Research Article

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Hydrogen energy horizon: balancing opportunities and challenges

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Abstract: The future of energy is of global concern, with hydrogen emerging as a potential solution for sustainable energy development. This paper provides a comprehensive analysis of the current hydrogen energy landscape, its potential role in a decarbonized future, and the hurdles that need to be overcome for its wider implementation. The first elucidates the opportunities hydrogen energy presents, including its potential for decarbonizing various sectors, in addition addresses the challenges that stand in the way of hydrogen energy large-scale adoption. The obtained results provide a comprehensive overview of the hydrogen energy horizon, emphasizing the need to balance opportunities and challenges for its successful integration into the global energy landscape. It highlights the importance of continued research, development, and collaboration across sectors to realize the full potential of hydrogen as a sustainable and low-carbon energy carrier.

Keywords: challenges; hydrogen energy; integration; opportunities; sustainability

1 Introduction

1.1 Global energy overview

Global energy consumption has been on a steady rise over the past few decades, driven by population growth, economic development, and the increasing demand for modern amenities and technologies (Ghaffour et al. 2015). As societies strive for higher standards of living and greater industrialization, the world's appetite for energy continues to grow. This trend poses significant challenges in terms of energy availability, environmental impact, and sustainability (Sorrell 2015). The growth of global energy consumption is closely linked to population growth and urbanization. As the world's population continues to expand, particularly in developing countries, the demand for energy to meet basic needs such as lighting, heating, and cooking is increasing. Moreover, rapid urbanization is driving the demand for energy-intensive infrastructure, transportation systems, and manufacturing industries (Avtar et al. 2019). These factors contribute to a surge in energy consumption across sectors, including residential, commercial, transportation, and industrial. According to the Energy Information Administration (EIA) report 2022, the global energy consumption and global electricity consumption in has been in the last years as presented in Figure 1 (Energy Information Administration 2022). From 2010 to 2022, global energy consumption witnessed a significant increase due to various factors such as population growth, economic development, and the expanding use of energy-intensive technologies (Hassan et al. 2023f).

From 2010 to 2022, global energy consumption witnessed a significant increase due to various factors such as population growth, economic development, and the expanding use of energy-intensive technologies (Hassan et al. 2023g). Figure 2 shows the countries, who have high energy consumption for the year of 2021 (World Energy Production and Consumption 2023). The following a 4.5 % drop in 2020, global energy consumption increased by 5 % in 2021 (see Figure 1) (Hassan et al. 2023g). This increase is three percentage points over the 2000–2019 average of 2 % each year. The value of global energy consumption in 2021 exceeds that of 2019 levels (World Energy Production and Consumption 2023). Energy consumption in China (+5.2 %), India (+4.7 %), the United States (+4.7 %), Russia (+9 %), and the European Union (+4.5 %) all increased from 2020 levels (World Energy Production and Consumption 2023). Also, energy use went up in most places: +9 % in the Commonwealth of Independent States (CIS), +5 % in Latin America, and +7 % in Africa. The Middle East (–0.4 %) and the Pacific (–2.5 %) were the only places where energy use went down (World Energy Production and Consumption 2023).

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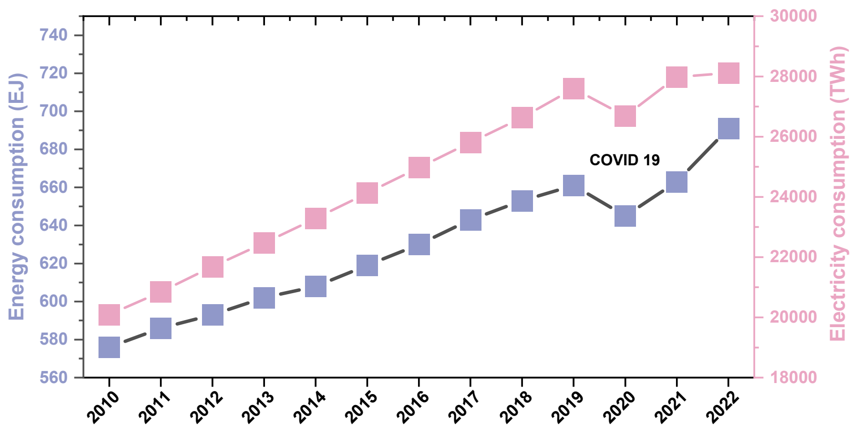

Figure 1: The global energy consumption for the years of (2010–2022) (Energy Information Administration 2022).

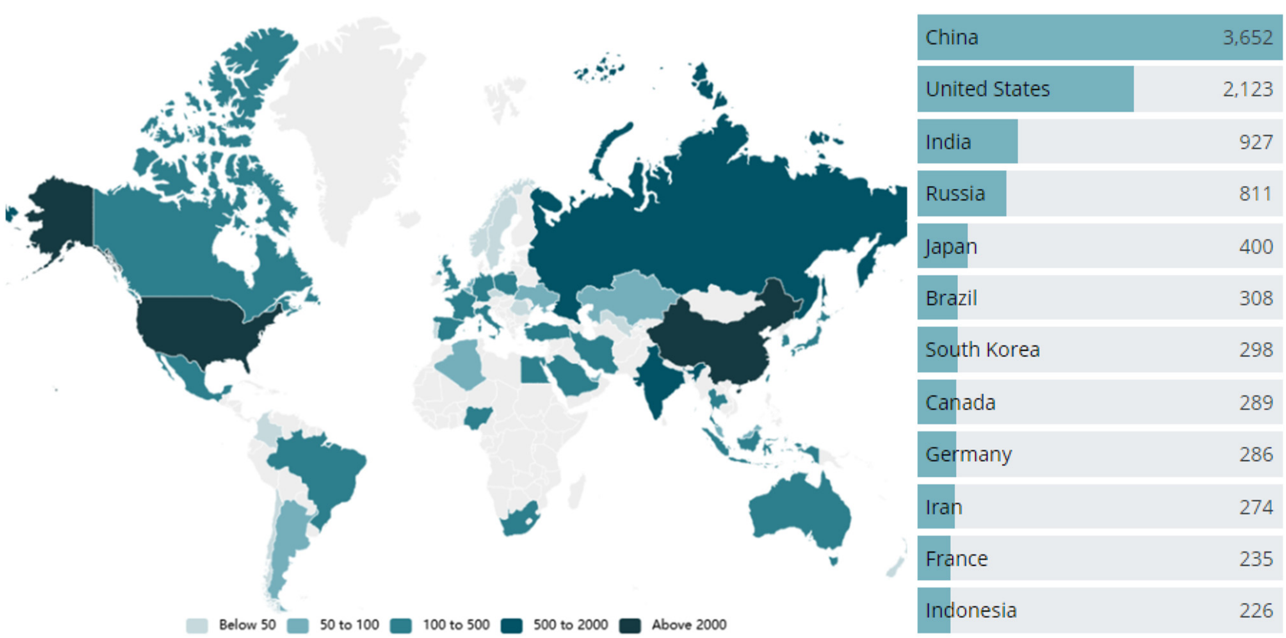

Figure 2: Energy consumption distribution in (Mtoe) for the year of 2021 (World Energy Production and Consumption 2023).

Fossil fuels, including coal, oil, and natural gas, have been the primary sources of energy for global consumption. These non-renewable resources have provided a reliable and relatively inexpensive energy supply (World Energy Production and Consumption 2023). However, their extensive use has led to significant environmental concerns, including greenhouse gas emissions, air pollution, and climate change. The reliance on fossil fuels also raises concerns regarding their finite availability, as well as geopolitical and economic implications associated with their extraction and distribution. The consequences of increasing global energy consumption are multifaceted. One of the most pressing concerns is the impact on the environment. The burning of fossil fuels for energy generation releases carbon dioxide (CO_2) and other greenhouse gases into the atmosphere, contributing to climate change (World Energy Production and Consumption 2023). The resulting effects, such as rising temperatures, extreme weather events, and sea-level rise, pose significant risks to ecosystems, human health, and socio-economic stability. Furthermore, the unsustainable extraction and consumption of fossil fuels have negative implications for energy security. Many countries heavily depend on imported energy resources, making them vulnerable to price fluctuations and geopolitical tensions (World Energy Production and Consumption 2023). The transition to more diverse and renewable energy sources can help reduce dependence on fossil fuels, enhance energy security, and promote a more resilient energy system.

Figure 3 shows the global energy production for the period from 1990 to 2021 (World Energy Production and Consumption 2023). The global energy production fell by

- Crude oil: +0.9%
- Gas: +4%
- Coal: +5.7%
- Electricity: +5.5%

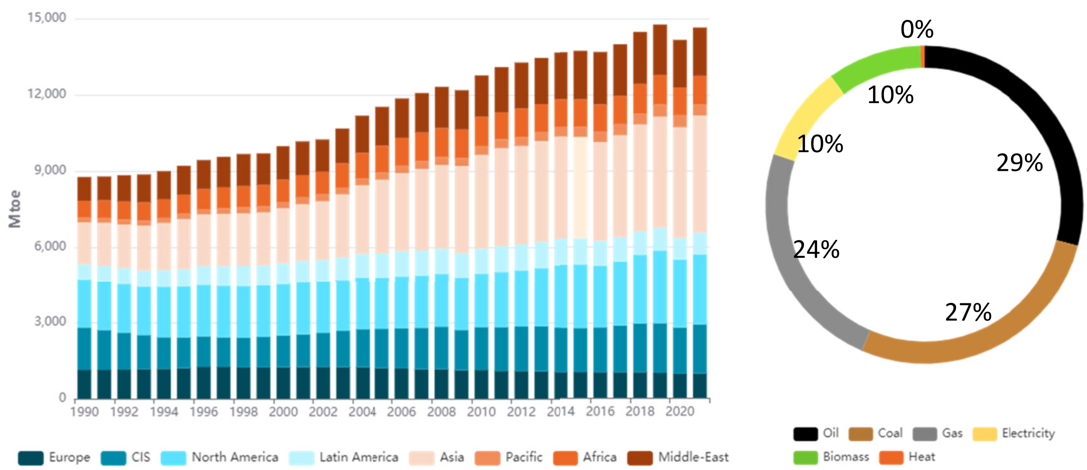

Figure 3: The global energy production (Mtoe) for the period from 1990 to 2021 (World Energy Production and Consumption 2023).

4.1 % in 2020 as a result of the COVID-19 pandemic, but recovered by 3.4 % in 2021.

The following are significant energy production for 2021 (World Energy Production and Consumption 2023):

- Crude oil: +0.9 %.
- Gas: +4 %.
- Coal: +5.7 %.
- Electricity: +5.5 %.

Industrialization and economic development are major drivers of energy consumption. As countries strive to improve their living standards and boost economic growth, there is a growing need for energy to power factories, manufacturing processes, and industrial operations. Energy-intensive industries such as steel, cement, and chemicals are particularly significant contributors to global energy consumption. Additionally, the increasing use of electronic devices, appliances, and transportation systems further amplifies energy demand (Hassan et al. 2023e).

Fossil fuels, including coal, oil, and natural gas, have been the primary sources of energy for global consumption. These non-renewable resources have provided a reliable and relatively inexpensive energy supply. However, their extensive use has led to significant environmental concerns, including greenhouse gas emissions, air pollution, and climate change (Rennings et al. 2012). The reliance on fossil fuels also raises concerns regarding their finite availability, as well as geopolitical and economic implications associated with their extraction and distribution. The consequences of increasing global energy consumption are multifaceted. One of the most pressing concerns is the impact on the environment. The burning of fossil fuels for energy generation releases CO_2 and other greenhouse gases into the atmosphere, contributing to climate change (Hassan 2022). The resulting effects, such as rising temperatures, extreme weather events, and sea-level rise, pose significant risks to ecosystems, human health, and socio-economic stability. Furthermore, the unsustainable extraction and consumption of fossil fuels have negative implications for energy security. Many countries heavily depend on imported energy resources, making them vulnerable to price fluctuations and geopolitical tensions. The transition to more diverse and renewable energy sources can help reduce dependence on fossil fuels, enhance energy security, and promote a more resilient energy system (Hassan et al. 2022b).

The increasing energy consumption also raises concerns about resource depletion. As demand continues to surge, there is a need to explore and develop alternative energy sources to meet future requirements. Renewable energy technologies, such as solar, wind, hydroelectric, and geothermal, offer promising solutions by providing clean, abundant, and sustainable energy options. However, their widespread adoption requires significant investments in research, development, and infrastructure. The global energy consumption is on an upward trajectory, driven by population growth, urbanization, and economic development (Winter 2005). While energy consumption is essential for socio-economic progress, it also presents challenges in terms of environmental impact, resource depletion, and energy security. The transition to cleaner and more sustainable energy sources is crucial for mitigating climate change, ensuring energy availability, and achieving long-term sustainability (Hassan et al. 2023i).

1.2 Trend to hydrogen energy

In recent years, there has been a notable trend towards hydrogen energy as a promising alternative to conventional energy sources. This trend is driven by several factors that highlight the potential of hydrogen as a clean, versatile, and sustainable energy carrier. The following are key trends in the adoption and development of hydrogen energy:

- **Decarbonization initiatives:** governments, industries, and international organizations worldwide are increasingly focused on decarbonizing their energy systems to mitigate climate change. Hydrogen has gained attention as a key solution due to its ability to produce energy without emitting greenhouse gases (Nasiritousi and Grimm 2022). The trend towards hydrogen energy aligns with global efforts to reduce carbon footprints and transition towards a low-carbon future.
- **Diverse applications:** hydrogen offers diverse applications across various sectors, including transportation, industry, power generation, and energy storage. The trend is to explore and expand the use of hydrogen in these sectors as a means to achieve clean and sustainable energy solutions (Alzahrani et al. 2022). Fuel cell vehicles, hydrogen-powered trains, hydrogen as a feedstock for industrial processes, and its role in grid balancing and energy storage are examples of the growing application trends for hydrogen energy (Hassan et al. 2023h).
- **Technological advancements:** significant technological advancements in hydrogen production, storage, and utilization have contributed to the growing trend towards hydrogen energy. Improved electrolysis methods, such as proton exchange membrane (PEM) and solid oxide electrolysis cells (SOEC), have made hydrogen production more efficient and cost-effective (Ahmed et al. 2022). Advancements in hydrogen fuel cell technologies have enhanced their performance and durability, making them increasingly viable for various applications.
- **Renewable hydrogen:** the trend towards renewable hydrogen has gained significant momentum. Renewable energy sources, such as wind and solar, are increasingly being integrated into hydrogen production processes, making it a carbon-neutral energy carrier (Maestre, Ortiz, and Ortiz 2021). Electrolysis powered by renewable electricity ensures that hydrogen is produced without relying on fossil fuels, further enhancing its sustainability and aligning with the trend towards renewable energy integration (Hassan et al. 2023b).
- **International collaboration:** the trend towards hydrogen energy is accompanied by increasing international collaboration and partnerships (Kovač, Paranos, and Marciuš 2021). Countries are forming alliances and establishing joint research and development initiatives to accelerate the development and deployment of hydrogen technologies. This collaboration aims to share knowledge, resources, and best practices, fostering a global approach to harnessing the potential of hydrogen energy (Milani, Kiani, and McNaughton 2020).
- **Supportive policy frameworks:** governments around the world are implementing supportive policy frameworks to incentivize the adoption of hydrogen energy (Pingkuo and Xue 2022). These policies include financial incentives, tax credits, regulatory frameworks, and research and development funding. The trend is towards creating an enabling environment that encourages investment and facilitates the growth of the hydrogen industry (Kazi et al. 2021).
- **Industry commitment:** various industries, including energy, transportation, and manufacturing, are recognizing the potential of hydrogen energy and are making commitments to integrate it into their operations (Hassan et al. 2023a). Companies are investing in hydrogen infrastructure, developing hydrogen-powered technologies, and implementing pilot projects to demonstrate the feasibility and benefits of hydrogen energy (Weger, Leitao, and Lawrence 2021).

There is a clear and growing trend towards hydrogen energy as a sustainable and clean energy solution (Hassan et al. 2023j). The increased focus on decarbonization, diverse applications, technological advancements, renewable hydrogen, international collaboration, supportive policies, and industry commitment all contribute to the momentum behind the adoption and development of hydrogen energy (Pal, Singh, and Bhatnagar 2022). As this trend continues, hydrogen has the potential to play a significant role in achieving a more sustainable and low-carbon energy future.

1.3 Study objectives

The study aims to achieve the following objectives:

- **Provide a comprehensive overview:** the study is to provide a comprehensive overview of the hydrogen energy horizon, including its opportunities and challenges. It seeks to examine the various aspects of hydrogen energy,

such as production methods, infrastructure requirements, safety considerations, integration into existing energy systems, and potential applications in different sectors.
- **Analyze the balancing of opportunities and challenges:** the study analyzed and evaluated the balancing act between the opportunities and challenges associated with hydrogen energy. It is explored the advantages and potential benefits of hydrogen energy, such as its versatility, energy density, and zero-emission nature. Simultaneously, addressed the challenges that need to be overcome, including infrastructure development, safety concerns, cost-effectiveness, and integration complexities.
- **Identify implications and pathways for success:** the study identified the implications of hydrogen energy adoption and propose pathways for success. Which examined the environmental and sustainability aspects, considering the life cycle emissions and the need for renewable energy sources in hydrogen production. Additionally, explored the economic, regulatory, and public acceptance factors required to unlock the full potential of hydrogen energy and facilitate its successful integration into the global energy landscape.

The study provides a comprehensive understanding of the hydrogen energy horizon, analyze the balancing of opportunities and challenges, and identify the implications and pathways for success in harnessing hydrogen energy as a sustainable and low-carbon energy solution.

2 The hydrogen energy landscape

Hydrogen holds great promise as a clean energy carrier, significant challenges remain in terms of improving efficiency, reducing costs, developing infrastructure, and implementing supportive policies and regulations (Figure 4).

2.1 Current state of hydrogen energy in the global energy mix

Hydrogen was still a relatively small part of the global energy mix. The majority of hydrogen production was for industrial purposes, such as refining, ammonia production for fertilizers, and methanol production. However, hydrogen was gaining attention as a potential clean energy carrier that could play a significant role in the transition to a sustainable energy system. The main aspects of the current state of hydrogen energy in the global energy mix:
- **Production**: the bulk of hydrogen production is currently generated from fossil fuels, mainly natural gas, through a process known as steam methane reforming (SMR). This type of hydrogen, often called “grey” or “brown” hydrogen, does produce significant CO_2 emissions. However, there growing interest and investment in producing “green” hydrogen, which is made by splitting water into hydrogen and oxygen using renewable electricity via electrolysis (Burton et al. 2021).
- **Usage**: Currently, hydrogen is primarily used in industrial applications, such as refining, treating metals, and in the production of ammonia and methanol. However, its use in energy applications is growing. For instance, hydrogen is increasingly being used in fuel cells to power vehicles and generate electricity, and it is being explored as a means of storing excess electricity from renewable sources (Fan, Tu, and Chan 2021; Griffiths et al. 2021). Hydrogen is also being considered as a potential fuel for heating homes and businesses in some countries.
- **Percentage in energy mix**: the IEA reports that hydrogen currently accounts for less than 2 % of the world energy consumption. However, the IEA also projects that this could rise to nearly 20 % by 2050 if aggressive steps are taken to promote the hydrogen economy (Energy Information Administration 2022).

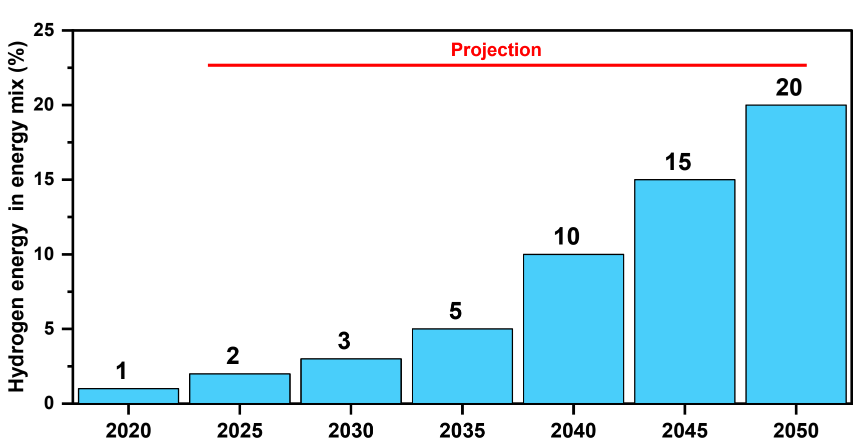

Figure 4: Hydrogen energy in total energy mix (projection to 2050) (Watanabe et al. 2022).

- **Investment and growth**: there are growing investment in hydrogen technology and infrastructure from both private and public sources. Major economies such as the EU, Japan, South Korea, and Australia have unveiled ambitious hydrogen strategies, and global corporations are increasingly investing in hydrogen projects (Espegren et al. 2021; Li et al. 2023).
- **Challenges**: Despite the growing interest and investment, significant challenges remain. These include improving the efficiency and reducing the cost of hydrogen production (especially green hydrogen), creating the infrastructure needed to store and distribute hydrogen, and finding ways to use hydrogen in different sectors of the economy (Hassan et al. 2022c; Yue et al. 2021).

While hydrogen currently plays a relatively small role in the global energy mix, its importance is expected to grow in the coming decades as the world seeks to transition to a more sustainable and low-carbon energy system. The potential of hydrogen to store and deliver energy, its diverse applications, and its compatibility with existing natural gas infrastructure make it a promising tool in the drive towards decarbonization.

2.2 Key players and stakeholders in hydrogen energy

Hydrogen energy, as an integral part of the future clean energy mix, involves various key players and stakeholders, each playing a vital role in shaping the hydrogen economy, as showed in Figure 5 and summarized in this section.

- **Energy producers**: these are the companies and organizations responsible for producing hydrogen. They might use a variety of methods such as steam methane reforming, electrolysis of water, or even biological methods (Hassan et al. 2023d). Some notable companies in this sector include Air Products & Chemicals, Linde, and Ballard Power Systems.
- **Energy consumers**: the industries that utilize hydrogen energy form a significant part of the stakeholder ecosystem. These include sectors like transportation (automobile manufacturers like Toyota and Hyundai with their fuel cell vehicles), power generation, and industrial processes (especially in sectors such as steel and chemicals) (Abbas et al. 2023).
- **Government bodies and regulatory authorities**: governments around the world have a crucial role to play in terms of policy-making, providing subsidies and incentives for hydrogen energy production and consumption, setting safety and emission standards. For instance, the Department of Energy in the US, the European Commission in the EU, and Ministry of Economy, Trade and Industry in Japan (Hassan et al. 2023c; Zhang, Chen, and Ling 2022).
- **Research institutions**: these are the academic institutions, non-profit research organizations, and corporate R&D departments that are involved in conducting research on improving hydrogen production efficiency, storage, and utilization methods. Examples include the National Renewable Energy Laboratory (NREL) in the US, the Fraunhofer Institute in Germany, and many leading universities globally (Dincer and Aydin 2023; Kim et al. 2023).
- **Infrastructure providers**: companies involved in the creation of infrastructure for hydrogen energy, such as fueling stations, pipelines, and storage facilities, are also key players (Liu and Ma 2020; Yoon, Seo, and Lee 2022). These include companies like Air Liquide and Plug Power.
- **Investors and financial institutions**: as with any industry, investors and financial institutions are crucial for providing the capital needed for growth and innovation. This can include venture capital firms investing in hydrogen startups, banks providing loans to build infrastructure, and government-led funds (Miao, Giordano, and Chan 2021).
- **Non-Governmental Organizations (NGOs)**: NGOs, both local and international, play a role in advocating for hydrogen energy, educating the public and policymakers about its benefits and potential, and conducting or supporting research and development in the field (Vergragt 2017).
- **Technology providers**: these stakeholders provide the necessary technology for producing, storing, and using hydrogen. This includes fuel cell manufacturers like Ballard Power Systems, electrolyzer manufacturers like Nel ASA, and storage system developers (Haghi, Raahemifar, and Fowler 2018).
- **Supply Chain stakeholders**: these stakeholders are involved in the delivery of hydrogen from production sites to points of use. This includes logistics companies, pipeline operators, and companies that build and operate hydrogen refueling stations (Emodi et al. 2021).
- **International agencies**: international energy agencies and organizations like the International Energy Agency (IEA), Hydrogen Council, and the International Renewable Energy Agency (IRENA) also play a critical role in promoting cooperation, setting standards, and sharing research and best practices related to hydrogen energy (Hydrogen Consul Report 2022; International Renewable Energy Agency Report 2022; Quarton et al. 2020).

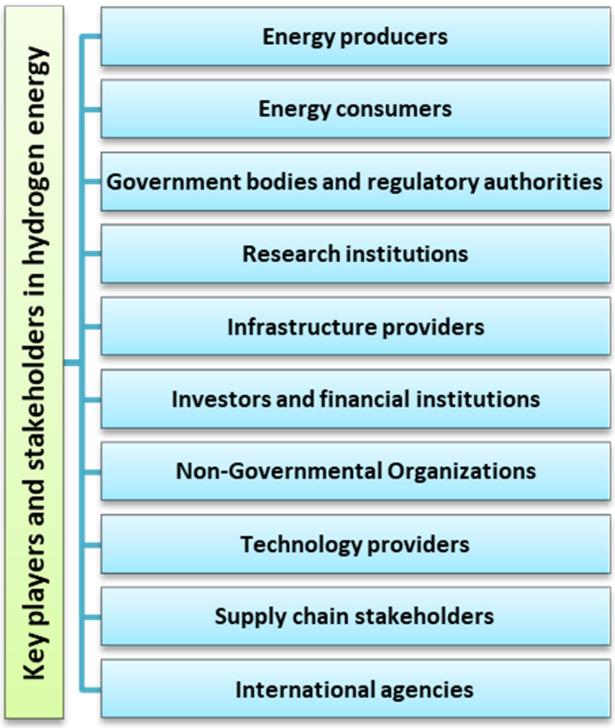

Figure 5: Main players and stakeholders in hydrogen energy.

The interaction of these various stakeholders helps to shape the direction of the hydrogen industry, determine which technologies are adopted and at what pace, and set the regulatory and policy frameworks that guide the industry's development.

3 Hydrogen production

Various energy sources and technologies can be utilized to produce hydrogen. Currently, fossil fuels dominate the worldwide production of hydrogen. Electrolyte solution hydrogen, or hydrogen formed from electricity and water, plays a very limited function. With the cost of renewable energy (especially solar PV and wind) going down, there is a lot of interest in the electrolysis of water to make hydrogen and the possibility of turning hydrogen into fuels based on hydrogen or renewable sources, like synthesized petroleum and nitrogen, that work better with current facilities than hydrogen (Gielen et al. 2019). Hydrogen produced from fossil fuels and biomass, water, or a combination of both described in this section a showed in Figure 6.

3.1 Natural gas and oil

The most common method for hydrogen production today is natural gas reforming sometimes referred to as steam methane reforming (SMR) (Sadeghi, Ghandehariun, and Rosen 2020). In this process, methane from natural gas is heated with steam and a catalyst, which causes a reaction that produces hydrogen and carbon monoxide. Further reaction with steam converts the carbon monoxide to CO_2 and more hydrogen. While this method is currently the most cost-effective, it produces significant amounts of greenhouse gases. Partial oxidation, another method, involves the reaction of natural gas with a controlled amount of oxygen, which results in hydrogen and carbon monoxide. In SMR, methane (CH_4) from natural gas is reacted with steam under high temperatures (700–1100 °C) and pressures in the presence of a metal catalyst to produce hydrogen, carbon monoxide, and a smaller amount of CO_2 (Andrews 2020). The reaction can be represented as follows:

$$CH_4(g) + H_2O(g) \rightleftharpoons CO(g) + 3H_2(g)$$

A subsequent water-gas shift reaction further maximizes the production of hydrogen by reacting the carbon monoxide with steam to produce CO_2 and more hydrogen:

$$CO(g) + H_2O(g) \rightleftharpoons CO_2(g) + H_2(g)$$

3.2 Coal

Hydrogen can also be produced from coal through a process called coal gasification. In this process, coal is reacted with oxygen and steam under high pressures and temperatures to form synthesis gas (a mixture of hydrogen and carbon monoxide) (Midilli et al. 2021). The carbon monoxide is then reacted with steam in a process called the water-gas shift reaction to produce additional hydrogen and CO_2. However, this method also emits significant amounts of CO_2. Research is ongoing to develop methods of carbon capture and storage to

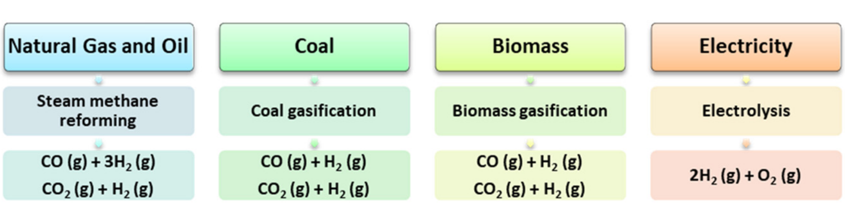

Figure 6: Hydrogen produced from fossil fuels, biomass, and water.

mitigate these emissions (Seyitoglu, Dincer, and Kilicarslan 2017). The reactions can be represented as follows:

$$C(s) + O_2(g) \rightarrow CO_2(g)$$

$$C(s) + H_2O(g) \rightarrow CO(g) + H_2(g)$$

Similar to natural gas reforming, the carbon monoxide in the syngas can undergo a water-gas shift reaction to produce more hydrogen and CO_2:

$$CO(g) + H_2O(g) \rightleftharpoons CO_2(g) + H_2(g)$$

3.3 Biomass

Hydrogen can be produced from biomass using similar processes to those used for coal gasification. Biomass (such as wood chips, agricultural residues, or dedicated energy crops) is heated with a controlled amount of oxygen and/or steam to produce synthesis gas, which can then be processed further to produce hydrogen (Wang and Yin 2018). The advantage of biomass gasification over coal gasification is that biomass is a renewable resource and can potentially be a carbon-neutral source of hydrogen if the CO_2 produced is captured and stored or utilized. The process involves heating the biomass under high temperature and pressure with steam and a limited supply of oxygen (Hassan et al. 2022a). This results in the formation of syngas (a mixture of hydrogen and carbon monoxide), which then undergoes the water-gas shift reaction to produce more hydrogen:

$$\text{Biomass} + H_2O(g) + \text{heat} \rightarrow CO(g) + H_2(g)$$

$$CO(g) + H_2O(g) \rightleftharpoons CO_2(g) + H_2(g)$$

3.4 Electricity (electrolysis)

Hydrogen can be produced from water through a process known as electrolysis. In this process, an electric current is passed through water, causing it to split into hydrogen and oxygen. If the electricity used is generated from renewable sources, such as wind or solar power, this process can produce hydrogen with zero greenhouse gas emissions (Kumar and Himabindu 2019). This is often referred to as "green" hydrogen. There are several types of electrolysis methods including alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis, each with its advantages and challenges (Hassan et al. 2022d). This can be performed in a device called an electrolyzer, and the process can be represented as follows:

$$\text{Anode (oxidation)}: 2H_2O(l) \rightarrow O_2(g) + 4H + (aq) + 4e-$$

$$\text{Cathode (reduction)}: 4H + (aq) + 4e - \rightarrow 2H_2(g)$$

$$\text{Overall reaction}: 2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$$

When the electricity used is sourced from renewable energy, this method produces "green hydrogen," as it results in zero carbon emissions.

Each of these methods has its pros and cons in terms of cost, scalability, and environmental impact. As of now, the majority of hydrogen is produced from natural gas due to its economic advantages. However, as the world seeks to transition to a low-carbon energy system, there is growing interest in producing hydrogen from renewable electricity and biomass, despite the current cost and technical challenges.

Reformed natural gas, biomass gasification, and water electrolysis are established processes for hydrogen generation that are used on an industrial level across the globe. Reforming natural gas with steam is the most prevalent technique in the petrochemical and chemical sectors; it is the simplest production technique and emits the least CO_2 of all fossil industrial applications (Arshad et al. 2019). Although biomass has limited potential and interacts with other biofuels as well as power and heat production, it is anticipated that biomass gasification for the production of hydrogen will become the cheapest hydrogen energy supply source during the next several decades (Hassan 2021).

Table 1 show a comparison of the hydrogen production methods, which this comparison can be modified due to the rapidly evolving nature of the production technologies and because exact costs and efficiencies can vary widely depending on many factors like geographic location, specific technology used, scale of operation, etc.

Table 1: Comparison of the hydrogen production methods (natural gas and oil, coal, biomass, and electricity).

Method	Estimated production cost ($/kg H_2)	Current global production (%)	Quality	Future trend (increase/ decrease/ stable)
Natural gas and oil	1.0–2.5	75 %	High	Increase
Coal	2.0–4.0	20 %	High	Decrease
Biomass	3.0–6.0	<1 %	Variable	Increase
Electricity (green hydrogen)	4.0–7.5	<5 %	High	Strong increase

4 Current and future of hydrogen applications

Hydrogen is gaining significant attention as a versatile and clean energy carrier that has the potential to play a crucial role in the transition towards a sustainable and low-carbon future. Its unique properties, such as high energy density, zero greenhouse gas emissions during use, and compatibility with various applications, make it an attractive option for diverse sectors. This section explores the current and future applications of hydrogen in energy and heat generation, transport, and industry, along with examples of companies that have already started investing in hydrogen technologies and future projections.

4.1 Energy and heat generation

Hydrogen has the potential to transform the energy landscape by providing a clean and renewable source of power generation. It can be utilized in various ways, including:

- **Fuel Cells:** fuel cells convert hydrogen and oxygen into electricity and heat through an electrochemical process, offering high efficiency and zero-emission electricity generation. Fuel cell technology is already being adopted in stationary power systems, backup power, and portable applications. Companies such as Ballard Power Systems, Plug Power, and Bloom Energy are leading the way in fuel cell deployment (Thomas et al. 2020).
- **Power-to-Gas:** excess renewable electricity can be used for electrolysis to produce hydrogen through power-to-gas technology. The produced hydrogen can be injected into the natural gas grid, stored, and later used for power generation or heat production (Hassan and Jaszczur 2021). This concept facilitates the integration of renewable energy sources into existing infrastructure and provides energy storage capabilities.
- **Heat generation:** hydrogen combustion can be used for heating applications in industrial processes, residential buildings, and district heating systems. Hydrogen boilers and burners are being developed as a clean alternative to natural gas-fired systems, aiming to decarbonize the heating sector (Stamenkovic et al. 2017).

Projections indicate that hydrogen-based power generation could represent a significant share of the global energy mix by 2050. Companies like Siemens Energy, ENGIE, and E.ON are investing in hydrogen projects, envisioning a future where hydrogen plays a key role in providing clean and sustainable energy (Kaur and Pal 2019).

4.2 Transport

Hydrogen has great potential as an alternative fuel for various modes of transportation, including cars, trucks, trains, ships, and even aircraft. Its advantages include zero-emission operation, fast refueling, and long-range capabilities. The transport sector can benefit from hydrogen through:

- **Fuel Cell Vehicles (FCVs):** hydrogen-powered FCVs use fuel cells to convert hydrogen into electricity, producing only water vapor as a byproduct. Companies like Toyota, Hyundai, and Honda have already commercialized FCVs, and there is growing interest in the development of a hydrogen refueling infrastructure (Hassan et al. 2022e).
- **Hydrogen Internal Combustion Engine (ICE) vehicles:** hydrogen ICE vehicles can run on hydrogen directly, similar to conventional gasoline or diesel engines. These vehicles offer a transition pathway for existing internal combustion engine technology and can utilize existing refueling infrastructure (Boretti 2020).
- **Hydrogen for aviation and maritime**: the aviation and maritime sectors are exploring hydrogen as a potential solution to decarbonize these high-emission industries. Companies like Airbus, ZeroAvia, and Viking Cruises are investing in hydrogen-based solutions, including hydrogen-powered aircraft and fuel cell-powered ships (Atilhan et al. 2021).

The future of hydrogen in transportation depends on the development of a robust refueling infrastructure, technological advancements, and policy support. Industry projections indicate that hydrogen-powered vehicles could reach significant market shares by 2050, especially in heavy-duty applications like trucks and buses.

4.3 Industry

Hydrogen plays a significant role in various industrial applications, enabling decarbonization and reducing emissions. Its versatility and clean properties make it a valuable resource for the industry. Let's explore the current and future applications of hydrogen in the industry, along with companies that have already started investing in hydrogen technologies and future projections.

4.3.1 Hydrogen as feedstock

Hydrogen serves as a crucial feedstock in industries such as refineries, ammonia production, and the production of other chemicals (Ahmed et al. 2020; Wang and Yin 2018). It is a key component in various processes, including:

- **Refineries**: hydrogen is used in refineries for processes such as hydrocracking and hydrotreating, where it helps remove impurities, upgrade fuels, and improve the quality of petroleum products. Companies like Chevron, Shell, and ExxonMobil have already invested in hydrogen infrastructure in their refineries.
- **Ammonia production:** ammonia, a vital chemical used in fertilizers, industrial processes, and the production of various chemicals, is primarily produced using hydrogen. Green hydrogen is being explored as a sustainable feedstock for ammonia production, reducing the carbon footprint of the process. Companies such as Yara and Nutrien are actively involved in ammonia production and exploring green hydrogen integration.
- **Chemical production:** hydrogen is a key ingredient for the synthesis of numerous chemicals, including methanol, ethylene, and propylene. Green hydrogen is expected to play a significant role in reducing the carbon footprint of chemical production processes. Companies like BASF, Dow, and SABIC are investing in hydrogen technologies for chemical production.

The use of hydrogen in the industry is driven by the need to decarbonize industrial processes. Projections indicate that the demand for hydrogen in industrial applications could increase. Companies across various sectors are investing in hydrogen technologies to transition to cleaner and more sustainable production processes.

4.3.2 Steel and metal production

The steel and metal production industry are one of the largest industrial emitters of CO_2. Hydrogen can play a transformative role in reducing emissions in this sector (Agüero et al. 2020; Liu et al. 2021). Key applications include:
- **Direct Reduction of Iron (DRI):** traditional iron production using blast furnaces emits significant amounts of CO_2. Hydrogen-based direct reduction processes can eliminate or reduce the need for coal and coke, reducing carbon emissions. Companies like ArcelorMittal, Thyssenkrupp, and Voestalpine are investing in hydrogen-based direct reduction technologies.
- **Steel annealing and heat treatment:** hydrogen can be used for annealing and heat treatment processes in steel manufacturing, replacing conventional fossil fuel-based methods. This helps reduce greenhouse gas emissions and improve the energy efficiency of the process.

The use of hydrogen in steel and metal production indicated that hydrogen-based steel production technologies, such as direct reduction, could become increasingly.

5 Hydrogen transmission, storage, and distribution

Hydrogen transmission, storage, and distribution are critical components of a robust hydrogen infrastructure. To realize the full potential of hydrogen as a clean and versatile energy carrier, efficient and reliable systems must be established for transporting hydrogen from production sites to end-users, storing it when not in immediate demand, and distributing it to various applications. This section explores the different aspects of hydrogen transmission, storage, and distribution in detail.

5.1 Hydrogen transmission

Hydrogen can be transported over long distances through various methods, including pipelines, trucking, and shipping. The choice of transmission method depends on factors such as distance, volume, infrastructure availability, and cost considerations. Let's explore each transmission method:
- **Pipelines**: pipelines are a well-established method for transporting gases, including hydrogen. Dedicated hydrogen pipelines or repurposing existing natural gas pipelines can be used to transport hydrogen. However, there are some challenges associated with hydrogen pipeline transmission, such as hydrogen embrittlement, leakage, and safety considerations. Pipeline materials and design must be carefully chosen to mitigate these challenges (Peschel 2020). Several hydrogen pipeline projects are underway, including the European Hydrogen Backbone initiative and the H_2H Salt Cavern Project in the United States (Hassan et al. 2019).
- **Trucking**: hydrogen can be transported by truck in compressed gas or liquid form. Compressed hydrogen gas is loaded into high-pressure tanks mounted on trucks for transportation. Liquid hydrogen, which requires cryogenic temperatures, is transported in specialized containers (Niermann et al. 2021). Trucking is suitable for shorter distances or when pipelines are not feasible. However, trucking has limitations in terms of capacity and efficiency, and it requires a well-coordinated logistics system to ensure timely and safe delivery.
- **Shipping**: hydrogen shipping involves transporting hydrogen in bulk quantities through specialized vessels. Liquid hydrogen is loaded onto cryogenic tanks onboard ships designed for hydrogen transportation. Shipping is suitable for long-distance transport, particularly for connecting regions with limited pipeline infrastructure (Kim et al. 2021). However, hydrogen shipping is still in the early stages of development, and challenges such as cryogenic

handling, safety, and cost need to be addressed for widespread adoption.

5.2 Hydrogen storage

Hydrogen storage is crucial for balancing the intermittent production and demand of hydrogen and ensuring a reliable supply. Various storage methods are available, each with its advantages and considerations. Let's explore the different hydrogen storage methods:

- **Compressed gas storage:** compressed hydrogen gas can be stored in high-pressure tanks. The gas is compressed to a specific pressure level, typically between 350 and 700 bar, depending on the application (Reddi et al. 2018). Compressed gas storage offers high energy density and is suitable for stationary applications, refueling stations, and industrial use. However, it requires strong and lightweight tanks to withstand the high pressure, and compression and decompression processes result in energy losses.
- **Liquid hydrogen storage:** hydrogen can be liquefied by cooling it to cryogenic temperatures (−253 °C) to achieve a high energy density (Yanxing et al. 2019). Liquid hydrogen storage requires specialized cryogenic containers that can maintain extremely low temperatures. Liquid hydrogen storage is suitable for applications that require large energy storage capacities, such as space applications and long-duration energy storage. However, it involves significant energy requirements for liquefaction and poses challenges related to boil-off and thermal insulation (Aasadnia and Mehrpooya 2018).
- **Chemical hydrogen storage:** chemical storage methods involve storing hydrogen in chemical compounds that can release hydrogen when needed. Examples include metal hydrides and chemical hydrides. Metal hydrides absorb hydrogen gas and release it upon heating (Andersson and Grönkvist 2019). Chemical hydrides store hydrogen in the form of a chemical compound and release it through various reactions. Chemical storage offers high storage densities and can potentially overcome the challenges of compression and liquefaction (Rivard, Trudeau, and Zaghib 2019). However, it requires additional processes for hydrogen extraction and regeneration.
- **Underground storage:** underground storage options include salt caverns, depleted natural gas reservoirs, and aquifers. Hydrogen can be injected and stored in these geological formations. Underground storage offers large-scale storage capacities and can be used to balance seasonal variations in hydrogen demand (Tarkowski and Czapowski 2018). However, site-specific geological considerations, containment integrity, and safety measures must be carefully evaluated for underground storage.

5.3 Hydrogen distribution

Hydrogen distribution involves the movement of hydrogen from production sites or storage facilities to end-users, such as refueling stations, industrial plants, and residential buildings. The development of a reliable and efficient distribution network is crucial to support the widespread adoption of hydrogen. The aspects of hydrogen distribution include:

- **Refueling stations:** hydrogen refueling stations are essential for supporting the adoption of hydrogen fuel cell vehicles (FCVs). Distribution networks need to be established to ensure sufficient coverage, allowing convenient and accessible refueling for FCV owners (Harichandan et al. 2023). This requires collaboration between governments, energy companies, and automobile manufacturers to invest in refueling infrastructure.
- **Industrial pipelines:** industrial facilities that use hydrogen as a feedstock or energy source require dedicated pipelines for hydrogen supply. These pipelines are typically built within industrial complexes or connect nearby hydrogen production facilities. Proper pipeline design, maintenance, and safety measures must be implemented to ensure reliable and safe hydrogen supply to industrial consumers (Taibi et al. 2018).
- **Residential and commercial buildings:** hydrogen can be utilized for heating and power generation in residential and commercial buildings. Distribution networks must be established to supply hydrogen to these applications, including the retrofitting of existing natural gas pipelines or the development of separate hydrogen pipelines. Hydrogen boilers, fuel cells, and combined heat and power (CHP) systems can be used to utilize hydrogen in buildings (Stern 2018).
- **Bulk distribution:** bulk distribution involves the transport of hydrogen to large industrial consumers in large quantities, such as refineries, chemical plants, and power plants. This typically involves pipeline connections or truck deliveries to meet the demand of these high-volume consumers (Taibi et al. 2018).

6 Future of hydrogen infrastructure reinforcement

The future of hydrogen as a clean and versatile energy carrier heavily depends on the development of a robust

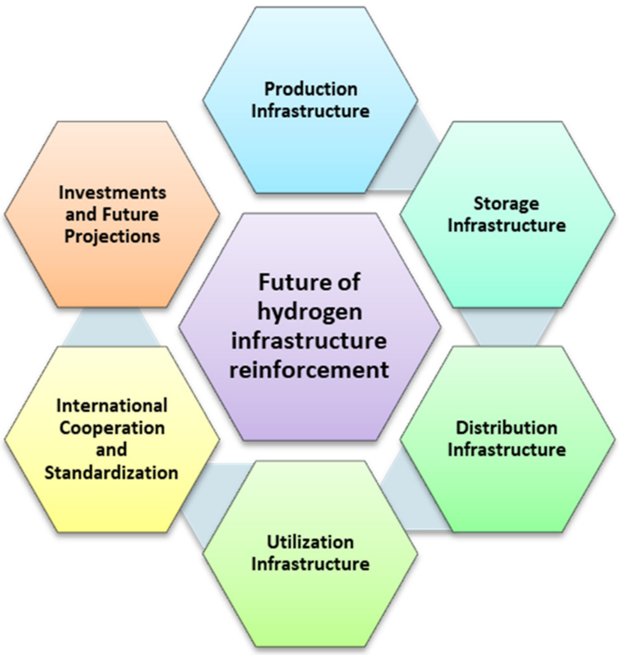

Figure 7: Future of hydrogen infrastructure reinforcement.

hydrogen infrastructure. A well-established infrastructure is essential to support the production, storage, distribution, and utilization of hydrogen across various sectors. This section explores the future of hydrogen infrastructure reinforcement, supported by future projections as presented in Figure 7.

6.1 Production infrastructure

To meet the growing demand for hydrogen, future projections emphasize the need for expanding and diversifying hydrogen production infrastructure. Key aspects include:

- **Scaling up electrolysis:** projections indicate a significant increase in the deployment of electrolyzers for hydrogen production through water electrolysis. Advanced electrolysis technologies, such as proton exchange membrane (PEM) and solid oxide electrolyzers, are expected to become more cost-effective and efficient. Future investments will focus on scaling up electrolysis capacities to support large-scale hydrogen production.
- **Renewable hydrogen production**: the future of hydrogen infrastructure is heavily tied to the expansion of renewable energy sources. Projections suggest an increase in the production of green hydrogen through electrolysis powered by renewable electricity. This requires the development of renewable energy projects, such as wind and solar farms, in close proximity to hydrogen production facilities.
- **Carbon Capture, Utilization, and Storage (CCUS):** hydrogen production from fossil fuels, such as natural gas, may still be prevalent in the future. However, these methods will need to incorporate CCUS technologies to capture and store or utilize the resulting carbon emissions. Future investments will focus on integrating CCUS technologies into hydrogen production processes to minimize greenhouse gas emissions.

6.2 Storage infrastructure

A robust hydrogen storage infrastructure is critical to ensure a reliable supply and facilitate the balance between hydrogen production and demand. Key considerations for hydrogen storage infrastructure include:

- **Large-scale storage solutions:** future projections highlight the need for large-scale hydrogen storage solutions to accommodate the intermittent nature of renewable energy sources. These may include underground storage facilities, salt caverns, or hydrogen carriers such as liquid organic hydrogen carriers (LOHCs) or ammonia. These storage options allow for the storage of excess hydrogen and its subsequent release when needed.
- **On-site storage:** on-site storage systems will be crucial for various applications, including hydrogen refueling stations, industrial facilities, and distributed power generation. Advances in hydrogen storage technologies, such as high-pressure tanks, metal hydrides, and cryogenic storage, will play a vital role in meeting future infrastructure requirements.

6.3 Distribution infrastructure

Efficient and widespread distribution networks are essential to transport hydrogen from production sites to end-users. Future projections indicate the following aspects for hydrogen distribution infrastructure:

- **Pipeline networks:** the expansion of hydrogen pipeline networks will be crucial to facilitate the long-distance transport of hydrogen. Dedicated hydrogen pipelines or repurposing existing natural gas pipelines, with necessary modifications, can help distribute hydrogen across regions.
- **Hydrogen hubs and corridors:** future hydrogen infrastructure is expected to develop regional hubs and corridors, connecting production centers with consumption areas. These hubs will feature integrated production, storage, and distribution facilities to

optimize the hydrogen supply chain and enable efficient transportation.
- **Hydrogen refueling stations:** the growth of hydrogen fuel cell vehicles requires the establishment of an extensive network of hydrogen refueling stations. Future investments will focus on expanding the number of refueling stations, ensuring sufficient coverage for long-distance travel and supporting the adoption of hydrogen-powered vehicles.

6.4 Utilization infrastructure

To fully realize the potential of hydrogen, future infrastructure development must support its utilization in various sectors. Key aspects of hydrogen utilization infrastructure include:
- **Industrial integration:** hydrogen infrastructure should enable the integration of hydrogen into existing industrial processes and facilities. This includes retrofitting existing plants, such as refineries and chemical production facilities, to utilize hydrogen as a feedstock or energy source.
- **Building and residential applications:** infrastructure development should support the use of hydrogen for heating and power generation in buildings and residential areas. Hydrogen boilers, fuel cells, and combined heat and power (CHP) systems can play a significant role in decarbonizing the heating sector.
- **Hydrogen in transportation:** the expansion of hydrogen infrastructure must support the adoption of hydrogen fuel cell vehicles (FCVs) and other hydrogen-powered transportation modes. This includes the establishment of a network of hydrogen refueling stations, hydrogen production and storage facilities for fleet applications, and the integration of hydrogen into public transportation systems.

6.5 International cooperation and standardization

To ensure the seamless integration and interoperability of hydrogen infrastructure on a global scale, international cooperation and standardization efforts are crucial. Key considerations include:
- **Harmonization of regulations and standards:** future hydrogen infrastructure development will require harmonized regulations and standards across regions to ensure safety, compatibility, and interoperability. Collaborative efforts among countries and international organizations are necessary to establish common frameworks for hydrogen infrastructure.
- **Cross-border hydrogen trade:** projections suggest that the future hydrogen market will involve international trade, with hydrogen being transported between countries. Agreements and frameworks for cross-border hydrogen trade need to be established, including protocols for transport, storage, and quality assurance.
- **Knowledge sharing and collaboration:** future hydrogen infrastructure development will benefit from knowledge sharing, research collaboration, and technology transfer among countries. International partnerships can accelerate advancements in hydrogen technologies, infrastructure deployment, and cost reductions.

6.6 Investments and future projections

The future of hydrogen infrastructure relies on substantial investments from governments, private companies, and financial institutions. Projections indicate significant growth in hydrogen-related investments and deployment in the coming years. Key areas of investments and future projections include:
- **Government support:** governments around the world are providing financial support, incentives, and policy frameworks to promote hydrogen infrastructure development. Projections suggest increased government funding and regulatory support to stimulate the growth of hydrogen infrastructure.
- **Private sector investment:** private companies are investing in hydrogen technologies, infrastructure, and projects. Major energy companies, industrial players, and technology developers are allocating significant funds for research and development, pilot projects, and commercial-scale deployment of hydrogen infrastructure.
- **Cost reduction and competitiveness:** future projections indicate a continuous reduction in the cost of hydrogen production, storage, and distribution, driven by technological advancements, economies of scale, and increased competition. As the costs decline, hydrogen is expected to become more competitive with fossil fuel alternatives in various applications.
- **Scale-up and market expansion:** projections suggest a significant increase in the deployment of hydrogen infrastructure and its utilization in various sectors. This includes the expansion of hydrogen production

capacities, the establishment of widespread distribution networks, and the integration of hydrogen into industry, transportation, and energy systems.

The reinforcement of hydrogen infrastructure is a complex, multifaceted endeavor that requires substantial investments, robust policy support, technological advancements, and close collaboration between various stakeholders. However, given the vast potential of hydrogen to contribute to global decarbonization efforts, these challenges are surmountable. The development of hydrogen infrastructure will not only enable the widespread adoption of hydrogen as a clean energy carrier but will also stimulate economic growth, create jobs, and lead to cleaner, more sustainable energy systems.

7 The challenges of future using hydrogen

The future use of hydrogen as a clean and versatile energy carrier presents several challenges that need to be addressed for its widespread adoption. While hydrogen offers numerous benefits, such as zero-emission operation and energy storage capabilities, there are various technical, economic, and societal challenges that must be overcome. This section explores the key challenges of future hydrogen use in detail.

7.1 Cost and economics

One of the primary challenges of hydrogen is its cost compared to conventional energy sources. The cost of producing, storing, and distributing hydrogen needs to be competitive to accelerate its adoption. The main cost drivers include:

- **Electrolyzer cost:** electrolysis, the process of producing hydrogen from water, requires significant energy inputs. The cost of electrolyzer technologies needs to be reduced through technological advancements, economies of scale, and improvements in manufacturing processes.
- **Renewable energy integration:** green hydrogen, produced through electrolysis powered by renewable energy, is more expensive compared to hydrogen produced from fossil fuels. The cost of renewable energy sources, such as solar and wind, needs to be further reduced for cost-effective hydrogen production.
- **Infrastructure investment:** establishing hydrogen infrastructure, including production facilities, storage systems, distribution networks, and refueling stations, requires substantial upfront investments. Governments and private companies need to allocate resources to build the necessary infrastructure and drive down the overall costs.
- **Economy of scale:** the scale-up of hydrogen production, storage, and distribution will play a crucial role in reducing costs. As production volumes increase, economies of scale can be realized, leading to cost reductions across the hydrogen value chain.

7.2 Hydrogen production and greenhouse gas emissions

While hydrogen is a clean fuel when used, its production methods can result in greenhouse gas emissions. Two primary challenges associated with hydrogen production and emissions are:

- **Grey and blue hydrogen:** the current dominant method of hydrogen production is through natural gas reforming, resulting in CO_2 emissions. Grey hydrogen refers to hydrogen produced from fossil fuels without carbon capture and storage (CCS), while blue hydrogen is produced with CCS technologies. The challenge is to transition from grey to blue or green hydrogen to minimize greenhouse gas emissions.
- **Renewable energy integration:** green hydrogen produced through renewable energy sources offers a pathway for zero-emission hydrogen production. However, the intermittent nature of renewable energy sources and the need for large-scale electrolysis pose challenges in terms of ensuring reliable and continuous hydrogen production.

7.3 Storage and distribution

The efficient storage and distribution of hydrogen are crucial for ensuring its availability and accessibility. Several challenges are associated with hydrogen storage and distribution, including:

- **Storage methods:** hydrogen has low energy density, requiring specialized storage methods. Compressed gas storage and cryogenic liquid storage have their challenges, including energy losses, safety considerations, and boil-off. Further advancements in storage

technologies, such as solid-state storage or chemical storage, are required to address these challenges.
- **Distribution infrastructure:** establishing a reliable and widespread hydrogen distribution infrastructure is crucial. Challenges include the construction of hydrogen pipelines, retrofitting existing pipelines, and ensuring compatibility with existing natural gas infrastructure. Investments in refueling stations for transportation applications and storage facilities for industrial applications are essential.
- **Safety concerns:** hydrogen has unique safety considerations, such as its high flammability and potential for embrittlement. Safety regulations, protocols, and public awareness programs need to be developed and implemented to address these concerns and ensure safe handling, storage, and distribution of hydrogen.

7.4 Technological advancements

Advancements in hydrogen technologies are necessary to overcome various technical challenges and enhance the efficiency, reliability, and cost-effectiveness of hydrogen systems. Key technological challenges include:
- **Electrolyzer efficiency:** electrolysis technology needs to improve in terms of energy efficiency to reduce the energy requirements for hydrogen production. Advances in catalysts, membranes, and system design can enhance electrolyzer efficiency and reduce costs.
- **Fuel Cell performance:** fuel cells play a critical role in various applications, including transportation and stationary power generation. Improvements in fuel cell performance, durability, and cost are necessary to accelerate their deployment and make them more competitive with other energy technologies.
- **Hydrogen infrastructure integration:** integrating hydrogen infrastructure with existing energy systems, such as natural gas networks and electricity grids, is challenging. This requires the development of hybrid systems, smart grid solutions, and grid balancing mechanisms to optimize the use of hydrogen and ensure a seamless transition to a hydrogen-based economy.

7.5 Public acceptance and policy support

Public acceptance and supportive policies are crucial for the successful deployment of hydrogen technologies. Key challenges include:
- **Perception and awareness:** the general public's perception of hydrogen as a fuel source and its safety aspects may hinder its acceptance. Educational programs and public awareness campaigns are necessary to address misconceptions and promote understanding of the benefits and safety of hydrogen.
- **Policy framework:** governments need to develop supportive policies, regulations, and incentives to drive the adoption of hydrogen technologies. These can include financial incentives for hydrogen production, tax breaks for hydrogen vehicles, and supportive regulations for hydrogen infrastructure development.
- **International cooperation:** the global nature of hydrogen infrastructure requires international cooperation to harmonize regulations, standards, and safety protocols. Collaborative efforts among countries can foster knowledge sharing, technology transfer, and cross-border hydrogen trade.

While hydrogen presents enormous potential as a clean energy carrier, several challenges must be addressed for its widespread use. Overcoming the cost barriers, reducing greenhouse gas emissions in hydrogen production, developing efficient storage and distribution systems, advancing hydrogen technologies, and garnering public acceptance and policy support are crucial steps towards a hydrogen-based future. With continued innovation, investment, and collaboration, these challenges can be overcome, paving the way for a sustainable and low-carbon energy system.

8 The balance: weighing opportunities against challenges

The future use of hydrogen as a clean and versatile energy carrier presents a myriad of opportunities, along with several challenges that need to be addressed. By carefully weighing these opportunities against the challenges, policymakers, industry leaders, and stakeholders can develop strategies to maximize the potential of hydrogen while actively addressing the barriers. Table 2 show the explore of the balance between opportunities and challenges in the future use of hydrogen.

9 Conclusions

Hydrogen energy presents a horizon of vast opportunities and significant challenges as we strive towards a sustainable and

Table 2: The explore of balance between opportunities and challenges in the future use of hydrogen.

	Opportunities	Challenges
1	Decarbonization: Hydrogen, particularly green hydrogen, has the potential to significantly reduce greenhouse gas emissions across various sectors, including power generation, transport, and industry	Production cost: As of now, producing green hydrogen is expensive compared to other fuels. Costs need to decrease to make hydrogen competitive
2	Energy storage: Hydrogen can serve a form of long-term energy storage, helping to balance the grid and address the intermittency of renewable energy sources	Infrastructure: Developing the necessary infrastructure for hydrogen production, storage, transport, and use is a major challenge, requiring substantial investments
3	Diversified energy mix: Hydrogen can complement other forms of energy, adding flexibility and resilience to the energy mix	Efficiency: The process of converting electricity to hydrogen and back to electricity (in fuel cells) involves energy losses
4	Transport: Hydrogen fuel cell vehicles could play a major role in decarbonizing the transport sector, particularly in heavy-duty and long-range applications where batteries are less suitable	Public perception: Safety concerns and lack of awareness could hinder the acceptance of hydrogen technologies. Public education and transparent communication will be crucial
5	Industry: Hydrogen could replace fossil fuels in various industrial processes, such as steelmaking, reducing their carbon footprint	Regulatory framework: A supportive regulatory environment is needed to incentivize the use of hydrogen and facilitate the development of hydrogen infrastructure
6	Job creation: The hydrogen economy could create millions of jobs worldwide, stimulating economic growth	Scale of production: Scaling up hydrogen production to the levels needed for a hydrogen economy is a massive undertaking, requiring technological advancements and substantial resources

low-carbon future. By carefully balancing these opportunities against the challenges, we can harness the potential of hydrogen as a clean and versatile energy carrier. In this conclusion, we will delve into the key insights gained from exploring the hydrogen energy horizon. The opportunities presented by hydrogen energy are remarkable. Hydrogen offers a clean and versatile energy source that can be utilized across various sectors, including transportation, industry, and power generation. Its decarbonization potential is significant, as it can be produced from renewable sources and used with zero greenhouse gas emissions. Hydrogen also provides a valuable energy storage capability, allowing for the integration of intermittent renewable energy sources and the balancing of supply and demand fluctuations. Furthermore, hydrogen contributes to fuel diversity and energy security, reducing dependence on fossil fuels and promoting energy independence. The development of a hydrogen economy creates new markets, technologies, and job opportunities, fostering economic growth and driving innovation.

However, several challenges must be overcome to realize the full potential of hydrogen energy. Cost and economics are major considerations, as the production, storage, and distribution of hydrogen must become competitive compared to conventional fuels. Continued technological advancements, economies of scale, and supportive policies are crucial to reducing costs throughout the hydrogen value chain. Addressing greenhouse gas emissions associated with hydrogen production is essential to maximize its environmental benefits. Scaling up renewable hydrogen production and integrating carbon capture, utilization, and storage (CCUS) technologies are key strategies to minimize the carbon footprint of hydrogen production. The establishment of a robust storage and distribution infrastructure is critical to enable widespread adoption. This includes the development of pipeline networks, storage facilities, and refueling stations, as well as repurposing existing infrastructure. Technological advancements in electrolysis, fuel cells, and storage materials are needed to improve efficiency, durability, and cost-effectiveness. Safety considerations are paramount to build public confidence and ensure the safe handling, storage, and distribution of hydrogen.

To address these challenges and maximize the opportunities, collaborative efforts among governments, industry stakeholders, and research institutions are essential. Governments play a vital role in providing supportive policies, regulations, and financial incentives to stimulate investment and market development. International cooperation is crucial to harmonize regulations, standards, and safety protocols for global hydrogen trade and infrastructure interoperability. Research and development efforts must continue to advance hydrogen technologies, improve efficiencies, and reduce costs. Public awareness and education programs are necessary to address misconceptions, promote understanding of the benefits and safety of hydrogen, and drive public acceptance.

The hydrogen energy horizon offers immense promise, but it requires a comprehensive and collaborative approach to navigate the opportunities and challenges. The path to a sustainable and low-carbon future lies in harnessing the potential of hydrogen as a clean and versatile energy carrier. By addressing cost barriers, reducing greenhouse gas emissions, developing infrastructure, advancing technologies, ensuring safety, and providing policy support, we can pave the way for a hydrogen-based economy. The successful integration and widespread adoption of hydrogen will contribute significantly to global efforts in combating climate change, enhancing energy security, and fostering economic growth. With a holistic and determined approach, we can shape a future where hydrogen plays a transformative role in creating a more sustainable and prosperous society.

10 Future recommendations

As we navigate the path towards a hydrogen-powered future, it is crucial to consider a recommendation that can guide the development and deployment of hydrogen energy. These recommendations aim to address the challenges and maximize the opportunities associated with hydrogen as a clean and versatile energy carrier. The future recommendations to accelerate the transition to a hydrogen-based energy and economy:

(1) **Enhance research and development efforts:** continued investment in research and development is vital to drive technological advancements and cost reductions in hydrogen production, storage, and utilization. Governments, industry stakeholders, and research institutions should collaborate to support research programs, foster innovation, and promote knowledge sharing in the field of hydrogen energy.

(2) **Scale up renewable hydrogen production:** increasing the scale of renewable hydrogen production is crucial to reduce greenhouse gas emissions and ensure a sustainable hydrogen value chain. Governments should provide incentives and policy support to accelerate the deployment of renewable energy projects and the production of green hydrogen through electrolysis.

(3) **Promote public-private partnerships:** collaboration between the public and private sectors is essential to drive investment, innovation, and infrastructure development. Governments should foster partnerships and provide financial incentives for private companies to invest in hydrogen technologies, storage infrastructure, and hydrogen-based applications.

(4) **Develop integrated energy systems:** the integration of hydrogen into existing energy systems is essential for maximizing its potential. Governments and industry stakeholders should encourage the development of integrated energy systems that combine hydrogen with other renewable energy sources, such as wind and solar, to create a more resilient and efficient energy ecosystem.

(5) **Establish hydrogen infrastructure:** significant investments are required to develop a robust hydrogen infrastructure, including production facilities, storage systems, distribution networks, and refueling stations. Governments should allocate resources for infrastructure development, incentivize private sector involvement, and support the repurposing of existing infrastructure for hydrogen use.

(6) **Foster international cooperation:** international cooperation and collaboration are crucial to harmonize regulations, standards, and safety protocols for the global hydrogen market. Governments should actively engage in international partnerships and initiatives to facilitate cross-border hydrogen trade, share best practices, and accelerate the development of a global hydrogen economy.

(7) **Drive policy support:** governments should develop and implement supportive policies, regulations, and financial incentives to stimulate investment and market development for hydrogen energy. These policies should address barriers, provide a clear and stable policy framework, and encourage the adoption of hydrogen technologies across various sectors.

(8) **Promote public awareness and acceptance:** public acceptance and awareness of hydrogen energy are key drivers for its successful deployment. Governments and industry stakeholders should implement public awareness campaigns, education programs, and community engagement initiatives to inform the public about the benefits, safety aspects, and potential of hydrogen energy.

(9) **Collaborate on safety and standards:** ensuring the safety of hydrogen production, storage, and distribution is of paramount importance. Governments, industry associations, and international organizations should collaborate to develop comprehensive safety guidelines, standards, and best practices for hydrogen infrastructure, ensuring uniform safety protocols worldwide.

(10) **Monitor and evaluate progress:** regular monitoring and evaluation of the progress in hydrogen deployment and infrastructure development are crucial to identify challenges, measure success, and adjust strategies accordingly. Governments and international organizations should establish frameworks to monitor the growth of the hydrogen industry, track emissions reductions, and assess the economic and environmental benefits.

By implementing these future recommendations, we can accelerate the transition to a hydrogen-based economy and unlock the full potential of hydrogen as a clean and versatile energy carrier. The collective efforts of governments, industry stakeholders, researchers, and the public are essential in creating a sustainable and low-carbon future powered by hydrogen energy.

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