage and Transmission

Energy storage is necessary to ensure that electricity is delivered when there is a deficit between supply and demand; therefore, the choices and costs of the delivery infrastructure are of crucial importance. H_2 is currently stored and delivered in the form of compressed gas or liquid, but the future will require a much broader variety of storage options. Since the 1970s in the United Kingdom and the 1980s in the United States, salt caverns have been employed by the chemical industry to store H_2. With costs generally lower than USD 0.6/kg, an efficiency of around 98%, and a low risk of contamination of the stored H_2, such caverns offer a viable and economical option. Mixing H_2 in existing natural gas networks may also be an economically attractive option. Depending on the method and post-treatment, the price could range from USD 3/kg to USD 6/kg [4,229].

To date, the technical viability and economic attractiveness for the large-scale development of lithium ion-based energy storage batteries can pose challenges to the implementation and provision of energy in periods of high demand. This limitation can be overcome by storing the excess renewable energy chemically in the form of H_2 in underground aquifers, salt caverns, and/or depleted hydrocarbon reservoirs (seasonal underground hydrogen storage) [229].

H_2 production is currently centralized near places of use, but some countries are focusing on the creation of H_2 hubs. If H_2 can be used near the production site, transportation and storage costs could be close to zero, but if the H_2 needs to travel a long distance prior to use, the transmission and distribution costs could be threefold higher than the production cost [229].

Long-distance transport is challenging, with shipping being the cheapest option for distances greater than 4000 km, according to the International Renewable Energy Agency [59]. The conversion to ammonia and reconversion to H_2 after transport is a promising option, despite the high energy demand and cost. Liquid organic hydrogen carriers (LOHCs) are being studied, but the process is considered expensive and energy intensive. For medium distances, new H_2-dedicated pipelines or existing natural gas pipelines that could be used for pure H_2 transport are considered the most effective in economic terms for transporting large volumes, whereas short-distance (local) transport is performed by trucks. The increase in the demand for low-emission H_2 means that more than 20,000 km of pipelines will be needed by 2030 in the NZE scenario in comparison to the current 5000 km distributed globally, along with 25 liquid H_2 tankers (160,000 m^3) and about 70 new ammonia tankers compared to the 40 currently existing in the world [67,210,230].

Due to the high costs associated with H_2 transport, the largest portion is expected to be consumed in the country or region of production. The two main energy markets (China and the USA) will likely achieve considerable self-sufficiency in H_2. Despite this, there is the prospect of establishing substantial flow in the global market of H_2 and H_2-based products if effective cooperation is achieved on the regional and global levels [67].

8.3. Future Prospects

According to the market research, the global market of H_2 generation is expected to increase from USD 158.8 billion in 2023 to USD 257.9 billion in 2028, with a CAGR of 10.2%. Even in this promising scenario, the cost of construction and operation of an H_2-generating plant remains significant compared to fossil fuels. Besides the need for cutting-edge technologies, there are no historical data or prior experience in this endeavor. Hydrogen production remains a sector marked by a set of uncertainties with regards to its future, disparate regulations, lack of infrastructure, and challenges associated with transport and storage that need to be addressed in order to accelerate the commercialization of this biofuel and the energy transition [129].

If all new projects announced by the industry come to fruition together with the planned increase in production capacity, it is possible that the cost of electrolyzers will diminish considerably, reaching a 70% reduction by the year 2030 in comparison to 2022 prices. This scenario resembles the significant drop in prices that drove greater adherence to wind and solar power, and would represent 55% of the level in the NZE scenario by 2030 [210,231].

The H_2 market is expected to be integrated into various industries by the year 2050, contributing to the expectation of the urgent reduction in greenhouse gases and the energy transition.

In recent years, significant advances have been made in innovative technologies for global decarbonization. Demonstrators of low-carbon H_2 production through the electrolysis of solid oxide began to be studied and sold in recent years as a promising, highly efficient technology [232]. In the second semester of 2021, steel was produced for the first time using H_2 rather than fossil fuels through HYBRIT technology in Sweden, and small-scale H_2 fuel cells began to operate in Norway and the Unites States in 2023. China has been gaining ground in the development of innovative technologies, such as nuclear reactor modules, offshore wind farms, and improved solar cells for future sales, together with solid ion batteries for electric cars, strengthening its position as a world leader in this segment [210,233,234].

9. Environment Impacts

Pure hydrogen is rare on Earth. Its reactivity allows it to be present only in water and organic compounds. As H_2 is obtained from other compounds, its production can have a strong environmental impact, depending on how it is generated. Approximately 95% of H_2 is currently obtained with the aid of fossil fuels, such as natural gas and coal, resulting in the emission of 830 million tons of CO_2 every year to produce 74 million tons of H_2. Combining the production of H_2 based on fossil fuels with carbon capture, utilization, and storage, and performing the electrolysis of water with renewable energy such as solar, wind, oceanic, and geothermal power, could diminish these emissions significantly [235].

According to recent studies, renewable H_2 released into the atmosphere can contribute to an increase in gases such as CH_4 (blue hydrogen), O_3, and water vapor, indirectly contributing to global warming. When H_2 is released into the atmosphere, it has basically two fates: An estimated 70 to 80% is removed by the soil through diffusion and bacterial assimilation (soil uptake), while the remaining 20 to 30% undergoes oxidation upon reacting with the hydroxyl radical ($OH^\cdot$). It will take less than one decade for the atmospheric radiative force to become balanced after the disturbance caused by H_2 emission, and its oxidation in the atmosphere contributes to an increase in the concentration of greenhouse gases in both the troposphere and the stratosphere [7,236–239].

In the troposphere, nearly 50% of the impact caused by H_2 emission is due to its reaction with $OH^\cdot$ radicals, which, because they are unable to react with CH_4, prolong its useful life in the atmosphere. Moreover, as hydroperoxide radicals ($HOO^\cdot$) formed by the oxidation of hydroxyl are present and there is an excess of methane in the atmosphere and troposphere, ozone is formed, which has a greenhouse effect that accounts for approximately 20% of the radioactive impacts of H_2, whereas the remainder is attributed to water vapor [7,237,239].

In the stratosphere, the oxidation of H_2 increases the amount of water vapor, which, in turn, increases the infrared radiative capacity of the stratosphere, resulting in stratospheric cooling. This leads to climate warming because heat exchange with space becomes less efficient, in addition to contributing to the destruction of the ozone layer. Recent studies show that the effects of such indirect heating are twofold greater than those previously reported because the stratospheric effects have only recently been considered. Studies reported that the influence of H_2 on global warming is short term compared to those of CO_2 and CH_4. In fact, while CO_2 requires hundreds of years to be naturally removed from the atmosphere, H_2 requires only 2 to 12 years [7,237,238,240].

Another point to consider is that the H_2 molecule in the gaseous state is the least dense of the entire periodic table, making it difficult to contain leaks during its production, storage, and distribution. Moreover, the need to travel long distances within the pipes of a facility or during transport through pipelines increases the potential for leakage. H_2 can leak throughout the entire value chain, including in electrolyzers, compressors, storage tanks, geological storage, pipelines, truck, trains, and filling stations [7,236].

In situations of considerable leakage, H_2 emissions can produce nearly twice the warming in the first five years after replacing its fossil fuel counterparts. However, if leakage rates are minimal, H_2 could lead to an 80% reduction in warming within the same period. Nonetheless, considering the enormous challenge posed by the energy transition in the event of an almost total replacement of fossil fuels with H_2, containing leaks will be a relatively simple challenge [236].

Therefore, the fundamental role of H_2 in achieving the global goals of decarbonization is evident. However, this entire scenario is permeated by uncertainties in the precise measuring and quantification of possible leakages; the projection of emissions due to the absence of a standard H_2 route, which can range between low and zero carbon; or the lack of specific climatic metrics to estimate its direct and indirect radiative effects. The prevalent metric in recent studies has been the global warming potential, which is the calculation of the relative effect of warming in a specific period based on the pulsed emission of a climatic agent in comparison to that of an equivalent mass of CO_2. However, using this method to compare the climatic effects of a short-term climatic agent, such as H_2 and especially CH_4, and a long-term agent, such as CO_2, is a complex task [7,239,241].

As H_2 does not emit CO_2 when burned or used in fuel cells, carbon-free H_2 and its derived fuels can play a crucial role in the decarbonization of industries in which emissions are particularly difficult to reduce, such as sea transportation, aviation, and long-distance trucking, as well as in the iron, steel, and chemical industries, also known as hard-to-abate industries. These fields face significant challenges in the implantation of other clean energy technologies. Natural gas and coal are currently the main sources for H_2 production, which is mainly intended for the fabrication of fertilizers and use in oil refineries [242].

According to the International Energy Agency, as part of the 2021–2050 NZE scenario, H_2 and H_2-based fuels could avoid up to 60 Gt of CO_2 emissions by the middle of the century. This agency states that the decrease in demand for fossil fuels will be so steep by 2050 that there will no longer be a need for new conventional long-term oil and gas projects or new coal mines or mining expansions. This could correspond to a 97% reduction in greenhouse gases resulting from fossil fuels [231].

In 2050, residual CO_2 emissions from fuel combustion will remain concentrated in the industrial (0.2 Gt) and transportation (0.6 Gt) sectors. Electricity generation, construction, and other transformations will account for 0.4 Gt of residual emissions, and industrial process will contribute another 0.4 Gt [210]. The main contributions for combustion are displayed in Figure 3.

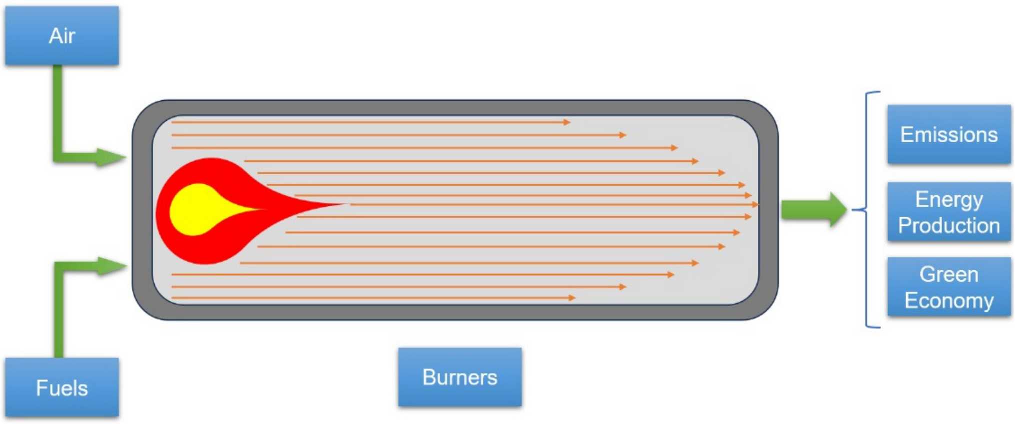

Figure 3. Main characteristics of combustion.

10. Conclusions

Despite their entrenched use and centrality in the global energy matrix, the combustion of fossil fuels significantly contributes to global warming due to CO_2 emissions and other pollutants. Price volatility and the high demand for these resources further underscore the need for energy diversification. While fossil fuels played a crucial role in industrialization, growing environmental awareness and advances in alternative technologies drive an urgent shift toward cleaner, more sustainable energy sources, like biomass and biofuels, aimed at reducing emissions and diversifying global energy options. Substantial investment in research and the development of clean technologies such as hydrogen is essential to support an energy transition that balances economic growth and sustainability.

Hydrogen is emerging as a promising solution in the energy transition towards reducing emissions due to its high energy density and clean combustion, which produces only water vapor as a byproduct. Its versatility allows applications across various sectors, from power generation to heavy industry, meeting the growing demand for less polluting energy sources. However, efficient and sustainable hydrogen production, particularly through low-carbon methods such as green hydrogen, remains a technical and economic challenge, requiring advancements in production, storage, and transportation. Hydrogen combustion is essential for fuels used in industrial heating and power generation, where efficiency depends on factors such as the fuel-to-air ratio, chamber temperature, and residence time to maximize energy conversion and minimize pollutant emissions.

Furnace burner systems, which are key components in combustion systems, play a crucial role in converting chemical energy into thermal energy. Traditionally powered by fossil fuels, burners are continuously evolving to support the energy transition and meet environmental standards, aiming to reduce pollutant emissions without sacrificing thermal efficiency. Innovations in design, such as premixed burners and direct injection systems, enable more precise control of the combustion process, contributing to a more complete and stable burn. Furnace optimization, including advanced control systems to reduce fuel consumption and emissions, promotes more efficient and environmentally responsible operations, driving sustainability across dependent sectors.

Emission control is a fundamental aspect of minimizing the environmental impact of fossil fuel combustion, especially as regulations grow increasingly stringent. Advanced technologies such as selective catalytic reduction (SCR) and electronic injection systems have proven effective in reducing pollutants like NOx, carbon monoxide, and particulate matter. Additionally, implementing computational fluid dynamics (CFD) strategies for combustion control and modeling helps optimize the combustion process and reduce the formation of harmful byproducts. The ongoing evolution of these technologies is essential for meeting international emission reduction commitments and improving air quality.

Thus, hydrogen represents a crucial step toward decarbonizing the global energy matrix, especially in sectors that are difficult to electrify, such as heavy industry and long-haul transport. It shows promise as an alternative to fossil fuels, significantly reducing greenhouse gas emissions and aligning with global climate goals. However, its widespread adoption faces considerable challenges. One of the primary issues is the high production costs, which currently range from approximately USD 5 to USD 9 per kilogram, depending on the production route and energy source. To make hydrogen a more economically viable option, it is essential to reduce these costs to less than USD 2 per kilogram. Additionally, storage difficulties exist, such as storing under high pressure or in liquid form, as do transportation complexities requiring specialized infrastructure to prevent leaks and minimize explosion risks. Furthermore, safety concerns due to hydrogen's highly flammable nature and the need for advanced technologies to detect and contain leaks demand strict regulations and protocols.

Despite these challenges, the potential to overcome these barriers is high, particularly with the growing global interest in and commitment to accelerating the energy transition. Political collaboration and investment in research, development, and infrastructure are essential for scaling up green hydrogen production and ensuring its safe use. Countries that invest in carbon capture and storage (CCS) technologies and secure hydrogen transport networks will be better positioned to lead this transition. Strengthening international agreements such as the Paris Agreement and setting clear emission reduction targets create an optimistic outlook where global efforts converge toward a low-carbon economy. With the combined efforts of governments, industries, and research institutions, a future where hydrogen becomes a central pillar of a sustainable energy system is within reach, overcoming current limitations and paving the way for a cleaner, more resilient planet.

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References

1. Nnabuife, S.G.; Ugbeh-Johnson, J.; Okeke, N.E.; Ogbonnaya, C. Present and Projected Developments in Hydrogen Production: A Technological Review. *Carbon Capture Sci. Technol.* **2022**, *3*, 100042. [CrossRef]
2. Abdin, Z. Bridging the energy future: The role and potential of hydrogen co-firing with natural gas. *J. Clean. Prod.* **2024**, *436*, 140724. [CrossRef]
3. Zainal, B.S.; Ker, P.J.; Mohamed, H.; Ong, H.C.; Fattah, I.M.R.; Rahman, S.M.A.; Nghiem, L.D.; Mahlia, T.M.I. Recent advancement and assessment of green hydrogen production technologies. *Renew. Sustain. Energy Rev.* **2023**, *189*, 113941. [CrossRef]
4. COP28; IRENA; GRA. *Tripling Renewable Power and Doubling Energy Efficiency by 2030: Crucial Steps Towards 1.5 °C*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2023.
5. Saccardo, R.R.; Domingues, A.M.; Battistelle, R.A.G.; Bezerra, B.S.; Siqueira, R.M.; Neto, J.B.S.S. Investment in photovoltaic energy: An attempt to frame Brazil within the 2030 passage target of the Paris agreement. *Clean. Energy Syst.* **2023**, *5*, 100070. [CrossRef]
6. Harichandan, S.; Kar, S.K.; Bansal, R.; Mishra, S.K.; Balathanigaimani, M.S.; Dash, M. Energy transition research: A bibliometric mapping of current findings and direction for future research. *Clean. Prod. Lett.* **2022**, *3*, 100026. [CrossRef]
7. Ocko, I.B.; Hamburg, S.P. Climate consequences of hydrogen emissions. *Atmos. Chem. Phys.* **2022**, *22*, 9349–9368. [CrossRef]
8. Zhang, L.; Jia, C.; Bai, F.; Wang, W.; An, S.; Zhao, K.; Li, Z.; Li, J.; Sun, H. A comprehensive review of the promising clean energy carrier: Hydrogen production, transportation, storage, and utilization (HPTSU) technologies. *Fuel* **2023**, *355*, 129455. [CrossRef]
9. Gomes, F.A.F.; Yang, Y.; Talei, M. Decarbonizing combustion with hydrogen blended fuels: An exploratory study of impact of hydrogen on hydrocarbon autoignition. *Fuel* **2024**, *364*, 131028. [CrossRef]
10. Frieden, F.; Leker, J. Future costs of hydrogen: A quantitative review. *Sustain. Energy Fuels* **2024**, *8*, 1806. [CrossRef]
11. Lamb, J.J.; Hillestad, M.; Rytter, E.; Bock, R.; Nordgård, A.S.R.; Lien, K.M.; Burheim, O.S.; Pollet, B.G. Traditional routes for hydrogen production and carbon conversion. In *Hydrogen, Biomass and Bioenergy*; Lamb, J.J., Pollet, B.G., Eds.; Academic Press: London, UK, 2020; Chapter 3, pp. 21–53. [CrossRef]
12. Shadidi, B.; Najafi, G.; Yusaf, T. A review of hydrogen as a fuel in internal combustion engines. *Energies* **2021**, *14*, 6209. [CrossRef]
13. Hanto, J.; Herpich, P.; Löffler, K.; Hainsch, K.; Moskalenko, N.; Schmidt, S. Assessing the implications of hydrogen blending on the European energy system towards 2050. *Adv. Appl. Energy* **2024**, *13*, 100161. [CrossRef]
14. Hurtubia, B.; Sauma, E. Economic and environmental analysis of hydrogen production when complementing renewable energy generation with grid electricity. *Appl. Energy* **2021**, *304*, 117739. [CrossRef]
15. Arcos, J.M.M.; Santos, D.M.F. The Hydrogen Color Spectrum: Techno-Economic Analysis of the Available Technologies for Hydrogen Production. *Gases* **2023**, *3*, 25–46. [CrossRef]
16. Hoang, A.T.; Pandey, A.; De Osés, F.J.M.; Chen, W.-H.; Said, Z.; Ng, K.H.; Ağbulut, Ü.; Tarełko, W.; Ölçer, A.I.; Nguyen, X.P. Technological solutions for boosting hydrogen role in decarbonization strategies and net-zero goals of world shipping: Challenges and perspectives. *Renew. Sustain. Energy Rev.* **2023**, *188*, 113790. [CrossRef]
17. Franco, A.; Rocca, M. Industrial Decarbonization through Blended Combustion of Natural Gas and Hydrogen. *Hydrogen* **2024**, *5*, 519–539. [CrossRef]
18. Lefebvre, A.H.; Ballal, D.R. *Gas Turbine Combustion: Alternative Fuels and Emissions*, 3rd ed.; CRC Press: Boca Raton, FL, USA, 2010. [CrossRef]
19. Zhang, C.; Zhang, J.; Zheng, A.; Xu, R.; Jia, G.; Zhu, J. Effects of hydrogen-rich fuel injection on the states of the raceway in blast furnace. *Energy* **2023**, *274*, 127237. [CrossRef]
20. Algayyim, S.J.M.; Saleh, K.; Wandel, A.P.; Fattah, I.M.R.; Yusaf, T.; Alrazen, H.A. Influence of natural gas and hydrogen properties on internal combustion engine performance, combustion, and emissions: A review. *Fuel* **2024**, *362*, 130844. [CrossRef]
21. Gee, A.J.; Proud, D.B.; Smith, N.; Chinnici, A.; Medwell, P.R. Hydrogen addition to a commercial self-aspirating burner and assessment of a practical burner modification strategy to improve performance. *Int. J. Hydrogen Energy* **2024**, *49*, 59–76. [CrossRef]
22. Zhou, H.; Xue, J.; Gao, H.; Ma, N. Hydrogen-fueled gas turbines in future energy system. *Int. J. Hydrogen Energy* **2024**, *64*, 569–582. [CrossRef]
23. Giacomazzi, E.; Troiani, G.; Di Nardo, A.; Calchetti, G.; Cecere, D.; Messina, G.; Carpenella, S. Hydrogen Combustion: Features and Barriers to Its Exploitation in the Energy Transition. *Energies* **2023**, *16*, 7174. [CrossRef]
24. Hu, M.; Wu, X.; Yuan, Y.; Xu, C. Competitive Analysis of Heavy Trucks with Five Types of Fuels under Different Scenarios—A Case Study of China. *Energies* **2024**, *17*, 3936. [CrossRef]

25. Dorel, S.; Lucian, M.; Gheorghe, L.; Cristian, L.G. Green Hydrogen, a Solution for Replacing Fossil Fuels to Reduce CO_2 Emissions. *Processes* **2024**, *12*, 1651. [CrossRef]
26. Hassanpouryouzband, A.; Joonaki, E.; Edlmann, K.; Heinemann, N.; Yang, J. Thermodynamic and transport properties of hydrogen containing streams. *Sci. Data* **2020**, *7*, 222. [CrossRef] [PubMed]
27. Cernat, A.; Pana, C.; Negurescu, N.; Lazaroiu, G.; Nutu, C.; Fuiorescu, D. Hydrogen—An Alternative Fuel for Automotive Diesel Engines Used in Transportation. *Sustainability* **2020**, *12*, 9321. [CrossRef]
28. Tutak, W.; Jamrozik, A.; Grab-Rogaliński, K. Co-Combustion of Hydrogen with Diesel and Biodiesel (RME) in a Dual-Fuel Compression-Ignition Engine. *Energies* **2023**, *16*, 4892. [CrossRef]
29. Mcallister, S.; Chen, J.; Fernandez-Pello, A.C. *Fundamentals of Combustion Processes*; Springer: New York, NY, USA, 2011. [CrossRef]
30. Speight, J.G. *Handbook of Industrial Hydrocarbon Processes*, 2nd ed.; Gulf Professional Publishing: Houston, TX, USA, 2019. [CrossRef]
31. Mullinger, P.; Jenkins, B. *Industrial and Process Furnaces: Principles, Design and Operation*, 3rd ed.; Butterworth-Heinemann: Oxford, UK, 2022; pp. 3–192.
32. Tillman, D. *The Combustion of Solid Fuels and Wastes*, 1st ed.; Academic Press: London, UK, 2012.
33. Danişmaz, M.; Demirtaş, C. An Experimental Investigation of Clean Syngas Production from Waste Biomass by Gasification Method. *Int. J. Comput. Exp. Sci. Eng.* **2024**, *10*, 314–322. [CrossRef]
34. Mishra, S.S.; Shanmugapriya, V. Pyrolysis of Biomass Using Renewable Energy as A Heating Medium: A Review. In Proceedings of the 2024 3rd International Conference on Computational Modelling, Simulation and Optimization—ICCMSO, Phuket, Thailand, 14–16 June 2024; pp. 367–376.
35. Li, B.; Xiao, D.; Xie, H.; Huang, J.; Yan, Z. Coal Classification Based on Reflection Spectroscopy and the IAT-TELM Algorithm. *ACS Omega* **2023**, *8*, 35232–35241. [CrossRef]
36. Minx, J.C.; Hilaire, J.; Müller-Hansen, F.; Nemet, G.; Diluiso, F.; Andrew, R.M.; Ayas, C.; Bauer, N.; Bi, S.L.; Clarke, L.; et al. Coal transitions—Part 2: Phase-out dynamics in global long-term mitigation scenarios. *Environ. Res. Lett.* **2024**, *19*, 033002. [CrossRef]
37. Šramková, K.; Šomplák, R.; Nevrlý, V.; Jirásek, P.; Smejkalová, V.; Popela, P. Stratification and multi-representative optimization approach to waste composition analysis. *Optim. Eng.* **2021**, *22*, 1727–1754. [CrossRef]
38. Schiavon, M.; Ravina, M.; Zanetti, M.; Panepinto, D. State-of-the-Art and Recent Advances in the Abatement of Gaseous Pollutants from Waste-to-Energy. *Energies* **2024**, *17*, 552. [CrossRef]
39. Shahbazi, M.J.; Rahimpour, M.R. Diesel, naphtha, gasoline, and wax production from syngas. In *Advances in Synthesis Gas: Methods, Technologies and Applications*; Elsevier: Amsterdam, The Netherlands, 2023; Volume 3, Chapter 9, pp. 225–234. [CrossRef]
40. Stout, S.; Douglas, G.S.; Uhler, A.D. Standard handbook oil spill. In *Environmental Forensics*, 2nd ed.; Academic Press: London, UK, 2016; pp. 509–564.
41. Al-Zaini, E.O.; Al-Kafani, M.H.; Al-Suhail, A.B.K.; Farhan, M.M.; Jabur, A.T.; Jaber, A.A.; Kadhim, K.N.; Nassef, K.D. A review of bio-kerosene and biodiesel existed production technologies. In Proceedings of the AIP Conference Proceedings, Istanbul, Turkey, 6–7 June 2022; Volume 2776, p. 050007. [CrossRef]
42. Knothe, G.; Razon, L.F. Biodiesel fuels. *Prog. Energy Combust. Sci.* **2017**, *58*, 36–59. [CrossRef]
43. Liu, Y.; Cruz-Morales, P.; Zargar, A.; Belcher, M.S.; Pang, B.; Englund, E.; Dan, Q.; Yin, K.; Keasling, J.D. Biofuels for a sustainable future. *Cell* **2021**, *184*, 1636–1647. [CrossRef] [PubMed]
44. Agaton, C.B.; Batac, K.I.T.; Reyes, E.M., Jr. Prospects and challenges for green hydrogen production and utilization in the Philippines. *Int. J. Hydrogen Energy* **2022**, *47*, 17859–17870. [CrossRef]
45. Xie, Z.; Jin, Q.; Su, G.; Lu, W. A Review of Hydrogen Storage and Transportation: Progresses and Challenges. *Energies* **2024**, *17*, 4070. [CrossRef]
46. National Aeronautics and Space Administration. Beginner's Guide to Aeronautics. Glenn Research Center. 2021. Available online: https://www.grc.nasa.gov/www/k-12/airplane/combst1.html# (accessed on 20 October 2022).
47. Falfari, S.; Cazzoli, G.; Mariani, V.; Bianchi, G.M. Hydrogen Application as a Fuel in Internal Combustion Engines. *Energies* **2023**, *16*, 2545. [CrossRef]
48. Armaroli, N.; Bandini, E.; Barbieri, A. Hydrogen as an energy carrier: Constraints and opportunities. *Pure Appl. Chem.* **2024**, *96*, 479–485. [CrossRef]
49. Keçebaş, A.; Kayfeci, M. Hydrogen properties. In *Solar Hydrogen Production*; Academic Press: Cambridge, MA, USA, 2019; pp. 3–29. [CrossRef]
50. Jeon, J.; Kim, S.J. Recent Progress in Hydrogen Flammability Prediction for the Safe Energy Systems. *Energies* **2020**, *13*, 6263. [CrossRef]
51. Desantes, J.M.; Molina, S.; Novella, R.; López-Juárez, M. Comparative global warming impact and NOX emissions of conventional and hydrogen automotive propulsion systems. *Energy Convers. Manag.* **2020**, *221*, 113137. [CrossRef]
52. Grigoriev, S.A.; Fateev, V.N.; Bessarabov, D.G.; Millet, P. Current status, research trends, and challenges in water electrolysis science and technology. *Int. J. Hydrogen Energy* **2020**, *45*, 26036–26058. [CrossRef]
53. Fortin, P.; Khoza, T.; Cao, X.; Martinsen, S.Y.; Barnett, A.O.; Holdcroft, S. High-performance alkaline water electrolysis using Aemion™ anion exchange membranes. *J. Power Sources* **2020**, *451*, 227814. [CrossRef]
54. Zhao, G.; Kraglund, M.R.; Frandsen, H.L.; Wulff, A.C.; Jensen, S.H.; Chen, M.; Graves, C.R. Life cycle assessment of H_2O electrolysis technologies. *Int. J. Hydrogen Energy* **2020**, *45*, 23765–23781. [CrossRef]

55. Haoran, C.; Xia, Y.; Wei, W.; Yongzhi, Z.; Bo, Z.; Leiqi, Z. Safety and efficiency problems of hydrogen production from alkaline water electrolyzers driven by renewable energy sources. *Int. J. Hydrogen Energy* **2024**, *54*, 700–712. [CrossRef]
56. Wang, Y.; Pang, Y.; Xu, H.; Martinez, A.; Chen, K.S. PEM Fuel cell and electrolysis cell technologies and hydrogen infrastructure development—A review. *Energy Environ. Sci.* **2022**, *15*, 2288–2328. [CrossRef]
57. Wang, T.; Cao, X.; Jiao, L. PEM water electrolysis for hydrogen production: Fundamentals, advances, and prospects. *Carbon Neutrality* **2022**, *1*, 21. [CrossRef]
58. Iyer, S.; Kaur, G.; Haque, N.; Giddey, S. Review of experimental and modelling investigations for solid oxide electrolysis technology. *Int. J. Hydrogen Energy* **2024**, *72*, 537–558. [CrossRef]
59. AlZahrani, A.A.; Dincer, I. Modeling and performance optimization of a solid oxide electrolysis system for hydrogen production. *Appl. Energy* **2018**, *225*, 471–485. [CrossRef]
60. Parawan, A.J.R.; Tayactac, R.G. Application of Sun Tracking Concentrated Solar Power (CSP) Technology with Parabolic Reflectors to Power an Electrolysis System for Yielding Green Hydrogen from Potable Water. In Proceedings of the E3S Web of Conferences, Online, 19 September 2024; Volume 566, p. 04002. [CrossRef]
61. Puig-Samper, G.; Bargiacchi, E.; Iribarren, D.; Dufour, J. Assessing the prospective environmental performance of hydrogen from high-temperature electrolysis coupled with concentrated solar power. *Renew. Energy* **2022**, *196*, 1258–1268. [CrossRef]
62. Incer-Valverde, J.; Korayem, A.; Tsatsaronis, G.; Morosuk, T. "Colors" of hydrogen: Definitions and carbon intensity. *Energy Convers. Manag.* **2023**, *291*, 117294. [CrossRef]
63. Fernández-Arias, P.; Antón-Sancho, Á.; Lampropoulos, G.; Vergara, D. Emerging Trends and Challenges in Pink Hydrogen Research. *Energies* **2024**, *17*, 2291. [CrossRef]
64. Luin, U.; Valant, M. Electrolysis energy efficiency of highly concentrated $FeCl_2$ solutions for power-to-solid energy storage technology. *J. Solid State Electrochem.* **2022**, *26*, 929–938. [CrossRef]
65. Kandah, M.I. Electrolysis Design for Hydrogen Production. *Res. Soc. Dev.* **2022**, *8*, 79–88. [CrossRef]
66. Krūmiņš, J.; Kļaviņš, M. Investigating the Potential of Nuclear Energy in Achieving a Carbon-Free Energy Future. *Energies* **2023**, *16*, 3612. [CrossRef]
67. Razi, F.; Dincer, I. Renewable energy development and hydrogen economy in MENA region: A review. *Renew. Sustain. Energy Rev.* **2022**, *168*, 112763. [CrossRef]
68. Amir, M.; Syed, A.A.; Iqra, S.; Saman, S.; Huma, K.; Mohd, F.; Nayeem, A.P.; Farha, N.; Tokeer, A. Hydrogen Energy as Sustainable Energy Resource for Carbon-Neutrality Realization. *ACS Sustain. Resour. Manag.* **2024**, *1*, 604–620. [CrossRef]
69. Garcia-Vallejo, M.C.; Alzate, C.A.C. Sustainability of hydrogen production considering alternative technologies towards a neutral carbon society. *Int. J. Hydrogen Energy* **2024**, *64*, 853–863. [CrossRef]
70. Khan, M.H.A.; Daiyan, R.; Neal, P.; Haque, N.; MacGill, I.; Amal, R. A framework for assessing economics of blue hydrogen production from steam methane reforming using carbon capture storage & utilization. *Int. J. Hydrogen Energy* **2021**, *46*, 22685–22706.
71. Khan, M.I.; Al-Ghamdi, S.G. Hydrogen economy for sustainable development in GCC countries: A SWOT analysis considering current situation, challenges, and prospects. *Int. J. Hydrogen Energy* **2023**, *48*, 10315–10344. [CrossRef]
72. Diab, J.; Fulcheri, L.; Hessel, V.; Rohani, V.; Frenklach, M. Why turquoise hydrogen will Be a game changer for the energy transition. *Int. J. Hydrogen Energy* **2022**, *47*, 25831–25848. [CrossRef]
73. Sanyal, A.; Malalasekera, W.; Bandulasena, H.; Wijayantha, K.G.U. Review of the production of turquoise hydrogen from methane catalytic decomposition: Optimising reactors for Sustainable Hydrogen production. *Int. J. Hydrogen Energy* **2024**, *72*, 694–715. [CrossRef]
74. Korányi, T.I.; Németh, M.; Beck, A.; Horváth, A. Recent advances in methane pyrolysis: Turquoise hydrogen with solid carbon production. *Energies* **2022**, *15*, 6342. [CrossRef]
75. Bamiteko, S.O.; Okiki, P.A.; Olarinde, E.S.; Adeniran, A.S. Microbial Production of Hydrogen as Alternative to Fossil Fuel—A Review. In Proceedings of the 2024 International Conference on Science, Engineering and Business for Driving Sustainable Development Goals (SEB4SDG), Online, 2–4 April 2024; pp. 1–7.
76. Pandey, B.K.; Mishra, S.; Dhar, R.; Srivastava, R. Biological hydrogen production driven by photo-fermentation processes. In *Solar-Driven Green Hydrogen Generation and Storage*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 223–235. [CrossRef]
77. Li, P. Photosynthetic hydrogen production bacteria breeding technologies. In *Waste to Renewable Biohydrogen*; Academic Press: Cambridge, MA, USA, 2021; pp. 179–199. [CrossRef]
78. Senthil, R.B.; Dinesh, A.V.; Ranjith, G.; Kishore, V.; Ewe, L.S.; Yew, W.K.; Baskaran, R. Sustainability considerations in bio-hydrogen from bio-algae with the aid of bio-algae cultivation and harvesting: Critical review. *MRS Energy Sustain.* **2024**, 1–26. [CrossRef]
79. Dari, D.N.; Freitas, I.S.; Aires, F.I.d.S.; Melo, R.L.F.; dos Santos, K.M.; da Silva Sousa, P.; Gonçalves de Sousa Junior, P.; Luthierre Gama Cavalcante, A.; Neto, F.S.; da Silva, J.L.; et al. An Updated Review of Recent Applications and Perspectives of Hydrogen Production from Biomass by Fermentation: A Comprehensive Analysis. *Biomass* **2024**, *4*, 132–163. [CrossRef]
80. El Bari, H.; Lahboubi, N.; Habchi, S.; Rachidi, S.; Bayssi, O.; Nabil, N.; Mortezaei, Y.; Villa, R. Biohydrogen production from fermentation of organic waste, storage and applications. *Clean. Waste Syst.* **2022**, *3*, 100043. [CrossRef]
81. Nouicer, I.; Kaghouche, B.; Ghenai, C.; Fares, M.; Nourdine, K. Effect of Solar Energy Technology on Green Hydrogen Production. In *Advancements in Renewable Energy and Green Hydrogen*; IGI Global: Hershey, PA, USA, 2024; pp. 76–83.

82. Zhang, C.; Li, N.; An, G. Review of Concentrated Solar Power Technology Applications in Photocatalytic Water Purification and Energy Conversion: Overview, Challenges and Future Directions. *Energies* **2024**, *17*, 463. [CrossRef]
83. Liu, J.; Wang, J.; Tang, Y.; Jin, J.; Li, W. Solar photovoltaic–thermal hydrogen production system based on full-spectrum utilization. *J. Clean. Prod.* **2023**, *430*, 139340. [CrossRef]
84. Gopinath, M.; Marimuthu, R. A review on solar energy-based indirect water-splitting methods for hydrogen generation. *Int. J. Hydrogen Energy* **2022**, *47*, 37742–37759. [CrossRef]
85. Song, H.; Luo, S.; Huang, H.; Deng, B.; Ye, J. Solar-driven hydrogen production: Recent advances, challenges, and future perspectives. *ACS Energy Lett.* **2022**, *7*, 1043–1065. [CrossRef]
86. Arunachalam, M.; Han, D.S. Efficient solar-powered PEM electrolysis for sustainable hydrogen production: An integrated approach. *Emergent Mater.* **2024**, *7*, 1401–1415. [CrossRef]
87. Al-Ezzi, A.S.; Ansari, M.N.M. Photovoltaic Solar Cells: A Review. *Appl. Syst. Innov.* **2022**, *5*, 67. [CrossRef]
88. Lovegrove, K.; Pye, J. Fundamental principles of concentrating solar power systems. In *Concentrating Solar Power Technology*; Woodhead Publishing: Sawston, UK, 2021; pp. 19–71.
89. García-Ferrero, J.; Merchán, R.P.; Santos, M.J.; Medina, A.; Hernández, A.C. Brayton technology for Concentrated Solar Power plants: Comparative analysis of central tower plants and parabolic dish farms. *Energy Convers. Manag.* **2022**, *271*, 116312. [CrossRef]
90. Jayathunga, D.S.; Karunathilake, H.P.; Narayana, M.; Witharana, S. Phase change material (PCM) candidates for latent heat thermal energy storage (LHTES) in concentrated solar power (CSP) based thermal applications-A review. *Renew. Sustain. Energy Rev.* **2024**, *189*, 113904. [CrossRef]
91. Al-Farajat, R.K.; Gomaa, M.R.; Alzghoul, M.Z. Comparison between CSP Systems and Effect of Different Heat Transfer Fluids on the Performance. *WSEAS Trans. Heat Mass Transf.* **2022**, *17*, 196–205. [CrossRef]
92. Dauletbay, A. Transportation of Hydrogen: Hydrogen Usage. In *Hydrogen Technologies-Advances, Insights, and Applications*; IntechOpen: London, UK, 2024.
93. Wu, X.; Zhang, H.; Yang, M.; Jia, W.; Qiu, Y.; Lan, L. From the perspective of new technology of blending hydrogen into natural gas pipelines transmission: Mechanism, experimental study, and suggestions for further work of hydrogen embrittlement in high-strength pipeline steels. *Int. J. Hydrogen Energy* **2022**, *47*, 8071–8090. [CrossRef]
94. Negro, V.; Noussan, M.; Chiaramonti, D. The potential role of ammonia for hydrogen storage and transport: A critical review of challenges and opportunities. *Energies* **2023**, *16*, 6192. [CrossRef]
95. Cui, J.; Aziz, M. Techno-economic analysis of hydrogen transportation infrastructure using ammonia and methanol. *Int. J. Hydrogen Energy* **2023**, *48*, 15737–15747. [CrossRef]
96. Yang, Y.; Tong, L.; Yin, S.; Liu, Y.; Wang, L.; Qiu, Y.; Ding, Y. Status and challenges of applications and industry chain technologies of hydrogen in the context of carbon neutrality. *J. Clean. Prod.* **2022**, *376*, 134347. [CrossRef]
97. Zhang, Y.; Liu, F.; Chen, W.; Han, W.; Zhai, W.; Lu, Y.; Li, M. Effective reduction of hydrogen consumption in ultra-deep hydrodesulfurization of diesel: Deep insights into the effect of thermodynamic limitations during hydrotreating. *Fuel* **2024**, *356*, 129640. [CrossRef]
98. Ghavam, S.; Vahdati, M.; Wilson, I.G.; Styring, P. Sustainable ammonia production processes. *Front. Energy Res.* **2021**, *9*, 580808. [CrossRef]
99. Saab, R.; Polychronopoulou, K.; Zheng, L.; Kumar, S.; Schiffer, A. Synthesis and performance evaluation of hydrocracking catalysts: A review. *J. Ind. Eng. Chem.* **2020**, *89*, 83–103. [CrossRef]
100. Olabi, A.G.; Abdelkareem, M.A.; Al-Murisi, M.; Shehata, N.; Alami, A.H.; Radwan, A.; Wilberforce, T.; Chae, K.; Sayed, E.T. Recent progress in Green Ammonia: Production, applications, assessment; barriers, and its role in achieving the sustainable development goals. *Energy Convers. Manag.* **2023**, *277*, 116594. [CrossRef]
101. Öztürk, A.; Yurtcan, A.B. Prospects for Hydrogen and Fuel Cells. In *Prospects of Hydrogen Fueled Power Generation*, 1st ed.; River Publishers: Maidstone, UK, 2024; p. 81.
102. Das, D.; Chakraborty, I.; Bohre, A.K.; Kumar, P.; Agarwala, R. Sustainable integration of green hydrogen in renewable energy systems for residential and EV applications. *Int. J. Energy Res.* **2024**, *2024*, 8258624. [CrossRef]
103. Grube, T.; Kraus, S.; Cerniauskas, S.; Linßen, J.; Stolten, D. The market introduction of hydrogen focusing on bus refueling. *Int. J. Hydrogen Energy* **2024**, *56*, 175–187. [CrossRef]
104. Halder, P.; Babaie, M.; Salek, F.; Haque, N.; Savage, R.; Stevanovic, S.; Bodisco, T.A.; Zare, A. Advancements in hydrogen production, storage, distribution and refuelling for a sustainable transport sector: Hydrogen fuel cell vehicles. *Int. J. Hydrogen Energy* **2024**, *52*, 973–1004. [CrossRef]
105. Fakhreddine, O.; Gharbia, Y.; Derakhshandeh, J.F.; Amer, A.M. Challenges and Solutions of Hydrogen Fuel Cells in Transportation Systems: A Review and Prospects. *World Electr. Veh. J.* **2023**, *14*, 156. [CrossRef]
106. Calandra, D.; Wang, T.; Cane, M.; Alfiero, S. Management of hydrogen mobility challenges: A systematic literature review. *J. Clean. Prod.* **2023**, *410*, 137305. [CrossRef]
107. Boretti, A. The perspective of hydrogen direct reduction of iron. *J. Clean. Prod.* **2023**, *429*, 139585. [CrossRef]
108. Özgün, Ö.; Dirba, I.; Gutfleisch, O.; Ma, Y.; Raabe, D. Green Ironmaking at Higher H2 Pressure: Reduction Kinetics and Microstructure Formation During Hydrogen-Based Direct Reduction of Hematite Pellets. *J. Sustain. Metall.* **2024**, *10*, 1127–1140. [CrossRef]

109. Chang, Y.; Wan, F.; Yao, X.; Wang, J.; Han, Y.; Li, H. Influence of hydrogen production on the CO_2 emissions reduction of hydrogen metallurgy transformation in iron and steel industry. *Energy Rep.* **2023**, *9*, 3057–3071. [CrossRef]
110. Kumar, N.R.S.; Suryan, A.; Manju, M.S. Hydrogen As An Alternative Aviation Fuel—A Review. In *Ammonia and Hydrogen for Green Energy Transition*; Springer: Berlin/Heidelberg, Germany, 2024; pp. 265–286.
111. Proesmans, P.; Vos, R. Hydrogen, medium-range airplane design optimization for minimal global warming impact. *CEAS Aeronaut. J.* **2024**, *15*, 781–806. [CrossRef]
112. Massaro, M.C.; Pramotton, S.; Marocco, P.; Monteverde, A.H.A.; Santarelli, M. Optimal design of a hydrogen-powered fuel cell system for aircraft applications. *Energy Convers. Manag.* **2024**, *306*, 118266. [CrossRef]
113. Zou, C.; Li, J.; Zhang, X.; Jin, X.; Xiong, B.; Yu, H.; Liu, X.; Wang, S.; Li, Y.; Zhang, L.; et al. Industrial status, technological progress, challenges, and prospects of hydrogen energy. *Nat. Gas Ind. B* **2022**, *9*, 427–447. [CrossRef]
114. Zier, M.; Stenzel, P.; Kotzur, L.; Stolten, D. A review of decarbonization options for the glass industry. *Energy Convers. Manag. X* **2020**, *10*, 100083.
115. Zhang, J.; Li, J. Revolution in Renewables: Integration of Green Hydrogen for a Sustainable Future. *Energies* **2024**, *17*, 4148. [CrossRef]
116. Oyewole, O.L.; Nwulu, N.I.; Okampo, E.J. Optimal design of hydrogen-based storage with a hybrid renewable energy system considering economic and environmental uncertainties. *Energy Convers. Manag.* **2024**, *300*, 117991. [CrossRef]
117. AlZohbi, G.; Almoaikel, A.; AlShuhail, L. An overview on the technologies used to store hydrogen. *Energy Rep.* **2023**, *9*, 28–34. [CrossRef]
118. Rasul, M.G.; Hazrat, M.A.; Sattar, M.A.; Jahirul, M.I.; Shearer, M.J. The future of hydrogen: Challenges on production, storage and applications. *Energy Convers. Manag.* **2022**, *272*, 116326. [CrossRef]
119. Kumari, E.; Choudhary, B. Hydrogen is the future of energy security and sustainability: A review. *J. Mech. Constr. Eng. JMCE* **2023**, *3*, 1–13. [CrossRef]
120. Jürgens, L.; Schäfers, H. Green hydrogen in the chemical industry—Key factors and cost competitiveness. In Proceedings of the 20th International Conference on the European Energy Market (EEM), Istanbul, Turkey, 10–12 June 2024; pp. 1–5. [CrossRef]
121. Marouani, I.; Guesmi, T.; Alshammari, B.M.; Alqunun, K.; Alzamil, A.; Alturki, M.; Hadj Abdallah, H. Integration of Renewable-Energy-Based Green Hydrogen into the Energy Future. *Processes* **2023**, *11*, 2685. [CrossRef]
122. Amin, M.; Shah, H.H.; Fareed, A.G.; Khan, W.U.; Chung, E.; Zia, A.; Farooqi, Z.U.R.; Lee, C. Hydrogen production through renewable and non-renewable energy processes and their impact on climate change. *Int. J. Hydrogen Energy* **2022**, *47*, 33112–33134. [CrossRef]
123. Revinova, S.; Lazanyuk, I.; Gabrielyan, B.; Shahinyan, T.; Hakobyan, Y. Hydrogen in Energy Transition: The Problem of Economic Efficiency, Environmental Safety, and Technological Readiness of Transportation and Storage. *Resources* **2024**, *13*, 92. [CrossRef]
124. Marc, A. Hydrogen For Mobility a Zero Carbon Transportation System. *Glob. J. Eng. Res.* **2024**, *24*, 1–9. [CrossRef]
125. Cheekatamarla, P. Hydrogen and the Global Energy Transition—Path to Sustainability and Adoption across All Economic Sectors. *Energies* **2024**, *17*, 807. [CrossRef]
126. Kim, D.M.; Lee, H.J. Estimation of flammable region through experimental observation of liquid hydrogen cloud leaked under various atmospheric conditions. *Int. J. Hydrogen Energy* **2024**, *61*, 1199–1211. [CrossRef]
127. Kleszcz, S.; Assadi, M. Hydrogen safety considerations: Mitigating risks and securing operations in enclosed spaces. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2023; Volume 1294, p. 012057.
128. Lin, Y.; Ling, X.; Yu, A.; Liu, Y.; Liu, D.; Wang, Y.; Wu, Q.; Lu, Y. Modeling of Hydrogen Dispersion, Jet Fires and Explosions Caused by Hydrogen Pipeline Leakage. *Fire* **2024**, *7*, 8. [CrossRef]
129. Calabrese, M.; Portarapillo, M.; Di Nardo, A.; Venezia, V.; Turco, M.; Luciani, G.; Di Benedetto, A. Hydrogen Safety Challenges: A Comprehensive Review on Production, Storage, Transport, Utilization, and CFD-Based Consequence and Risk Assessment. *Energies* **2024**, *17*, 1350. [CrossRef]
130. Guy, P.; Julien, C. Risks Associated with the Use of Hydrogen as an Energy Carrier or Source. *J. Energy Power Technol.* **2022**, *4*, 1–34. [CrossRef]
131. Girão, A.F.; Completo, A. Eye-readable sensors for intuitive hydrogen monitoring. *Int. J. Hydrogen Energy* **2024**, *65*, 593–605. [CrossRef]
132. Oh, D.-W.; Kang, K.; Lee, J.-H. Minimum Detection Concentration of Hydrogen in Air Depending on Substrate Type and Design of the 3ω Sensor. *Sensors* **2023**, *23*, 9009. [CrossRef]
133. Bi, S.; Tan, D.; Fang, C.; Peng, Y.; Zeng, L.; Wang, Y.; Sun, N.; Zhang, Z.; Sun, H.; Jiang, C.; et al. High-performance palladium nanotube network as fast, high-resolution, and wide range hydrogen detector in atmosphere. *Sens. Actuators B Chem.* **2024**, *404*, 135307. [CrossRef]
134. Zhang, F.; Yin, W.; Zhang, J. High Sensitivity Hydrogen Sensor via the Coupling of Tamm Plasmon Polaritons and Defect Mode. *Chemosensors* **2024**, *12*, 67. [CrossRef]
135. Liu, Z.; Zhang, R.; Duan, Z.; Fan, L.; Zhang, S.; Cheng, L.; Xu, X. A hydrogen sensor based on an acoustic topological material with a coiled structure. *J. Appl. Phys.* **2024**, *136*, 024503. [CrossRef]

136. Rao, R.R.A.; Srividya, R.; Sameera, V.S.; Bethi, B.; Prasad, K.S.N.V.; Srinivas, T.; Ganesh, B.; Praveen, B.V.S. Safety first: Managing hydrogen in production, handling, and applications. In *Sustainable Hydrogen Energy: Production, Storage & Transportation*; Arya, R., Tiwari, A., Verros, G., Malik, P., Davim, J., Eds.; Walter de Gruyter GmbH & Co KG: Berlin, Germany, 2024; pp. 275–304. [CrossRef]
137. Lamari, F.; Weinberger, B.; Langlois, P.; Fruchart, D. Instances of Safety-Related Advances in Hydrogen as Regards Its Gaseous Transport and Buffer Storage and Its Solid-State Storage. *Hydrogen* **2024**, *5*, 387–402. [CrossRef]
138. Kumar, S.; Nanan-Surujbally, A.; Sharma, D.P.; Pathak, D. Hydrogen safety/standards (national and international document standards on hydrogen energy and fuel cell). In *Towards Hydrogen Infrastructure*; Elsevier: Amsterdam, The Netherlands, 2024; pp. 315–346.
139. Adithya, S.; Meda, U.S. A Review on the Development of Iot Enabled Hydrogen Sensing Systems. *ECS Trans.* **2022**, *107*, 4767–4789. [CrossRef]
140. Yang, Z.; Hao, D.; Wang, F.; Qin, C.; Chen, X.; Tian, Y. Quantitative analysis of hydrogen leakage and diffusion processes based on real-time concentration measurement at different spatial positions in a customized chamber. *Int. J. Hydrogen Energy* **2024**, *66*, 231–241. [CrossRef]
141. Ramaiyan, K.; Tsui, L.K.; Brosha, E.L.; Kreller, C.; Stetter, J.; 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]
142. Hossain, M.A. Computational study of methane-air combustion using the species transport model. In *AIAA SCITECH 2022 Forum*; American Institute of Aeronautics and Astronautics, Inc.: Orlando, FL, USA, 2022; p. 1102. [CrossRef]
143. Li, T.; Geschwindner, C.; Dreizler, A.; Böhm, B. Particle-resolved optical diagnostics of solid fuel combustion for clean power generation: A review. *Meas. Sci. Technol.* **2023**, *34*, 122001. [CrossRef]
144. Kohse-Höinghaus, K. Combustion, chemistry, and carbon neutrality. *Chem. Rev.* **2023**, *123*, 5139–5219. [CrossRef]
145. Rego, F.C.; Morgan, P.; Fernandes, P.; Hoffman, C. From Fuels to Smoke: Chemical Processes. In *Fire Science: From Chemistry to Landscape Management*; Springer: Cham, Switzerland, 2021; pp. 19–37. [CrossRef]
146. Qiu, L.; Hua, Y.; Qian, Y.; Cheng, X. On the Radiative, Diffusion and Chemical Effects of Soot Formation in a Nonsmoking Laminar Ethylene Diffusion Flame. *Combust. Sci. Technol.* **2023**, *195*, 778–792. [CrossRef]
147. Likhanov, V.A.; Anfilatov, A.A. Formation and burning of soot particles in a diesel cylinder when working on ethanol-fuel emulsion. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2020; Volume 862, p. 032044. [CrossRef]
148. Stepanova, O.A.; Kasengaliev, M.K.; Umyrzhan, T.N.; Khazhidinova, A.R. Research combustion efficiency of unprojected coal. *Bull. Shakarim Univ. Tech. Sci.* **2024**, *2*, 364–370. [CrossRef]
149. Gao, Y. The Impacts of Combustion Reaction on the Environment. *Highlights Sci. Eng. Technol.* **2024**, *83*, 51–55. [CrossRef]
150. Cabascango, V.Q.; Bazhin, V.Y. Combustion optimization in gas burners of reverberatory furnaces during the melting of nickel alloys. *J. Phys. Conf. Ser.* **2021**, *1728*, 012019. [CrossRef]
151. Tutunea, D.; Dumitru, I.; Stănciuc-Oţăt, O.V. Overview of the use of oxygen sensors in automotive applications. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2024; Volume 1303, p. 012014. [CrossRef]
152. Inumaru, J.; Hasegawa, T.; Shirai, H.; Nishida, H.; Noda, N.; Ohyama, S. Fossil fuels combustion and environmental issues. In *Advances in Power Boilers*; Elsevier: Amsterdam, The Netherlands, 2021; Volume 2, pp. 1–56. [CrossRef]
153. Guo, X.; Xiao, Y.; Zhao, L.; Shi, L.; Xue, X.; Li, X.; Liu, Z. Combustion behaviors of various coals and chars: From covalent bonds' and radicals' perspective. *Fuel* **2021**, *297*, 120749. [CrossRef]
154. Karamitros, D.; Ibraimova, A.; Konstantinidis, K.; Koltsakis, G.; Choi, S.; Cho, J. Methane Conversion in Stoichiometric Natural Gas Engine Exhaust. *SAE Tech. Pap.* **2024**. [CrossRef]
155. Yaşar, M.F.; Ergen, G.; Cesur, I. Investigating the Use of Methane as an Alternative Fuel in Diesel Engines: A Numerical Approach. *Int. J. Automot. Sci. Technol.* **2023**, *7*, 349–359. [CrossRef]
156. Cabrales, S.; Valencia, C.; Ramírez, C.; Ramírez, A.; Herrera, J.; Cadena, A. Stochastic cost-benefit analysis to assess new infrastructure to improve the reliability of the natural gas supply. *Energy* **2022**, *246*, 123421. [CrossRef]
157. Sahoo, M.; Dey, S. A comparative study on the characterisation and combustion behaviour of high ash coals from two different geographical origins. *Fuel* **2021**, *286*, 119397. [CrossRef]
158. Zheng, J.; Du, M.; Xiao, Z.; Zhu, X. Simulation of Soot Formation in Pulverized Coal Combustion under O_2/N_2 and O_2/CO_2 Atmospheres. *ACS Omega* **2024**, *9*, 22051–22064. [CrossRef]
159. Feng, Y.; Chen, J.; Luo, J. Life cycle cost analysis of power generation from underground coal gasification with carbon capture and storage (CCS) to measure the economic feasibility. *Resour. Policy* **2024**, *92*, 104996. [CrossRef]
160. Wang, F.; Li, P.; Wang, G.; Mi, J. Moderate and intense low-oxygen dilution (MILD) combustion of liquid fuels: A review. *Energy Fuels* **2022**, *36*, 8026–8053. [CrossRef]
161. Ismael, M.A.; Rosli, M.A.; Aziz, A.R.A.; Mohammed, S.E.; Opatola, R.A.; El-Adawy, M. Gas to liquid (GTL) role in diesel engine: Fuel characteristics and emission: A review. *C Eng. Technol.* **2023**, *18*, 100706. [CrossRef]
162. Agrawal, A.K. *Fuels: Sources, Conversion, and Utilization*, 1st ed.; Cambridge University Press: Cambridge, UK, 2022; pp. 414–450. [CrossRef]
163. Akomolafe, O.O.; Olorunsogo, T.; Anyanwu, E.C.; Osasona, F.; Ogugua, J.O.; Daraojimba, O.H. Air quality and public health: A review of urban pollution sources and mitigation measures. *Eng. Sci. Technol. J.* **2024**, *5*, 259–271. [CrossRef]

164. Rosato, D.A.; Thornton, M.; Sosa, J.; Bachman, C.; Godwin, G.B.; Ahmed, K.A. Stabilized detonation for hypersonic propulsion. *Proc. Natl. Acad. Sci. USA* **2021**, *118*, e2102244118. [CrossRef] [PubMed]
165. Thakur, P. *Advanced Mine Ventilation*, 1st ed.; Woodhead Publishing: Cambridge, UK, 2019; pp. 79–92. [CrossRef]
166. Turns, S.R. *An Introduction to Combustion: Concepts and Applications*, 3rd ed.; McGraw-Hill Companies: New York, NY, USA, 2012; pp. 2–17.
167. Kiviluoma, J.; Helistö, N.; Putkonen, N.; Smith, C.; Koivisto, M.; Korpås, M.; Flynn, D.; Söder, L.; Taibi, E.; Guminski, A. Flexibility From the Electrification of Energy: How Heating, Transport, and Industries Can Support a 100% Sustainable Energy System. *IEEE Power Energy Mag.* **2022**, *20*, 55–65. [CrossRef]
168. Habib, M.A.; Abdulrahman, G.A.; Alquaity, A.B.; Qasem, N.A. Hydrogen combustion, production, and applications: A review. *Alex. Eng. J.* **2024**, *100*, 182–207. [CrossRef]
169. Kim, J.H.; Park, S.W.; Seo, J.K. An Experimental Study on the Diffusion Characteristics of Hydrogen by Ventilation System. In Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering, Singapore, 9–14 June 2024. [CrossRef]
170. Yuan, M.; Hu, Q.; Yang, H.; Wang, X.; Wang, J.; Qian, X.; Li, P.; Pang, L.; Gao, Y. Evolution of Explosion-Venting Flow Field and Hazard Induced by a Vented Hydrogen Explosion in a 45 m3 Container. *Energy Fuels* **2024**, *38*, 16924–16935. [CrossRef]
171. Rogalev, A.; Rogalev, N.; Kharlamova, D.; Shcherbatov, I.; Karev, T. Development of Solutions for Increasing the Combustion Efficiency of Hydrogen in Water Vapor in a Hydrogen-Oxygen Steam Superheater. *Inventions* **2023**, *8*, 6. [CrossRef]
172. Guo, L.; Ba, Q.; Zhang, S. Research on Characteristics of Hydrogen Dynamic Leakage and Combustion at High Pressure. *Int. J. Energy Res.* **2023**, *2023*, 6644038. [CrossRef]
173. Paulitsch, N.; Giuliani, F.; Hofer, A.; Hofer, J.; Andracher, L. An innovative Concept for the complete and low-NOx Combustion of non-carbon Eco-fuels using a thermo-acoustically-driven, hydrogen-powered Pilot Stage. In Proceedings of the ASME Turbo Expo 2022: Turbomachinery Technical Conference and Exposition. Volume 2: Coal, Biomass, Hydrogen, and Alternative Fuels; Controls, Diagnostics, and Instrumentation; Steam Turbine, Rotterdam, Netherlands, 13–17 June 2022; American Society of Mechanical Engineers: New York, NY, USA, 2022. [CrossRef]
174. Meulemans, M.; Durocher, A.; Bourque, G.; Bergthorson, J.M. NO measurements in high temperature hydrogen flames: The crucial role of the hydrogen oxidation chemistry for accurate NO predictions. *Combust. Flame* **2024**, *261*, 113279. [CrossRef]
175. Schwarz, S.; Daurer, G.; Gaber, C.; Demuth, M.; Hochenauer, C. Experimental investigation of hydrogen enriched natural gas combustion with a focus on nitrogen oxide formation on a semi-industrial scale. *Int. J. Hydrogen Energy* **2024**, *63*, 173–183. [CrossRef]
176. Rueda-Vázquez, J.M.; Serrano, J.; Pinzi, S.; Jiménez-Espadafor, F.J.; Dorado, M.P. A Review of the Use of Hydrogen in Compression Ignition Engines with Dual-Fuel Technology and Techniques for Reducing NO_x Emissions. *Sustainability* **2024**, *16*, 3462. [CrossRef]
177. Özyalcin, C.; Sterlepper, S.; Roiser, S.; Eichlseder, H.; Pischinger, S. Exhaust gas aftertreatment to minimize NOX emissions from hydrogen-fueled internal combustion engines. *Appl. Energy* **2024**, *353*, 122045. [CrossRef]
178. Payri, R.; Novella, R.; Nasser, K.I.; Bori-Fabra, O. Spray Characterization of Direct Hydrogen Injection as a Green Fuel with Lower Emissions. *Energies* **2024**, *17*, 2405. [CrossRef]
179. Marzouk, O.A. Expectations for the Role of Hydrogen and Its Derivatives in Different Sectors through Analysis of the Four Energy Scenarios: IEA-STEPS, IEA-NZE, IRENA-PES, and IRENA-1.5°C. *Energies* **2024**, *17*, 646. [CrossRef]
180. Chen, P.S.-L.; Fan, H.; Enshaei, H.; Zhang, W.; Shi, W.; Abdussamie, N.; Miwa, T.; Qu, Z.; Yang, Z. Opportunities and Challenges of Hydrogen Ports: An Empirical Study in Australia and Japan. *Hydrogen* **2024**, *5*, 436–458. [CrossRef]
181. Zabanova, Y. The EU in the Global Hydrogen Race: Bringing Together Climate Action, Energy Security, and Industrial Policy. In *The Geopolitics of Hydrogen: Volume 1: European Strategies in Global Perspective*; Quitzow, R., Zabanova, Y., Eds.; Springer: Cham, Switzerland, 2024; Volume 1, pp. 15–47. [CrossRef]
182. Jaradat, M.; Almashaileh, S.; Bendea, C.; Juaidi, A.; Bendea, G.; Bungau, T. Green Hydrogen in Focus: A Review of Production Technologies, Policy Impact, and Market Developments. *Energies* **2024**, *17*, 3992. [CrossRef]
183. Baukal, C.E., Jr. *The John Zink Hamworthy Combustion Handbook: Volume 3–Applications*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 2013; pp. 16–51.
184. Baukal, C.E., Jr. *Industrial Burners Handbook*, 1st ed.; CRC Press: Boca Raton, FL, USA, 2003. [CrossRef]
185. Sengupta, A.; Mukherjee, R.; Mishra, V.K. Performance and emission characteristic of burners: A review. In Proceedings of the AIP Conference Proceedings, Jamshedpur, India, 29–30 August 2020; Volume 2341, p. 030027. [CrossRef]
186. Ighodalo, O.A. Current trend in furnace technology in the melting industries. *Res. J. Appl. Sci. Eng. Technol.* **2011**, *3*, 540–545.
187. Lezcano-Benítez, J.C.; Correa-Restrepo, D.; Amell-Arrieta, A.; Cadavid-Sierra, F. Numerical simulation of high-pressure burner with partially premixed flame. *CTF Cienc. Tecnol. Y Futuro* **2011**, *4*, 89–104. [CrossRef]
188. Brumbaugh, J.E. *Audel HVAC Fundamentals, Volume 2: Heating System Components, Gas and Oil Burners, and Automatic Controls*, 4th ed.; John Wiley & Sons: Indianapolis, IN, USA, 2004; pp. 32–35.
189. Ugboya, A.P. The design and development of a dual fuel burner. *J. Multidiscip. Eng. Sci. Technol.* **2019**, *6*, 9586–9591.
190. Basu, P.; Kefa, C.; Jestin, L. *Boilers and Burners: Design and Theory*, 1st ed.; Springer Science & Business Media: New York, NY, USA, 2000; pp. 80–126.
191. Deheri, C.; Acharya, S.K.; Thatoi, D.N.; Mohanty, A.P. A review on performance of biogas and hydrogen on diesel engine in dual fuel mode. *Fuel* **2020**, *260*, 116337. [CrossRef]
192. Gupta, R.C. *Fuels, Furnaces and Refractories*, 1st ed.; PHI Learning Pvt. Ltd.: Delhi, India, 2016.

193. Yusupbekov, N.R.; Kholmanov, U.U. System of automatic control of the technological process of combustion in gas combustion furnaces. In Proceedings of the AIP Conference Proceedings, Tashkent, Uzbekistan, 26–27 May 2023; Volume 3119. [CrossRef]
194. Sotelo, D.; Favela-Contreras, A.; Lozoya, C.; Beltran-Carbajal, F.; Dieck-Assad, G.; Sotelo, C. Dynamic simulation of a crude oil distillation plant using Aspen-Hysys. *Int. J. Simul. Model.* **2019**, *18*, 229–241. [CrossRef]
195. Ibrahim, S.; Jagannath, A.; Raj, A. Aromatics oxidation in the furnace of sulfur recovery units: Model development and optimization. *J. Nat. Gas Sci. Eng.* **2020**, *83*, 103581. [CrossRef]
196. Wang, L.; Li, H.; Huang, Z.; Wang, L.; Chen, W. Impact of hydrogen direct injection on engine combustion and emissions in a GDI engine. *Adv. Mech. Eng.* **2023**, *15*, 16878132231189117. [CrossRef]
197. Toumasatos, Z.; Zhu, H.; Durbin, T.D.; Johnson, K.C.; Cao, S.; Karavalakis, G. Real-world particulate, GHG, and gaseous toxic emissions from heavy-duty diesel and natural gas vehicles. *Atmos. Environ.* **2024**, *327*, 120512. [CrossRef]
198. Cai, Z.; Yan, F.; Shao, Y.; Liao, J.; Wu, Y.; Zheng, S.; Li, Y.X.; Hu, J.; Wang, Z.; Li, Z. Lumped model for evaluating dynamic filtration and pressure drop behaviour in diesel particulate filters. *Fuel* **2024**, *365*, 131311. [CrossRef]
199. Elkaee, S.; Phule, A.D.; Yang, J.H. Advancements in Selective Catalytic Reduction (SCR) Technologies for NOx Reduction: A Comprehensive Review of Reducing Agents. *Process Saf. Environ. Prot.* **2024**, *184*, 854–880. [CrossRef]
200. Wu, J.; Liu, G.; Zhang, X.; Zhang, C.; Li, C.; Gong, C.; Zhou, X.; Gong, Q.; Cheng, S.; Jiang, J. Design and Verification of Key Components of a New Selective Catalytic Reduction System in a Petrochemical Captive Power Plant. *Processes* **2023**, *11*, 2837. [CrossRef]
201. Commane, R.; Schiferl, L.D. Climate mitigation policies for cities must consider air quality impacts. *Chem* **2022**, *8*, 910–923. [CrossRef]
202. Tibrewal, K.; Tanaka, K.; Boucher, O.; Ciais, P. Levers of climate pledges influencing the Paris Agreement target. In Proceedings of the EGU General Assembly 2023, Vienna, Austria, 24–28 April 2023; p. EGU23-6566. [CrossRef]
203. Sikora, A. European Green Deal–legal and financial challenges of the climate change. *Era Forum* **2021**, *21*, 681–697. [CrossRef]
204. Bistline, J.; Blanford, G.; Brown, M.; Burtraw, D.; Domeshek, M.; Farbes, J.; Fawcett, A.; Hamilton, A.; Jenkins, J.; Zhao, A.; et al. Emissions and energy impacts of the Inflation Reduction Act. *Science* **2023**, *380*, 1324–1327. [CrossRef]
205. Hennessy, E.M.; Singh, M.; Saltzer, S.; Azevedo, I.M. Pathways to zero emissions in California's heavy-duty transportation sector. *Environ. Res. Infrastruct. Sustain.* **2024**, *4*, 035001. [CrossRef]
206. Ghassabian, A.; Titus, A.R.; Conderino, S.; Azan, A.; Weinberger, R.; Thorpe, L.E. Beyond traffic jam alleviation: Evaluating the health and health equity impacts of New York City's congestion pricing plan. *J. Epidemiol. Community Health* **2024**, *78*, 273–276. [CrossRef] [PubMed]
207. Chamberlain, R.C.; Fecht, D.; Davies, B.; Laverty, A.A. Health effects of low emission and congestion charging zones: A systematic review. *Lancet Public Health* **2023**, *8*, e559–e574. [CrossRef]
208. Arshad, K.; Hussain, N.; Ashraf, M.H.; Saleem, M.Z. Air pollution and climate change as grand challenges to sustainability. *Sci. Total Environ.* **2024**, *928*, 172370.
209. Abe, J.O.; Popoola, A.P.I.; Ajenifuja, E.; Popoola, O.M. Hydrogen energy, economy and storage: Review and recommendation. *Int. J. Hydrogen Energy* **2019**, *44*, 15072–15086. [CrossRef]
210. Pleshivtseva, Y.; Derevyanov, M.; Pimenov, A.; Rapoport, A. Comprehensive review of low carbon hydrogen projects towards the decarbonization pathway. *Int. J. Hydrogen Energy* **2023**, *48*, 3703–3724. [CrossRef]
211. Franzmann, D.; Heinrichs, H.; Lippkau, F.; Addanki, T.; Winkler, C.; Buchenberg, P.; Hamacher, T.; Blesl, M.; Linβen, J.; Stolten, D. Green hydrogen cost-potentials for global trade. *Int. J. Hydrogen Energy* **2023**, *48*, 33062–33076. [CrossRef]
212. Grand View Research. *Global Hydrogen Generation Market Size Report, 2030*; Grand View Research: San Francisco, CA, USA, 2022. Available online: https://www.grandviewresearch.com/industry-analysis/hydrogengeneration-market (accessed on 8 November 2023).
213. International Energy Agency. *Global Hydrogen Review 2021*; IEA Publications: Paris, France, 2021; pp. 103–140.
214. Qusay, H.; Sameer, A.; Aws, S.; Marek, J.; Hayder, S.; Haitham, M.; Emad, A. Saudi Arabia energy transition: Assessing the future of green hydrogen in climate change mitigation. *Int. J. Hydrogen Energy* **2024**, *55*, 124–140. [CrossRef]
215. Manaf, Z.; El Manaa, B.; Paul, O.; Ikram, B.; Wesam, B.; Ibrahim, M. Analytical model for a techno-economic assessment of green hydrogen production in photovoltaic power station case study Salalah city-Oman. *Int. J. Hydrogen Energy* **2022**, *47*, 14171–14179. [CrossRef]
216. Yang, L.; Wang, S.; Zhang, Z.; Lin, K.; Zheng, M. Current Development Status, Policy Support and Promotion Path of China's Green Hydrogen Industries under the Target of Carbon Emission Peaking and Carbon Neutrality. *Sustainability* **2023**, *15*, 10118. [CrossRef]
217. Shi, J.; Xia, R.; Zheng, X.; Yao, R.; Zheng, J. A Review on Hydrogen Production from Ocean Renewable Energy and the Application Status. In Proceedings of the ASME 2023 Pressure Vessels & Piping Conference, Atlanta, GA, USA, 17 July 2023. [CrossRef]
218. Sidhartha, H.; Sanjay, K.; Prashant, R. A systematic and critical review of green hydrogen economy in India. *Int. J. Hydrogen Energy* **2023**, *48*, 31425–31442. [CrossRef]
219. Willian, N.; Eduarda, S.; Vitor, L. Green hydrogen-based pathways and alternatives: Towards the renewable energy transition in South America's regions–Part B. *Int. J. Hydrogen Energy* **2022**, *7*, 1–15. [CrossRef]
220. Taís, G.; Fernando, S.; José, R.; Julio, S. Unlocking Brazil's green hydrogen potential: Overcoming barriers and formulating strategies to this promising sector. *Int. J. Hydrogen Energy* **2024**, *49*, 553–570. [CrossRef]

221. de Castro, F.A.; de Oliveira, M.L.M.; de Lima, L.C.; Serra, D.S. Green Hydrogen: Perspectives and Challenges in Using the Natural Gas Network in Ceará/Brazil. *J. Geosci. Environ. Prot.* **2024**, *12*, 70–94. [CrossRef]
222. Costa, T.; Monteiro, A.; Vicente, J.; Vasconcelos, A.; Malveira, M. Survey of Technical-Economic Perspectives and Challenges for the Green Hydrogen Market in Brazil. In Proceedings of the 2023 15th IEEE International Conference on Industry Applications (INDUSCON), São Bernardo do Campo, Brazil, 22–24 November 2023. [CrossRef]
223. Gischler, C.; Daza, E.; Galeano, P.; Ramirez, M.; Gonzalez, J.; Cubillos, F.; Hartmann, N.; Pradelli, V.; Márquez, J.; Gutiérrez, J.; et al. *Unlocking Green and Just Hydrogen in Latin America and the Caribbean*; IDB: Washington, DC, USA, 2023; pp. 8–30. [CrossRef]
224. Gökçek, M. Hydrogen generation from small-scale wind-powered electrolysis system in different power matching modes. *Int. J. Hydrogen Energy* **2010**, *35*, 10050–10059. [CrossRef]
225. Greiner, C.J.; Korpås, M.A.; Holen, A.T. Norwegian case study on the production of hydrogen from wind power. *Int. J. Hydrogen Energy* **2007**, *32*, 1500–1507. [CrossRef]
226. Jørgensen, C.; Ropenus, S. Production price of hydrogen from grid connected electrolysis in a power market with high wind penetration. *Int. J. Hydrogen Energy* **2008**, *33*, 5335–5344. [CrossRef]
227. Hassan, Q.; Abdulateef, A.M.; Hafedh, S.A.; Al-samari, A.; Abdulateef, J.; Sameen, A.Z.; Salman, H.M.; Al-Jiboory, A.K.; Wieteska, S.; Jaszczur, M. Renewable energy-to-green hydrogen: A review of main resources routes, processes and evaluation. *Int. J. Hydrogen Energy* **2023**, *48*, 17383–17408. [CrossRef]
228. Osman, A.I.; Mehta, N.; Elgarahy, A.M.; Hefny, M.; Al-Hinai, A.; Al-Muhtaseb, A.H.; Rooney, D.W. Hydrogen production, storage, utilization and environmental impacts: A review. *Environ. Chem. Lett.* **2022**, *20*, 153–188. [CrossRef]
229. Małachowska, A.; Łukasik, N.; Mioduska, J.; Gębicki, J. Hydrogen storage in geological formations—The potential of salt caverns. *Energies* **2022**, *15*, 5038. [CrossRef]
230. Miao, B.; Giordano, L.; Chan, S.H. Long-distance renewable hydrogen transmission via cables and pipelines. *Int. J. Hydrogen Energy* **2021**, *46*, 18699–18718. [CrossRef]
231. Nemmour, A.; Inayat, A.; Janajreh, I.; Ghenai, C. Green hydrogen-based E-fuels (E-methane, E-methanol, E-ammonia) to support clean energy transition: A literature review. *Int. J. Hydrogen Energy* **2023**, *48*, 29011–29033. [CrossRef]
232. Kupecki, J.; Niemczyk, A.; Jagielski, S.; Kluczowski, R.; Kosiorek, M.; Machaj, K. Boosting solid oxide electrolyzer performance by fine tuning the microstructure of electrodes–Preliminary study. *Int. J. Hydrogen Energy* **2023**, *48*, 26436–26445. [CrossRef]
233. Pei, M.; Petäjäniemi, M.; Regnell, A.; Wijk, O. Toward a Fossil Free Future with HYBRIT: Development of Iron and Steelmaking Technology in Sweden and Finland. *Metals* **2020**, *10*, 972. [CrossRef]
234. Zhou, T.; Xu, H.; Gosens, J.; Jotzo, F. *China's Hydrogen Plans: Near-Term Policy Challenges & Australia-China Links in Decarbonization. Policy Brief*; The Australian National University: Camberra, Australia, 2022.
235. Pareek, A.; Dom, R.; Gupta, J.; Chandran, J.; Adepu, V.; Borse, P.H. Insights into renewable hydrogen energy: Recent advances and prospects. *Mater. Sci. Energy Technol.* **2020**, *3*, 319–327. [CrossRef]
236. AlHumaidan, F.S.; Halabi, M.A.; Rana, M.S.; Vinoba, M. Blue hydrogen: Current status and future technologies. *Energy Convers. Manag.* **2023**, *283*, 116840. [CrossRef]
237. Paulot, F.; Paynter, D.; Naik, V.; Malyshev, S.; Menzel, R.; Horowitz, L.W. Global modeling of hydrogen using GFDL-AM4.1: Sensitivity of soil removal and radiative forcing. *Int. J. Hydrogen Energy* **2021**, *46*, 13446–13460. [CrossRef]
238. Warwick, N.; Griffiths, P.; Keeble, J.; Archibald, A.; Pyle, J. *Atmospheric Implications of Increased Hydrogen Use*; Crown: London, UK, 2022.
239. Arrigoni, A.; Diaz, B.L. *Hydrogen Emissions from a Hydrogen Economy and Their Potential Global Warming Impact*; Technical Report; Publication Office of the European Union: Luxembourg, 2022. [CrossRef]
240. Forster, P.; Storelvmo, T.; Armour, K.; Collins, W.; Dufresne, J.; Frame, D.; Lunt, D.J.; Mauritsen, T.; Palmer, M.D.; Watanabe, M.; et al. The Earth's energy budget, climate feedbacks, and climate sensitivity. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2023; pp. 673–1054. [CrossRef]
241. Jayachandran, M.; Gatla, R.K.; Flah, A.; Milyani, A.H.; Milyani, H.M.; Blazek, V.; Prokop, L.; Kraiem, H. Challenges and opportunities in green hydrogen adoption for decarbonizing hard-to-abate industries: A comprehensive review. *IEEE Access* **2024**, *12*, 23363–23388. [CrossRef]
242. Islam, M.H.; Burheim, O.S.; Pollet, B.G. Sonochemical and sonoelectro-chemical production of hydrogen. *Ultrason. Sonochem.* **2019**, *51*, 533–555. [CrossRef]