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Perspective

Roadmap to Achieving Sustainable Development via Green Hydrogen

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Abstract: The conversion to renewable energy can be achieved when cities and communities start to depend on sustainable resources capable of providing for the basic needs of the community, along with a reduction in the daily problems and issues that people face. These issues, such as poverty, hunger, sanitation, and economic difficulties are highlighted in the Sustainable Development Goals (SDGs), which aim to limit and eradicate these problems along with other environmental obstacles including climate change and Greenhouse Gases (GHGs). These SDGs, containing 17 goals target each sector and provide propositions to solve such devastating problems. Hydrogen contributes to the targets of these sustainable developments, since through its implementation in different industries the levels of GHG will drop and thus contribute to the climate change which Earth is facing. Further, through the usage of such resources, many job opportunities will also be developed, thus enhancing the economy, and lifting the status of society. This paper classifies the four different types of hydrogen and outlines the differences between them. The paper then emphasizes the importance of green hydrogen use within the shipping industry, transportation, and infrastructure, along with economic and social development through job opportunities. Furthermore, this paper provides case studies tackling green hydrogen status in the United Kingdom, United States of America, and European Union as well as Africa, United Arab of Emirates, and Asia. Finally, challenges and recommendations concerning the green hydrogen industry are addressed. This paper aims to relate the use of green hydrogen to the direct and indirect goals of SDG.

Keywords: green hydrogen; sustainable development goals; climate change; carbon emissions

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1. Introduction

Including 17 Sustainable Development Goals (SDGs), the 2030 Agenda for Sustainable Development was adopted by the General Assembly of the United Nations in September 2015; it highlights achieving sustainable development for all, especially individuals with disabilities [1]. SDGs aims at eliminating or reducing issues that threaten the future of human beings, the environment, and the economy as detailed in Figure 1 [2,3]. For many decades, humanity has suffered from poverty, hunger, ignorance, and the spread of diseases, especially in developing countries. Thus, the SDGs paved the way for improving the human beings' standard of life through implementing several effective targets [4].

The effective targets of the SDG include reducing the proportion of individuals living in poverty irrespective of their gender or age at least by half, eliminating all forms of malnutrition, ensuring individuals' access to knowledge, and achieving a universal health coverage [2]. Furthermore, the SDGs interconnect countries worldwide through effective collaboration in research, infrastructure, and technology sectors [5–7]. It is worth noting that the SDGs give special attention to developing countries through mobilizing financial, educational, and technological funds to ensure their engagement and development [8–10]. In addition, the SDGs highlight the severity of climate change and natural resource depletion. They advocate for developing sustainable cities to reduce their environmental impact and decelerate climate change [11,12]. This would also ensure conservation of marine, terrestrial, and inland freshwater ecosystems preserving the biodiversity and natural habitats [13,14].

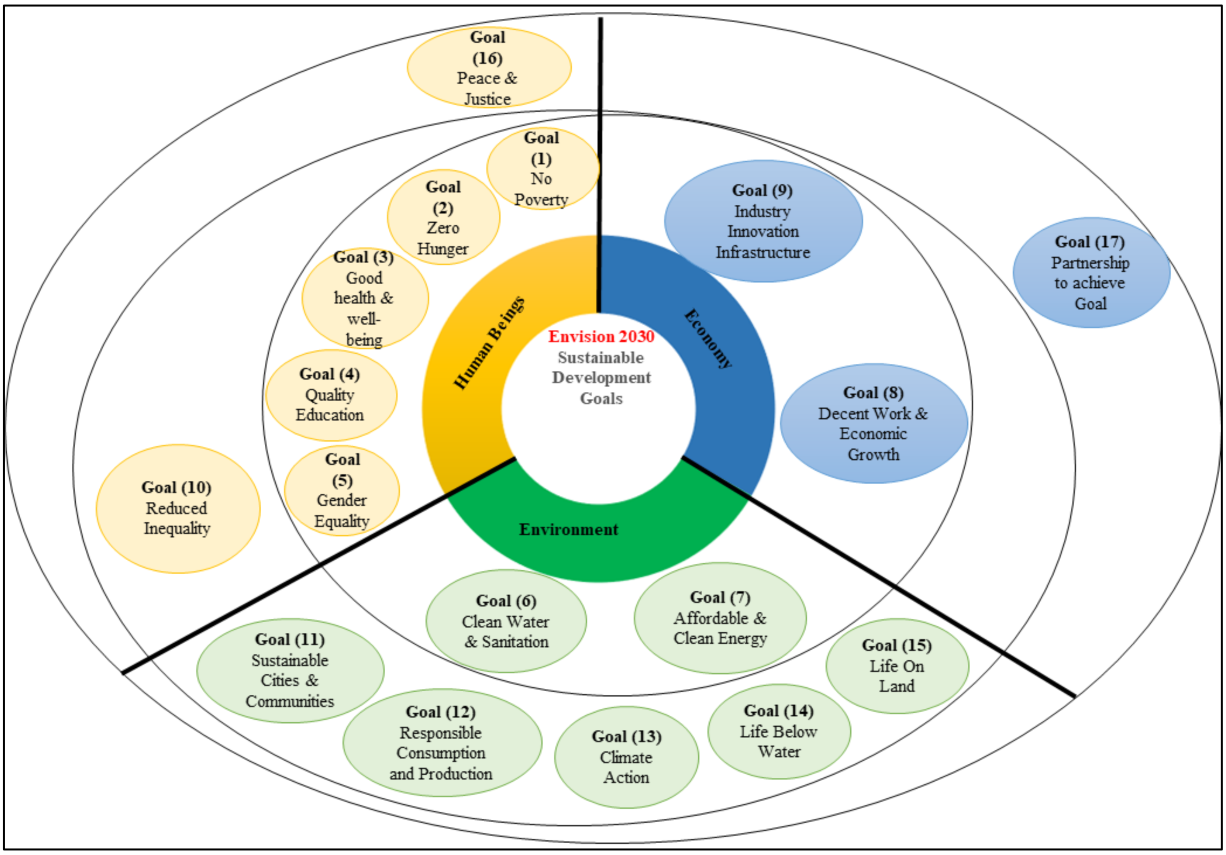

Figure 1. Global sustainable goals.

To combat climate change and reduce greenhouse gases (GHGs) emissions, it is intuitive to look for clean energy solutions. One of the most promising alternative energy sources is hydrogen [15–18]. Recently, it received a world-wide attention due to its significant potential in contributing to sustainable development [18–20], and more profoundly, its global market is expected to increase by 50 million tons in 2024 [21,22]. Hydrogen can assist in addressing a number of major energy concerns, as stated in the report of International Energy Agency in 2019 [18]. It proposes solutions for decarbonizing a variety of industries, including long-distance transportation, chemicals, and iron and steel, where major reductions in emissions are proving challenging [23,24]. It can also contribute to better air quality and increased energy security [15]. Consequently, it is worthwhile to examine to what extent the use of hydrogen can meet the SDGs, and whether any specific type of hydrogen production is recommended, while also looking at its technical and financial challenges.

There are four main types of hydrogen: brown, grey, blue, and green hydrogen. This classification of hydrogen is based on the raw material and production route as shown in Figure 2 [21,25,26]. It is worth noting that about 55 million tons per annum, constituting 96% of the total produced hydrogen, is generated from fossil fuel [21,27]. Brown hydrogen is produced through burning coal or lignite. It is considered the least environmentally friendly, creating as much carbon dioxide as burning the source fuel would have in the first place. For every ton of brown hydrogen produced, around 10–12 tons of CO_2 are produced [26]. Whereas, the most common yet the least ecofriendly type of hydrogen is the grey hydrogen, which is mainly created from natural gases through a process called steam methane reforming (SMR) [25,28]. In this endothermic process, in the presence of a catalyst, the reaction of methane with steam under 3–25 bar pressure results in the production of hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide [26]. Unlike the production of grey hydrogen, where released carbon dioxide is not captured, blue hydrogen production involves carbon capture and storage (CCS) although both employ the same production process, SMR [29]. Up to 90% of the produced carbon dioxide could be captured by CCS technology reducing the environmental impact of blue hydrogen yet raising significantly the financial and technical challenges [21]. Finally, green hydrogen is considered the ultimate ecofriendly approach for the production of fuel and electricity from emission-free sources. Powered by a renewable energy source, such as wind or solar power, electrolysis, the splitting of water into hydrogen and oxygen, is mainly implemented to produce green hydrogen [21,30,31]. With potentially zero GHGs emissions, researchers believe that green hydrogen will become an increasingly important energy source internationally in the next five to ten years due to its environmentally benign production and potential for powering heavy industries and transportation [26,32–34]. More profoundly, while although only 4% of the produced hydrogen is considered green, its production is forecasted to increase significantly to 22% by 2050 to be used in all industries [21,27].

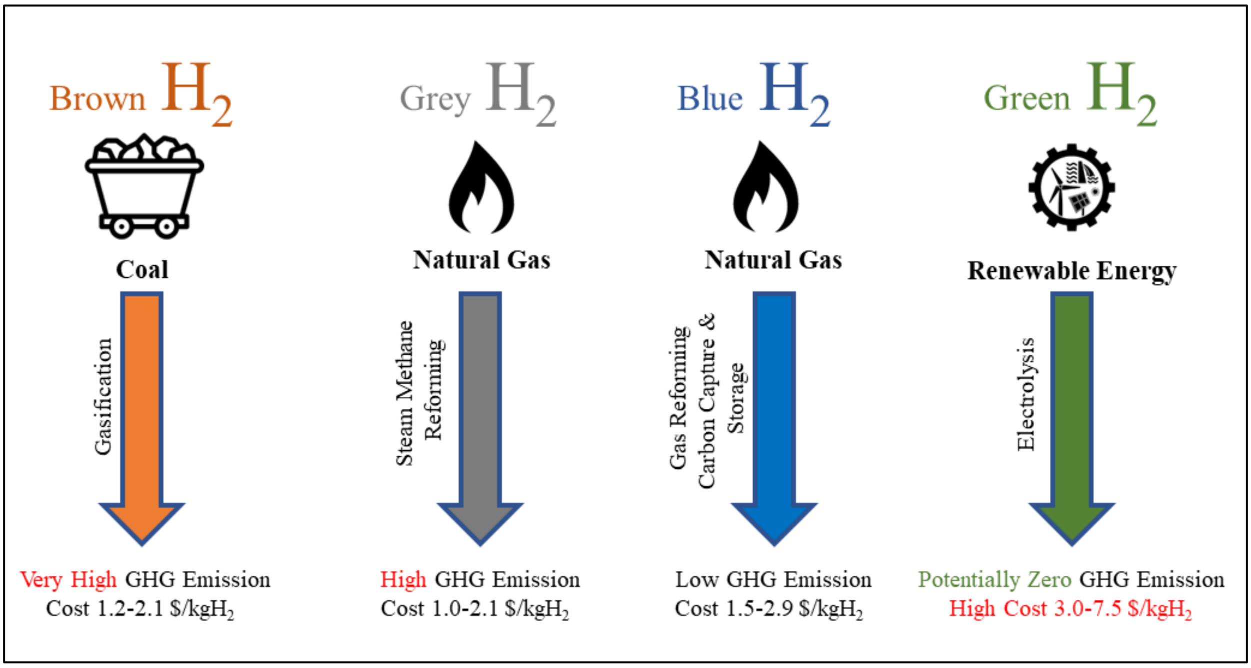

Figure 2. Colours of Hydrogen.

Because the new agenda for sustainable development of the General Assembly stressed a comprehensive approach to attaining sustainable development for all, based on the idea of "leaving no one behind" [1], it is of great interest to explore how the use of green hydrogen can impact the welfare and life quality of individuals, the environment, and the economy of countries. Therefore, this paper aims at investigating the different implementations of green hydrogen and how these implementations can achieve SDGs' direct and indirect targets (see Figure 3). It talks about the means of implementing green hydrogen in the industrial field, including shipping, transportation, and infrastructure. It also discusses how the use of green hydrogen can meet the gender equality goal of SDGs, which is a key approach to encourage the investors and stakeholders to engage in this sustainable clean technology. In addition, this study demonstrates how the applications of green hydrogen vary between the developed countries including the United Kingdom (UK), United States of America (USA), and European Union (EU) and the developing countries including Africa and the United Arab of Emirates (UAE), as well as Asia. Finally, it is essential to discuss the challenges that this promising technology may encounter, and what possible recommendations can be made to ease its production and use.

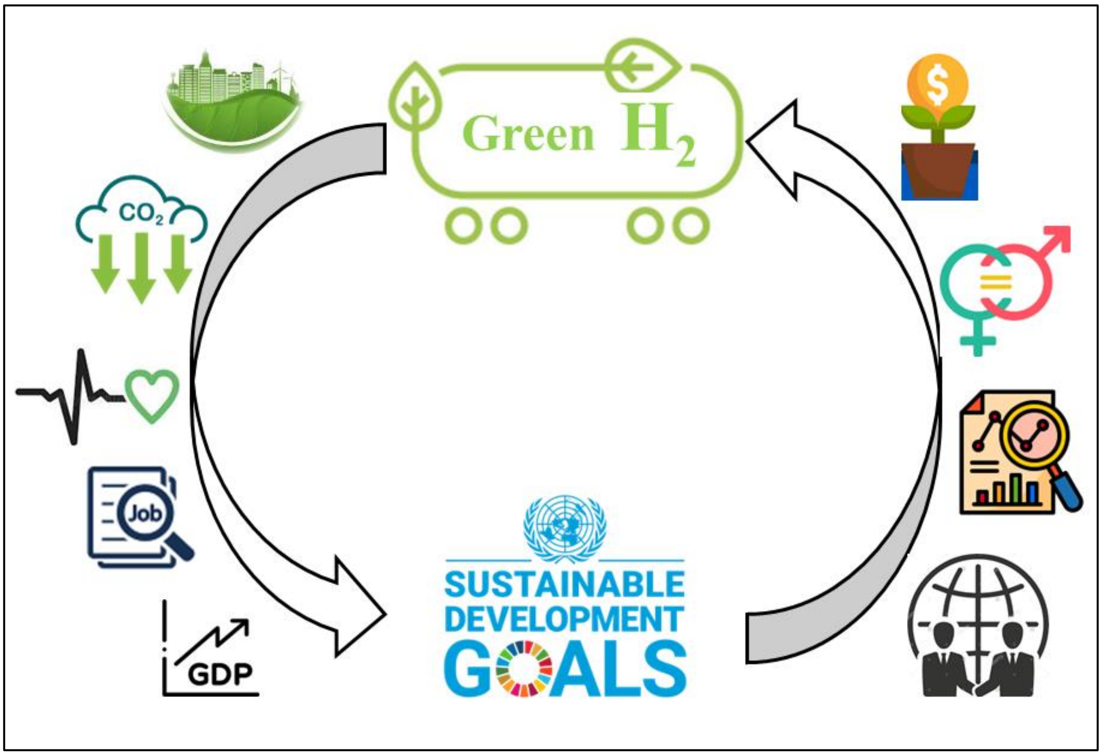

Figure 3. Green Hydrogen use in compliance with SDGs.

2. Implementing Green Hydrogen in the Shipping Industry

With the maritime industry accounting for 2.2% of the global CO_2 emissions, the International Maritime Organization aims at achieving at least a 40% reduction in carbon emissions by 2030, and a 70% reduction by 2050, relative to 2008 emissions [21]. This complies with the SDGs which advocate for protecting the maritime and coastal ecosystems, improving the water quality, and decelerating climate change [35,36]. Green hydrogen is considered to be one of the promising approaches to achieving these targets in the maritime industry, bearing in mind the challenges associated with green hydrogen as fuel (safety, storage time, supply chain and space onboard the ship) [37–39].

The main advantage of the hydrogen, over conventional fossil fuel, is that zero carbon emission, particulate matter, or sulfur dioxide (SO_x) are produced during combustion [40]. Moreover, unlike other types of hydrogen, the production of which results in GHG emissions, green hydrogen is mainly produced by electrolysis, eliminating any hazardous emissions during both the production and application in the shipping industry [21,40]. Due to mass production, standardized manufacturing, and several other factors, the green hydrogen industry has witnessed a 50% cost reduction since 2015, and a further reduction by 30% is expected by 2025 [40]. Another advantage of hydrogen over conventional fossil fuels: about 90% less pollution, in form of nitrous oxide (NOx), results from different hydrogen combustion methods, preserving natural resources such as air and water, and ensuring the safety of human health [41]. Instead of using the green hydrogen, ships implement scrubbers which removes sulfur dioxide from the exhaust; yet, more acidic and turbid water than the surrounding water is discharged overboard, containing severe contaminants such as polycyclic aromatic hydrocarbons and heavy metals [21]. An example of the possible effects is given by an event which took place on the coast of British Columbia in 2017, as approximately 35 million tons of discharge water was dumped, drastically affecting the threatened and endangered Northern and Southern Resident killer whales [42]. This shines the light on the importance of replacing conventional fossil fuels in the shipping industry with clean green hydrogen, to reduce not only GHGs emissions but also to preserves the life under water, such as marine and coastal ecosystems [21,37].

In addition to the above, Liquid Hydrogen (LH_2) can be used an alternative fuel in the maritime industry [37]. A reduction in GHG emissions was recorded upon the implementation of green LH_2 by 4.6, 11.7, and 43.3 g CO_2e/MJ fuel from wind, solar, and grid respectively [21,43]. Up to 9% of global emissions could be reduced upon implementing an additional 5% hydrogen-fired power generation in the maritime industry [21]. In the meantime, the implementation of LH_2 as an alternative fuel requires a comprehensive study to investigate its implication on logistics, infrastructure, and most importantly, safety [21]. There are five main significant factors which affect the cost and environmental impact of the production of LH2: raw materials' type, conversion technology, energy source, process (mass and energy) integration utilization, and the degree of carbon sequestration and implementation within the process [21,44]. A reduction in GHGs emissions, yet a significant increase in cost and complexity upon the production of green LH_2—due to the implementation of a renewable energy such as wind energy—were recorded [21,45]. Moreover, an essential component in the production of green LH_2 is still absent in many developing countries, where more than one billion people in these countries depend on traditional energy sources [46,47]. This highlights the need to support the least developed countries financially and technically in order to introduce renewable energy [8].This could be achieved through the SDGs targets which aim at supporting developing countries in attaining a long-term debt sustainability as well as employing investment promotion regimes for the least developed countries [48].

In can be concluded that the green hydrogen is gaining ground as a competitive substitute to conventional fossil fuels in the shipping industry, especially due to the fact that the financial aspect of this approach has witnessed some reduction. This would encourage investors and stakeholders to use green hydrogen as a clean energy alternative to meet the targets of the SDGs. In detail, pollutants' emissions would be limited, decelerating climate change and limiting human diseases [49,50]. Hence, two major elements, human-beings and the environment, would be affected positively by green hydrogen implementation.

3. Hydrogen Implementation in Transportation Sector

There are around 50 targets, mandates, and policy incentives in place today that directly support hydrogen, with the majority focused on transport [18]. Green transportation is one of the most important initiatives that can be deployed to reduce the dependence on petroleum and, accordingly, cut down the GHGs emissions [51,52]. Accordingly, Hydrogen-powered cars are becoming recognized as vital assets that, by replacing traditional oil-dependent vehicles, have the potential to significantly cut greenhouse gas emissions [53]. As a result, experts believe that hydrogen should be created near fueling stations, which would minimize transportation costs and improve the dependability of hydrogen supplies [54,55]. While onsite green hydrogen production avoids hydrogen transport costs, it is still expensive and needs policy support to become economically viable [56]. Moreover, when both the oil process and BTU prices are high (BTU tax is a type of energy tax based on the heat content of the fuel source, except for wind, solar, and geothermal), hydrogen would account for 76% of the road transportation sector [57]. This would be accompanied by a reduction in carbon dioxide emissions, improvement of energy efficiency, and achievement of energy security [57].

Nowadays, the transportation sector has witnessed the implementation of hydrogen through two energy conversion technologies: Hydrogen Fuel Cell (HFC) and Hydrogen Fueled Internal Combustion Engine (HFICE) [3,27,58]. In a HFC vehicle, the chemical energy from hydrogen and oxygen is transferred into electrical energy, while the combustion energy in a HFICE vehicle is transformed into mechanical energy. Bearing in mind the flexibility of a more straightforward transition from conventional vehicles, switching between fuels, and the higher tolerance to the fuel impurities, HFICE is considered superior to HFC technology [27]. Besides the fact that the hydrogen direct injection in spark-ignited ICEs achieve a high engine power output and efficiency, hydrogen significantly eliminates carbon-based emissions such as CO, CO_2, and soot [27]. Furthermore, in its current condition, HFC technology is costly and requires pure hydrogen and a high-performance compressor to deliver compressed air [59]. Furthermore, massive batteries would be necessary to store the electricity needed to meet the transitory nature of power demands for vehicle applications [59]. Whereas, HFICE has a low total cost of ownership, particularly in heavy-duty on-road and off-road applications [59]. Last but not least, because HFICEs are manufactured in the same facilities and using the same procedures as traditional fossil-fuel ICEs, they help to secure jobs by offering sustainable industrial and employment opportunities in the automotive sector. Nevertheless, currently, there are only two models of vehicles using HFC in the market and are demonstrated by Toyota and Hyundai, while no vehicles exist using the technology HFICE, as it is still under investigation [60].

Like any other country, Poland's source of energy depends on fossils fuels [61,62]. However, due to European Union policy indicating that specific environmental laws connected to the reduction in harmful chemicals should be fulfilled using renewable energy, the research of a suitable but easy technique to satisfy these standards is critical. The major objective of these policies is to ensure a safe shift in the government's energy use to a green source that could positively improve several sectors including transportation [62,63]. These targets could be developed using hydrogen buses in Poland. This idea was developed through an investigation towards the usage of hydrogen infrastructure conducted in 2022. The implementation of these vehicles necessitated using a fuel cell, and the path of buses included several cities in Poland starting from Katowice and ending in Silesia. After the comparison between the hydrogen buses and those previously used, which used diesel, several advantages were identified, including the reduced emissions of pollutants and the reduced cost needed to implement these buses, and thus the cost for bus users [62]. These conclusions signify that the switch to a more reliable green source such as hydrogen is vital due to its significant impact environmentally and economically [62,64].

In addition to this, the implementation of green hydrogen could also involve heavy duty vehicles [32,65]. The following investigation was directed towards hydrogen fuel cell trains along with their corresponding infrastructure and was applied in 2021. The analysis concerning the viability of such implementation in trains involved the determination of its efficiency, along with the resulting economic cost. Concerning the detailed inputs, the hydrogen trains were used in a 140 km regional line in the South of Italy and the implementation was targeted towards buses that were used by passengers and freight purposes. It should be highlighted that during the implementation, variation in the passenger and freight inputs was done to ensure the feasibility of such a demonstration. Moreover, since the trains consumed hydrogen, about 250 kg of hydrogen daily, a hydrogen refueling station was used, consisting of a 670 kW-PEM electrolyze that produces about 260 kg of hydrogen daily. In addition, the required power train inputs involved two 180 kW fuel cells and a Lithium iron phosphate battery. After five daily trips and two journeys were completed for passengers and freight respectively, 40% fuel cell efficiency along with 50% facility efficiency resulted. In addition, in terms of cost, the 19% return on the investment was distinguished with a 4.2-year payback period. The following results signify that the application of hydrogen is not limited to cars, and can also involve buses with an encouraging feasibility in terms of efficiency and cost [66].

In short, the use of hydrogen in the transportation sector can provide a dependable, long-lasting, and cost-effective solution based on the well-established current technology, contributing to a rapid transition to carbon-free transportation. Given the global trend of mitigating climate change, the contribution of a ubiquitous, dependable, and economical propulsion technology such as the ICE can be considerable once a renewable fuel is utilized in place of the traditional fossil fuels. In this regard, hydrogen and hydrogen-dense liquid fuels can play an important role by permitting zero CO_2 emissions and zero-impact pollutant emissions from ICE powertrains. In the light of the SDGs' targets, GHGs emission reduction via green transportation reflects positively on climate change, as well as human health and wellbeing, reducing the number of deaths and illnesses caused by the exposure to hazardous pollutants [49,50,67].

4. Ease Use of Green Hydrogen Technology via Infrastructure

Infrastructure such as pipelines and distribution networks are especially important for a novel energy carrier such as hydrogen. In fact, green hydrogen can be implemented using the already existing infrastructure used for natural gas distribution [68]. This would be applied in countries such as the UK, USA, Republic of Korea, and other European countries [27]. Introducing clean hydrogen to replace only 5% of a country's natural gas sources would greatly increase demand for hydrogen and drive down costs [18]. Additionally, further decarbonization can be achieved through a smooth switch to hydrogen-methane blend [18]. Blending hydrogen into existing natural gas infrastructure would save the considerable capital expenses associated with creating new transmission and distribution systems [68]. Furthermore, unlike high pressure pipelines, implementing low pressure pipelines reduces transportation GHG emissions upon blending H_2; a 12.5% reduction in the emission factor was recorded at 15% H_2 in low-pressure lines [69]. Low-level blending may raise the cost of natural gas supply to customers; however, it will result in lower CO_2 emissions. Blending would be much easier to execute if actions were taken to clarify current national hydrogen in natural gas legislation and to unify restrictions across borders. Moreover, in the case of hydrogen usage for road transportation, where a network of refueling stations is required for broad acceptance of ICE vehicles, the present rate of infrastructure development can be improved to overcome the barrier to adoption [18].

Perhaps the evaluation of the hydrogen infrastructure could be achieved through identifying the number of installed Hydrogen Refueling Station (HRS). Several countries are working to increase their number of HRS including Japan, Germany, and United Stated of America. In addition, new countries entering this list include Malaysia, Saudi Arabia, and Croatia. In fact, from 2015 till 2019 the number of installed HRS around the world increased significantly, from 214 to 432, respectively [64]. Moreover, by 2021, more recent data distinguished that the number of installed HRS had reached 729 [70]. This signifies that there is an increased demand for installation, which could be correlated with the relatively practical procedures required for the hydrogen infrastructure [64,71,72]. Moreover, towards more sustainable transport, the European Union (EU) seeks to reduce the emissions of GHG by setting a new target through the Alternative Fuels Infrastructure Regulation (AFIR) [73]. The AFIR sets certain measures and objectives, aimed at reducing the continuous dependency on fossils fuels in the transport sector [74]. The capability of the infrastructure to satisfy people's needs, in terms of the resource used, such as green hydrogen, could be attained through the AFIR. In fact, there are about 13.4 million vehicles that run on alternative fuels, and it is estimated that such numbers will have increases in 2030 by 16%, and in 2050 by 50%. In terms of HRS, stations should be present every 100 km with the importance of increasing the number of HRS installed in urban areas. Moreover, to ensure a smooth experience for users, the infrastructure should take into consideration electronic payments and informing users about the pricing options. Therefore, the shift to a more sustainable resource capable of meeting such requirements will likely minimize the emissions of GHG [21,74].

Recently, the hydrogen industry has received the attention of many developed countries such as Australia, Japan, and Germany, which are competing to take part in the future hydrogen economy [75–77]. This will pave the way for accomplishing one of the critical SDGs through establishing sustainable cities and communities [78]. With the significant investment and development, the hydrogen industry is expected to expand beyond the transportation sector [32]. Benefiting from their abundant land and renewable energy resources, some countries have realized the promising potential of producing hydrogen at a low cost; hence, they would be able to satisfy their domestic need for energy as well as export excess hydrogen to other countries with a high energy demand [27,64]. In the energy sector, hydrogen outweighs electricity, as it is stored and transported at a lower cost [27]. For example, China, Japan, and Korea's energy demand could be satisfied by the potential hydrogen suppliers such as Australia and Chile; 900,000 tons of hydrogen are expected to be imported from Australia to Japan by 2030, providing Australia's economy with AUD 10 billion [27]. Furthermore, the carbon-free hydrogen economy in Northern Netherlands is expected to receive a EUR 17.5–25 billion investment by 2025 [27]. Thus, new supply chains will be established fostering commercial activities among countries which will witness a rise in the Gross Domestic Product (GDP) and consequently the standard of life in these countries [79].

Most of the developing countries lack the necessary infrastructure, funds, and expertise to engage in the hydrogen economy [8]. Consequently, this would widen the gap between these countries and other developed countries and negatively affect the targets of the SDGs by increasing poverty, hunger, and ignorance in developing countries. However, effective engagement of developing countries in the hydrogen economy could be achieved by establishing partnerships among countries [80]. The SDGs' targets, such as mobilizing additional financial resources for developing countries, patronizing access to science and technology, and introducing environmentally sound technologies contribute to the advancement of developing countries [81].

5. Social and Economic Aspects of Green Hydrogen Industry

The advantage of using such a clean energy as green hydrogen is not only limited to the environmental aspect; there are also several social aspects. Investments in hydrogen can help foster new technological and industrial development in economies around the world, creating skilled jobs [18]. For example, to produce, transfer, and use hydrogen, chemical technologies such as carbon capture solvents or fuel cell membranes, as well as new precision-engineered items such as storage tanks or pipeline materials and burners, may be required. This indicates that several new approaches are being developed for the production of green hydrogen other than the electrolysis of water. They are expected to expand, supporting the economy and enhancing commercial scale production by 2030 [27]. Hence, countries have the opportunity to grow leadership, technological skills, and new jobs in these fields, especially when they are combined with existing abilities and talents.

Such technological transformation can play a remarkable role in providing the youth with decent jobs, reducing unemployment, and ensuring economical growth due to the increase in GDP [27,82]. This matches the targets of the SDGs related to the economy and human beings. Along with the economic and social benefit, achieving access to green hydrogen should take into consideration the availability of such a resource for the present and future generations in a way that benefits both. This is known as maintaining the inter- and intra-generational equity, and making sure that green hydrogen is present in certain amounts, to ensure its presence and fulfil its role [83]. Hence, this falls under the SDGs, relating to "sustainable cities and communities" and "responsible consumption and production" [1].

Adding to the above, until now, only 20% of the panel speakers at green hydrogen conferences are women [84]. However, a group of successful women formed a network in 2020 to enhance the role of women in this sector called the Women in Green Hydrogen (WiGH) [84]. This network found, through research which tackles gender diversity and its distribution on panels, congress, and management boards, that women occupy only 1 in 5 speakers at green hydrogen conferences. Such results are even lower than other energy sectors including oil and gas, which has an average of 22% women speakers, 22% in transportation, 35% in the chemical industry, and 32% in renewable energy [84]. Hence, there should be rising gender awareness among the stakeholders in the green hydrogen energy sector, in order to facilitate evidence-based gender mainstreaming [85,86]. This may match the SDGs of gender equality and reduced inequality.

6. Green Hydrogen Meeting SDGs and Corresponding Targets

The green hydrogen tackles various Sustainable Development Goals (SDGs) as detailed in Table 1, starting with the production of green hydrogen, through electrolysis, which implements renewable energy and results in zero carbon emissions. In, addition, the wide applications of green hydrogen result in further decarbonization of different sectors such as the domestic, transportation, and energy sectors. Hence, hydrogen plays a promising role in reducing hazardous pollutants in the atmosphere, fostering the implementation of renewable energy, and decelerating climate change. This highlights hydrogen contribution to Goal 3 (Good Health and Well-Being), Goal 7 (Affordable and Clean Energy), and Goal 13 (Climate Action). Hydrogen, as an alternative for fossil fuel in shipping sector, not only reduces GHG emissions but also ensures quality of water by eliminating water contamination; this would protect organisms and preserve marine and coastal ecosystems, contributing to Goal 6 (Clean Water and Sanitation) and Goal 14 (Life Below Water).

Hydrogen Implementation requires development of new infrastructure or already existing infrastructure; new job opportunities would be created, eliminating youth unemployment. Hence, GDP would witness an increase which would positively affect individuals' standards of life and the economy in general; individual would be able to satisfy their basic needs, such a food, health-service, and education. At the same time, countries would witness economic prosperity eradicating social issues such as poverty. Thus, hydrogen contributes to Goal 1 (No Poverty), Goal 2 (Zero Hunger), Goal 4 (Quality Education), Goal 8 (Decent Work and Economic Growth), and Goal 9 (Industry, Innovation, and Infrastructure). Furthermore, hydrogen mobilizes collaboration between countries, contributing to Goal 17 (Partnership to Achieve Goal). New supply chains would be established, and developing countries would benefit from financial, technological, and social support emphasized by the targets of the SDGs.

Goal 5 (Gender Equality) which aims at ending all forms of discrimination against all women and girls everywhere could also be achieved through green hydrogen. This could be achieved through the creation of a network of successful women, to enhance and empower their place in various energy sectors. Along with gender equality, Goal 10 (Reduced Inequality) focuses on empowering and promoting the social, economic, and political inclusion of all, irrespective of age, sex, disability, race, ethnicity, origin, religion or economic or other status, by 2030. Such a target could be reached through green hydrogen, by providing job opportunities through the industry which disregard the individual's gender. In addition, various opportunities in developed and developing countries could be established, regardless of the country's status, through the cooperation between countries on the development of green hydrogen.

In summary, the development of green hydrogen goes hand in hand with the achievement of the SDGs which emphasizes the unique interconnection between them. Green hydrogen, which is gaining ground recently, relies heavily on the SDGs to prosper and develop. For instance, since green hydrogen relies on renewable energy for its production, the SDGs will help accelerate the production of green hydrogen by calling for production of clean energy from renewable energy resources. In addition, the SDGs advocate for partnership and collaboration between countries worldwide, to overcome financial and economic difficulties that decelerate the advancement of green hydrogen. In return, green hydrogen complies with the SDGs and facilitates its achievements in numerous ways. Implementing green hydrogen instead of fossil fuel to produce energy has a direct impact on GHG emissions and consequently decelerates global warming. Thus, green hydrogen had an effective role in combatting climate change and reducing the carbon footprint of human beings. This shows green hydrogen's direct contribution to the SDGs. Yet, green hydrogen also contributes implicitly through improving human health and living standards, by reducing pollution and providing additional opportunities in the growing hydrogen industry. In short, the implementation of the SDGs will facilitate the growth of green hydrogen, and as the industry of green hydrogen develops, it will contribute implicitly and explicitly to the achievement of the SGDs.

Table 1. Contribution of Green Hydrogen to Sustainable Development Goals.

Sustainable Development Goals	Targets	Green Hydrogen Contribution
Goal 1: No Poverty	• By 2030, eradicate extreme poverty for all people everywhere. • By 2030, reduce at least by half the proportion of men, women and children of all ages living in poverty.	➔ Creates job opportunities in different sectors, improving the standards of life of individuals.
Goal 2: Zero Hunger	• By 2030, end hunger and ensure access by all people to safe, nutritious and sufficient food all year round. • By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and address the nutritional needs of adolescent girls, pregnant and lactating women and older persons.	➔ Enables individuals to satisfy their basic needs. Mainly food, through engaging them in hydrogen economy.
Goal 3: Good Health & Well-being	• By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination.	➔ Significantly reduces GHG emissions during both production and application limiting the spread of pollutants in atmosphere.
Goal 4: Quality Education	• By 2030, ensure that all girls and boys complete free, equitable and quality primary and secondary education. • By 2030, ensure equal access for all women and men to affordable and quality technical, vocational and tertiary education, including university. • By 2030, ensure that all youth and a substantial proportion of adults, both men and women, achieve literacy and numeracy.	➔ Empower the educational level of individual's children through the development of green hydrogen industry which allows the improvement of the life status of people.
Goal 5: Gender Equality	• End all forms of discrimination against all women and girls everywhere • Ensure women's full and effective participation and equal opportunities for leadership at all levels of decision making in political, economic, and public life	➔ Creates a network of successful women to enhance and empower their belonging in varies energy sectors.
Goal 6: Clean Water and Sanitation	• By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally. • By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes.	➔ Substitutes conventional fossil fuels in the shipping industry, reducing GHG emissions. ➔ Eliminates the water contamination due to pollutants removed by scrubbers. ➔ Improves the quality of air and water preserving different ecosystems.

Table 1. *Cont.*

Sustainable Development Goals	Targets	Green Hydrogen Contribution
Goal 7: Affordable & Clean Energy	• By 2030, ensure universal access to affordable, reliable and modern energy services. • By 2030, increase substantially the share of renewable energy in the global energy mix. • By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology. • By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programs of support.	➔ Eliminates GHG emission in hydrogen production through implementing renewable energy. ➔ Fosters research and development in hydrogen production methods aiming to reduce both environmental impact and cost. ➔ Substitutes conventional fossil fuels in energy sector producing clean zero-carbon emission energy. ➔ Enhancing the partnership between countries such as the Paris Climate Agreement enhancing the economy and the development of various technologies in developed and developing countries
Goal 8: Decent Work & Economic Growth	• Achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high value added and labor-intensive sectors. • By 2030, achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value. • By 2020, substantially reduce the proportion of youth not in employment, education or training.	➔ Benefits the country's economy through fostering development in different sectors. ➔ Eliminates unemployment through providing individuals with job opportunities. ➔ Raises the GDP and ensures economic prosperity.
Goal 9: Industry, Innovation, and Infrastructure	• Develop quality, reliable, sustainable and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all. • By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities. • Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, including, by 2030, encouraging innovation and substantially increasing the number of research and development workers per 1 million people and public and private research and development spending.	➔ Develops new infrastructure for hydrogen implementation. ➔ Improves the existing infrastructure to ensure a safe shift from conventional fossil fuel to hydrogen. ➔ Mobilize research to reduce the cost of hydrogen production, storage, and transportation. ➔ Fosters the development of new technologies of green hydrogen production other than electrolysis. ➔ Develops various sectors including transportation, enhancing the economy, and raising the GDP of the country.

Table 1. *Cont.*

Sustainable Development Goals	Targets	Green Hydrogen Contribution
Goal 10: Reduced Inequality	• By 2030, empower and promote the social, economic, and political inclusion of all, irrespective of age, sex, disability, race, ethnicity, origin, religion or economic or other status. • Ensure equal opportunity and reduce inequalities of outcome, including by eliminating discriminatory laws, policies and practices and promoting appropriate legislation, policies, and action in this regard • Ensure enhanced representation and voice for developing countries in decision-making in global international economic and financial institutions in order to deliver more effective, credible, accountable, and legitimate institutions	➔ Provides job opportunities through the development such industry disregarding the individual's gender, green hydrogen. ➔ Create various opportunities in developed and developing countries disregarding of the country status through the cooperation between them on the development on the green hydrogen.
Goal 11: Sustainable Cities and Communities	• By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.	➔ Substitutes conventional fossil fuels in transportation sector and energy sector. ➔ Eliminates GHG emissions preserving the quality of air.
Goal 12: Responsible Consumption and Production	• By 2030, achieve sustainable management and efficient use of natural resources.	➔ Replaces non-renewable energy resources in domestic, transportation, and energy sector. ➔ Benefits from renewable energy resources for green hydrogen production. ➔ Applies inter- and intra-generational equity taking into consideration the presence of such a resource for future generations
Goal 13: Climate Change	• Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries. • Integrate climate change measures into national policies, strategies and planning.	➔ Limit the spread of hazardous pollutants in the atmosphere. ➔ Eliminates carbon emissions decelerating climate change.
Goal 14: Life Below Water	• By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution. • By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and act for their restoration in order to achieve healthy and productive oceans	➔ Limits the water pollution caused by harmful contamination dumped by ships. ➔ Represents an alternative for fossil fuels in shipping industry limiting emissions as well as preserving marine organisms.

Table 1. *Cont.*

Sustainable Development Goals	Targets	Green Hydrogen Contribution
Goal 17: Partnerships to achieve the Goal	• Strengthen domestic resource mobilization, including through international support to developing countries, to improve domestic capacity for tax and other revenue collection. • Promote the development, transfer, dissemination, and diffusion of environmentally sound technologies to developing countries on favorable terms, including on concessional and preferential terms, as mutually agreed. • Significantly increase the exports of developing countries, in particular with a view to doubling the least developed countries' share of global exports by 2020.	➔ Establish partnerships between developed and developing countries to implement hydrogen economy. ➔ Contribute to the development of new supply chains in hydrogen economy. ➔ Supports developing countries who have a potential to become major players in hydrogen economy.

7. Case Studies—Developed and Developing Countries

This section explains how the application of green hydrogen differs between the developed countries including the United Kingdom (UK), United States of America (USA), and European Union and the developing countries including Africa, the United Arab of Emirates (UAE), and Asia. Table 2 summarizes the case studies of the coming sections.

Table 2. Case Studies of green hydrogen.

Region	Case Study	Reference
Domestic Sector in UK and USA	• Green hydrogen is shown to be a promising substitute for natural gas which is used for heating apartments and water. • This complies with the SDGs reducing GHG emissions and consequently decelerating climate change. • The domestic sector needs 7.8 and 38.3 million tons hydrogen per year in the UK and USA respectively if the energy content is considered to be 142.18 MJ. • Leakage should be thoroughly investigated since it would lead to an increase in GHG emissions.	[43,87]
European Union approach towards green hydrogen use	• More than 9.7 million tonnes (Mt) of hydrogen are produced in Europe; yet this amount is produced from non-renewable resources. • European Union aiming to reduce GHG emissions significantly have emphasized to critical steps to develop hydrogen industry and ensure carbon neutrality: decarbonizing the hydrogen production and introducing green hydrogen to various industries. • High technical potentials of the studied European regions have supported decarbonization of hydrogen by relying entirely on renewable energy to produce green hydrogen. • The reduction in cost of hydrogen from renewable energy as well as the expected revenues and economic growth will encourage the development of green hydrogen especially in countries rich in renewable energy.	[34,88]
Assessment of Green Hydrogen in Africa	• Africa which is rich in renewable energy resources has great potential to produce green hydrogen. • African countries such as Egypt and Morocco have signed agreements and partnerships to implement hydrogen related projects. • Methods of storing hydrogen should be thoroughly investigated; hydrogen could be transmitted using tanks, vessels, and pipes. • Population growth and the consequent economic problems slow down the development of hydrogen industry in Africa.	[89–95]

Table 2. *Cont.*

Region	Case Study	Reference
Strategy for a sustainable development in the UAE through hydrogen energy	• UAE has witnessed a rapid increase in the population followed by a growing energy demand. • Even though UAE is a major player in the oil market, possessing around 10% of the world's crude oil supply, UAE has a great potential to produce green hydrogen. • Mainly, green hydrogen could be produced from electrolysis powered by solar energy; Second, wind energy has also shown great potential where a 2 million euros wind power plant was built in UAE. • Green hydrogen could be employed in various industries such as transportation and electricity production which would be reflected positively on GHG emissions and climate change.	[21,27,96–100]
Green Hydrogen Analysis in Asia	• China is considered the major contributor to carbon emissions. In general, Asian countries have relied heavily on fossil fuel to satisfy their energy demand. • Few projects were implemented in China such as medium scale wind power plant in Zhangjiakou that produces 6000 tons of hydrogen annually. • Even though numerous road maps were published by different prominent Chinese institutions, no national strategy was presented Chinese Government to develop hydrogen industry in China and consequently combat climate change. • Surveyed experts in the study have highlighted the time needed to introduce hydrogen into the market and to depend entirely on green hydrogen; They also emphasized the critical roles that should be played by the government (policies and restrictions) and private sector (investments).	[101,102]

7.1. Case Study 1—Green Hydrogen Implementation in Domestic Sector in UK and USA

A recent study in the literature investigated the global warming potentials of hydrogen and the leakage rate of hydrogen distribution systems in two developed countries, USA, and UK [87]. It discussed whether the use of green hydrogen implementation in the domestic sector can be effective. The abundance of hydrocarbon reserves in the USA paves the way for hydrogen production using natural gas as a feedstock [87]. Meanwhile, natural gas is in high use for heating apartments and water in Europe [87]. Hence, substituting natural gas with hydrogen can meet one of the critical SDGs to reduce carbon dioxide emissions and combat climate change [87]. However, this presents multiple challenges for European countries, such as infrastructure modification; flow velocity and pipe diameter would undergo modification [87]. Hydrogen could be distributed using low-pressure pipelines used for natural gas. However, hydrogen leakage threatens the effectiveness of hydrogen implementation and consequently the achievement of the SDGs. The stratospheric ozone layer and global climate system could be affected due to the increased amount of hydrogen in the atmosphere [87].

Prior to hydrogen implementation, leakage rates of natural gas from the present distribution systems in both UK and USA were investigated; different approaches were employed to reach an estimation of these rates. In the UK, upon the application of ethane tracer method, around 0.64 Tg CH_4/ year (2.3%) was the estimated leakage rate. On the other hand, determination of natural gas leakage in the US was relatively more complicated than that in the UK [87]. The existing inventory values were 5 to 9 times less than recently measured emission values from well pads in the Permian Basin in New Mexico. Requiring more investigation, the leakage rate of natural gas in the US was estimated, based on the previously published reports, to be 0.69–2.9 Tg CH_4/ year (0.5–2.1%) [87].

Concerning the global warming impacts of the natural gas and hydrogen, the domestic sector was found to consume 309,934 million kWh of natural gas in the UK, equivalent to 28 million tons per year based on a conversion factor of 11,055.6 kWh/ton [87]. In the USA, the domestic sector consumed 5184 trillion cubic feet of natural gas in 2019 for heating and cooking. Consequently, 57 (0.184 kg CO_2/kWh) and 275 (53.12 kg CO_2 per thousand cubic feet of gas) million tons CO_2/year resulted from natural gas combustion in the UK and USA, respectively [87]. Thus, 76 and 295–360 million tons CO_2 equivalent per year represented the global warming consequences of natural gas in UK and USA, respectively (see Figure 4) [87].

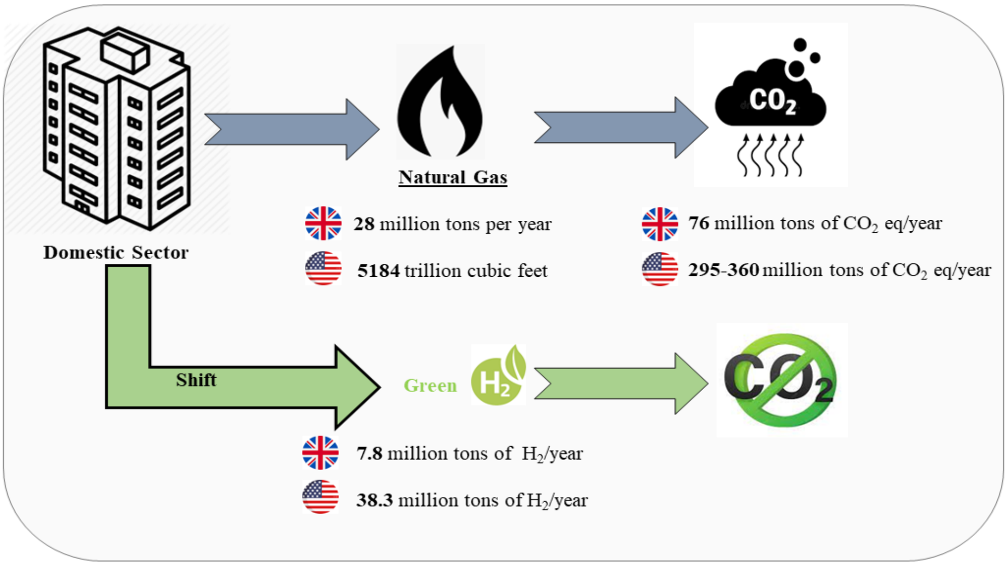

Figure 4. Carbon emissions of natural gas vs. green hydrogen in UK and USA.

Green hydrogen would significantly contribute to the SDG's targets through eliminating carbon emissions which result from natural gas utilization in the domestic sector [43]. As in seen Figure 4, 1116 and 5448 PJ of hydrogen would be required to satisfy the domestic needs of the UK and USA, respectively, assuming that no increase in the energy consumption is recorded in the future [87]. This represents 7.8 and 38.3 million tons hydrogen per year in the UK and USA, respectively, considering the energy content to be 142.18 MJ [87]. However, implementation of hydrogen should ensure a perfectly sealed green hydrogen distribution system. Savings of GHG emission would reduce by 0.3–0.4 % upon recording a 1% leakage rate [87]. Thus, minimizing its leakage, green hydrogen implementation in the domestic sector in the UK and USA achieves promising outcomes environmentally, which would contribute effectively to the SDGs such as climate action and human well-being.

7.2. Case Study 2—European Union Approach towards Green Hydrogen Use

Following the global awareness about climate change, the EU has taken steady steps towards reducing GHG emission. In its energy strategy, the EU has emphasized two critical elements which are energy consumption and carbon emission. According to the EU binding agreement, primary energy consumption should be reduced by 30% compared to its level in 1990 [88]. This would be accompanied by a reduction in carbon emission which originates mostly from primary energy consumption [88]. Green hydrogen has proved its promising potential to combat climate change [34]. Aiming at achieving net-zero GHG emissions by 2050, the European Green Deal that was presented by the European Commission in 2019 has prioritized green hydrogen to achieve this goal [34].

Currently, the EU consumes 9.7 million tonnes (Mt) of hydrogen annually, yet this amount is produced from non-renewable resources [34]. Thus, the first step towards carbon neutrality begins with decarbonization of hydrogen production. Then, the second step would be introducing hydrogen to the transportation and other industries to achieve a reduction in GHG emissions [34]. Between 2020 and 2024, according to EU's hydrogen strategy, 0.8 Mt of clean hydrogen should be produced annually from 6 GW of installed electrolysers; renewable energy will power these electrolysers [34]. As the demand for green hydrogen is expected to increase to 16.9 Mt by 2030 according to Hydrogen Roadmap Europe's ambitious scenario, the amount of green hydrogen produced is also expected to increase to 40 GW by that time [34]. Moreover, according to Hydrogen Roadmap Europe report, 24% of total energy demand in the EU and United Kingdom will be satisfied by hydrogen by 2050 [34]. In 2021, the total amount of produced hydrogen worldwide was 120 Mt; approximately 66% of this amount corresponds to pure hydrogen [34]. Yet, 95% of hydrogen production relies on non-renewable resources, such as natural gas and coal. The remaining produced hydrogen relied on electrolysis where hydrogen was produced as a by-product of chlorine production. Consequently, the current hydrogen industry has received growing attention recently since an insignificant amount of hydrogen is produced from clean renewable energy resources [34]

The expected decline in cost of clean hydrogen provokes the growing interest to decarbonize the process of hydrogen production; in 2020, the production of green hydrogen with zero carbon emissions costs $ 6.00 per kilogram. This cost is expected to drop by more than 50% ($2.50) considering average European wind energy productivity [34]. Hence, on the economic level, the shift towards hydrogen in countries and regions that are dependent heavily on fossil fuels will lead to new economic prospects.

To sum up, green hydrogen has gained ground worldwide, specifically in Europe where it is currently produced from non-renewable energy resources. Following the decline in cost of production of green hydrogen due to the extensive and continuous development of the renewable energy industry, Europe has shown a great potential to produce green hydrogen to satisfy the energy demand and at the same time reduce GHG emissions to decelerate climate change.

7.3. Case Study 3—An Assessment for the Green Hydrogen Uses in Africa

Africa is one of the continents that can meet the requests for energy production, improve the economy, and achieve the CO_2 global target of reduction. Africa is considered a rich source of renewable energies, including the green hydrogen [89,90]. However, the implementation of green hydrogen technology varies within African countries.

In South Africa, targeting the development of hydrogen technology, "Hydrogen South Africa" was set in motion in 2008 to discuss the use of fuel cells to enlarge the clean energy scale and provide sufficient energy to the community [91]. With such a path, South African's energy demand can be solved progressively through the hydrogen-fuel development [92]. In Egypt, an agreement was made for the establishment of the first green hydrogen center involving the cooperation between the Norwegian company "Scatec", Egypt's Sovereign Fund, and the company "Fertiglobe" along with a partnership between OCI and Abu Dhabi National Oil Company. Such a huge project involved the development of 50–100 MW electrolyzer, through which several benefits could be reached, including empowering the growth market [89]. Finally, Morocco signed a partnership with Germany in June 2020, the contract for which included two main projects aiming to upgrade the technical procedure of green hydrogen. The first hydrogen plant will be the first project to minimize 100,000 tons of CO_2 emissions. While the establishment of a research program will be the other project [89,93].

Having addressed technical difficulties, various techniques can be developed and implemented to ensure the storage of such a resource in Africa [94]. The storage methods can vary from compressing air, dealing with liquid material, or even storage in geological storage. However, what determines and distinguished each method is the duration needed through such storage [89]. Moreover, tanks, vessels, and pipes could be a beneficial way to transmit hydrogen from one location to the other [89].

In short, taking steady steps towards green hydrogen development, Africa shows a great potential to become part of the list of countries that are advocating for green hydrogen. Yet, the development of green hydrogen could be decelerated by socioeconomic problems such as rapid population growth, as well as other alarming economic problems [89,95].

7.4. Case Study 4—Strategy for a Sustainable Development in the UAE through Hydrogen Energy

Sustainable development has been receiving a significant amount of attention in the UAE, in order to overcome major challenges the country is facing [96]. Rapid population increase and unprecedent high economic growth have made the UAE one of the highest energy consumers per capita in the world [97,98]. In fact, in the past 23 years, the UAE's emission per capita was approximately double that of developed countries. Thus, the UAE's energy needs could be satisfied by implementing hydrogen energy, resulting in sustainable development [96,99].

Possessing around 10% of the world's crude oil supply (100 billion barrels of oil reserves) and 215 trillion cubic feet of natural gas, the UAE is major player in the energy market [96,100]. The abundance of these conventional energy resources in the UAE advocates for the production of hydrogen [96]. Renewable energy resources that could be implemented in green hydrogen production are numerous in the UAE [30]. With an average solar insolation exceeding 8.5 GJ/m^2 year, the UAE could benefit from the availability of solar energy to produce green hydrogen. With this approach, hydrogen solar production can have a huge impact on the economy, raising the income per capita of the UAE. In 2042, it is expected that the income of fossil fuels would drop, while the percentage of hydrogen accounting from total income of UAE is expected to reach 50%, which is approximately 65×10^9 $ [96]. Another suitable clean resource to produce green hydrogen in the UAE is wind energy. The average wind speed in the UAE is 6 m/s which makes it very suitable for implementation of wind turbines for power generation [96]. The first wind power plant built in the UAE, costing 2 million Euros, is capable of generating 850 kW. It can also reach maximum capacity when the wind speed increases to 12–14 m/s. Hence, the significance of these commonly used and implemented energy sources is their ability to produce green hydrogen, eliminating pollutants emitted by fossil fuels [21,96].

Green hydrogen can be employed in the UAE for several applications such as electricity production and transportation [21,27,96]. Hence, air pollution, climate change, and spread of illnesses would drop, contributing to the targets of the SDGs [49,50]. Human beings' standards of life would also be improved. Finally, the additional income generated from hydrogen sales would enable individuals to satisfy their needs such as food, shelter, education, and other necessities.

7.5. Case Study 5—Analyzing Green Hydrogen in Asia

Asia, which includes around 60% of the world's population, has shown an excessive use of fossil fuels. This has resulted in a massive environmental degradation due to the significant increase in total carbon emissions from fossil fuels combustion from 2.002 billion metric ton in 1990 to 5.158 billion metric tons in 2015 [101]. In fact, China is considered the major contributor to carbon emissions which increased by 3.02 billion metric tons from 2005 to 2014 [101]. This could be attributed to two main factors, economic and population growth, provoking an increase in production of goods and consequently a rise in demand for energy [101]. Asian countries have relied heavily on non-renewable energy sources, mainly fossil fuel, to satisfy the growing demand for energy; in East Asia, West Asia, and Central Asia, the percentage of energy generated from renewable sources was 6.28%, 6.30%, and 20.75%, respectively [101].

Over the past few decades, hydrogen has received global growing attention due to the urgent need to mitigate GHG emissions, as well as the cost reduction in green hydrogen production [102]. In China, despite the fact that government and policy makers have promoted hydrogen energy development, few projects were implemented. For instance, 6000 tons of hydrogen per year are produced from wind power in a medium-scale project completed in Zhangjiakou, the first city in China to produce green hydrogen [102]. Furthermore, unlike Australia, Japan, the European Union, and South Korea, China has not presented a national strategy for hydrogen development [102]. Yet, a roadmap on the development of hydrogen energy infrastructure was published by the China National Institute of Standardization and the National Standardization Technical Committee for

Hydrogen Energy in 2016 [102]. Moreover, a technological roadmap, presented by China Hydrogen Alliance, emphasized that by 2026-35, hydrogen will be produced mainly from renewables-based electrolysis and coal. Over the long term (2036-50), hydrogen production from coal gasification would be improved by implementing carbon capture sequestration (CCS) [102]. According to roadmap proposed by China EV100, the estimated target supply cost of hydrogen by 2025 would reach CNY40/kg; this cost is expected to drop by 50% by 2050 [102].

To decarbonize the transportation sector, China's Society of Automotive Engineers have developed a technological roadmap that called for development of medium-sized to large fuel cell commercial vehicles; hydrogen would be produced from either renewable energy resources or industrial by-products. This stage is followed by extension of fuel cell application to include heavy-duty and long-distance vehicles [102]. Besides, the Global Energy Interconnection Development and Cooperation Organization emphasizes the importance of coupling electricity and hydrogen, which would reflect positively on the power, transport, and industrial sectors by reducing carbon emissions [102]. By 2030, 4 million tons of green hydrogen will be produced from water electrolysis. Thus, various studies have tackled hydrogen development in China, specifically green hydrogen, and numerous roadmaps were developed [102]. However, a study was conducted to investigate the barriers, which include policy and market issues, to providing a complete strategic roadmap for green hydrogen development in China [102]. For this reason, a two round expert survey was developed; the first was formulated with a SWOT framework. The survey followed the Delphi method where the participating experts were provided with the summarized results of first round survey. Then, the second round of the survey was conducted aiming for a convergence of opinions [102]. Survey results showed that participating experts emphasized the urgency of establishing an official national hydrogen energy roadmap which would help in investment and action coordination [102]. The government should also accompany the different stages of hydrogen energy development by establishing steady and predictable policies that attract investments in this growing industry. They also highlighted green hydrogen's potential, since by 2026-30 it would reach a developed stage [102].

Yet, weaknesses in regulation, technology development, and investment would decelerate the development of green hydrogen. Consequently, a detailed strategy plan was developed to account for all the challenges that limit green hydrogen development [102]. In the first place, green hydrogen demonstration projects as well as research and development should be highly encouraged. The infrastructure should be developed to facilitate the introduction of hydrogen into the energy and transportation sector [102]. It is worth noting that in the early stages, hydrogen produced from non-renewable resources would be used since it would take 5 years for the green hydrogen to become cost-competitive [102]. Upon the implementation of hydrogen, highest value applications should be prioritized such as public transport over the aviation and shipping industry [102]. The most important aspect of the strategic road map is reducing the government's presence in the green hydrogen industry to allow the private sector to lead advancements [102]. To sum up, green hydrogen is gaining ground in countries worldwide. In China, many strategies were developed to accelerate the growth of green hydrogen. The previously conducted studies have enforced green hydrogen's potential to reduce carbon emissions which complies with the SDGs advocating for combatting climate change, building sustainable cities, and generating clean and renewable energy.

8. Green Hydrogen Industry Challenges and Recommendations

8.1. Challenges

Besides the benefits of the green hydrogen industry, several challenges and difficulties exist through such an application [15,18,21,103]. Two major drawbacks upon the implementation of green LH_2 were recorded: a loss of 30% of the hydrogen energy content due to hydrogen liquification; along with the difficulty in LH_2 storage due to the demanded low temperature (−253 °C under 1 bar) and insulation [21]. Examination of the potential hazards of the implementation of hydrogen into global maritime transportation shows that LH_2 which has higher auto-ignition temperature and lower vapor density, is safer in comparison with other fuels [21,24]. In fact, the US National Fire Protection Association which implements a standard system to evaluate the material hazards for emergency response, rated LH_2 with zero in the health and instability categories taking into consideration that the degree of hazard falls between 0–4 where four indicates highest severity [21,24].

Moreover, due to the high flammability of hydrogen, as well as the possibility of diluting oxygen concentration, hydrogen can be considered a threat to humans safety [103,104]. As well as this, there is the wide flammable limit range, lower boiling temperature, lower flash temperature, and most importantly, lower heating value (LHV) of 120 MJ/kg, 2.8 times the Heavy Fuel Oil's LHV which signifies the high energy intensity of hydrogen [21]. Thus, because of the increase in the number of deaths and illnesses through several hazardous accidents, green hydrogen can be threat to the goals of the SDGs [21].

Other challenges associated with the use of a green resource include technology, transport and storage, cost, and electricity. Green hydrogen technology is prone to technical difficulties, related to the high temperature or high pressure, which make it challenging to store [94]. Likewise, the cost of hydrogen gas must be reduced to a benchmark of 2 $/kg to become competitive [21,26,105]. Moreover, the application of green hydrogen demands a large amount of electricity [21]. Thus, a larger amount of wind blowing, and solar energy are needed to support such an application. For that, for the next 30 years, and every year, more offshore wind capacity must be developed than the past 20 years [105].

8.2. Recommendations

Achieving the sustainability goals was pushed by the Paris Climate Agreement and the UN SDGs in 2015. As time passes, the development of technology is needed, and thus a greater diversity of services is required. Such development involves the decarbonizing of the economy, knowing that no one should be left behind as mentioned in SDG 7 [106]. The use of such a strategy enables the usage of different sectors including transportation, buildings, and industrialization. Nevertheless, the application of such targets and goals proposed by the Paris Agreement necessitates the cooperation of different countries. Such a cooperation was made through the European Green Deal that will hold several effective opportunities for the region. For instance, several economic and social benefits to African society can be reached through the production and trade of green hydrogen. The positive outcomes are not limited to Africa, but also involve Europe, which will be able to achieve its respective clean energy transitions in the long term [106].

The dependency on fossil fuels associated with Its negative outcome on the environment, cost, and safety led to a change in the ideology of several countries [107]. This ideology considered several scenarios that could modify the followed path to a more sustainable and eco-friendly one [28,107]. The most promising solution that could be followed was through renewable energies, including the use of green hydrogen [28,108]. The adaptation of this path necessitated a well-equipped technology capable of meeting various needs in a practical and viable manner. Thus, the development of green hydrogen techniques was necessary to increase the efficiency and feasibility of the procedure along with a reduction in its cost.

This advancement included four main phases including production, storage, safety, and utilization [28]. While hydrogen production could be achieved through various processes such as electrolysis, photolysis, biolysis, and thermolysis, the material required an energy source and the catalysts used are the main factors that determine which method should be followed [28,109]. Specifically, energy sources range from being an electric, photonic, bioenergy, chemical, heat source or even through fossil fuels [28,108]. Following one method, using one of the proposed energy sources, rather than the others determines that capability and extent of such procedures is more sustainable and thus achieves the required SDGs [28,110]. In fact, it should be highlighted that the shift from producing hydrogen using fossil fuels to the usage of renewable energies minimized the daily impact humans cause to the environment, along with the capability to reach the SDGs [108].

9. Conclusions

Poverty and hunger are spread across many countries, greenhouse gas emissions are rapidly disrupting the earth's biodiversity, climate change is affecting many countries and altering their daily life. This paper sheds light on the significant role played by green hydrogen in solving such devastating difficulties. In fact, the usage of a clean green resource opens the door to reaching the targets presented in the SDGs. Hence, green hydrogen holds a remarkable role in achieving sustainability, decelerating climate change, and limiting the spread of diseases.

The beneficial impacts green hydrogen possesses are imperative to humans, governments, and Earth, but such positive outcomes cannot be reached without a controlled plan, taking into consideration the different challenges and difficulties that might face such an implementation. Such challenges include the high flammability of hydrogen, difficulty in its storage, and the large amount of electricity and cost needed (see Figure 5). Accommodating these different aspects and becoming fully aware of developing successful solutions to solve them will likely turn such a dream into reality. In fact, this demonstration should be guided with a logical, appropriate, and scientific strategy guided by daily research allowing the application to be more authentic, beneficial, and less time consuming.

The difficulties accompanied with green hydrogen including its storage, safety, and efficiency make its implementation a challenging issue. Thus, future research should focus more on the possible solutions needed to minimize these barriers and find suitable ways to shift the ideology of people towards green hydrogen as a safe source which provides benefits that outweigh its possible drawbacks.

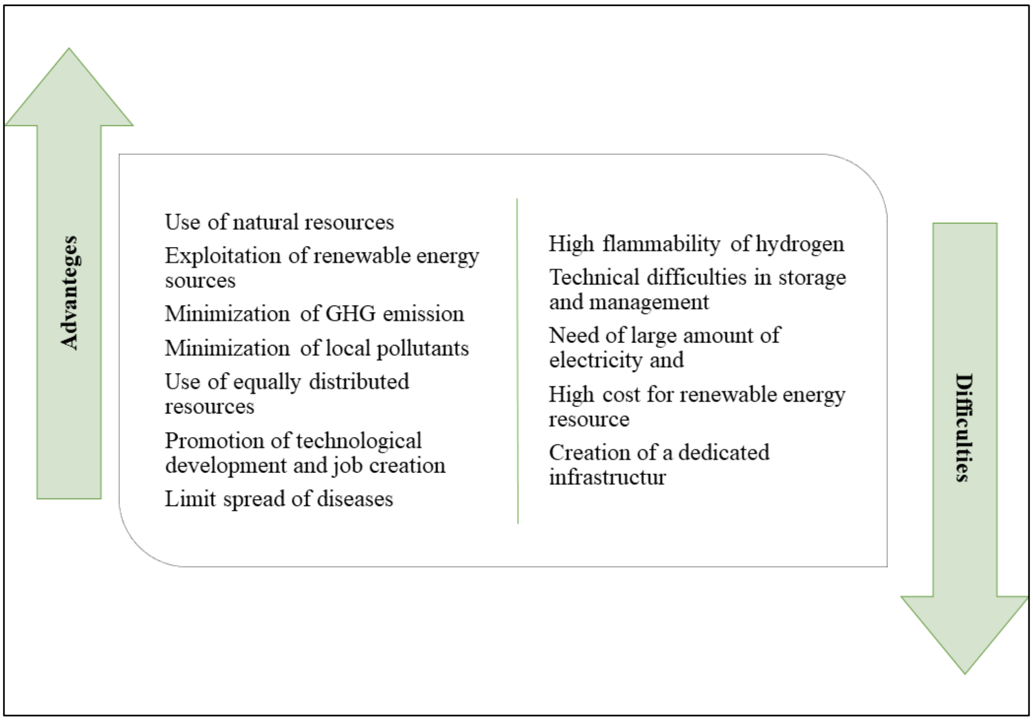

Figure 5. Advantages and difficulties of green hydrogen industry.

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Nomenclature

SDGs	Sustainable Development Goals
GHG	Greenhouse Gases
SMR	Steam Methane Reforming
LH2	Liquid Hydrogen
CCS	Carbon Capture and Storage
HFC	Hydrogen Fuel Cell
HFICE	Hydrogen Fueled Internal Combustion Engine
ICE	Internal Combustion Engine
GDP	Gross Domestic Product
WiGH	Women in Green Hydrogen
LHV	Lower Heating Value
HRS	Hydrogen Refueling Station
EU	European Union
AFIR	Alternative Fuels Infrastructure Regulation

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