sustainability

MDPI

Review

Greenhouse Gas Emission Dynamics of Saudi Arabia: Potential of Hydrogen Fuel for Emission Footprint Reduction

Adeola Akinpelu [1], Md Shafiul Alam [1], Md Shafiullah [2,*], Syed Masiur Rahman [1,*] and Fahad Saleh Al-Ismail [1,2,3]

1 Applied Research Center for Environment and Marine Studies, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia
2 Interdisciplinary Research Center for Renewable Energy and Power Systems, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia
3 Electrical Engineering Department, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia
* Correspondence: shafiullah@kfupm.edu.sa (M.S.); smrahman@kfupm.edu.sa (S.M.R.)

Abstract: The growth of population, gross domestic product (GDP), and urbanization have led to an increase in greenhouse gas (GHG) emissions in the Kingdom of Saudi Arabia (KSA). The leading GHG-emitting sectors are electricity generation, road transportation, cement, chemicals, refinery, iron, and steel. However, the KSA is working to lead the global energy sustainability campaign to reach net zero GHG emissions by 2060. In addition, the country is working to establish a framework for the circular carbon economy (CCE), in which hydrogen acts as a transversal facilitator. To cut down on greenhouse gas emissions, the Kingdom is also building several facilities, such as the NEOM green hydrogen project. The main objective of the article is to critically review the current GHG emission dynamics of the KSA, including major GHG emission driving forces and prominent emission sectors. Then, the role of hydrogen in GHG emission reduction will be explored. Finally, the researchers and decision makers will find the helpful discussions and recommendations in deciding on appropriate mitigation measures and technologies.

Keywords: greenhouse gas emissions; hydrogen; renewable energy; Saudi Arabia

Citation: Akinpelu, A.; Alam, M.S.; Shafiullah, M.; Rahman, S.M.; Al-Ismail, F.S. Greenhouse Gas Emission Dynamics of Saudi Arabia: Potential of Hydrogen Fuel for Emission Footprint Reduction. *Sustainability* **2023**, *15*, 5639. https://doi.org/10.3390/su15075639

Academic Editor: Reza Daneshazarian

Received: 10 February 2023
Revised: 16 March 2023
Accepted: 20 March 2023
Published: 23 March 2023

1. Introduction

It is one of the most significant challenges of our time to ensure that everyone on the planet has access to affordable, reliable, and sustainable energy, considering population growth, climate change, fossil fuel reserves, and energy security concerns. The energy sector is booming around the world, and this is particularly true in Saudi Arabia. Because of this phenomenon, the demand for fossil fuels is rising on a national and global scale. The country's oil industry heavily influences socioeconomic development in Saudi Arabia. In 2010, Saudi Arabia was the world's largest producer and exporter of total petroleum liquids and the world's second-largest crude oil producer [1–3]. Oil accounts for over 80% of Saudi Arabia's budget revenues, 45% of GDP, and 90% of export earnings. This makes the economy vulnerable to the volatile global oil market [4]. Furthermore, the oil industry is highly exposed to international trade. Global climate change policy will significantly impact the world's development in a carbon-constrained manner.

As one of the world's carbon dioxide (CO_2) emitters, Saudi Arabia has a wide range of sectors that contribute to its high emissions levels, including electricity generation, road transportation, chemical, construction, and petroleum industries [5–7]. The GHG emissions reduction strategies from various sectors have been examined in several studies [8,9]. For example, Rahman et al. [10] summarized GHG emissions from the KSA's transportation sector, including several mitigation measures. Based on a comprehensive literature review, it is observed that there is no comprehensive study on multisector GHG emission dynamics with an alternative mitigation approach in the Kingdom. Particularly, the contribution of H_2 in mitigating GHG emissions in the Kingdom is not comprehensively discussed in the literature. Therefore, this study included an analysis of the historical fossil fuel-based energy consumption trend, a method of forecasting energy consumption, and a study of projected and estimated GHG emissions. Different mitigation options and the contribution of H_2 in the mitigation of GHG are reviewed in this work. Among the several energy sectors, the electricity generation system emits a large amount of GHG due to burning many fossil fuels. Thus, in [7], GHG emission reduction from the electricity generation sector of the KSA is discussed considering several aspects such as electric power generation dynamics, strategies and initiatives towards the mitigation of GHG from the electricity sector, carbon capture, utilization, and sequestration (CCUS), and energy efficiency measures. The role of CO_2 capture and storage (CCS) in shaping Saudi Arabia's future energy policy is broadly discussed in [11]. First, a thorough evaluation of the CCS strategic context should consider Saudi Arabia's CCS research activities and CO_2 emissions and storage potential. Then, it examines stakeholder views on Saudi Arabia's role in CCS by surveying oil and gas professionals in the Middle East and North Africa (MENA). Adopting a strategy, policy, or program is essential to reduce GHG emissions from several sectors. These strategies focus on rationally using energy and energy-efficient technologies and devices.

A promising alternative to the future fossil fuel-based energy systems seems to be hydrogen-based. This is because it is an environmentally friendly fuel and has increased efficiency [12]. With almost zero greenhouse gas emissions potential, hydrogen can be produced from various resources, including wind, solar, natural gas, geothermal, and biomass [13]. In [14], considering the long-term energy scenario, the economic benefits and role of hydrogen and synthetic energy carriers in Germany were studied. The excellent correlation between de-carbonization aims and the fraction of hydrogen-based carriers in final energy demand highlights the importance of meeting climate targets. Furthermore, value creation benefits of around 16 billion EUR/a can be anticipated for hydrogen-based carriers in 2050. On the other hand, poor lignocellulose waste management creates severe environmental contamination and health problems. Due to the ongoing depletion of traditional biofuels, converting such wastes, particularly sugarcane bagasse, into bioenergy is a sustainable solution. In [15], biogenic H_2 production from sugarcane bagasse with a sustainable fermentation approach was introduced. In [16], a graphene/hydroxyapatite nano-composite was reported to increase H_2 productivity from delignified duckweed.

The top global economies, including the United States, China, Japan, Germany, India, the United Kingdom, France, and others, have initiated developing hydrogen projects to reduce GHG emissions. For instance, a road map to a USA hydrogen economy has been developed by a consortium of the fuel cell, fuel oil, hydrogen, electricity, and automotive industries [17]. This in-depth road map explains how, if policymakers and businesses take the appropriate actions, the USA can increase its position as a global energy leader by increasing engagement in the quickly developing and growing hydrogen economy. One of the world's largest producers and users of hydrogen is China. China has raised its annual hydrogen output by 6.8% since 2010 to reach 33 million tons in 2020 [18]. Since 2020, a process that has been gaining momentum, hydrogen has been incorporated into several high-level national energy and technology development strategies. A hydrogen development plan for the years 2021 to 2035 was published in March 2022 by China's top economic planner, further accelerating the country's use of hydrogen. Other G20 nations, including the KSA, have developed a long-term plan for hydrogen generation, specifically renewable energy-based green hydrogen, to fight climate change [19,20].

As per the intergovernmental panel on climate change (IPCC) Sixth Assessment Report, in some situations and land-based transportation sectors, hydrogen and hydrogen derivatives with low greenhouse gas emissions, such as synthetic fuels, may provide promise for mitigation [21]. The hydrogen for energy and feedstock, carbon capture and utilization technologies, and innovation in circular material flows can help decarbonize most industrial processes. While Net Zero CO_2 energy systems will have some commonalities, the implementation in each nation will vary depending on local conditions. Net zero CO_2 energy systems will typically have the following characteristics [22–26]: (1) Electricity systems that produce no net CO_2 or remove CO_2 from the atmosphere. (2) Widespread electrification of end uses, such as light-duty transportation, space heating, and cooking. (3) Significantly lower use of fossil fuels than today. (4) Use of alternative energy carriers, such as hydrogen, bioenergy, and ammonia to replace fossil fuels in sectors less amenable to electrification. (5) More efficient electrical systems. How rapidly and far production technology advances, such as from electrolysis bio-gasification and fossil fuel reforming with CCS sources, will determine the future role of hydrogen and hydrogen derivatives [27,28]. In general, and across all industries, using energy is directly more efficient than creating hydrogen, ammonia, or artificial low-GHG hydrocarbons, which results in ever higher conversion losses. However, hydrogen does give power generated from clean variable sources more flexibility in time and place. This flexibility can be used to make hydrogen, store electricity in fuel cells or turbines, or provide raw materials for manufacturing.

According to the discussions, the available literature lacks a thorough analysis of multisector GHG emission dynamics with potential mitigation approaches in the Kingdom. Particularly, the contribution of H_2 in mitigating GHG emissions in the Kingdom is not comprehensively discussed in the literature. To bridge this gap, H_2 in mitigating GHG emissions is reviewed in this work. This study critically investigates the GHG emissions of the KSA from several sectors. It discusses the major driving forces for emissions, sectorial emissions, and emissions from different sources. Another distinguishing feature of this review is that it provides a comprehensive list of recommendations to reduce GHG emission in the KSA from several factors so that the country can achieve net zero emissions by 2060. In addition, the prospects of green hydrogen in the KSA are discussed to mitigate GHG emissions. Moreover, it is expected that the researchers will find the discussions and recommendations of the article worthwhile while shaping up their future research in developing technologies for GHG emission reduction with hydrogen fuel.

The remainder of the article has the following structure: Section 2 describes the current GHG emission scenario of the country, focusing on emissions and factors of emissions. Then, Section 3 presents the role of hydrogen in GHG emission mitigation after providing its potential uses. Finally, this review is concluded in Section 4.

2. Historical Greenhouse Gas Emission Trends

2.1. Major Driving Forces of GHG Emission

The KSA stands at the crossroads of the Arab and Islamic worlds. Saudi Arabia is the Middle East's largest country and has the world's 18th-largest economy [29]. Saudi Arabia now has 0.45% of the world's population [29]. However, Saudi Arabia's population continues to rise due to its thriving economy and the influx of expatriates worldwide. According to the United Nations, Saudi Arabia's population will be 35.34 million in 2021 [30]. This represents a 1.50% increase from 34.81 million in 2020, which is expected to continue to rise until 2060. Saudi Arabia's average population growth rate is 1.59%. If the current trend continues, the population will reach 44.6 million by 2050 [31]. As seen in Figure 1, the Kingdom's population has been on the rise for several decades. However, due to the government's new expatriate depopulation policies, the population growth rate is expected to drop by 1.09% by 2030 and another 0.27% in the next 30 years. It is generally known that energy demand and supply increase as the population rises. Therefore, associated CO_2 emissions will also rise. According to the CO_2 emission data released by 'Our World in Data' as presented in Figure 1, it is clear that as the population increases, CO_2 emission increases over the years [32,33].

The proportion of a country's population living in cities is called urbanization. In 2020, cities accounted for 84.29% of Saudi Arabia's population. As a result, the Kingdom of Saudi Arabia is one of the world's most urbanized countries, with eight out of ten inhabitants living in cities. Saudi Arabia has witnessed substantial urbanization since the 1950s. Saudi Arabia's urban population has grown from 21% in 1950 to 58% in 1975 to 83%

in 2015 and is expected to reach 86% by 2030 and 90% by 2050 [34]. Due to the rapid urban population growth, major urban settlements have sprung up to accommodate the demand for new housing, companies, industrial sectors, and transportation infrastructure. New road infrastructures are being created to handle rising urbanization and meet the travel demand. These new road infrastructures will give access and mobility to the increased traffic. As a result, the transportation sector's use of fossil fuel-based energy increases, as does the sector's GHG emissions, particularly when private transportation is used by 92% of urban residents [35]. To serve the city's people and improve the Kingdom's economic fortunes, many utility businesses and significant GHG emissions sectorial drivers are concentrated in the cities. As a result, metropolitan areas likely account for most of the Kingdom's GHG emissions. As shown in Figure 1, CO_2 emissions follow a similar trajectory to urbanization.

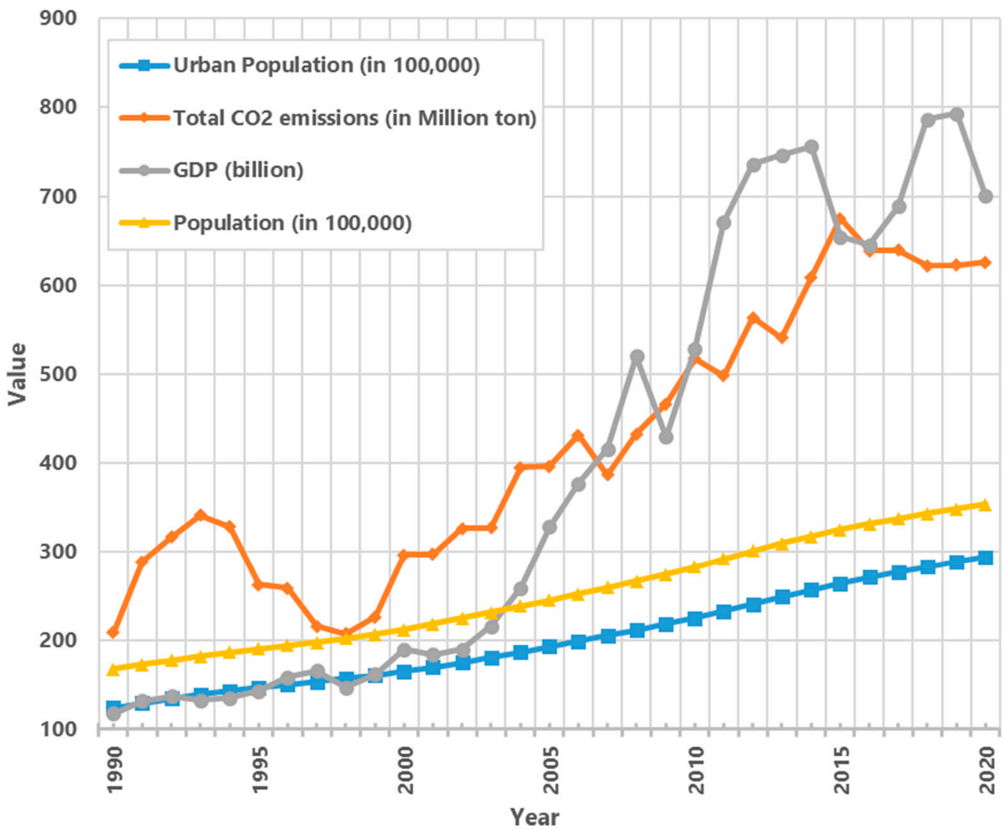

Figure 1. Saudi Arabia's CO_2 emission, urban population, total population, and GDP [32–36].

Another vital component of the Kingdom's progression is its economy. The GDP has been upward over the years. The Kingdom has been increasing its economic fortunes over the years. The Kingdom's economic importance was globally recognized in 2008 by enlisting the country among the G20 due to its crucial importance as a pricing force in the world's energy markets. In addition, the Kingdom has the world's eighth sovereign wealth fund [37]. Its entry into the G20, which includes the world's largest and fastest-growing economies, has increased its influential role as a solid industrial and financial base in the global economy. Aggressive economic activities are going on locally to achieve this global economic feat. Significant expansion of oil infrastructures has been pursued while new resources are being extensively explored. This positive economic trajectory implies that there will be more GHG emissions, except green scientific approaches are applied to the current processing infrastructures. Therefore, like the urbanization rate, the GDP has a very close positive correlation with CO_2 emission.

2.2. Sectorial Emissions

Dissecting each sector's contribution to the Kingdom's CO_2 emission is pertinent. The performance of different sectors such as energy, industrial processes, product use, waste, agriculture, land use change, and forestry decide the Kingdom's CO_2 emission curve pattern. One of the most powerful energy sources in the world today is fossil fuel. Saudi Arabia is the world's largest producer and exporter of total petroleum products, and its economy is heavily dependent on oil and petroleum-related industries [38]. Similarly, Saudi Arabia's domestic energy consumption has dramatically risen during the last three decades [39]. The rising population, rising living standards, and the population movement to the urban areas contributed to the high domestic energy consumption. As a result, energy consumption is growing, and as a result, GHG emissions are rising [40]. Therefore, according to the 2019 fourth assessment report (AR4), the total emissions of GHG were estimated at 646.42 Mt, of which the energy sector contributed 81.7%, 10.2% from the industrial process sector, 5.5% from waste, 2.1 % from agriculture, and 0.53 % from others [33].

Figure 2 shows the GHG contribution of critical sectors to the Kingdom's total GHG emissions for the years 1990, 2000, 2010, and 2019. As can be seen, the energy sector has the highest share (more than 80% for all studies years), so it is more sensible to investigate the energy source categories. The primary source categories of the energy sector were electricity generation, road transportation, industry, and residential, which accounted for around 36.7 %, 21%, 14%, and 0.77% of total CO_2 emissions, respectively, in 2019, according to International Energy Agency (IEA) [41]. The total CH_4 emissions were estimated at 4.7 Mt, of which 29% were contributed by the waste sector, 68% by the energy sector, and 1.9% by the agriculture sector in 2019 [33]. The total emissions of N_2O in Saudi Arabia were 60 Kt in 2019. Approximately 66.6% of the total N_2O emissions were generated only by agriculture. The waste sector contributed about 7.9% of the total N_2O emissions. Industrial process and product use contributed 8.6%, while energy contributed 5.3% [42]. After the energy sector, industrial processes and product use contributed 10.2% to the Kingdom's GHG emissions in 2019. Industrial processes and product use include cement manufacturing, petrochemical manufacturing, fertilizer manufacturing, iron and steel manufacturing, and other industries. Fuel combustion is a significant source of energy for these sectors. Therefore, according to a national report released in 2016, total emissions from fuel combustion in these activities were 60,179 Gg CO_2, 4.94 Gg CH_4, and 0.15 Gg N_2O. The major contributors to CO_2 and CH_4 emissions in this category were activities associated with the petrochemical, cement, and fertilizer sectors. Aside from GHG emissions from the energy source, the operation of these industries also generates GHG. In the industrial sector, cement production produced the most CO_2 (52%), followed by iron and steel manufacturing (38%) and ammonia production (9%). Chemical manufacturing was this industry's single source of 35.7 Gg of CH_4 emissions. The cement sector was the leading source of N_2O emissions from the manufacturing and construction industries, followed by the petrochemical and fertilizer industries [43].

The generation of solid waste (SW) in the Kingdom of Saudi Arabia has been increasing due to population increase, urbanization, and industrial development. Hence, the accompanying greenhouse gas (GHG) emissions are also rising. The waste sector produces greenhouse gases because of industrial and municipal solid waste management and wastewater treatment facilities. Saudi Arabia's waste sector accounted for 5.5% of the country's total greenhouse gas emissions in 2019. Landfilling, recycling, and incineration are all options for solid waste disposal. In specific landfill regions, recyclables are separated. In Saudi Arabia, solid waste incineration is strictly controlled and prohibited on landfill grounds. As a result, landfills account for most greenhouse gas emissions from solid waste management. CH_4 accounts for around half of the greenhouse gas produced in landfills. The amount of CH_4 produced by solid waste management is projected to be 598 Gg, accounting for 76% of total methane produced. Municipal and industrial wastewater treatment plants additionally produce about 4.24 Gg of CH_4. Methane emissions from total waste are expected to increase at an average annual rate of 5.13% between 2020 and

2050, reaching over 4000 Gg by the end of the year 2050, according to a study based on various population and GDP development scenarios [44].

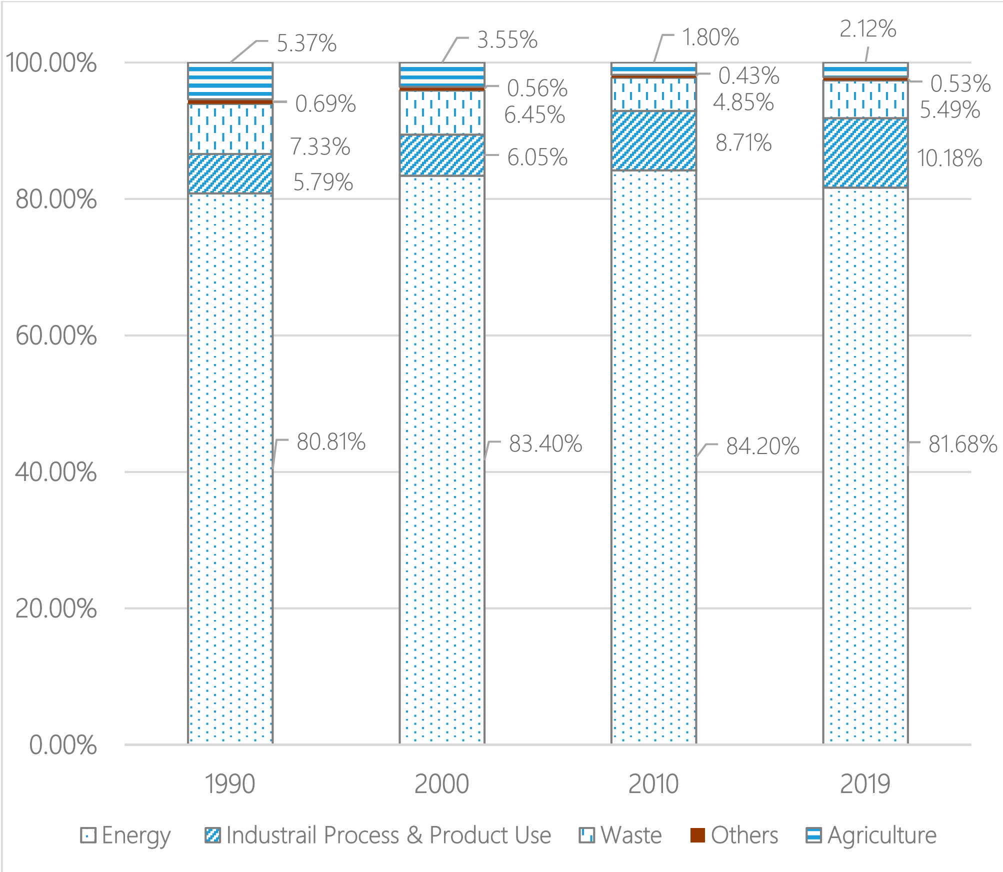

Figure 2. Saudi Arabia's Sectorial GHG Emission (Mt) over the decades [42].

Agriculture is another sector that insignificantly contributes to the Kingdom's CO_2 emission. According to 2019 GHG emission data, agriculture contributed 13.7 Mt (2.1%) of GHG to the Kingdom's total GHG. Over the last few decades, the Kingdom's agricultural development has seen substantial changes because of new policies to ensure food security. The government has supported this trend by transforming vast swaths of desert into farming land. This was made possible through the implementation of large-scale irrigation projects and the adoption of large-scale mechanization. Saudi Arabia's agriculture is currently centered on the production of wheat, dates, fish, poultry, and other agricultural products, as well as the export of part of these volumes to neighboring nations and worldwide players. The government has launched many policies to maintain continuous development in the sector [43]. Under agriculture, according to the 2016 report of the 2010 GHG data inventory, field burning of agricultural leftovers was responsible for 100% of the CO_2 emissions of the agriculture sector. Enteric fermentation accounted for 80% of CH_4 emissions (59,270.6 tons), manure management accounted for 17.6% (13,085.6 tons), and field burning of agricultural residues accounted for 0.02% (1707.7 tons). Agricultural soils were responsible for 70% (19,772.8 tons) of agricultural N_2O emissions, with manure management accounting for 30% (8590.1 tons) [43].

3. Role of Hydrogen in GHG Emissions Reduction

3.1. Uniqueness of Hydrogen

This energy and hydrogen have a long history; more than 200 years ago, hydrogen powered the first internal combustion engines and is now a crucial component of the modern refining sector. It emits no greenhouse gases or pollutants and is light, storable, and energy dense. However, it is necessary to adopt hydrogen in areas where it is virtually nonexistent, such as transportation, buildings, and power generation, to significantly contribute to clean energy transitions. The future of hydrogen is a thorough and unbiased examination that outlines the industry's current state, how it may contribute to developing a clean, secure, and cost-effective energy future, and how to realize its promise [45]. In normal earth conditions, hydrogen is a colorless, tasteless, odorless, and non-poisonous gas. Although hydrogen is an abundant element, it is not found in its pure form, as it easily mixes with other ingredients. It is also the lightest element, with a density of 0.08988 g per liter at standard pressure. The utilization of hydrogen as a fuel depends on several significant chemical properties mentioned below [46]:

- ✓ The hydrogen can be kept under higher pressure or as a liquid at extremely low temperatures to boost the volumetric energy density.
- ✓ It has an effective energy content per weight (almost three times that of gasoline), but at typical temperatures and pressure, the energy density per volume is relatively low.
- ✓ Due to excellent flammability, hydrogen may be ignited and burned with little energy.
- ✓ Hydrogen combustion releases no sulfur, carbon dioxide (CO_2), or particle pollutants. Thus, it supports sustainable development.
- ✓ Renewable resources can be used to make hydrogen by electrolyzing water generally fed to the gas network to bypass the constrained electricity systems.

Several factors, such as storage of fluctuating renewable energy, emission reductions from transportation and industry sectors, and utilization of existing storage and pipeline infrastructure, dominate the current interest in hydrogen as an energy source and commodity.

3.2. Use of Hydrogen

Hydrogen has been considered a promising alternative fuel for various industries and technologies due to its high energy content and zero greenhouse gas emissions when used in fuel cells. Therefore, it can be used for various industries and technologies. Hydrogen fuel cell vehicles (FCVs) have been manufactured as an alternative to gasoline and diesel vehicles for transportation. FCVs are powered by hydrogen fuel cells that convert hydrogen and oxygen into electricity, with the only byproducts being water and heat. According to a report by the International Energy Agency, the number of FCVs on the planet's roads will reach approximately 10 million by 2030 [47].

It can be used as an energy storage medium, particularly for intermittent renewable energy sources such as wind and solar power. This excess energy can be used to produce hydrogen via water electrolysis and stored for later use. When hydrogen is required, it can be used to generate electricity in fuel cells [48]. It can be utilized in gas turbines and other combustion engines to produce electricity. It can also be used to generate electricity in fuel cells with high efficiency and no greenhouse gas emissions [49]. It can also be utilized as a building fuel for heating and cooling. It can be burned in furnaces and boilers to generate heat or in fuel cells to generate electricity and heat [50].

It can serve as a feedstock to produce chemicals in the industrial sector, including ammonia, methanol, and hydrogen peroxide. These chemicals are widely employed in producing fertilizers, plastics, and pharmaceuticals in the chemical industry.

3.3. Hydrogen Value Chain

Production, storage, distribution, and consumption make up the three segments of the hydrogen value chain. To assure safety, reduce costs, and ensure adherence to rules, norms, and standards in each domain requires experts [51]. The value chain of hydrogen can be realized in Figure 3. Hydrogen, produced by water electrolysis, is used in the fuel cell. During chemical reactions in the fuel cell, water appears again as a byproduct to complete a circular cycle. The use of renewable energy for the production of green hydrogen is considered a sustainable way. This has been made possible in nations such as the United States, China, Canada, Brazil, and others where hydroelectric power plants generate a large amount of electrical energy and where there are times of the year when there is excess energy supply than the actual demand. Thus, this extra energy is utilized in the electrolysis process to generate hydrogen. It provides an alternative method of utilization of electric power. The resulting hydrogen can then be stored or applied to various chemical processes, whether traditional or energetic. Similarly, electrical energy derived from other renewable energies, such as wind, solar, or ocean energy, may also be used for the electrolysis of water to produce hydrogen [52–54]. In these circumstances, producing hydrogen by water electrolysis with renewable energy has two additional advantages.

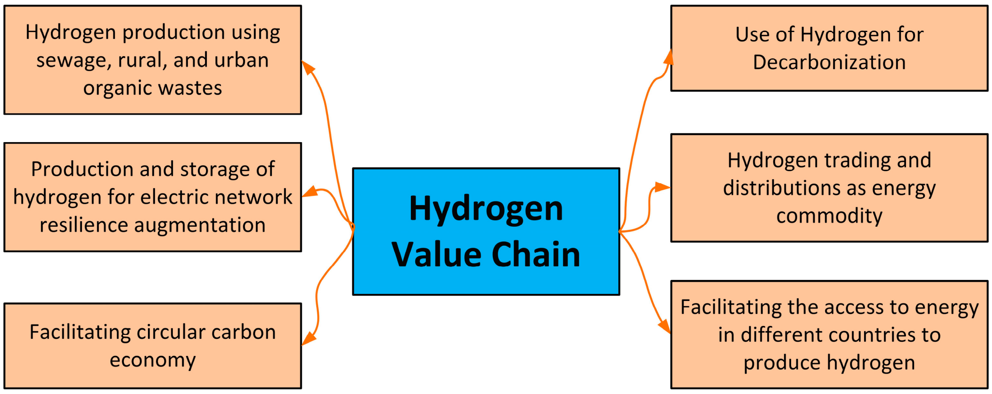

Figure 3. Representation of hydrogen value chain.

The first is that hydrogen production facilitates uncertainty management of renewable energy generation, which is inherently intermittent. When there is a lack of water, wind, sun, or ocean activity but still a need for energy, the hydrogen that has previously been produced and stored can be used to make electricity using fuel cells and turbines [55–57]. The second advantage of storing hydrogen is that it can serve as a buffer to increase the robustness of an entire country's or region's energy system, considering all methods used to produce renewable electricity and stabilizing a localized electric energy distribution network [58]. Most of the waste produced in metropolitan and rural areas is organic. A significant amount of sewage is also produced, left untreated, or only partially treated before being released into the environment. Bacteria, viruses, protozoa, and parasites are typically present in sewage and are carried by it. All sewage and organic waste from cities and rural areas can be processed to create hydrogen or hydrogen-rich gases. This decarbonization with hydrogen has two different effects on the industry. The first concerns the accessibility of superior thermal energy and pure electricity. Many devices and systems can be powered by fuel cells, and feeding hydrogen to burners and heat exchangers can provide low-grade and high-grade heat. The second is the availability of feedstock, especially for the chemical industries, which was formerly produced using fossil fuels and was made up of a variety of hydrocarbons but can now be alternatively produced using hydrogen and biomasses, making them of renewable origin and allowing the use of the same industrial processes already in use to create the end products [59].

The use of hydrogen is likely to reduce carbon emissions in two more industries: transportation and distributed combined heat, power, and cooling generation [60]. First, the increasing number of cars in cities and heavy-duty vehicles for long distances create a significant environmental and social barrier. Even though people use vehicles for personal purposes and because of the freedom of movement they symbolize, light- and heavy-duty vehicles, such as buses and forklifts, have quickly acquired market share thanks to hydrogen fuel cells [61]. The second one offers the additional benefit of switching from centralized combined heat and power generation and distribution over long distances, which results in energy losses and high overall inefficiency, to distributed combined heat and power generation. This technique takes advantage of the technological advancements made to avoid and control the dispersion of harmonics into the grid and the existing legal framework for exploiting the well-established distributed power generation using wind and solar energy systems [62]. On the other hand, harmonics have several negative impacts, such as damaging equipment and reducing life expectancy and dependability. A summary of the hydrogen value chain is provided in Table 1.

Table 1. Summary of hydrogen value chain (adopted from Ref. [63]).

Value Chain	Applications	Evaluation
Use of hydrogen as electricity storage	Electric energy sector	✓ High cost ✓ De-carbonization only in the electricity sector
Hydrogen production from excess electric energy	Electric energy and heat sector	✓ Hydrogen generation entirely depends on excess electric energy. ✓ This works under only specific conditions.
Use of hydrogen as a commodity	Energy, green chemicals, and mobility	✓ Low cost. ✓ The market potential is very high. ✓ Importing hydrogen through pipelines facilitates de-carbonization. ✓ Centralized and decentralized plants can be used for the production mix.

3.4. Applications of Hydrogen in Saudi Arabia for GHG Emission Reduction

As per the 2030 vision of the KSA, the ministry of energy has an ambitious plan to integrate about 40 GW of PV systems by 2030. Also, the KSA is working to achieve zero carbon emissions by 2060 [64]. Thus, the KSA is exploring ways to become the top hydrogen supplier in the world to help reach this goal. In response to growing requests worldwide to reduce climate change risk, major economies, including the US, China, India, EU, and Saudi Arabia, announced Net Zero emissions strategies in 2021. Energy production, use, and transportation will significantly change as society moves closer to a net zero economy. This implies that the energy industry will drastically reduce its carbon footprint to provide cleaner and more environmentally friendly electricity in the future.

Due to its unique properties, hydrogen is anticipated to significantly decarbonize the entire global energy supply chain over the next three decades. According to the IEA Designing and Communicating Net-Zero Special Report [65], as the production of H_2 is anticipated to increase six-fold by 2050 to meet rising demand in shipping, road transportation, and heavy industry, approximately 75% of the cumulative emissions reductions in the net zero emissions scenario are related to H_2. It is regarded as a type of energy carrier, much like electricity. Most of the present production and usage occurs in petrochemical and refinery plants, which process hydrocarbons such as diesel or create chemicals such as ammonia and methanol. As a result, the potential of hydrogen as an energy carrier has not yet been fully realized [66]. According to the most recent hydrogen insights report by the hydrogen council, however, there has been a rapid acceleration toward the H_2 economy, with over three hundred announced large-scale projects spanning from renewable-based H_2 to industrial use and infrastructure development.

The current methods for producing hydrogen need a lot of energy and emit carbon into the atmosphere. This type of hydrogen is commonly known as "grey hydrogen". Grey hydrogen also comprises grid-connected water electrolysis, a sizeable hydrocarbon-dependent component of the power mix [67]. Environmentally friendly hydrogen manufacturing processes capture the accompanying carbon emissions. For instance, steam reforming of hydrocarbons in conjunction with CCUS (carbon capture, utilization, and storage) technology can reduce atmospheric carbon dioxide emissions. Blue hydrogen is produced using this technique. Alternately, hydrogen can be made by electrolyzing water and utilizing clean electricity to separate the hydrogen atoms from the oxygen molecules. "Green hydrogen" is the term used to describe this process. At the moment, green hydrogen is pricey. However, improvements in performance and economies of scale for electrolyzers, along with dropping costs for renewable energy, may eventually make them competitive [68]. These improvements include the development of alternative production technologies such as electrolysis and advances in hydrogen production methods' efficiency and capital costs [69,70]. The economic viability of hydrogen is rising because of these technological advancements and the falling price of renewable energy. The development of further improvements in hydrogen-based technology is also accelerating. By 2030, gas turbines might exclusively run on hydrogen instead of the blended fuels they currently use, which range in volume from 5 to 95% [71]. Since the early 2000s, fuel cell costs have been reduced by 80–95% while power density and durability have increased [72,73]. Planning for the significant growth of low-carbon energy infrastructure, including low-carbon power generation and hydrogen production, is becoming increasingly necessary to support emissions reductions in the transportation sector [74].

In 2020, Saudi Arabia presided over the G20 countries. Throughout its tenure, the KSA played a leading role in advancing the circular carbon economy framework, a practical international strategy for managing fugitive carbon emissions. As a result, the G20 member countries' energy ministers accepted this framework, which is viewed as a comprehensive approach to lowering emissions. The conventional "take-use-dispose" paradigm is the linear economy's foundation. In contrast, the CCE emphasizes energy and carbon flows while using circularity to advance sustainability. Four pillars—reduce, reuse, recycle, and remove—form the foundation of the CCE. The effectiveness of each pillar in reducing carbon emissions depends on the technology, resources, and conditions in each country, as well as supportive policies [68]. A technology-agnostic strategy, such as the CCE, is essential for lowering atmospheric carbon emissions at the lowest possible cost because no single solution works for all nations. In the CCE, hydrogen serves as a cross-cutting facilitator [75]. It can cross the four pillars due to its adaptability in various applications and low-carbon manufacturing methods, as shown in Figure 4. On the supply side, carbon emissions can be decreased by switching from grey hydrogen production to blue or green hydrogen production.

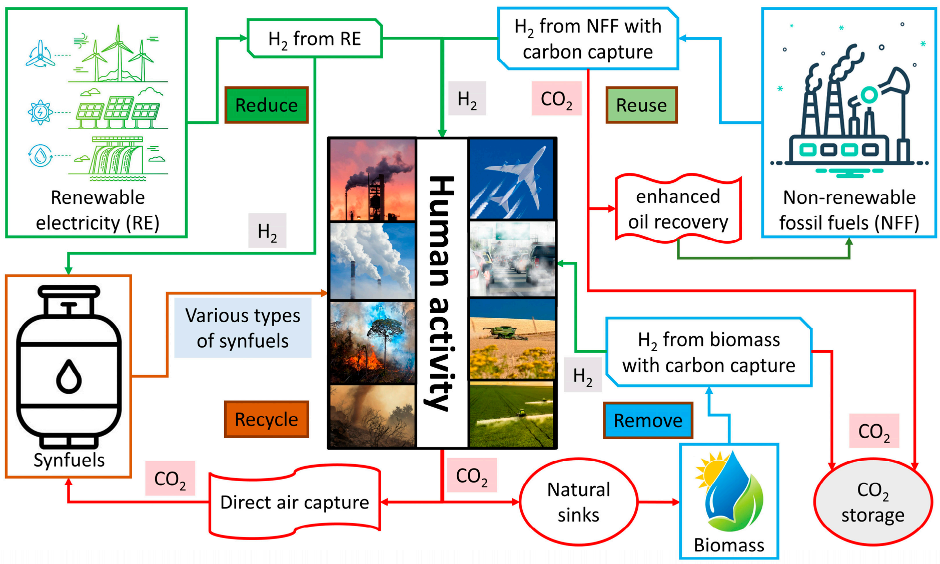

Figure 4. Hydrogen in circular carbon economy (adopted from the International Energy Agency report of Ref. [75]).

The largest utility-scale, commercial-based hydrogen facility fueled by renewable energy is the NEOM green hydrogen project [76]. The joint venture between NEOM, Air Products, and ACWA Electricity project would incorporate cutting-edge integration of a combined capacity of over four gigawatts of renewable power from solar, wind, and storage and is based on proven world-class technology. When put into operation in 2026, it will create 1.2 million tons of green ammonia annually using Haldor Topsoe technology, 650 tons per day of hydrogen by electrolysis using ThyssenKrupp, and nitrogen by air separation using air products technology. Once completed, the project will reduce the annual impact of 3 million tons of carbon dioxide.

4. Conclusions

Greenhouse gases can have a wide range of environmental and health consequences. Due to their role in trapping heat, they play a role in global warming and respiratory disease caused by smog and other air pollution. Other consequences of human-caused climate change include increased wildfires, weather extremes, and disruptions to food supplies. Therefore, reducing GHG emissions is crucial for sustainable development. This paper summarized the GHG emission dynamics of Saudi Arabia and found the energy sector as the dominant GHG emitter (almost 82% in 2019), followed by other sectors, industrial process and product use, waste, and agriculture. Energy sector CO_2 emissions have risen by nearly 300% in 2019 compared with those in 1990. Developing green hydrogen facilities in several ongoing ambitious projects may lead to significant emission reduction in the country. The initiative will also help the Kingdom become a leading hydrogen supplier. The government has already investigated ways to establish a hydrogen supply chain by making hydrogen a cross-cutting facilitator within a circular carbon economy framework. The Kingdom has also constructed several facilities to reduce GHG emissions, such as the NEOM green hydrogen project. Therefore, the researchers and decision makers can regard this paper as essential guidelines for mitigating GHG emissions.

Author Contributions: Conceptualization, S.M.R., A.A. and M.S.; methodology, S.M.R., M.S.A. and M.S.; resources, A.A., M.S.A. and F.S.A.-I.; data curation, A.A., M.S. and M.S.A.; writing—original draft preparation, A.A. and M.S.A.; writing—review and editing, S.M.R., M.S. and F.S.A.-I.; visualization, S.M.R., M.S. and M.S.A.; supervision, M.S., F.S.A.-I. and S.M.R.; project administration, M.S., S.M.R. and F.S.A.-I.; funding acquisition, S.M.R., M.S.A. and F.S.A.-I. All authors have read and agreed to the published version of the manuscript.

Funding: The King Fahd University of Petroleum & Minerals (KFUPM) funded this research through the direct funded project no. ER221005.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The authors would like to acknowledge the support provided by the Deanship of Research Oversight and Coordination (DROC) at King Fahd University of Petroleum & Minerals (KFUPM) for funding this work through project no. ER221005.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. E.U. Information Adminstration—Department of Energy. Annual Energy Review 2011—Released September 2012. 2011. Available online: https://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf (accessed on 1 August 2022).
2. Shafiullah, M.; Ahmed, S.D.; Al-Sulaiman, F.A. Grid Integration Challenges and Solution Strategies for Solar PV Systems: A Review. *IEEE Access* **2022**, *10*, 52233–52257. [CrossRef]
3. Ahmed, S.D.; Al-Ismail, F.S.M.; Shafiullah, M.; Al-Sulaiman, F.A.; El-Amin, I.M. Grid Integration Challenges of Wind Energy: A Review. *IEEE Access* **2020**, *8*, 10857–10878. [CrossRef]
4. Lynch, M.C. Causes of Oil Price Volatility on JSTOR. *JSTOR J.* **2002**, *28*, 107–141.
5. Chart of the Day: These Countries Create Most of the World's CO_2 Emissions | World Economic Forum. Available online: https://www.weforum.org/agenda/2019/06/chart-of-the-day-these-countries-create-most-of-the-world-s-co2-emissions/ (accessed on 5 June 2022).
6. The Climate Transparency Report 2021 | Climate Transparency. Available online: https://www.climate-transparency.org/g20-climate-performance/g20report2021 (accessed on 5 June 2022).
7. Rahman, S.M.; Al-Ismail, F.S.M.; Haque, M.E.; Shafiullah, M.; Islam, M.R.; Chowdhury, M.T.; Alam, M.S.; Razzak, S.A.; Ali, A.; Khan, Z.A. Electricity generation in Saudi Arabia: Tracing opportunities and challenges to reducing greenhouse gas emissions. *IEEE Access* **2021**, *9*, 116163–116182. [CrossRef]

8. Samargandi, N. Sector value addition, technology and CO_2 emissions in Saudi Arabia. *Renew. Sustain. Energy Rev.* **2017**, *78*, 868–877. [CrossRef]
9. Rahman, S.M.; Khondaker, A.N. Mitigation measures to reduce greenhouse gas emissions and enhance carbon capture and storage in Saudi Arabia. *Renew. Sustain. Energy Rev.* **2012**, *16*, 2446–2460. [CrossRef]
10. Rahman, S.M.; Khondaker, A.N.; Hasan, M.A.; Reza, I. Greenhouse gas emissions from road transportation in Saudi Arabia—A challenging frontier. *Renew. Sustain. Energy Rev.* **2017**, *69*, 812–821. [CrossRef]
11. Liu, H.; Tellez, B.G.; Atallah, T.; Barghouty, M. The role of CO_2 capture and storage in Saudi Arabia's energy future. *Int. J. Greenh. Gas Control* **2012**, *11*, 163–171. [CrossRef]
12. Derwent, R.; Simmonds, P. Global Environmental Impacts of the Hydrogen Economy. *Int. J. Nucl. Hydrog. Prod. Appl.* **2006**, *1*, 57–67. [CrossRef]
13. Alternative Fuels Data Center: Hydrogen Benefits and Considerations. Available online: https://afdc.energy.gov/fuels/hydrogen_benefits.html (accessed on 29 August 2022).
14. Scheller, F.; Wald, S.; Kondziella, H.; Gunkel, P.A.; Bruckner, T.; Keles, D. Future role and economic benefits of hydrogen and synthetic energy carriers in Germany: A review of long-term energy scenarios. *Sustain. Energy Technol. Assess.* **2023**, *56*, 103037. [CrossRef]
15. Tawfik, A.; Moanis, R.; Qyyum, M.A.; Kumari, S.; Bux, F.; Ayub, H.M.U.; Khan, M.S.; Bokhari, A.; Mubashir, M.; Khoo, K.S.; et al. Sustainable fermentation approach for biogenic hydrogen productivity from delignified sugarcane bagasse. *Int. J. Hydrog. Energy* **2022**, *47*, 37343–37358. [CrossRef]
16. Tawfik, A.; Tan, X.; Elsamadony, M.; Qyyum, M.A.; Azzam, A.M.; Mubashir, M.; Ng, H.S.; Akhtar, M.S.; Khoo, K.S. Graphene/hydroxyapatite nano-composite for enhancement of hydrogen productivity from delignified duckweed. *Fuel* **2022**, *330*, 125537. [CrossRef]
17. US Hydrogen Road Map—Fuel Cell & Hydrogen Energy Association. Available online: https://www.fchea.org/us-hydrogen-study (accessed on 29 August 2022).
18. Factsheet on China, the World's Largest Hydrogen Producer and Consumer—PtX Hub. Available online: https://ptx-hub.org/factsheet-on-china-the-worlds-largest-hydrogen-producer-and-consumer/ (accessed on 29 August 2022).
19. Accelerating Green Hydrogen Technologies and Energy Storage for The Energy Transition | G20 Side Events: Recover Together Recover Stronger. Available online: https://g20sideevents.id/news/photo/202/accelerating-green-hydrogen-technologies-and-energy-storage-for-the-energy-transition.html (accessed on 29 August 2022).
20. Raman, R.; Nair, V.K.; Prakash, V.; Patwardhan, A.; Nedungadi, P. Green-hydrogen research: What have we achieved, and where are we going? Bibliometrics analysis. *Energy Rep.* **2022**, *8*, 9242–9260. [CrossRef]
21. Climate Change 2022: Mitigation of Climate Change. Available online: https://www.ipcc.ch/report/ar6/wg3/ (accessed on 18 October 2022).
22. Abdin, Z.; Zafaranloo, A.; Rafiee, A.; Mérida, W.; Lipiński, W.; Khalilpour, K.R. Hydrogen as an energy vector. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109620. [CrossRef]
23. Brändle, G.; Schönfisch, M.; Schulte, S. Estimating long-term global supply costs for low-carbon hydrogen. *Appl. Energy* **2021**, *302*, 117481. [CrossRef]
24. Davis, S.J.; Lewis, N.S.; Shaner, M.; Aggarwal, S.; Arent, D.; Azevedo, I.L.; Benson, S.M.; Bradley, T.; Brouwer, J.; Chiang, Y.-M.; et al. Net-zero emissions energy systems. *Science* **2018**, *360*, 6396. [CrossRef] [PubMed]
25. DeAngelo, J.; Azevedo, I.; Bistline, J.; Clarke, L.; Luderer, G.; Byers, E.; Davis, S.J. Energy systems in scenarios at net-zero CO_2 emissions. *Nat. Commun.* **2021**, *121*, 6096. [CrossRef]
26. Pye, S.; Broad, O.; Bataille, C.; Brockway, P.; Daly, H.E.; Freeman, R.; Gambhir, A.; Geden, O.; Rogan, F.; Sanghvi, S.; et al. Modelling net-zero emissions energy systems requires a change in approach. *Clim. Policy* **2020**, *21*, 222–231. [CrossRef]
27. El Mrabet, R.; Berrada, A. Hydrogen production and derivatives from renewable energy systems for a best valorization of sustainable resources. *Hybrid Energy Syst. Model.* **2021**, *2021*, 343–363. [CrossRef]
28. Tarhan, C.; Çil, M.A. A study on hydrogen, the clean energy of the future: Hydrogen storage methods. *J. Energy Storage* **2021**, *40*, 102676. [CrossRef]
29. Aljarallah, R.A. An assessment of the economic impact of natural resource rents in kingdom of Saudi Arabia. *Resour. Policy* **2021**, *72*, 102070. [CrossRef]
30. Yusuf, N.; Shesha, L.S. Economic Role of Population Density during Pandemics—A Comparative Analysis of Saudi Arabia and China. *Int. J. Environ. Res. Public Health* **2021**, *18*, 4318. [CrossRef] [PubMed]
31. The World Bank. *Population, Total | Data*; The World Bank: Washington, DC, USA, 2020.
32. Friedlingstein, P.; O'sullivan, M.; Jones, M.W.; Andrew, R.M.; Hauck, J.; Olsen, A.; Peters, G.P.; Peters, W.; Pongratz, J.; Sitch, S.; et al. Global Carbon Budget 2020. *Earth Syst. Sci. Data* **2020**, *12*, 3269–3340. [CrossRef]
33. Andrew, R.M.; Peters, G.P. *The Global Carbon Project's Fossil CO_2 Emissions Dataset*; Zenodo: Geneva, Switzerland, 2021.
34. United Nations/DESA. *World Urbanization Prospects—Population Division*; United Nations: New York, NY, USA, 2019.
35. Ritchie, H. Sector by sector: Where do global greenhouse gas emissions come from?—Our World in Data. *Our World Data*. 2020. Available online: https://ourworldindata.org/ghg-emissions-by-sector (accessed on 19 March 2023).
36. Friedlingstein, P.; Jones, M.W.; O'Sullivan, M.; Andrew, R.M.; Bakker, D.C.; Hauck, J.; Le, Q.C.; Peter, G.P.; Peters, W.; Pongratz, J.; et al. Global Carbon Budget 2021. *Earth Syst. Sci. Data* **2022**, *14*, 1917–2005. [CrossRef]

37. Bazoobandi, S. Old Fund, New Mandate: Saudi Arabia's Public Investment Fund (PIF). *Int. Polit. Econ. Ser.* **2021**, 207–231. [CrossRef]
38. Khondaker, A.N.; Rahman, S.M.; Malik, K.; Hossain, N.; Razzak, S.A.; Khan, R.A. Dynamics of energy sector and GHG emissions in Saudi Arabia. *Clim. Policy* **2014**, *15*, 517–541. [CrossRef]
39. Krane, J.; Wilson, W.S. *Energy Governance in Saudi Arabia: An Assessment of the Kingdom's Resources, Policies, and Climate Approach*; Rice University's Baker Institute for Public Policy: Houston, TX, USA, 2019.
40. Rahman, S.M.; Khondaker, A.N.; Hossain, M.I.; Shafiullah, M.; Hasan, M.A. Neurogenetic modeling of energy demand in the United Arab Emirates, Saudi Arabia, and Qatar. *Environ. Prog. Sustain. Energy* **2017**, *36*, 1208–1216. [CrossRef]
41. International Energy Agency. *Energy and Carbon Tracker Users Guide 2020 Edition Energy and Carbon Tracker Users Guide How to Use This Product*; International Energy Agency: Paris, France, 2019.
42. Gütschow, J.; Jeffery, M.L.; Gieseke, R.; Gebel, R.; Stevens, D.; Krapp, M.; Rocha, M. The PRIMAP-hist national historical emissions time series. *Earth Syst. Sci. Data* **2016**, *8*, 571–603. [CrossRef]
43. Ministry of Energy Industry and Mineral Resources. *Third National Communication of the Kingdom of Saudi Arabia*; Ministry of Energy Industry and Mineral Resources: Riyadh, Saudi Arabia, 2016; pp. 173–174.
44. Selimuzzaman, S.M. Present and Future Solid Waste Management Practices in Saudi Arabia to combat Greenhouse Gas Emissions. In Proceedings of the 12th International Conference on Computational Science and Its Applications, Bahia, Brazil, 18–21 June 2012; pp. 1–13.
45. De Miranda, P.E.V. *Science and Engineering of Hydrogen-Based Energy Technologies: Hydrogen Production and Practical Applications in Energy Generation*; Academic Press: Cambridge, MA, USA, 2019; pp. 1–38.
46. Hydrogen Properties | Connecticut Hydrogen-Fuel Cell Coalition. Available online: https://chfcc.org/hydrogen-fuel-cells/about-hydrogen/hydrogen-properties/ (accessed on 2 August 2022).
47. Global EV Outlook 2020—Analysis—IEA. Available online: https://www.iea.org/reports/global-ev-outlook-2020 (accessed on 14 March 2023).
48. Hydrogen Production and Delivery | Hydrogen and Fuel Cells | Hydrogen and Fuel Cells | NREL. Available online: https://www.nrel.gov/hydrogen/hydrogen-production-delivery.html (accessed on 14 March 2023).
49. Pan, G.; Bai, Y.; Song, H.; Qu, Y.; Wang, Y.; Wang, X. Hydrogen Fuel Cell Power System— Development Perspectives for Hybrid Topologies. *Energies* **2023**, *16*, 2680. [CrossRef]
50. The Future of Hydrogen—Analysis—IEA. Available online: https://www.iea.org/reports/the-future-of-hydrogen (accessed on 14 March 2023).
51. Belikov, J.; Błoński, K.; Mańkowska, M.; Rzeczycki, A. Research on the Concept of Hydrogen Supply Chains and Power Grids Powered by Renewable Energy Sources: A Scoping Review with the Use of Text Mining. *Energies* **2022**, *15*, 866. [CrossRef]
52. Northeastern Brazil to Build World's Biggest Green Hydrogen Plant | Wilson Center. Available online: https://www.wilsoncenter.org/blog-post/northeastern-brazil-build-worlds-biggest-green-hydrogen-plant (accessed on 2 August 2022).
53. Hydrogen Projects in the US—Clean Energy Group. Available online: https://www.cleanegroup.org/ceg-projects/hydrogen/projects-in-the-us/ (accessed on 2 August 2022).
54. China Sets Green Hydrogen Target for 2025, Eyes Widespread Use | Reuters. Available online: https://www.reuters.com/world/china/china-produce-100000-200000-t-green-hydrogen-annually-by-2025-2022-03-23/ (accessed on 2 August 2022).
55. Hassan, Q.; Abdulateef, A.M.; Hafedh, S.A.; Al-samari, A.; Abdulateef, J.; Sameen, A.Z.; Salman, H.M.; Al-Jiboory, A.K.; Wieteska, S.; Jaszczur, M. Renewable energy-to-green hydrogen: A review of main resources routes, processes and evaluation. *Int. J. Hydrog. Energy* **2023**. [CrossRef]
56. Alam, M.S.; Al-Ismail, F.S.; Salem, A.; Abido, M.A. High-Level Penetration of Renewable Energy Sources into Grid Utility: Challenges and Solutions. *IEEE Access* **2020**, *8*, 190277–190299. [CrossRef]
57. Banihabib, R.; Assadi, M. A Hydrogen-Fueled Micro Gas Turbine Unit for Carbon-Free Heat and Power Generation. *Sustainability* **2022**, *14*, 13305. [CrossRef]
58. Shafiullah, M.; Refat, A.M.; Haque, M.E.; Chowdhury, D.M.H.; Hossain, M.S.; Alharbi, A.G.; Alam, M.S.; Ali, A.; Hossain, S. Review of Recent Developments in Microgrid Energy Management Strategies. *Sustainability* **2022**, *14*, 14794. [CrossRef]
59. Ozalp, N. Energy and material flow models of hydrogen production in the U.S. Chemical Industry. *Int. J. Hydrog. Energy* **2008**, *33*, 5020–5034. [CrossRef]
60. Tashie-Lewis, B.C.; Nnabuife, S.G. Hydrogen Production, Distribution, Storage and Power Conversion in a Hydrogen Economy—A Technology Review. *Chem. Eng. J. Adv.* **2021**, *8*, 100172. [CrossRef]
61. Mohideen, M.M.; Subramanian, B.; Sun, J.; Ge, J.; Guo, H.; Radhamani, A.V.; Ramakrishna, S.; Liu, Y. Techno-economic analysis of different shades of renewable and non-renewable energy-based hydrogen for fuel cell electric vehicles. *Renew. Sustain. Energy Rev.* **2023**, *174*, 113153. [CrossRef]
62. Javaid, M.S.; Irshad, U.B.; Abido, M.A.; Khalid, Z.; Alam, M.S.; Rana, M.J. Direct control of three-phase smart load for neutral current mitigation. In Proceedings of the 2016 19th International Multi-Topic Conference INMIC, Kolkata, India, 5–6 December 2017. [CrossRef]
63. The Hydrogen Value Chain from Production to Applications. Available online: https://energy.danube-region.eu/wp-content/uploads/sites/6/sites/6/2019/12/Matthias_Schl%C3%A9gel_FICHTNER-Hydrogen-Value-Chain.pdf (accessed on 5 August 2022).

64. Reducing Emissions—Saudi Green Initiative. Available online: https://www.saudigreeninitiative.org/targets/reducing-emissions/ (accessed on 2 August 2022).
65. Net Zero by 2050—Analysis—IEA. Available online: https://www.iea.org/reports/net-zero-by-2050 (accessed on 2 August 2022).
66. Hydrogen: A Clean, Flexible Energy Carrier | Department of Energy. Available online: https://www.energy.gov/eere/articles/hydrogen-clean-flexible-energy-carrier (accessed on 2 August 2022).
67. Park, C.; Koo, M.; Woo, J.R.; Hong, B.I.; Shin, J. Economic valuation of green hydrogen charging compared to gray hydrogen charging: The case of South Korea. *Int. J. Hydrog. Energy* **2022**, *47*, 14393–14403. [CrossRef]
68. Hasan, S.; Shabaneh, R. *The Economics and Resource Potential of Hydrogen Production in Saudi Arabia*; KAPSARC: Riyadh, Saudi Arabia, 2021. [CrossRef]
69. Alrashed, F.; Zahid, U. Comparative analysis of conventional steam methane reforming and PdAu membrane reactor for the hydrogen production. *Comput. Chem. Eng.* **2021**, *154*, 107497. [CrossRef]
70. Boretti, A.; Banik, B.K. Advances in Hydrogen Production from Natural Gas Reforming. *Adv. Energy Sustain. Res.* **2021**, *2*, 2100097. [CrossRef]
71. Siemens. Power-to-X: The crucial business on the way to a carbon-free world. *Tech. Pap. Siemens AG* **2019**. Available online: https://www.siemens-energy.com/global/en/offerings/technical-papers/download-power-to-x.html (accessed on 19 March 2023).
72. Kurtz, J.M.; Sprik, S.; Saur, G.; Onorato, S. *Fuel Cell Electric Vehicle Durability and Fuel Cell Performance*; National Renewable Energy Lab: Golden, CO, USA, 2019. [CrossRef]
73. Jouin, M.; Bressel, M.; Morando, S.; Gouriveau, R.; Hissel, D.; Péra, M.C.; Zerhouni, N.; Jemei, S.; Hilairet, M.; Bouamama, B.O. Estimating the end-of-life of PEM fuel cells: Guidelines and metrics. *Appl. Energy* **2016**, *177*, 87–97. [CrossRef]
74. Knobloch, F.; Pollitt, H.; Chewpreecha, U.; Daioglou, V.; Mercure, J.F. Simulating the deep decarbonisation of residential heating for limiting global warming to 1.5 °C. *Energy Effic.* **2019**, *12*, 521–550. [CrossRef]
75. International Energy Agency. Cross-Cutting: Hydrogen. 2020. Available online: https://www.cceguide.org/wp-content/uploads/2020/08/07-IEA-Cross-cutting.pdf (accessed on 13 October 2022).
76. ACWA POWER | NEOM Green Hydrogen Project. Available online: https://acwapower.com/en/projects/neom-green-hydrogen-project/ (accessed on 13 October 2022).