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Review

The urgency of hydrogen: environmental issues and the need for change

Karyssa Locke*
Combustion and Sustainable Energy Laboratory (ComSEL), Department of Mechanical Engineering, Arkansas Tech University, Russellville, AR, USA

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*Corresponding author
Email address:
klocke1@atu.edu

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ABSTRACT

While hydrogen adoption is progressing in different industries, challenges remain. The availability of a well-developed hydrogen infrastructure, including production, storage, and distribution, is a prerequisite for broader adoption. Additionally, cost reduction through technological advancements and economies of scale is essential to make hydrogen competitive with existing energy sources. Collaborative efforts between industry, governments, and research institutions are necessary to address these challenges. Hydrogen has the potential to play a significant role in achieving decarbonization goals and transitioning to a sustainable energy future. By completely changing to a hydrogen model, the rise in global temperatures would start to revert to a normal stage after multiple years. In light of these considerations, this article aims to comprehensively review the imperative need to transition to hydrogen fuel as a pivotal component of our sustainable energy future. Furthermore, it seeks to scrutinize and dissect the unique challenges that different regions across the globe face in embracing hydrogen as a clean energy solution. By shedding light on these challenges and emphasizing the collaborative efforts required between industry, governments, and research institutions, this article aims to contribute to the discourse on harnessing hydrogen's potential to combat climate change and steer us toward a more sustainable and decarbonized future.

1. Introduction

Fossil fuels have been the primary energy source for human civilization for centuries. These fossil fuels include but are not limited to coal, oil, and natural gas. The widespread and continuous use of fossil fuels has resulted in numerous environmental issues that pose significant challenges to the earth. Air pollution is a large environmental concern when dealing with fossil fuels based on the amount of greenhouse gasses being emitted in the production and after use of the fuels. The combustion of fossil fuels releases a variety of pollutants into the atmosphere, leading to severe air pollution. These pollutants include sulfur dioxide, nitrogen oxide, carbon monoxide, and other particulate matter [1]. When released into the air, the pollutants can have detrimental effects on both human health and the environment. When dealing with human health, the basis of the issues is exposure to the pollutants in the air. Exposure to these air pollutants from fossil fuels has been linked to respiratory problems. Particulate matter can be concerning as it can get deep into the lungs and even enter the bloodstream, which can cause cardiovascular diseases. The environmental impact of discerning air pollution from fossil fuels contributes to the formation of smog and acid rain. Smog, formed by the interaction of sunlight with nitrogen oxides and volatile organic compounds, poses a risk to human health and damages vegetation. Acid rain, caused by the emissions of sulfur dioxide and nitrogen oxides, damages forests, bodies of water, and soil. All of these will eventually lead to harmful environments for humans [2]. Fossil fuel combustion is the primary driver of climate change due to the release of greenhouse gases into the atmosphere. The combustion of these fuels leads to carbon dioxide being the top greenhouse gas being emitted. In 2022 there was around 40.5 Gt of carbon dioxide emitted into the atmosphere. The rise in the amount of carbon dioxide is shown in Figure 1. The effect this has on the atmosphere has been named the Greenhouse Gas Effect. This is where the carbon dioxide, methane, nitrous oxide, and many other greenhouse gasses cause the sunlight and heat to reflect off the atmosphere back onto the earth's crust. Since the light is unable to escape, the temperature will therefore rise [1]. The increased concentrations of carbon dioxide and other greenhouse gasses in the atmosphere intensify this greenhouse effect. The globe warms based on the temperatures between the crust and the ozone layer. The warmer climate has led to rising sea levels due to the melting of glaciers and polar ice caps. This has also led to more frequent severe heatwaves, changes in precipitation patterns, and has changed ecosystems worldwide. Many meteorologists believe that the rise in temperature has led to more destructive storms and unpredictable weather patterns [3]. The finite resource of fossil fuels is being depleted at an alarming rate. It has been noted by multiple scientists that the resource of fossil fuels will be fully depleted in 2060, if not before. There is a quick drop in the resource when compared to the need for energy. As their extraction becomes increasingly difficult and costly, the environmental impact of accessing and exploiting new resource reserves intensifies. Extracting fossil fuels often involves deforestation and habitat destruction, particularly in the case of coal and oil extraction. Forest ecosystems, which are crucial for carbon sequestration and biodiversity, are cleared to make way for mining operations [2]. The Paris Agreement has a large impact on the necessary means to stop resource depletion as well. This agreement states that the temperature rise should be limited to 2°C if not 1.5°C by the year 2050. This could be done by managing the unextractable oils all around the world. The different reserve holders' shares vary depending on the region they are in. The Middle East and Russia are the largest reserve holders, meaning they will have above-average standards [4]. Considering these concerns, hydrogen has emerged as a promising clean and sustainable energy source that has the potential to address the environmental challenges associated with fossil fuels. It offers several advantages in terms of its production, storage, and usage, making it a versatile solution for a wide range of applications.

One of the key benefits of hydrogen is its ability to produce energy without generating harmful emissions. When used in fuel cells, hydrogen combines with oxygen from the air to produce electricity, with water as the only byproduct [3]. This process, known as electrochemical conversion, avoids the release of greenhouse gases and pollutants that contribute to air pollution and climate change [5]. Figure 2 shows the process inside of a fuel cell and how it creates electricity. Hydrogen can be produced from a variety of renewable sources, such as solar, wind, tidal, hydropower, and geothermal, through a process called electrolysis. By using renewable electricity to split water molecules into hydrogen and oxygen, we can achieve "green hydrogen" production, which ensures a sustainable and carbon-free source of energy. This makes hydrogen a valuable energy carrier that can store and deliver renewable energy to power various sectors, including transportation, industry, and residential applications [6].

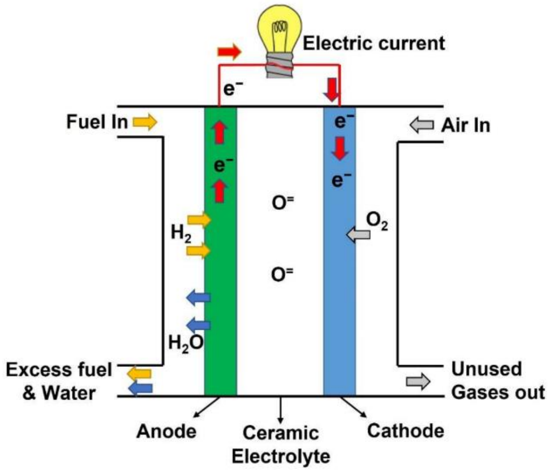


Figure 2. Hydrogen fuel cell process [5]

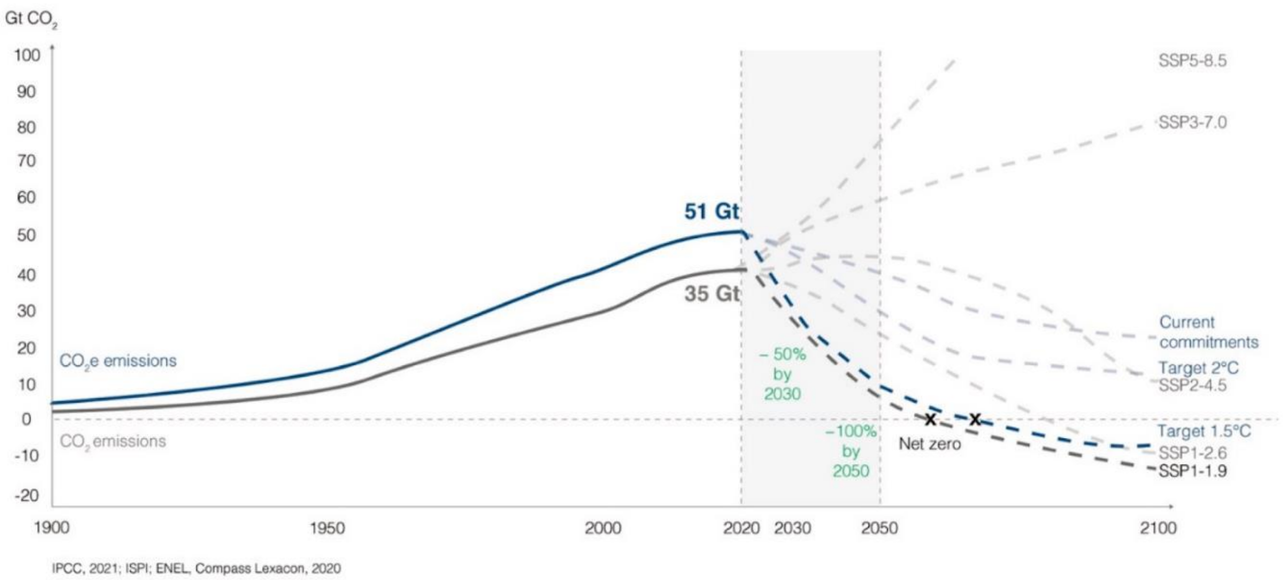


Figure 1. Carbon Emission bases on Global Carbon Budgets since 1950 [3]

When produced in other ways with electrolysis like using nuclear power, the hydrogen is then dubbed "pink hydrogen." Hydrogen produced with nuclear energy is still clean due to not releasing carbon dioxide, but nuclear power is not a green energy source. When producing hydrogen with steam methane reformation (SMR) the hydrogen is then either dubbed "blue" if using carbon capture or "gray" when not using carbon capture [7]. In terms of storage, hydrogen has a high energy density, allowing for large amounts of energy to be stored in a relatively small volume. This makes it suitable for applications where energy needs to be stored for longer durations or transported over long distances. By utilizing hydrogen as an energy storage medium, excess renewable energy generated during low-demand periods can be stored and used during peak demand, enhancing the reliability and stability of renewable energy systems. In this case, many studies have been done on the use of hydrogen as a battery for renewable energy. These hydrogen batteries would utilize hydrogen to generate the electricity needed. The lifespan of the hydrogen batteries would be much longer than that of a typical lithium-ion battery. In this case, switching to a hydrogen battery could increase the quality of the environment based solely on how lithium-ion batteries are produced [8]. Hydrogen can play a significant role in decarbonizing the transportation sector. It can be used as a fuel in hydrogen fuel cell vehicles, providing a clean alternative to conventional internal combustion engines. Fuel cell vehicles powered by hydrogen produce zero tailpipe emissions, other than the production of heat, contributing to improved air quality and reduced greenhouse gas emissions [6]. Additionally, hydrogen fuel cell technology offers advantages such as faster refueling times and longer driving ranges when compared to battery electric vehicles, making it a viable option for various transportation applications. However, it is important to note that the widespread adoption of hydrogen as a clean energy source faces certain challenges. These include the high cost of hydrogen production, the development of infrastructure for hydrogen storage and distribution, and the need for advancements in fuel cell technology. Overcoming these challenges requires continued research, development, and investment to drive down costs, improve efficiency, and expand the hydrogen infrastructure [5]. In the United States, the Biden-Harris Administration has promised $1 billion for hydrogen production and sales. The investment will help improve the amount of hydrogen being produced and the quality of research being done to find the most efficient and environmentally friendly ways to produce and transport hydrogen [9].

2. Hydrogen and GHG reduction

As mentioned before, reducing greenhouse gas emissions is of paramount importance in addressing climate change and mitigating its adverse impacts. Greenhouse gases, such as carbon dioxide, methane, and nitrous oxide, trap heat in the Earth's atmosphere, leading to global warming and associated climate-related hazards [6]. In the transportation sector, hydrogen fuel cell vehicles offer a clean and sustainable alternative to internal combustion engines. Fuel cells convert hydrogen into electricity through an electrochemical process, producing zero-emission transportation with longer driving ranges and shorter refueling times compared to battery-powered electric vehicles. By the adoption of hydrogen fuel cell vehicles, CO2 emissions and air pollution van be reduced, thereby leading to an enhancement of air quality and the mitigation of transportation-related environmental impacts [10]. Hydrogen also has the potential to decarbonize other industries that are challenging to electrify directly, such as steel manufacturing, chemical production, and heavy-duty manufacturing processes. By utilizing hydrogen as a feedstock or fuel in these sectors, we can replace carbon-intensive processes and reduce emissions significantly [11]. Figure 3 explains the difference in emissions between internal combustion engine vehicles and fuel cell vehicles. Section (a) shows the well-to-wheel emissions of oil for a gasoline-powered vehicle. The other sections (b), (c), and (d) show how the final emissions from the fuel cell vehicle is just water. The process of solar energy and wind energy for a fuel cell vehicle are very similar after the initial electricity is generated. section (b) shows where natural gas participates in the hydrogen industry [12].

Hydrogen can facilitate the integration of renewable energy sources into the electricity grid. As renewable energy generation, such as wind and solar, is intermittent, storing excess energy in the form of hydrogen can provide a reliable and dispatchable energy supply. This allows for better grid balancing, reduced curtailment of renewable energy, and more efficient utilization of renewable resources. By enabling the large-scale deployment of renewable energy and reducing the reliance on fossil fuels for electricity generation, hydrogen contributes to a significant reduction in greenhouse gas emissions [13]. The widespread adoption of hydrogen as a clean energy solution requires careful consideration of its production methods. While green hydrogen, produced using renewable energy, is the ideal option for achieving emission reductions, the current production of hydrogen primarily relies on fossil fuels, resulting in carbon emissions. Therefore, scaling up the production of green hydrogen and investing in renewable energy infrastructure are crucial steps in maximizing the environmental benefits of hydrogen [14]. When thinking about producing hydrogen with "green energy," one should also consider the energy sources. Some may forget that the process of producing solar panels and wind turbines is not environmentally friendly, as solar panels are made of precious metals. When mining for these metals, fossil fuels are used in the equipment, meaning that, in the end, the process as a whole is not completely free of greenhouse gasses. One should also realize that the factories that make solar panels and wind turbines also produce greenhouse gases [15]. Even when comparing the environmental impact of solar panel production in Europe to that in China, there is a difference in carbon emissions. China has less of an environmental standard than Europe does. The increasing demand for silicones and metals required for solar panels in China has prompted the use of less efficient energy sources in the mining process. To address this environmental concern, both environmental and hydrogen activists must expand their research efforts to incorporate this aspect. Finding innovative ways to make the entire production process of these critical materials for renewable energy sources gas-free is essential for a sustainable and environmentally responsible energy transition [16].

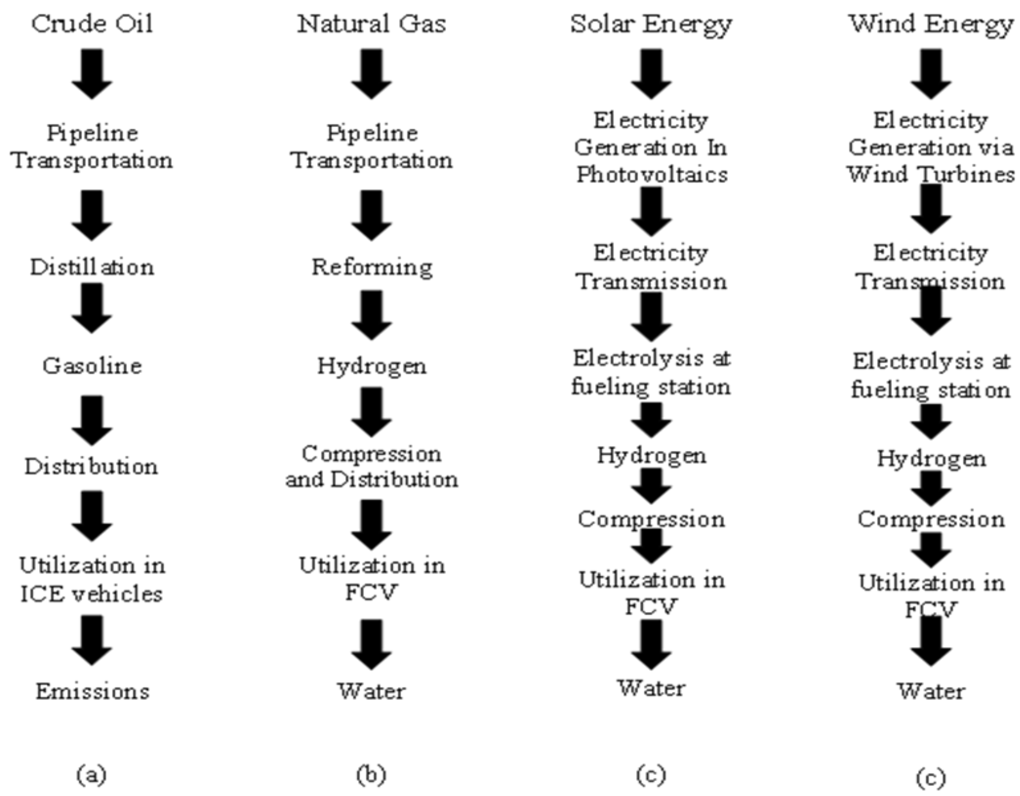


Figure 3. Steps in utilizing transportation to decrease carbon emissions

3. The need for transition

The current state of the energy industry is characterized by a growing recognition of the urgent need to transition towards a more sustainable and low-carbon future. While fossil fuels continue to dominate the global energy production field, their detrimental environmental impacts are becoming increasingly apparent. Figure 4 shows the dominant amount of energy being consumed by these fossil fuels in comparison to renewable resources. The growing concerns over climate change and the need to reduce greenhouse gas emissions have highlighted the necessity of exploring alternative energy sources. In this context, the concept of a hydrogen economy has gained significant attention as a viable solution.

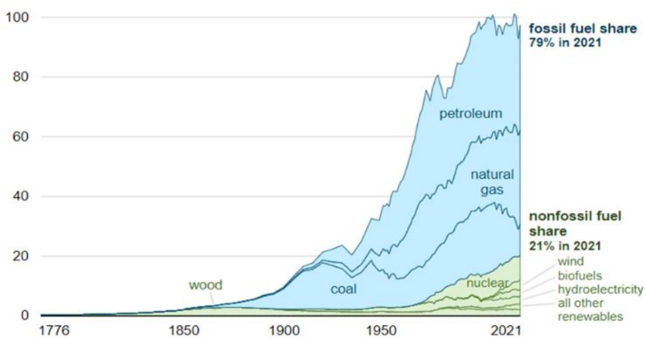


Figure 4. Energy consumption comparison: Fossil fuels to renewable resources [17]

Hydrogen, as a versatile energy carrier, has the potential to address the limitations of traditional fossil fuel [11]. The production amount of these renewable energy resources has risen rapidly in the United States and other countries since the federal tax credit was initialized. This tax credit will be mentioned later [16]. A hydrogen economy has the potential to revolutionize multiple sectors, including transportation, industry, and power generation. In transportation, hydrogen fuel cell vehicles can offer zero-emission mobility with longer driving ranges and shorter refueling times compared to battery-powered electric vehicles. In industries, hydrogen can be used as a clean alternative for processes that are difficult to decarbonize using conventional methods, such as steel manufacturing and chemical production. Hydrogen can contribute to the decarbonization of the power sector by enabling the storage and utilization of excess renewable energy, ensuring a reliable and sustainable energy supply. However, several challenges need to be addressed for the transition to a hydrogen economy. These include the development of cost-effective and efficient hydrogen production methods, the establishment of an extensive infrastructure for hydrogen storage, transportation, and distribution, and the need for supportive policies and regulations to foster market growth and investment in hydrogen technologies [18].

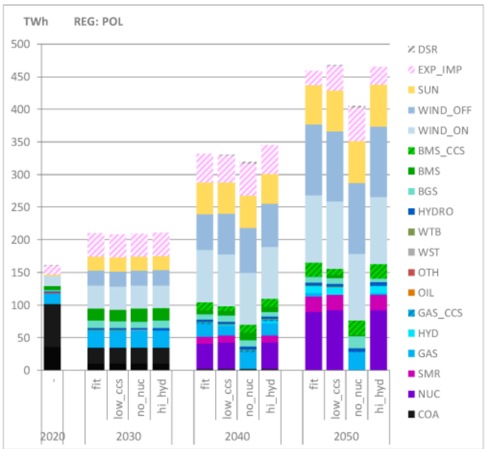
4. Potential benefits

Hydrogen offers several potential benefits that can contribute to reduced dependence on foreign oil, improved energy security, and increased economic growth. Hydrogen production can reduce reliance on imported oil, which is a significant factor in many countries' energy security concerns. By utilizing domestic sources of energy, such as renewable resources, to produce hydrogen, nations can decrease their dependence on foreign oil and enhance their energy independence. This reduces vulnerability to geopolitical tensions and price fluctuations in global oil markets, providing greater stability and control over energy supplies [14]. Figure 5 shows the projected increase in the production of hydrogen in multiple different countries. This projection is based on today's interest in hydrogen within each country and may not be 100% accurate. However, Figure 6 shows the number of green hydrogen plants by country in 2022. The widespread adoption of hydrogen can significantly enhance energy security. As a versatile energy carrier, hydrogen can be used across various sectors, including transportation, industry, and power generation. Its versatility and potential for renewable production enable diversification of energy sources, reducing the dependence on a single energy sector or fuel type. This diversification strengthens energy resilience and helps mitigate the risks associated with supply disruptions or fluctuations in specific energy markets [18]. Additionally, the transition to a hydrogen economy has the potential to stimulate economic growth and create new employment opportunities. The development and expansion of hydrogen-related technologies, infrastructure, and industries can lead to job creation in the manufacturing, research and development, construction, and maintenance sectors. Based on the grant from the Biden-Harris Administration in the United States, there is potential to add 100,000 new jobs by 2030 [9]. The development of a hydrogen market can create export opportunities, boost trade, and contribute to a country's economic competitiveness on the global stage. The potential benefits extend beyond energy and economic factors [19].

As countries recognize the advantages that come with hydrogen utilization, the development and deployment of hydrogen technologies will start to play a significant role in shaping a more secure, sustainable, and prosperous future [20].

5. Challenges with hydrogen adaptations

While hydrogen technology holds significant promise, several challenges need to be addressed for its widespread adoption. These challenges span technical, economic, and political aspects, impeding the transition to a hydrogen-based economy. From a technical perspective, one of the key challenges is the production of hydrogen. While hydrogen can be produced through various methods such as electrolysis, steam methane reforming, and biomass gasification, the cost-effectiveness and efficiency of large-scale hydrogen production need improvement [11]. Developing technologies that enable low-cost and sustainable hydrogen production, particularly from renewable sources, is crucial. In Figure 7, a comparison is made between the cost and other hydrogen expenses from 2020 and 2030. The storage and transportation of hydrogen can pose technical challenges. Hydrogen has low energy density compared to fossil fuels, requiring specialized storage and infrastructure. Effective storage and transportation methods, such as compressed or liquefied hydrogen, need to be further developed to ensure safe, efficient, and cost-effective distribution [19]. Without this development, a larger amount of hydrogen leaks would occur due to the small atomic structure of the hydrogen molecule. Hydrogen can also cause embrittlement to many different types of metal, including steel. This embrittlement is difficult to fix unless the hydrogen is liquified [20].



DSR	Demand Side Response	OTH	Other sources
EXP_IMP	Net Export-Import Balance	OIL	Oil
SUN	PV_Large and PV_Small	GAS_CCS	Natural Gas with CCS
WIND_OFF	Wind Offshore	HYD	"Green Hydrogen" co-firing
WIND_ON	Wind Onshore	GAS	Natural Gas
BMS_CCS	Biomass with CCS	SMR	Small Modular Reactor
BMS	Biomass	NUC	Nuclear (large-scale)
BGS	Biogas	COA_CCS	Hard Coal with CCS
HYDRO	Hydro	COA	Hard Coal
WSB	Biomass Waste	LIG_CCS	Lignite with CCS
WST	Non-Biomass Waste	LIG	Lignite

Figure 5. Projected production of hydrogen [18]

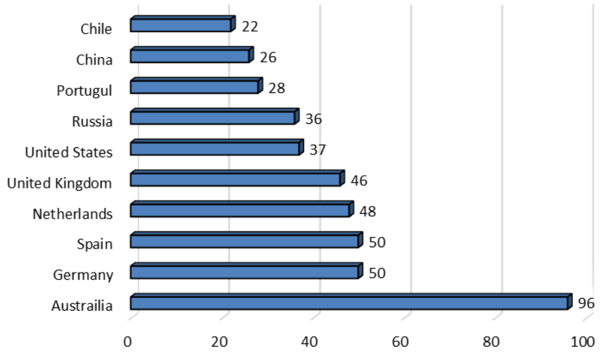


Figure 6. Number of Green Hydrogen Plants in 2022

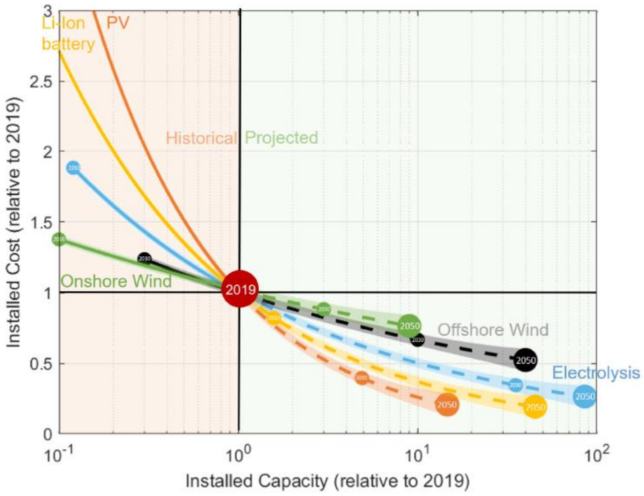


Figure 7. Comparison between cost [20]

Currently, hydrogen production and infrastructure deployment are relatively expensive. Scaling up hydrogen production and building the necessary infrastructure requires substantial investments. Cost reduction through technological advancements, economies of scale, and supportive policies is essential to make hydrogen more economically competitive with existing energy sources. In Figure 7, the costs of CapEx and OpEx are included to show the importance of other costs, excluding hydrogen cost [21]. CapEx costs for hydrogen production would include the buildings and machinery needed for the plant. Opex costs would include energy costs for lights, employees' salaries, and other bills needed for production. Including the cost of physical assets is important for research purposes due to the amount some of these assets will cost during the full production process. The development of a hydrogen market faces economic challenges related to supply and demand. For now, the cost of hydrogen is much higher because the supply and demand are still low. Once the demand starts to rise along with the supply, the cost will inevitably start to lower. This concept can be known as the law of supply and demand [22]. Policy frameworks, regulations, and incentives play a crucial role in driving the transition to a hydrogen-based economy. In many countries, including the United States, there is a tax incentive for other renewable resources like solar. Solar installers are eligible for a 26% tax credit for this. In Canada, the tax credit is the same. They are still encouraging businesses and individuals to transfer to renewable resources. If Canadians switch to any type of renewable energy source, solar, wind, or hydrogen, they will get a tax incentive of 30% refundable capital investment [23]. Capital investments in hydrogen can be separated into the different ways hydrogen can be produced. As hydrogen production begins to shift from steam methane reformation and other gray and black hydrogen methods to more green methods, the investments and costs will change [24].

5.1 Economic challenges

The economic challenges associated with hydrogen adoption encompass several key factors, including the cost of production and distribution, the need for government subsidies and incentives, and the competition from established energy sources. One major hurdle is the cost of producing hydrogen. Current production methods, such as electrolysis, can be expensive due to the high electricity requirements. To make hydrogen cost-competitive, advancements in electrolysis technologies and the use of renewable energy sources are crucial to drive down production costs. A university in Turkey was able to compare the capital costs and the finalized hydrogen cost based on the different production methods. Table 1 is able to go more in depth into the different costs depending on the production method in 2019 [15]. The distribution of hydrogen also poses economic challenges. Adapting existing energy grids and building new pipelines or tanker fleets adds to the overall cost. Moreover, the low energy density of hydrogen necessitates more storage and transportation capacity compared to conventional fuels, further increasing cost [13].

5.2 Political challenges

The political challenges associated with hydrogen adoption encompass several key aspects, including regulatory frameworks, public perception, and the role of international agreements and collaborations. Establishing comprehensive regulatory frameworks is crucial to ensure the safe and effective integration of hydrogen into existing energy systems. Governments need to develop and enforce regulations that cover aspects such as production, storage, transportation, and usage of hydrogen. These regulations must address safety standards, technical specifications, quality control, and environmental considerations. The development of harmonized international standards is also important to facilitate the global adoption of hydrogen technologies and enable cross-border trade [25]. Public perception and acceptance of hydrogen as an energy source present political challenges as well. Building public trust and awareness regarding the safety, environmental benefits, and long-term viability of hydrogen is essential. Governments and industry stakeholders need to engage in effective communication campaigns to educate the public about hydrogen, address concerns, and highlight its potential as a clean and sustainable energy solution. Public support can influence policy decisions and incentivize investments in hydrogen infrastructure [26].

6. Production in different regions

6.1 Asia

China has been actively working to produce hydrogen as a clean and sustainable energy source. The country recognizes the importance of transitioning to low-carbon alternatives and reducing its reliance on fossil fuels. To achieve this, China has adopted a multi-faceted approach to hydrogen production. One of the key methods employed by China is electrolysis, particularly using renewable energy sources. China is investing heavily in wind, solar, and hydroelectric power generation, which provide a renewable and abundant energy supply for electrolysis. By utilizing these clean energy sources, China aims to produce green hydrogen, which has no carbon emissions during its production process [16].

The difference between China and the United States is that China is actively building hydrogen infrastructure, including hydrogen refueling stations, pipelines, and storage facilities. These infrastructure developments are crucial for the widespread adoption of hydrogen as a fuel for various sectors, including transportation, industry, and power generation. China's government has implemented supportive policies and provided financial incentives to promote the deployment of hydrogen infrastructure and encourage private sector participation. In addition to domestic efforts, China is also engaging in international collaborations and partnerships to accelerate hydrogen development. The country is working with other nations to share knowledge, invest in research and development, and establish global supply chains for hydrogen technologies [17]. China is actively exploring various applications and sectors for hydrogen utilization as part of its efforts to promote a sustainable and low-carbon economy. The country recognizes the potential of hydrogen as a versatile energy carrier and is investing in its integration into different industries. The targets set by the country for the deployment of fuel cell vehicles are incentivizing their production and purchase through policies and subsidies [7]. Hydrogen is also being used in various industrial processes to reduce emissions. China is exploring hydrogen as a feedstock for industries like steel, chemicals, and refining. For example, using hydrogen instead of coal in the steelmaking process can significantly lower carbon dioxide emissions.

Table 1. Cost comparison of different production methods [23]

Process	Energy Source	Feedstock	Capital Cost (M$)	Hydrogen Cost ($/kg)
SMR with CCS	Standard Fossil Fuels	Natural gas	226.4	2.27
SMR without CCS	Standard Fossil Fuels	Natural gas	180.7	2.08
CC with CCS	Standard Fossil Fuels	Coal	545.6	1.63
CG without CCS	Standard Fossil Fuels	Coal	435.9	1.34
ATR of methane with CCS	Standard Fossil Fuels	Natural gas	183.8	1.48
Methane pyrolysis	Internally Generated steam	Natural gas	//	1.59-1.70
Biomass pyrolysis	Internally Generated steam	Woody biomass	53.4-3.1	1.25-2.20
Biomass gasification	Internally Generated steam	Woody biomass	149.3-6.4	1.77-2.05
Solar PV electrolysis	Solar	Water	12-54.5	5.78-23.27
Solar Thermal Electrolysis	Solar	Water	421-22.1	5.10-10.49
Wind Electrolysis	Wind	Water	504.8-499.6	5.89-6.03
Nuclear Electrolysis	Nuclear	Water	//	4.15-7.00
Nuclear Thermolysis	Nuclear	Water	39.6-2107.6	2.17-2.63
Solar Thermolysis	Solar	Water	5.7-16	7.98-8.40

China is investing in pilot projects and demonstration facilities to test and scale up hydrogen utilization in industries [13]. Hydrogen has the potential to play a role in power generation, particularly as a backup or seasonal energy storage solution. China is investigating the integration of hydrogen into its power grid, including the use of hydrogen fuel cells for distributed power generation. Figure 8 illustrates the installed generation capacity in China from 2010 to 2021. By coupling hydrogen with other renewable energy sources, excess energy can be stored and utilized during periods of high demand. Along with this, China is exploring the use of hydrogen for heating residential and commercial buildings. Hydrogen can be used in fuel cells to generate heat and electricity. This will provide a clean and efficient energy source for heating systems. Many projects have been conducted in the region to evaluate the feasibility and safety of hydrogen utilization in this sector [7].

One of the key initiatives is the "Hydrogen Energy and Fuel Cell Industry Development Plan" released by China's National Development and Reform Commission (NDRC) in 2020. According to this plan, China aimed to establish a comprehensive hydrogen infrastructure and become a global leader in hydrogen production and utilization by 2030. The plan outlined specific targets for hydrogen production capacity, stating that China aimed to have more than 1,000 hydrogen refueling stations and produce more than 1 million tons of hydrogen per year by 2030.

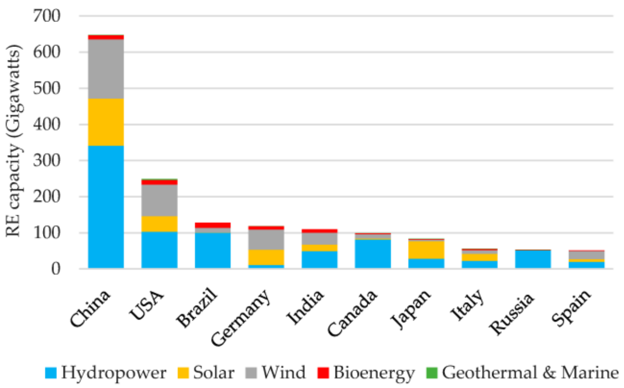


Figure 8. Installed renewable energy generation capacity compared to China [27]

Regarding the amount of money dedicated to hydrogen production, the plan called for significant financial support from the government, including investment from both central and local authorities, as well as private sector participation. The exact financial figures were not specified in the public documents. However, China's target of bringing fifty thousand hydrogen fuel cell vehicles on the road by 2025 shows an immense amount of support on the subject [27].

Like China, South Korea has been making efforts to pursue the production of hydrogen as a key component of its energy transition strategy. The country is able to recognize the potential of hydrogen as a clean, sustainable energy source and has already started to implement initiatives to promote production. To start with, they are investing in a diverse range of hydrogen production technologies, similar to other countries. The biggest difference that South Korea has over other countries is the hydrogen liquefaction and transport technologies. These technologies enable long-distance transportation of hydrogen due to the enlargement of molecules [27]. South Korea has spent most of its time finding ways to store hydrogen. In 2021, the hydrogen storage market in South Korea cost around 4.7 million U.S. dollars. Figure 9 shows the projected market price of hydrogen storage in South Korea alone. The increase in hydrogen vehicle production has led to this large projected price. As long as environmentally friendly vehicles production grows in South Korea it is expected hydrogen storage production will also increase [28].

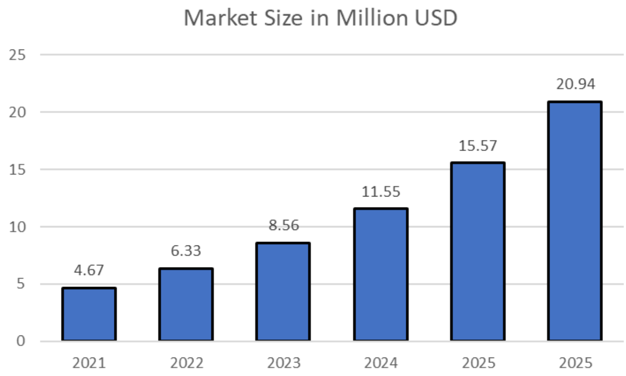


Figure 9. The 2021 hydrogen storage market price investments in South Korea

Liquid hydrogen is a large focus in South Korea. Two separate countries have started to build liquid hydrogen plants with a projected production rate of 13,000 mt per year. The Korean car manufacturing company Hyundai Motors has had a large impact on the increased hydrogen production rate in South Korea. Hyundai has done multiple hydrogen vehicle tests and has started to focus its research on hydrogen-powered vehicles being produced in South Korea [13]. Their roadmap has been set to produce around 6 million hydrogen-powered vehicles by 2040. In 2022, around 26 thousand hydrogen-powered vehicles had been registered in South Korea. The roadmap also mentioned electricity production by 2024. A projected amount of 15 GW of electricity should be produced by hydrogen by this time [18].

Saudi Arabia has been pursuing a multi-faceted approach to producing hydrogen as part of its broader energy diversification and sustainability goals. Leveraging its vast natural resources and commitment to innovation, the country employs several strategies for hydrogen production. Saudi Arabia uses multiple of the same methods as other countries, such as SMR, CCS, and green methods, for producing hydrogen with solar and wind. The country has put the Neom Hydrogen Project in place. This 8.4 billion dollar investment has moved towards a solar and wind-producing hydrogen plant. This follows the standards they have set in place [29]. The current hydrogen cost in Saudi Arabia as of 2022 can be seen in Figure 10. The figure depicts the different hydrogen methods and the costs within each sector. As shown, hydrogen produced by electrolysis is the most expensive, but this is due to the small amount being produced this way. However, Saudi Arabia has set $8.4 billion green hydrogen production plants. This plant is projected to produce 600 tons of green hydrogen per day. They will then be transporting this hydrogen to other countries. This amount of hydrogen is able to reduce carbon emissions by five million metric tons per year. Like other countries, Saudi Arabia has climate goals. Their plan is projected to produce 3 million tons per year of hydrogen, namely by blue and green methods, by 2030 [28].

6.2 Europe

Russia's invasion of Ukraine has caused the renewable hydrogen industry to be of higher importance in Europe. This is because Russia is the second largest producer of natural gas. Since natural gas is what powers the largest percent of hydrogen production plants. The EU started to refocus on the renewable hydrogen industry. The EU wants to see Europe produce ten million tonnes of renewable hydrogen by 2030. Along with that, the EU wants to import up to ten million tonnes to reach the net zero goal. This goal is to cut emissions by 55 percent when comparing it to the levels in 1990. Spain has one of the largest solar energy opportunities in Europe based on the high sunshine averages per year [30]. In 2022, over 20,000 tonnes were produced overall. Spain has been ramping up its hydrogen production and is seen to have double the hydrogen production capacity compared to the demand by 2030. This means they have already achieved their original hydrogen production goals that were set back in 2020. Of the four gigawatts, they have already reached 15 gigawatts. Based on the submitted projects, Spain has the potential to produce 8.7 million tonnes of hydrogen a year by 2040 by using the proposed 84.3 gigawatts of electrolysis capacity. The issue with these numbers is that the demand within Spain would not reach over 1.5 million tonnes of hydrogen per year. This would mean the hydrogen would need to be transported further out of the country, causing a loss of energy [31].

Scientists from the eastern Lorraine region in France have found deposits of natural hydrogen. This is called white hydrogen and is a green natural energy. This was discovered based on a probe that allowed the scientist to measure and collect gasses present in the groundwater over 1000 meters underground. They found that the highest hydrogen concentrations were found around 1250 meters. The scientist believes that the deposit is the largest found containing up to 250 million tonnes of hydrogen. In Paris, the scientists have focused on how hydrogen is produced in the earth's crust. Their experiments have been on how iron and water can produce hydrogen. Since there is no oxygen present in the earth's crust, they have to have a controlled environment in order to recreate what could happen deep underground. These experiments can not only tell how much hydrogen can be produced but also where to look for it based on the different rock compounds that are being experimented with. France has such a large focus on natural hydrogen because it has the potential to be the cheapest energy since it will not need to be produced anyway. It will just need to be drilled for, collected, and transported [31].

Germany has been one of the top hydrogen producers in the world. Hence, they have been trying to find ways to only produce green hydrogen. RWE and Westfalen Group have been working in sync to provide hydrogen for hydrogen vehicles. Their aim is to have at least seventy fueling stations by 2030. When choosing where these stations are put, they decided to put them in the largely populated areas along with different locations on the autobahns. Their idea is that a majority of people will use the new fueling stations and realize that they are being put in easy-access areas. The German government is projecting a hydrogen production capacity of five gigawatts by 2030 and just an extra five gigawatts by 2040. This slow addition is due to the amount of plants Germany will be building outside of the country [23]. The added demand for hydrogen has led Germany to find an updated strategy for the use of hydrogen in vehicles. Germany will soon have the largest percentage of hydrogen imported in the world. This large import increase is due to the partnerships Germany has made with other countries. In Canada, a hydrogen plant is being built that is owned by Germany. The location of the plant was chosen in order to decrease the amount of greenhouse gases being emitted. The hydrogen production facility will replace the White Rose oil production platform in Placentia Bay, Newfoundland. Newfoundland and Labrador is the perfect place to build a wind-powered plant due to the large amounts of winds that happen almost every day [24]. Germany has also planned to build a hydrogen production plant in Indonesia. This plant will cost around $500 million and will have a production capacity of 35,000 mt per year. This green hydrogen plant is planned to be on the coast of the Aceh province. The construction is projected to start in early 2024 but is not expected to be fully ready to start until 2026. Indonesia's deal with Germany is that the hydrogen would also be exported to other countries in Asia and not just back to Germany to make a profit [32].

6.3 Americas

The United States government has put money aside for hydrogen production and industrialization multiple times by this point in 2023. This has led to a large amount of hydrogen being produced. Approximately ten million metric tons are produced annually.

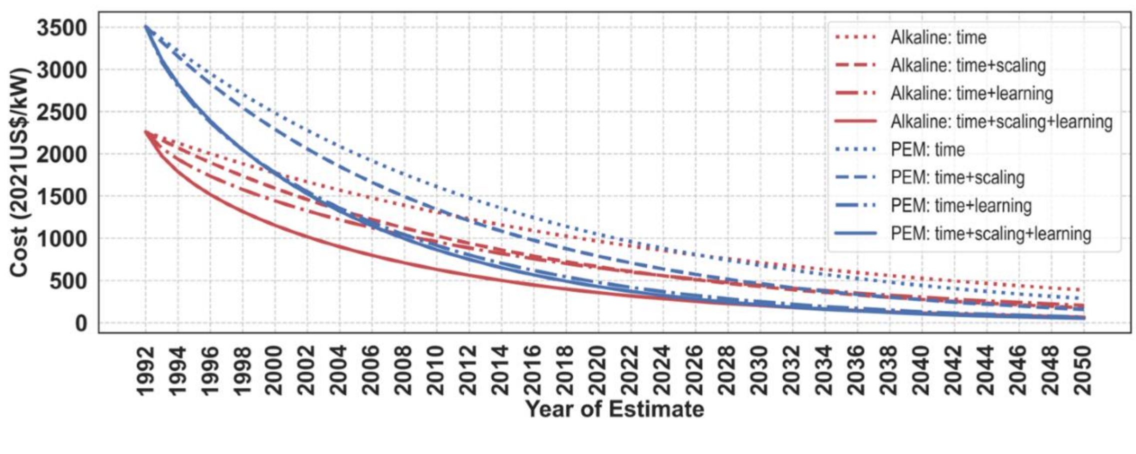


Figure 10. Hydrogen production cost in Saudi Arabia [33]

However, in the U.S., over 95 percent of hydrogen being produced is using steam methane reformation without carbon capture. As mentioned before, in efforts to lower carbon emissions, President Biden allocated eight billion dollars to clean hydrogen facilities. These efforts should act faster than that of President George W. Bush [13]. In 2003, President Bush put $1.2 billion towards the development of hydrogen-powered vehicles alone rather than the hydrogen production plants. While hydrogen-powered vehicles would lower carbon emissions slightly, if there is no change in hydrogen production, there is still a large number of greenhouse gasses being emitted [34]. The United States has already started construction on five different green hydrogen production plants in 2023. Two of these plants are in Louisiana: St. Gabriel Green Hydrogen Plant and Donaldsonville Green Hydrogen Project. The St. Gabriel Green Hydrogen Plant is projected to produce 15 tons of hydrogen per day. In Donaldsonville, the plant will be integrated into the ammonia plant already existing there. This plant will then be able to produce green hydrogen and green ammonia, adding up to 20,000 tons combined per year. When this construction is finished in late 2023, it will be the largest combined plant in the Americas [32]. In Illinois, the Sauk Valley Green Hydrogen Plant will also be completed by the end of 2023. All of the electricity for this production plant will be generated from a nearby solar plant. This plant will not only produce 52 tons of hydrogen, but it is able to store 400 kg of hydrogen at the plant. This is around three days of work for the plant. The other green hydrogen plants planned to be finished with construction in 2023 are the Casa Grande Green Hydrogen Plant and the Kingsland Green Hydrogen Plant. Both of these are able to produce 15 tons of hydrogen per day, and both will first liquefy the hydrogen before transport [23]. In the United States and many other countries, hydrogen is typically produced close to where it is used. The distribution of hydrogen has been a hurdle for the United States due to the lack of funding for distribution projects. The funding for hydrogen has recently been allocated only to the green hydrogen production plants planned for construction. However, distribution and storage are important in delivering hydrogen to potential fueling stations in the future. The distribution of hydrogen has been an underrated issue in the United States even after President Bush's hydrogen initiative [24]. Currently, hydrogen is only distributed in the United States using a small number of pipelines, liquified hydrogen tanks, or high-pressure tanks. The small amount of hydrogen pipelines is equal to only around 1,600 miles of pipe. These pipelines are near the few hydrogen plants and deliver to specific refineries nearby instead of larger hydrogen distribution centers [19]. Hydrogen pipelines would be the best option for hydrogen distribution based on the low energy per unit volume hydrogen has. This low energy is causing more fuel, meaning today's most used fuel, gasoline, to be consumed than the amount of hydrogen being transported. Essentially, transporting hydrogen by vehicle consumes more energy than the output of hydrogen energy. If an increase in local hydrogen production facilities and distribution centers were to be built, this issue of energy consumption would be managed [24].

7. Successful adoption

Case studies of successful hydrogen adoption provide valuable insights into the practical application and benefits of hydrogen in different sectors. One notable example is the hydrogen fuel cell vehicle industry. Japan has been a frontrunner in this field, with companies like Toyota and Honda introducing commercially available hydrogen fuel cell electric vehicles to the market. The Mirai from Toyota and the Clarity from Honda have demonstrated the feasibility of fuel cell vehicles, offering long driving ranges, fast refueling times, and zero emissions. Japan has also invested in building a comprehensive hydrogen infrastructure, including a network of refueling stations, to support the widespread adoption of fuel cell vehicles [19]. Another successful case study is the use of hydrogen in industrial processes. The Norwegian company Yara, a leading producer of ammonia, has successfully integrated hydrogen into its ammonia production process. By replacing natural gas with hydrogen, Yara's ammonia production facility in Porsgrunn has significantly reduced carbon emissions. The project, known as "Yara Pilbara," demonstrates the potential of hydrogen as a clean alternative in the production of chemicals, particularly in the ammonia industry. The success of Yara Pilbara showcases the technical feasibility and environmental benefits of hydrogen adoption in industrial processes [17]. The Hyundai Steel Dangjin plant in South Korea serves as another noteworthy case study. The steel industry is one of the most carbon-intensive sectors, and Hyundai Steel has implemented hydrogen-based technologies to reduce emissions. The plant incorporates hydrogen in the direct reduction of iron ore, a key step in steelmaking. By using hydrogen instead of coal, Hyundai Steel has achieved a significant reduction in carbon emissions, making notable strides towards producing low-carbon steel [29]. Figure 11 depicts the annual fuel cell vehicle sales in the world. It shows a large increase in fuel cell vehicles in South Korea and a slight drop in sales in the United States. This drop in the U.S. is due to the increase in demand for electric vehicles due to the newly increasing amount of charging stations. The increase in fuel cell vehicles in Japan started later than that in South Korea. This is due to Japan focusing on hydrogen production before they focused on hydrogen transportation vehicles [35].

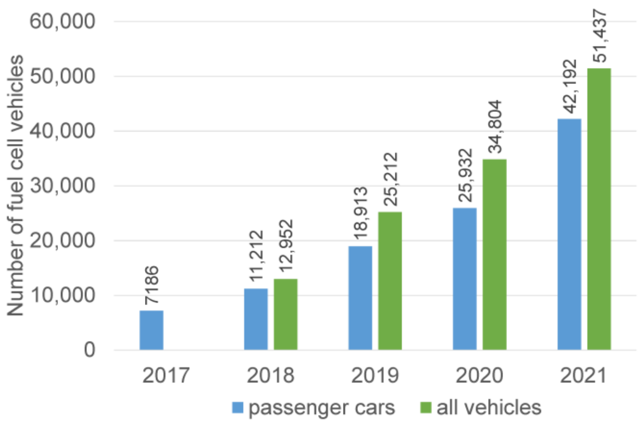


Figure 11. Annual fuel cell vehicle sales [36]

8. Conclusions

Hydrogen adoption will continue to progress in different industries in many countries. There are many countries not mentioned in this paper that have also gone on to switch to hydrogen or other green methods of energy production. The amount of funding designated for hydrogen production and distribution in different countries has seen a large increase in the past few years and is expected to continue to see an increase until greenhouse gas emissions decrease. The collaborative efforts between, industries, governments, and research institutions have the opportunity to decrease greenhouse gas emissions at a rapid rate. This decarbonization potential will lead to a future of sustainable energy. The hydrogen road maps being produced by different countries are increasing the chances of a complete return to normal temperature rises in the globe after multiple years. This article enhanced the importance of hydrogen energy to the decrease in emissions. Without the switch to green hydrogen or other green energy production methods, the rate of fossil fuel depletion will not change and future generations will not have fuel for energy production. As the population increases the energy consumption rate will continue to increase. The switch to hydrogen will be increasingly more necessary as the space for solar panels and wind turbines begin to decrease. Hydrogen may not be the most safe option for fuel, but other fuels used today have also been seen as unsafe during different times of production and utilization. While there have been some severe experiences with hydrogen in the past, engineers and scientists will continue to gain knowledge of the gas and continue to find safer ways to handle the gas. Hydrogen may always have a stigma, but fossil fuels will have the stigma of continuously ruining the atmosphere with greenhouse gas emissions. In the end, a hydrogen initiative will improve the quality of life and help reach goals made for the quality of future lives.

Ethical issue

The author is aware of and complies with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The author adheres to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

This paper does not involve data sharing since no datasets were generated or analyzed during the current study.

Conflict of interest

The author declares no potential conflict of interest.

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