energies

Review

The Development of a Green Hydrogen Economy: Review

Eugeniusz Mokrzycki * and Lidia Gawlik *

Mineral and Energy Economy Research Institute of the Polish Academy of Science, 31-261 Krakow, Poland
* Correspondence: mokrzy@min-pan.krakow.pl (E.M.); lidia.gawlik@min-pan.krakow.pl (L.G.)

Abstract: Building a hydrogen economy is perceived as a way to achieve the decarbonization goals set out in the Paris Agreement to limit global warming, as well as to meet the goals resulting from the European Green Deal for the decarbonization of Europe. This article presents a literature review of various aspects of this economy. The full added value chain of hydrogen was analyzed, from its production through to storage, transport, distribution and use in various economic sectors. The current state of knowledge about hydrogen is presented, with particular emphasis on its features that may determine the positives and negatives of its development. It was noted that although hydrogen has been known for many years, its production methods are mainly related to fossil fuels, which result in greenhouse gas emissions. The area of interest of modern science is limited to green hydrogen, produced as a result of electrolysis from electricity produced from renewable energy sources. The development of a clean hydrogen economy is limited by many factors, the most important of which are the excessive costs of producing clean hydrogen. Research and development on all elements of the hydrogen production and use chain is necessary to contribute to increasing the scale of production and use of this raw material and thus reducing costs as a result of the efficiencies of scale and experience gained. The development of the hydrogen economy will be related to the development of the hydrogen trade, and the centers of this trade will differ significantly from the current centers of energy carrier trade.

Keywords: hydrogen economy; green hydrogen; electrolysis

check for updates

Citation: Mokrzycki, E.; Gawlik, L. The Development of a Green Hydrogen Economy: Review. *Energies* **2024**, *17*, 3165. https://doi.org/10.3390/en17133165

Academic Editors: David Borge-Diez and Jay Zarnikau

Received: 16 May 2024
Revised: 10 June 2024
Accepted: 24 June 2024
Published: 27 June 2024

1. Introduction

The use of green hydrogen as a fuel may accelerate the transformation towards a low-emission energy system. This would be a step towards limiting global warming to +1.5 °C and fulfilling the Paris Agreement.

Only 0.1% of current global hydrogen production is emissions-free (green) hydrogen, and increasing the share of this hydrogen is difficult [1]. In the process of moving towards net zero emissions, other energy sources must also be taken into account for now.

As the demand for clean hydrogen increases, the costs of its production should decrease, because economies of scale will reduce the average cost of hydrogen. Greater supply thanks to increasing the scale will allow for the expansion of possible uses of hydrogen not only in power systems but also in industrial processes. This will help achieve a 40% reduction in emissions by 2030 [1].

Green hydrogen is still not competitive with hydrogen production from fossil fuels. This is due to lower production efficiency rates. Another problem is the low availability of renewable energy. The currently produced renewable energy is used in the zero-emission electricity market, and this market's demand for hydrogen production requires an increase in production capacities.

Blue hydrogen production could pave the way to green hydrogen. Adapting and modernizing hydrogen storage and deployment, along with international trade regulations, must be a priority.

Green hydrogen will help reduce greenhouse gas emissions in the coming years. This is not only a potential technology of the future but it is already being successfully implemented around the world [2].

The strategy of combatting global warming through the development of clean hydrogen and its use in many sectors, especially where it is currently difficult to reduce greenhouse gas emissions, was presented by the European Union in July 2020 [3]. This hydrogen strategy assumes that electrolyzers will become mature technologies and be implemented by 2030. It also assumes the development of an open and competitive hydrogen market and expresses the view that the decarbonization of industry—thanks to the increased use of clean hydrogen there—will take place before 2050. At the same time, the hydrogen strategy does not set any further specific goals or methods to meet this demand for hydrogen [4].

The hydrogen economy is a priority of the EU's economic recovery package after COVID-19; this package is based on the European Green Deal [5], which commits Europe to becoming the world's first climate-neutral continent by 2050. Net zero requires a complete withdrawal from fossil fuels, including natural gas, which has so far been considered a transitional fuel [6].

This article is a review, and its purpose is to present issues related to hydrogen which have been of particular interest to scientists in recent years. The next part will present the idea of the hydrogen economy and its origins and describe the specific features of hydrogen as an energy source and vector of transition. Next, the most important risks related to hydrogen production and its storage, transport and use in various sectors of economy are described. Section 5 is devoted to the role of hydrogen in the fight against global warming. Works on the assessment of the hydrogen potential in many countries around the world are presented, and centers for the development of this gas production are indicated. The next section, in line with the interests of scientific experts, discusses some dilemmas related to the development of the hydrogen economy. These are as follows: the problem of demand for freshwater for electrolysis purposes, the possibility of using seawater and wastewater for electrolysis and the issue of hydrogen storage. Section 7 discusses the issues of developing the hydrogen economy. Attention has been paid to research directions aimed at increasing the efficiency of the hydrogen value chain and consequently reducing its production and use costs in various sectors of the economy. The need to build a hydrogen market was noted, with an indication of the bottlenecks blocking the development of this market. In addition to technical and economic research, attention should be paid to the emerging research trends related to sociological and political science issues. These issues try to respond to the current demands of the modern world.

2. The Concept of the Hydrogen Economy

The theoretical foundations of the hydrogen economy were introduced in 1970 by John Bockeris [7–9]. A few years later in his article [10], Bockeris presented the facts and historical events that prompted him to formulate the assumptions of such development. This is a theoretical concept of an energy system where hydrogen is the main energy source. The production of hydrogen from easily accessible sources should allow for its easy use in transport, industry and various domestic and commercial applications. This will gradually eliminate fossil fuels from these uses. Currently, the hydrogen economy is perceived as a panacea for several problems facing the world, such as the following [11]:

- Care for the global environment;
- The depletion of natural resources;
- Food shortages and malnutrition in third-world countries;
- A growing world population.

The hydrogen economy is developing. It now finds more and more applications in almost all parts of the energy system [9], including electricity generation and transport [12–15], and according to some assessments, hydrogen has turned out to be technically and economically viable for decarbonizing heating [16,17].

There are many intractable problems related to the economics of fossil fuels. These are even more overwhelming when it comes to the economics of hydrogen. However, successfully solving the economic problems of hydrogen production and use will bring significant benefits to the environment, energy supply, the economy and end users [18]. Hydrogen is a clean fuel that meets the conditions of sustainable development and may be a source of global energy in the future. Potentially, energy systems based on fossil fuels could be replaced by hydrogen systems [19]. However, it is not possible to quickly switch from fossil fuel energy to a hydrogen energy system. There are serious socio-economic, technological and scientific challenges to overcome. For example, the low density of hydrogen makes its storage during transport a key challenge [20]. Although the chemical and refining industries use hydrogen widely, its production, storage and delivery costs are too high for most energy applications [21].

Hydrogen production technologies have been understood for a long time, but the traditional methods use fossil fuels, which results in carbon dioxide being a by-product. Currently, the hydrogen economy is not green, which is a problem, as it contributes to climate change: over 99% of hydrogen production uses fossil fuels, and petroleum refining accounts for 42% of hydrogen demand [22].

Hydrogen fuel may be produced using many different processes:

- Thermal processes: Hydrogen is produced by the high-temperature reaction of steam with hydrocarbon fuel. The following are used to produce hydrogen in thermal processes: natural gas, diesel oil, gasified coals and renewable liquid fuels. Steam reforming processes are the most widely used methods of producing hydrogen from natural gas. These processes produce gray hydrogen and substantial amounts of carbon dioxide and carbon monoxide, which are greenhouse gases that are harmful to our planet and will contribute to global warming.
- Solar processes: Processes of this type include photobiological systems, semiconductor systems, hybrid systems and others. To produce hydrogen, these systems use solar energy, which is a common renewable resource found in nature.
- Electrolytic processes: These processes are carried out in an electrolyzer, where water is separated into hydrogen and oxygen. It is an emissions-free hydrogen production process from nuclear and renewable resources. This is, however, an expensive process due to the amount of electricity needed.
- Biological processes: In these processes, microbes break down organic matter (e.g., biomass, sewage) to produce hydrogen. This type of hydrogen production is one of the best alternative methods, where hydrogen is a by-product of microorganisms (algae, bacteria) that have the potential to produce usable hydrogen from various renewable resources.

The development of technologies related to water electrolysis and hydrogen fuel cells, combined with the growing problem of climate change due to greenhouse gas emissions, has resulted in an increase in interest in hydrogen around the world and the search for ways to replace fossil fuels and their derivatives in various areas of the economy and industry [23].

The "greening" processes of the hydrogen economy are so encouraging that decision-makers from around the world have not hesitated to invest in it, hoping to improve the prospects of the energy system. The European Commission High Level Group on Hydrogen and Fuel Cell Technologies already suggested in 2003 that the European Union would achieve a hydrogen-based economy by 2050 and predicted that by 2040, 35% of new cars produced would be powered by zero-emission hydrogen [11]. In turn, the Energy Efficiency and Renewable Energy, Fossil Energy, Nuclear Energy, and Science offices of the US Department of Energy recommended switching to hydrogen fuel cell cars by around 2020 [11].

Science and business have noticed the potential of global decarbonization through the development of green hydrogen technologies and appreciate the positive sides of hydrogen. Now, we are dealing intensely with solving problems to decrease its currently undesirable features.

3. Advantages and Disadvantages of Hydrogen

Hydrogen is a simple element that consists of only one proton and one electron. It does not occur alone in nature, and hydrogen molecules have to be produced from a given source [24]. Hydrogen can be produced from many different primary energies and can be used in various sectors and different processes, such as industry (oil refining processes and ammonia production), transport (sea, air, roads), energy, etc. Many further applications are currently being tested due to its general advantages and the possibility of using hydrogen without a carbon footprint (produced by water electrolysis from renewable electricity). Green hydrogen is a solution enabling the decarbonization of sectors such as the steel, chemical, cement and refinery industries [25]. These are sectors difficult to decarbonize. If it finds wider application in different sectors, then—just like electricity today—it may become a basic energy carrier in the future [26,27]. Hydrogen can be stored in the medium and long term, unlike electricity, which is very difficult to store [28]. Hydrogen storage is possible in the form of liquid hydrogen (LH2), compressed gas and slush, solid or metallic hydrogen [29].

The advantages of hydrogen fuel [24,30–32] are as follows:

- Easily accessible: Hydrogen is a basic element of the Earth and is abundant. It takes a long time to separate hydrogen from accompanying substances, but the result is a source of clean energy.
- Does not cause harmful emissions: The electrochemical reaction of hydrogen and oxygen does not emit carbon dioxide; therefore, hydrogen is the cleanest fuel.
- Environmentally friendly: Hydrogen is a non-toxic substance, which is rare among fuel sources.
- Highly efficient: Hydrogen produces more energy per unit of mass of fuel than diesel or gas. Hydrogen fuel cells are two to three times more efficient than traditional combustion technologies. A conventional coal-fired power plant typically generates electricity with an efficiency of 33 to 35%. Hydrogen fuel cells can produce electricity with an efficiency of up to 65%. In addition, fuel cells run quietly, have fewer moving parts and are well suited to a variety of applications.
- Renewable: Hydrogen can be produced many times, unlike other, non-renewable energy sources. Hydrogen therefore represents an unlimited source of fuel.
- Fast charging: Hydrogen fuel cell power units are charged very quickly. Charging an electric vehicle takes from 30 min up to several hours, while hydrogen fuel cells can be charged in 5 to 10 min.
- The safest form of energy for energy-intensive tasks: Hydrogen is even used to power spacecraft due to its efficiency. Hydrogen energy is three times more powerful than gasoline and other fossil fuels. Ideally, this means less hydrogen is needed to get the job done. It also offers motive power for aircraft, boats, cars, and portable and stationary fuel cell applications.
- Versatile: Hydrogen fuel cells are the best alternative to renewable energy and can reduce the use of fossil fuels. Hydrogen fuel is so versatile that it can be used in various sectors of the economy.

Hydrogen has several features that make it suitable for use as a secondary energy vector, which is then used in an unconventional way [27]:

- As a fuel of high gravimetric density, hydrogen is a more concentrated energy source compared to other fuels.
- Hydrogen's high-efficiency conversion processes can be used to convert water into other forms of energy.
- The production and consumption of hydrogen produced by water electrolysis constitutes a closed cycle.
- Hydrogen combustion is almost completely free of polluting emissions.

- Hydrogen can be stored in many ways—in gaseous form under normal or high pressure and in liquid or solid form.
- It is possible to transport it over long distances (although there are some related difficulties).

With hydrogen, energy security and prices are more stable, as it levels the competition between different energy sources [27,33].

There are also many disadvantages of hydrogen fuel when compared with conventional fuels [24,30–32,34].

- The production of hydrogen is expensive. This especially concerns the green hydrogen extracted from water by electrolysis. If separated from fossil fuel, the cost is lower, but the methods of obtaining it are not in the spectrum of interest of the decarbonization strategy.
- Hydrogen is difficult to store and transport in comparison to the transportation or storage of fossil fuels. Crude oil and natural gas can be transported through pipelines, and coal can be transported by road, rail or sea. However, there are no good methods for transmitting even insignificant amounts of hydrogen. Fossil fuel storage technologies were developed long ago and are reliable and not expensive. These issues in comparison with hydrogen are the subject of many studies. Hydrogen fuel cells can be used to store hydrogen, but the hydrogen then becomes more expensive. Hydrogen is usually transported via pipelines rather than vehicles. There are two reasons for this: firstly, there are security concerns, and secondly, the volume of hydrogen is very large, which limits the possibility of transporting it by truck. To obtain the energy equivalent of a petrol tank truck, 22 trucks of hydrogen at 200 bars or 3 liquefied hydrogen tank trucks (a 40-ton truck transports a maximum of 3.5 tons of liquid H2) are required [35].
- Hydrogen is highly flammable; therefore, safety measures must be taken when working with this energy carrier.
- Currently, hydrogen does not have the prepared infrastructure that would constitute a simple supply chain for this fuel from production to its end use. Each element of the chain requires research, implementation and large capital outlays to build this infrastructure. New thinking about the end uses of hydrogen is also needed. For example, replacing gasoline with hydrogen in cars requires their refitting or new construction.
- So far, the legal issues necessary to build and develop the hydrogen market have not been sufficiently supported. The issue of safety regulation has not been adequately addressed. Rules for subsidies and competitiveness have not been developed and unified.

Fossil fuels still dominate global energy supplies. Although one of the most advanced uses of hydrogen in new applications is its use in road transport, there is still no framework in place that provides cheap and sustainable hydrogen energy to ordinary car owners on the horizon. Even if hydrogen quickly becomes a cheap fuel, it will take years before it is a mainstream energy source because vehicles and fuel stations must be adapted, which will require additional capital outlays.

Nevertheless, using hydrogen as a fuel in transport is advantageous because it is a clean fuel, uses more efficient technology and is convenient for heavy road and rail transport [36].

- Hydrogen is a perfectly clean fuel because the only waste it produces during combustion is water vapor. Meanwhile, the currently used hydrocarbons burned with oxygen produce carbon dioxide (CO_2) and other wastes harmful to the environment and human health (nitrogen and sulfur oxides). The process will be zero-emission if green hydrogen is used in cars, i.e., hydrogen obtained through water electrolysis—a simple method in which a low-voltage current is passed through water, creating oxygen and hydrogen gas. Green hydrogen is the only sustainable form of hydrogen because it is obtained through the electrolysis of water, powered by electricity generated from renewable sources. However, if cars are powered by so-called gray hydrogen, where electricity produced from fossil fuels is used for electrolysis, it cannot be said that such hydrogen has no impact on the environment because the process of generating electricity causes greenhouse gas emissions.

- Hydrogen uses more efficient technology. A car equipped with an internal combustion engine moves thanks to mechanical energy, which is generated by converting the energy generated in the engine by the combustion of fuel and air. It is an invention from the mid-19th century and is still used. Its efficiency has reached its maximum. However, because the waste it produces pollutes the environment, it is considered unsustainable.
- A gasoline engine consumes only 20–25% of the energy produced, and the rest (75–80%) is dissipated. In an electric motor, 80% of the energy is used, and 20% is dissipated. Hydrogen used in cars must first be converted into electricity, which consumes 50% of the energy. This means that a hydrogen car can use 40% of the energy consumed. However, this amount is twice as much as in a gasoline engine.
- Hydrogen performs well in heavy road and rail transport. Trucks and railways should be the first to use hydrogen propulsion. The hydrogen drive is more compact than others currently used for these purposes. Another advantage is the short refueling time and long range. Some industrial vehicle manufacturers (for example in South Korea) offer turnkey services, supplying customers with cargo trucks and ensuring a green hydrogen distribution network. Almost 50% of railway lines in Europe are not yet electrified. There are many routes in Europe where installing an overhead power line would be difficult or simply impossible, which is why trains run on diesel oil, a highly polluting fuel. Replacing such trains with hydrogen propulsion is rational.
- There are, on the other hand, disadvantages of using hydrogen as a fuel.
- If hydrogen falls into the category of ”gray”—not produced using electricity from renewable sources—it is polluting. To date, more than 96% of the hydrogen used is gray hydrogen. The costs of gray hydrogen are currently lower that the costs of green hydrogen, but its impact on the environment is high. For every kilogram of hydrogen obtained, 10 kg of carbon dioxide is produced. Global hydrogen production is approximately $70-75$ million tons, emitting almost 1 billion tons of carbon dioxide.
- The gas is difficult to process. Pouring gasoline into a tank is quick and easy, as is connecting the cable that charges an electric car’s battery. Hydrogen must be compressed at high pressure (350–700 bar) because it has a low volumetric energy density, and, without compression, the tank capacity would have to be substantial to provide enough fuel to travel a reasonable distance. Therefore, hydrogen is a difficult gas to handle. It takes 5–6 kg of hydrogen to travel approximately 600 km. A standard-sized car fuel tank can hold enough hydrogen at normal pressure to drive only 5 km.
- Hydrogen is difficult to transport. There is the question of how to bring hydrogen to refueling stations. Here, the first problem is that special pipelines are needed for its distribution since those for methane and natural gas are not fully compatible unless low-hydrogen natural gas mixtures are used. The alternative would be to keep it in a liquid state, like petroleum derivatives, but the liquid state of hydrogen is reached at -253 degrees Celsius, which involves a lot of energy to transform it and then keep it in a liquid state. There are several hydrogen pipelines, but they only span a few thousand kilometers around the world. Germany is the leader in distribution infrastructure, with almost 100 stations, a number which is constantly growing. These are located along highways, thanks to which hydrogen cars can move throughout the country. In Paris, hydrogen is produced locally, and half of the city’s taxi fleet runs on hydrogen. A refueling station for hydrogen cars was built in the Italian mountains in Bolzano Sud, where hydrogen is produced in a nearby hydroelectric power plant.
- Hydrogen is less beneficial than electricity for car propulsion. Ranking the possible car propulsion methods according to energy conversion efficiency, the most effective is a battery-powered electric motor—its efficiency reaches 80%. Hydrogen propulsion

achieves approximately 40% energy conversion efficiency, but this is more than can be obtained from the most efficient internal combustion engines—gasoline or diesel. For light road transport, green hydrogen is less favorable than renewable electricity. The environmental benefits are the same, but the cost of refueling and the availability of charging networks for electric cars are better. Green hydrogen production costs are high ($5–7 per kilogram), and suppliers sell it for at least twice that amount due to challenges related to poor infrastructure. Diesel offers a financial advantage over hydrogen, but if environmental losses are considered, hydrogen ultimately turns out to be cheaper.

- Hydrogen energy is a renewable resource because it is widely available and its environmental impact during use is negligible. However, to produce hydrogen, other forms of energy are needed—currently, this means mainly non-renewable energy, from fossil fuels (coal, natural gas and crude oil). The idea of using renewable energy sources for this reduces the dependence of the hydrogen economy on fossil fuels. However, this is conditioned by the pace at which energy from renewable sources will develop and the possibilities of reducing its costs.

A hydrogen-based energy system is considered a viable and beneficial option for providing high-quality energy services across a wide range of applications in an efficient, clean and safe manner while meeting sustainable development goals. Hydrogen can compete with electricity in all these aspects. Its advantage over electricity is the possibility of its storage, while the storage of electricity is limited [37].

4. Risks Related to Hydrogen Use

The development of the hydrogen economy, like any original activity, involves many risks that must be considered. The risk factors can be of several types. They are also classified differently, often non-objectively, but they are important for the pace of development of the undertaken activity. Several formulations for the classification of perceived risks in the development of the hydrogen economy are quoted here. The green hydrogen supply chain includes renewable energy suppliers, electrolyzers, distribution facilities and finally consumers. The following risk factors have been identified in this chain:

- High investment costs [25].
- Lack of or insufficient capacities for electrolysis [25].
- Lack of changes in policies and regulations [25].
- Social injustices that could occur across the value chain [38,39].
- Risks associated with hydrogen, technical, social, environmental or lethal, which requires the development of appropriate methods to reduce the risks [35].
- Three categories of risks linked to the wider use of green hydrogen: geopolitical, market and trade [40].

Hydrogen differs from methane in many respects, as it has a much higher hazard profile. It should be emphasized that there is a wide range in the explosion limit for air/hydrogen mixtures, with the LEL (Lower Explosion Limit) being 4% and the HEL (Higher Explosion Limit) being 74%, compared to the much smaller difference between LEL/HEL for methane, of 5 to 15%.

The hazards associated with the use of hydrogen result from the fact that this gas has the following traits [41]:

- It is very light and, when released into the atmosphere, has a high dispersion in the air.
- It has a high hash rate and LEL/HEL, making it extremely dangerous when limited.
- It has an extremely low ignition energy (~0.02 MJ), while the ignition energy of methane is about 0.29 MJ [42,43].
- It will always ignite if quickly released from a compressed form after providing activation energy, which can be delivered as static electricity.
- It can penetrate steel and other limiting materials, causing brittleness [35].

- It becomes a liquid at a very low temperature, 20.28 K, while propane (LPG) does so at 231.2 K and methane at 111.6 K—liquid hydrogen (LH_2) requires care in handling, and the costs of its maintenance are relatively high; it requires specialized cryogenic infrastructure and a highly trained service team, and the disadvantage of using hydrogen in cars is that it is practically difficult to equip cars with cryogenic or high-pressure tanks.
- It has no smell and is difficult to detect.
- It burns with a clean, almost invisible flame.
- It detonates as a mixture with air (or O_2) (deflagration may turn into detonation).
- It presents difficulties in detecting leaks, which are difficult to detect, and is dangerous to remove.

Maintaining safe conditions during the widespread use of hydrogen is much more difficult than in the case of other gaseous fuels [44,45]. Given its threat profile, the introduction of hydrogen will entail higher insurance premiums and difficulties in financing energy projects. Communities aware of the risks will likely oppose the introduction of hydrogen in their regions.

To implement hydrogen at a large scale, it is necessary to develop appropriate, safe procedures at every stage of hydrogen-related activities, from production to storage, distribution and use [46].

In some applications, the risks are better identified. For example, in hydrogen cars, there is a risk of hydrogen leakage or diffusion. The gas ignites very easily (it requires only 4% of the energy needed to ignite methane). Since hydrogen combustion generates high temperature and high pressure, the threat increases. The most common cause of hydrogen ignition is the failure of pipes/valves/filters in the hydrogen installation [47].

It should be also taken into account that if hydrogen leaks into the atmosphere, it will be very harmful, causing positive feedback with methane (CH_4). The concentration of CH_4 (which is the second most harmful greenhouse gas) may increase or decrease depending on the relative proportion of hydrogen and methane in the atmosphere. Therefore, hydrogen emissions under certain conditions may contribute to an increase in the greenhouse effect [48].

In developing the hydrogen market, an essential element is to set up norms and standards that include proper indicators instead of relying on general principles for deciding the emissions intensity of production based on colors. If numerical indicators of the emissions intensity associated with hydrogen production are set up and included in the definitions of national hydrogen regulations, governments can facilitate market and regulatory interoperability [49].

Regulation and certification remain key barriers, and only strong international cooperation can lead to universally recognized solutions. Several countries have started to introduce regulations on the environmental properties of hydrogen and to develop related certification systems. They have some similarities but also significant differences, which may lead to difficulties in the emergence of an international hydrogen market [50,51]. National hydrogen strategies outline the regulatory framework for green hydrogen. The solutions vary depending on the country. This includes penalties for the use of fossil fuels, hydrogen certificates, support for innovative activities and deadlines for abandoning coal in the energy sector [52].

5. The Importance of the Development of the Hydrogen Economy for the Decarbonization of Energy

The technology of using water electrolysis to produce hydrogen as a raw material or energy carrier has been understood for a long time. A low conversion efficiency has prevented the technology from being widely used. Hydrogen or products made from it can be used in many ways as the final energy carrier in all energy-intensive sectors of the economy: industry, heating and transport. For this reason, with the development of electricity production from renewable energy sources and the possibility of using clean energy in electrolyzers, green hydrogen production has come to play a key role in connecting all energy-intensive sectors, which is a long-term goal necessary to achieve the decarbonization of the economies of various countries.

The European Commission has recognized this potential in its recent policy plans. The European Green Deal [5] places hydrogen as the key to a clean and circular economy. In addition, in 2020, the European Union issued a dedicated hydrogen strategy [3] to promote the rapid and targeted development of green hydrogen production capacities. The Council and Parliament of the EU are constantly setting up common rules to develop the usage of hydrogen. The decarbonization of the transportation sector (shipping [53], roads [54] and aviation [55]) was at the top of the elaborated topics.

Figure 1 shows the global hydrogen consumption by sector, including historical volumes (2020–2022) and the volumes for 2030 predicted in the International Energy Agency's Net Zero Emission by 2050 Scenario forecast [51].

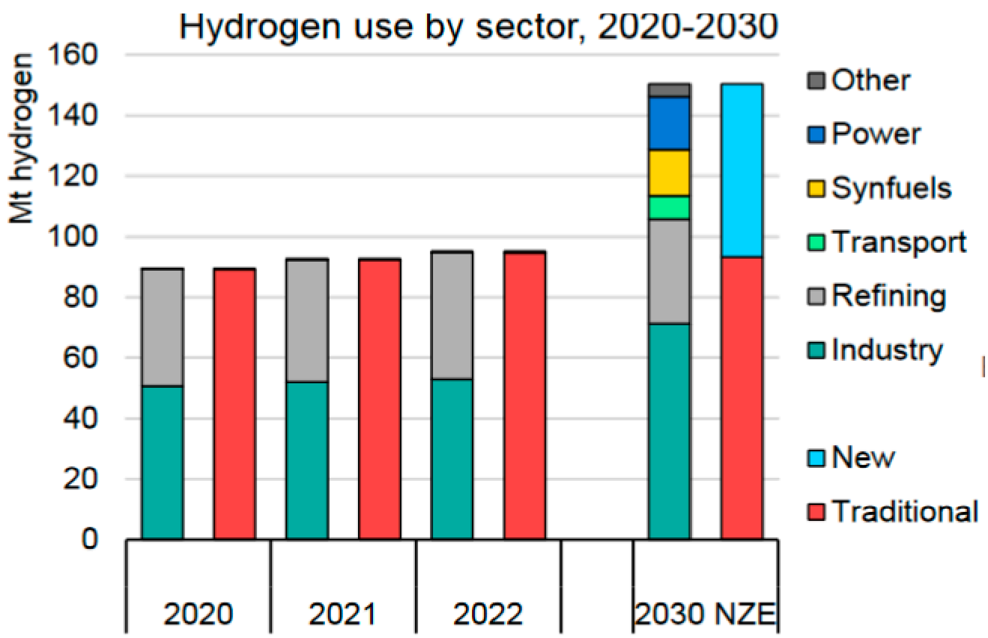

Figure 1. Global hydrogen use: current (2020–2022) and in 2030 [51].

The division into sectors indicates that the current traditional use of hydrogen is in industry—mainly for chemical production, including ammonia and methanol, and for refining. In the future, we should also expect the development of new applications of hydrogen, including changing the iron production technology to DRI (direct reduced iron), the use of hydrogen in transport and the production of hydrogen-based fuels, as well as the use of hydrogen in the energy industry for the production of electricity and as an energy storage method.

Nevertheless, successful implementation requires national initiatives.

In response to EU documents, all European Union countries have prepared their hydrogen strategies, in which they have expressed their intentions to develop the hydrogen economy. These documents were followed by studies analyzing and comparing the proposed paths [56] and policy designs [4,57] and evaluating perspectives on the green hydrogen economy [58–60].

Studies on the strategies of individual European countries are of particular importance in terms of comparing the model of the European hydrogen strategy with national solutions, like in Germany [61–63], Portugal [64], Poland [65–67], Italy [68] or France [69].

Detailed analyses concerning the potential for green hydrogen production are important in African countries –especially the renewable energy potential [70]. Specific weather conditions as well as economic aspects of renewable energy developments and green hydrogen production were analyzed in Egypt and Algeria [71], Niger [72], Morrocco [73] and the RSA [74], as well as in the Economic Community of West African States (ECOWAS countries) [75].

Interesting reports on development intentions can be found in publications regarding the United States [76,77] and Australia [46,78,79], as well as some South American countries, like Brazil [80,81] and Colombia [82].

The first country to develop its national hydrogen strategy was Japan. Other Asian countries soon became interested in the possibilities of developing the hydrogen economy. Hence, there are now numerous analyses of the possibilities of developing the hydrogen economy in various countries, including India [83], China [84,85], Vietnam [86], South Korea [87,88], Taiwan [8,89], Malaysia [90], Pakistan [91], Nepal [92], Turkey [56] and Kazakhstan [93].

Especially interesting is the comparison of the green hydrogen potential in the Association of Southeast Asian Nations (ASEAN) [94] and in Middle East and North African (MENA) countries [95,96].

Figure 2 shows the development of the required emissions reduction and the declared potential of hydrogen production/consumption in EU countries. It would be expected that countries with a higher hydrogen potential would have higher levels of emission reductions. However, these relationships are not proportional. The countries of Northern and Western Europe have high reduction goals, but their hydrogen potential is not remarkably high. Eastern European countries have a similar level of hydrogen potential and have significantly lower emission reduction requirements. Portugal has a special position here, with a very high hydrogen potential resulting from having the appropriate conditions to generate energy from the Sun and wind and being at a convenient distance from North Africa, from which it will be possible to import green hydrogen [97,98], while the country has a relatively low target for emissions reduction.

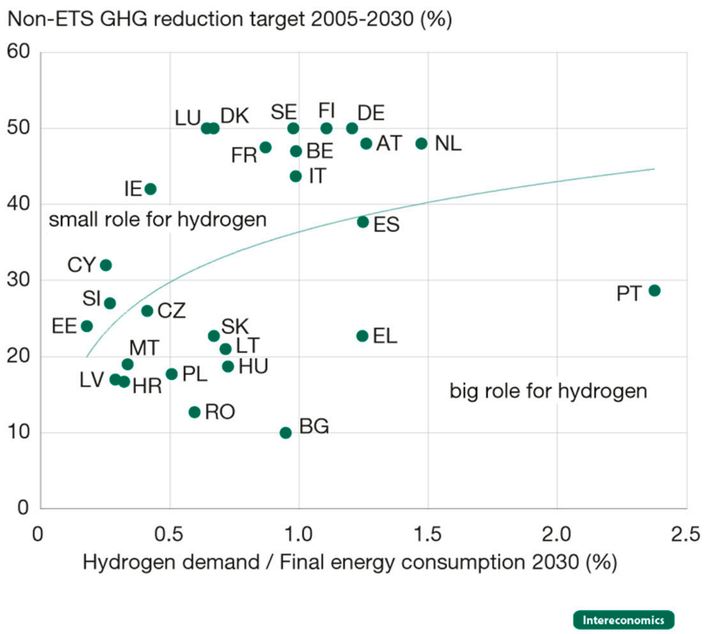

Figure 2. Relationship between emission reduction targets and hydrogen potential in EU countries [99–102].

To be able to use the identified potential requires adjusting the strategy at the country level, with a suitable focus on the use of development opportunities.

But the relationship between the national potential for hydrogen production and national plans for its use is not similar in individual countries (Figure 3). For example, France has a higher production capacity target than Germany, although Germany's hydrogen consumption plans are more than twice as high as France's.

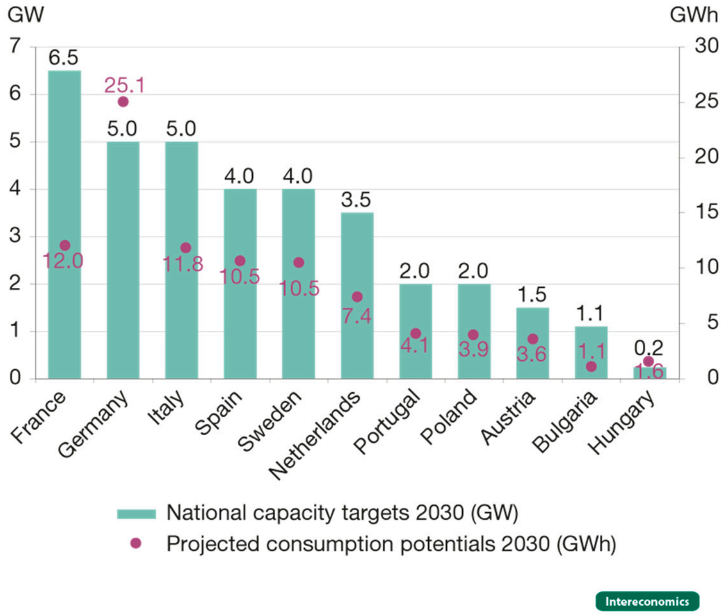

Figure 3. Targets for the production capacity and consumption potential of green hydrogen in the EU [102].

Spain has only slightly lower hydrogen production potential but much less ambitious plans for its use. Hungary has almost completely withdrawn from this race. For other countries, including potential major consumers such as Italy, Sweden and the Netherlands, their plans are more in line with medium-term consumption opportunities.

In the context of ambitious EU climate goals, green hydrogen production technology is becoming increasingly important. This also applies to national plans related to the implementation of energy transformation. However, the plans are not similar. They differ not only in the goals that are set but also in the methods of achieving them. Structural differences between EU countries are clearly visible, but new divisions are possible in terms of production dominance or consumption dominance when establishing a hydrogen market and creating a common hydrogen network [103]. Green hydrogen could make a significant contribution to decarbonization in Mediterranean countries. It could also make a significant contribution to the energy transformation of Eastern Europe, although the reduction targets set there are lower. Achievements in electrolysis efficiency will be crucial in ranking hydrogen-producing countries. The most important thing is cooperation between countries in planning European hydrogen infrastructure.

The EU's climate ambitions have only recently started to be combined with support for the production of low-emission hydrogen, and this is attracting the attention of politicians. Less attention is paid to the development of the demand side. Here, opportunities are lower and often focus on existing hydrogen applications. Without sufficiently high demand, producers of low-carbon hydrogen will not be able to justify the profitability that could underpin large-scale investment [100].

Hydrogen is fully environmentally friendly only if it is green, that is, produced using renewable energy sources. Since the development of electricity generation from renewable sources in Europe is not fast enough, the potential to produce green hydrogen is limited. The situation may be improved by importing green hydrogen. Decisions should be made within the developed political frameworks of individual countries. Investments in hydrogen infrastructure are expensive and risky, and only a realistic strategy for implementing a well-thought-out supporting policy can promote green hydrogen [103].

6. Dilemmas about the Development of the Hydrogen Economy

As shown in the earlier parts of this study, the development of an environmentally friendly hydrogen economy is hindered by several problems that must be definitively solved before rapid, market-based and environmentally friendly expansion is possible. We will discuss the key challenges below.

6.1. Is There Enough Water to Produce Hydrogen?

Hydrogen was discovered in 1766 by Henry Cavendish. Soon after, Antoine Lavoisier called it "water forming", i.e., "hydrogen", simply because when burned in air, it turned into water [104,105].

When electricity is introduced into water, the reverse reaction will occur, and hydrogen will be produced from the water. This process does not cause greenhouse gas emissions. If electricity is produced from renewable energy sources, there are no emissions during the entire hydrogen production cycle. This is the reason for the significant interest in this so-called clean (or green) hydrogen as a fuel, the use of which does not affect climate change. If the production of clean hydrogen and its use are to become widespread, the question arises of whether there is enough water that the hydrogen economy will not cause a lack of water for other purposes. Since the demand for water in the hydrogen production process is significant, there are some suggestions that there will not be enough water, especially since water in this process is a raw material (in the electrolysis process), as well as a coolant in thermoelectric hydrogen production methods such as steam methane reforming. When considering the impact of hydrogen production on global water resources, it is not necessary to consider water that is used in processes that are not "green" because ultimately they will have to be abandoned—only the water that is directly used for water electrolysis.

If the entire expected demand for clean hydrogen is taken into account, including in heating, construction, transport, chemical synthesis and energy storage, the target water demand mid-century will be 2.3 Gt/year [106].

If hydrogen is produced by water electrolysis powered by renewable energy, carbon dioxide emissions from the energy sector could even be reduced by 10.2 Gt per year [106,107]. Based on the stoichiometry of the reaction, for each kg of hydrogen produced, 9 kg of water should be used. Therefore, 2.3 Gt of hydrogen requires 20.5 Gt or 20.5 billion cubic meters of freshwater per year, which is only 1.5 ppm of the available freshwater on Earth. When hydrogen is used, water is produced (in the combustion process or when used in a fuel cell), and although it can be recovered, it is often treated as spent. However, water cannot be recovered from the chemical synthesis process. Assuming the production of 540 Mt of hydrogen in such a process, approximately 4.8 billion m^3 of water will be used, i.e., 0.3 ppm of global freshwater per year [106].

It therefore appears that the hydrogen economy uses less water than technologies that currently operate in various economic sectors. Water demand in technological processes is not only the water that is consumed in the process but also the water that must be withdrawn from the environment, used in the process and then returned.

In 2014, 251 billion m^3 of freshwater was withdrawn from the environment to generate energy from fossil fuels (coal, natural gas and crude oil). Moreover, 31 billion m^3 ultimately had to be used to create this energy, i.e., for purposes related to fuel extraction (hydraulic mining and fracturing), its processing (refining) or in the process of producing electricity (for cooling purposes) [108]. Even if 20.5 billion m^3 of water were used to produce hydrogen in the electrolysis process, this would still be 33% less than the consumption associated with the production of energy from fossil fuels. Moreover, the use of electrolysis will enable the energy sector to switch to renewable technologies, saving 10 billion m^3 of freshwater. Therefore, the use of hydrogen will save water.

Comparisons of the global demand for freshwater with its actual consumption were given by Beswick [105] and Oliveira [106]:

- In energy production processes from fossil fuels and energy production—251 and 31 billion m^3
- In agriculture—2770 and 1080 billion m^3

Meanwhile, in the case of full implementation of the global hydrogen economy, these volumes amount to 21 billion m^3 each.

Water consumption during electrolysis is low when compared to, for example, the agricultural sector, which manages 70% of freshwater usage in the world, i.e., over 2700 billion m^3 per year [107]. Nevertheless, concerns about freshwater scarcity require limiting its intake from every possible angle [108,109].

Since freshwater is a valuable and increasingly scarce resource, the use of water for H2 production processes should be preceded by proper analysis. There are many potential sources that can be used, ranging from seawater to surface water (streams, rivers and lakes), groundwater and rainwater. Less obvious water resources can also be considered, such as rainwater or treated sewage (industrial or municipal) [110]. Saving drinking water should be taken seriously.

Sewage and other non-traditional water sources could be used after treatment for green hydrogen production. Thus, the usage of drinking water for these purposes would be avoided. The costs of treating used water, such as municipal sewage, industrial sewage, mine water and seawater desalination, are negligible compared to the costs of water electrolysis. Therefore, when performing electrolysis at a small scale, it is worth using dispersed non-traditional water sources to the benefit of the environment [111]. This is particularly beneficial in places with high renewable energy potential and where drinking water is scarce (e.g., Australia). Moreover, a by-product of electrolysis is oxygen. It can be used in the water and sewage industries for wastewater treatment. This not only decreases the cost of the hydrogen produced but also reduces the environmental footprint of wastewater [112].

6.2. Desalination of Salt Water

The freshwater available to humans is a little less than 1% of the world's water resources [113,114]; therefore, excessive water consumption for industrial purposes should be avoided, especially in places where drinking water is scarce. However, the remaining 99%, or approximately 1.4 billion km^3, is seawater. Seawater can be used as a raw material for electrolysis after purifying it (desalination). The reverse osmosis (RO) method is currently the most commonly used technology. This technology uses a semi-permeable membrane to remove ions present in the water. This desalination method is less energy-intensive than others, such as distillation [105].

The amount of water obtained in the osmosis process is only a fraction of the amount of water introduced into this process. The Ashkelon factory in Israel, which is one of the most modern RO installations, achieves recovery of up to 50% [113]. This means that the process of producing hydrogen using desalinated seawater would require approximately 41 billion m^3 of seawater per year. This is only about 30 ppb of global seawater resources per year, which is really minuscule, especially since the unused part of this water (about 50%) is released back into the same reservoir.

The desalination process adds more energy consumption to an electrolyzer' life cycle for hydrogen production, but this is negligible compared to its power supply. In general, RO needs 3.5–5 kWh of energy for each m^3 of clean water produced [105]. With a global hydrogen demand of 2.3 Gt, this requires 0.26–0.37 EJ of energy annually to perform RO for water electrolysis. Economically, RO desalination has an energy cost of USD 0.53–1.50 per m^3 of clean water produced [113], which does not add more than USD 0.01 to the production cost of 1 kg of hydrogen. Thus, desalination accounts for 0.1% of the electrolysis energy requirement and adds $0.02 to the cost of producing 1 kg of hydrogen [105]. Therefore, even if desalination processes have been incorporated into hydrogen production, the DOE calculates that it is possible to produce hydrogen for less than $2.00 per kg [115].

These figures suggest that the water supply will not be a constraint for electrolyzers. The water consumption footprint is much less than that reported in the associated literature, and a large part of the water could be consumed indirectly outside of hydrogen-producing countries [116].

However, the focus should continue to be on technological improvements of the electrolyzers to increase their energy efficiency, which is currently a limiting factor in their use. It should be noted that the "water problem" in the context of hydrogen is not discussed particularly often by scientists. This is a topic raised by journalists. However, it must be admitted that ill-considered journalistic articles can do a lot of damage to society's acceptance of hydrogen.

6.3. Hydrogen Storage

The successful development of the hydrogen economy is determined by the possibilities of storing and transporting hydrogen. The current state of knowledge about hydrogen storage possibilities is insufficient and requires further research. It is true that natural gas storage methods can be considered, but the specific properties of hydrogen do not allow their direct use. Meanwhile, the integration of renewable energy into the existing energy infrastructure requires the development of proper storage solutions along the energy supply chain. Underground methods tend to favor long-term storage. Storage takes place in underground geological structures such as salt caverns, depleted hydrocarbon deposits, aquifers and hard rock caves. The suitability of geostructures must be carefully examined each time, dependent on the operating parameters of the planned storage facility, such as storage cycles, the capacities needed and the purity of the stored hydrogen. Surface storage is useful in various cases of stationary and mobile hydrogen use. Depending on the requirements of the end users, such warehouses usually have a lower capacity, and the storage cycles are short. Physical storage of hydrogen causes it to become trapped in vessels in various physical states, such as compressed gas, as well as cryogenic and compressed forms.

Hydrogen storage can be based on various physical principles (mechanical, electrical, chemical). Material-based storage involves adsorbing or absorbing hydrogen using solid-state materials [117]. Electrochemical compression is also applied [118].

The (P2G) process, i.e., the conversion of electricity from renewable energy sources (P) into hydrogen (G), is consistent with the principle of chemical storage. This conversion of electrical energy into chemical energy through water electrolysis does not result in emissions of substances toxic or harmful to humans or the climate [119].

The efficiency of storage techniques depends on many parameters. Surface storage is characterized by, among other things, gravimetric and volumetric density, the uptake and release kinetics during storage, the associated cost and operational safety.

No single storage technique can be considered best suited to all applications, and each technique requires intensive work to be accepted for energy applications [117].

Storage technologies but also large-scale green hydrogen transport technologies (compressed hydrogen storage, liquid hydrogen, mixed hydrogen for natural gas pipelines and ammonia as an ecological hydrogen carrier) are the subject of economic evaluations [120]. The profitability of storing and transporting green hydrogen at a large scale is important for market development. Drawing conclusions on the costs, challenges and potential advances in green hydrogen storage and transport will have an impact on ongoing and intended global projects and policies.

Regional studies on the competitiveness of energy storage have led to the formulation of the necessary directions for changes in energy policy so that the profitability of storage can be demonstrated, which is not possible in the current tariff systems [121].

Chemical storage is an element of the development of the hydrogen economy in the P2X system, where the generated electricity from renewable sources is converted into hydrogen in the electrolysis process. The hydrogen produced in this process can be stored and used later. It can also be subjected immediately (or after storage) to the methanation process, where, after adding CO_2, methane (CH_4) or methanol (CH_3OH) is created, or to the electrochemical process, in which ammonia (NH_3) is produced. These fuels can also be stored [122].

Hydrogen energy storage systems are necessary for the water economy to flourish. Currently, the most essential element of progress is cost reduction. Meanwhile, safety considerations are also extremely important. Hydrogen storage projects should conduct a risk analysis of hazardous phenomena. Such risks must be mitigated, and the costs associated with mitigating them should be considered in the design of the hydrogen storage system [123].

7. Advances in Hydrogen Technologies and Market Developments

The role of hydrogen will increase when non-carbon H_2 is able to partially replace methane as a source of energy. Hydrogen will never completely replace methane as an energy carrier in fuel. Electricity will be the main energy carrier, and methane as LNG and/or natural gas from pipelines will play a smaller but still significant role. The concept of the hydrogen economy is proposed to reduce and ultimately decarbonize the world's energy consumption. It is believed that hydrogen could replace methane (natural gas) and generally remove all fossil fuels from the energy supply. However, this concept has some disadvantages [41]. Hydrogen's properties differ enough from commonly used methane, preventing its simple substitution. This applies to both gas and liquid forms. Moreover, the properties of hydrogen, especially its extremely low energy activation, cause high risks during use.

The replacement of many currently used energy sources with hydrogen depends on the development of innovative technologies, which may reduce the disadvantage of this fuel. For example, using hydrogen in cars is limited by the fact that it is practically difficult to store a car's fuel in cryogenic or high-pressure tanks. The existing green hydrogen technologies are more expensive than the currently applied methods and technologies, so without special incentives, the replacement will not take place easily. This is a crucial constraint on the development of the hydrogen economy.

Detailed processes according to which hydrogen may be produced or used can be found in many publications. These processes are constantly improving, leading to step-by-step increases in efficiency and decreases in costs. Some of these improvements include the following:

- Wind and solar technologies in hydrogen production [124].
- Biological upgrading of hydrogen-assisted biogas in carbon sequestration by converting carbon dioxide into biomethane using hydrogen produced mainly from other renewable energy sources. By converting the carbon dioxide produced during anaerobic digestion into additional biomethane, biogas can reduce the demand for fossil natural gas [125].
- The production of hydrogen via biomass electrolysis and/or biomass gasification [126].
- The production of green biohydrogen using anaerobic photosynthetic bacteria [127].
- The waste-to-energy concept in hydrogen production [128].
- Conducting the methanation process at sea using offshore wind energy in combination with electrolysis. A proposal for an artificial island with an entire undersea power-to-gas power plant [129].
- Regeneratively obtained hydrogen in power-to-gas technology [130,131].
- Research on materials needed for electrolyzers, including research on anion exchange membranes (AEMs), new, cheap catalysts that do not use platinum-group metals and bipolar stainless steel plates [132].
- Waste-derived catalysts for water electrolysis [133].
- The issue of using hydrogen in natural gas admixtures (hythane) [134–136].
- Hydrogen transport via traditional natural gas pipeline infrastructure [129].

In the production of clean hydrogen, the technology of choice is water electrolysis [137]. This technology has been understood for a very long time, but the process of improving it is still ongoing. Figure 4 shows the challenges that this technology has faced and still faces. The current fifth generation of electrolyzers is struggling with challenges related to costs, efficiency and durability, as well as with increasing the scale of production [138,139]. The research is exploring, for example, water electrolysis at high temperatures and pressures [140].

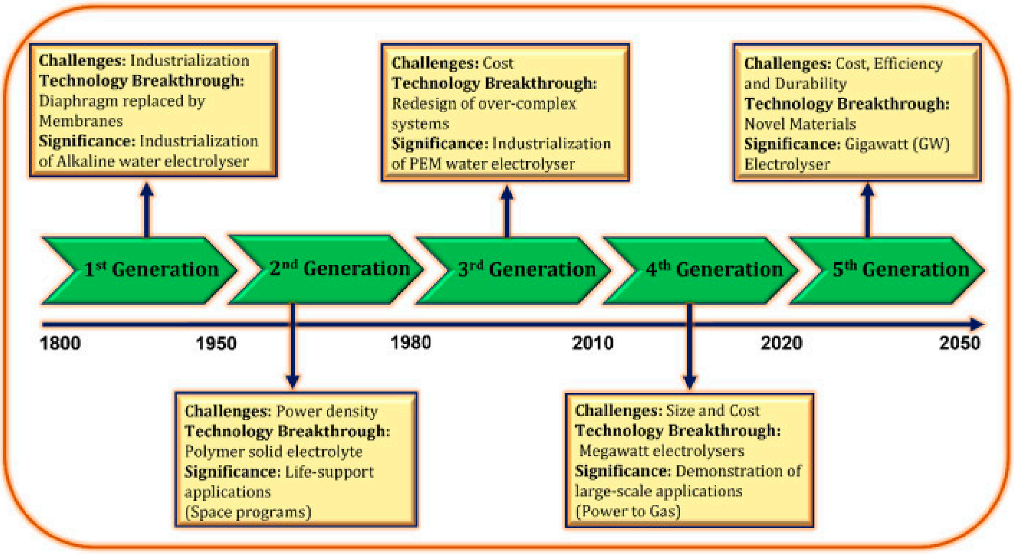

Figure 4. Developments of typical water electrolysis technologies [141].

Research on the development of hydrogen technologies is carried out in many countries and regions of the world. The use of various technologies to produce renewable energy, which is then used in electrolysis processes, is of special interest. Future research into different clean hydrogen technologies should prioritize improving their overall efficiencies [142]. Water splitting is a process of particular importance. The applied methods include photo-electrochemical, photocatalytic, radiolysis, photo-biological and thermal decomposition [143].

Techno-economic analyses are most often performed using various modeling methods, and the model is built either for the entire value chain or for its significant elements. The models of green hydrogen production are studied with the prediction of final costs now and in the future [144–146].

Some research [147] concerns the production of hydrogen through water electrolysis using offshore wind energy. It proposes using the produced hydrogen at hydrogen fuel stations. Attention has been paid to the ways of addressing transport and storage limitations under the conditions of offshore wind energy. The cost of producing green hydrogen from offshore wind energy in 2023 is expected to be EUR 6.26/kg and will drop significantly to EUR 1.13/kg by 2050. Considering its use as a transport fuel, the total cost of hydrogen is estimated at EUR 10.7/kg in 2023 and EUR 2.42/kg in 2050. Considering the current state of hydrogen vehicle technology, the cost per kilometer is expected to be EUR 0.0927/km in 2023, and it is expected to decline to EUR 0.021/km by 2050 [147]. In another analysis [148], producing hydrogen locally through electrolysis using photovoltaic panels directly at refueling stations was proposed. The research concerned various installation performance scenarios. An example of the use of distributed green hydrogen infrastructure for heavy transport in Italy consists of hydrogen production, storage, compression and on-site refueling systems. Energy supplies can be provided either through connection to a green energy grid or direct connection to a photovoltaic field [149].

Research related to hydrogen fuel cells deserves special attention [150]. An in-depth review of the latest research on hydrogen fuel cells and their importance for a sustainable hydrogen economy leads to the conclusion that hydrogen fuel cells can significantly improve energy efficiency and contribute to achieving sustainable development goals [151,152]. The solid oxide electrolysis cell (SOEC) currently outperforms others, with anion exchange membranes (AEMs) and electrified steam methane reforming (ESMR) also showing promise [153].

For mobile applications, it is important to use light, high-density tanks to store hydrogen. Therefore, scientists' attention has focused on the use of materials based on carbon and graphene. It seems that such solutions will be more widely used in the future in the field of H_2 storage.

In fuel cell cars, it is very important to solve the problem of storing hydrogen on board a car. The hydrogen fuel cell needs to be integrated with the batteries and the control system. Since hydrogen is one of the most efficient energy carriers, a sustainable hybrid car can be produced [154]. From the point of view of mobile applications, an extremely important aspect is the storage of hydrogen using light tanks with a relatively high density. Therefore, scientists' attention has been focused on the use of materials based on carbon and graphene as a prospective solution in the field of H_2 storage [155].

Cost analyses are being conducted to optimize the spatial arrangement of value chain elements in the use of hydrogen for power buses [156].

The assumption that clean hydrogen is to play an active role in the decarbonization of hard-to-abate sectors, including heavy industry and heavy transport, as well as achieving climate neutrality by 2050, requires that the clean hydrogen market be 170 MtH_{2eq} (hydrogen equivalent) by 2030, and beyond that, increase to approximately 600 MtH_{2eq} in 2050 [157].

The EU goals demand the use of low-emission hydrogen in hard-to-abate sectors. Thus, special attention is paid to the metallurgical industry [158]. Hydrogen is also proposed for households—for example, hydrogen produced from natural gas by steam methane reforming combined with carbon capture and sequestration (SMRCCS) is proposed as a fuel for consumer heating and cooking systems [159].

Currently, the costs of producing zero-emission hydrogen are remarkably high. Therefore, the research focuses on developing the main stages of the hydrogen value chain, exploring the main methods for blue and green hydrogen production and examining the possibilities for its handling. Blue hydrogen—i.e., that produced from gas with carbon capture and storage technology—seems to be a transitional option, as possibilities to produce green hydrogen are now too scant to fulfill the EU goals [160,161].

The problem of the mutual complementation of green and blue hydrogen has not yet been resolved. This depends on whether and when cost parity is achieved, and this, in turn, depends on the emissions from individual fuels over their life cycle. Currently, the production costs of green hydrogen are higher than those for blue hydrogen. If the CO_2 capture rate is higher than 90% during the production of blue hydrogen and there is no methane leakage during the life cycle, blue hydrogen will remain competitive with green hydrogen produced 90% from renewable energy [162]. Meanwhile, other sources report that the use of green H_2 can reduce the amount of methane in the atmosphere if the hydrogen losses in the entire value chain are below $9 \pm 3\%$, while for blue H_2, only if its leakage is less than 1% is this possible [42]. Therefore, low-carbon blue hydrogen can play a key role in overcoming the green hydrogen shortage. However, depending on the local conditions, its competitiveness will be limited eventually. Nevertheless, model-based analysis shows that low-emission hydrogen production has the potential to become a significant user of natural gas and thus stabilize global LNG demand. Additionally, commercial and operational synergies could help the LNG industry develop a value chain around low-emission natural-gas-based hydrogen [163]. The use of renewable energy resources at sea creates new conditions for shipping and ports, and it is an opportunity for the upstream part of the oil and gas industry to seriously engage in the hydrogen economy [164].

There are additional ways to reduce economic and environmental costs. The use of concentrated solar energy (CSE) is proposed [165]. As a result of its use, the following may be generated:

- White hydrogen (through catalytic thermochemical splitting of the H_2O molecule);
- Aquamarine hydrogen (thanks to thermochemical pyrolysis of CH_4 with a carbon catalyst).

The use of electrolysis vessels for the flexible production of green hydrogen has also been proposed. It has been shown [81] that the investment costs of such a solution can be three times lower than in stationary electrolysis installations.

Open-field photovoltaics (PV) and onshore wind have huge hydrogen potential, at a cost below 2.3 Euro/kg in 2050. Cost–potential curves show that in the case of decentralized hydrogen production, photovoltaics is the preferred source of electricity over on-shore wind [166].

Scientists also present innovative systems producing green hydrogen and electricity using the seawater desalination process. Such a solution, perhaps widespread in the future, is the Hybrid Solar Chimney Power Plant (HSCPP) method, combined with the water splitting process [167].

Comparative analysis of the hydrogen production costs from offshore and onshore wind parks in 2030 and 2050 shows lower costs for offshore wind in the long term. Under Polish conditions, hydrogen from offshore wind could range in price between €3.60 and €3.71/kg H_2 in 2030, while in 2050, it may range from €2.05 to €2.15/kg H_2 [168].

Power-to-gas technologies cover global energy issues (generation, distribution, consumption, markets), hydrogen production through electrolysis, its transport and storage and its conversion into another form [169]. These are elements that reduce the costs of hydrogen production using electricity from unstable renewable sources. They can also partially solve energy storage problems.

One of the most important elements (apart from costs) influencing the development of hydrogen production technologies is their environmental efficiency. Among the selected sources of hydrogen production—biomass, geothermal energy, hydropower, nuclear energy, solar energy and wind energy—it is wind energy that has the highest environmental efficiency and nuclear energy that has the lowest. If the selected hydrogen production methods are considered—biological, thermal, photonic and electrical—photonic options have the highest environmental efficiency ranking, while thermal options have the lowest [170]. These sources and methods should be developed and improved first.

Global trade plays a key role in minimizing costs and is expected to cover around one-fifth of the total demand from 2030 (32 MtH_{2eq}) to 2050 (almost 110 MtH_{2eq}) [157]. Products made from hydrogen (ammonia, methanol and e-kerosene), which are easier to transport over long distances, play a dominant role in global trade. Market development requires new investments, and the increase in demand for hydrogen is changing the network of trade routes. However, it is important to remember that global trade is essential to facilitate the development of a cost-competitive clean hydrogen market. The potential for green hydrogen production and leadership in industrial applications is unevenly distributed around the world. Countries such as the United States and China could become leaders in future green hydrogen markets and excel in industrial applications such as ammonia, methanol and steel production [171]. But other countries can also compete for jobs and market shares. Changes in existing value chains will create new dynamics and changes in market and geopolitical dependencies [172,173].

Export competitiveness depends on the availability and potential of resources, the economic and financial potential of a country, its political and regulatory circumstances and industrial knowledge. Research [174] shows that the countries with the highest rankings in terms of hydrogen export competitiveness include the United States, Australia, Canada, Great Britain, China, Norway, India, Russia, the Netherlands and Germany. These countries have a chance to become significant players in the hydrogen market.

The development of the clean hydrogen market at this stage requires strategic actions carried out by the governments of individual countries. Research on this topic is an important contribution to building future mechanisms and shaping international competitiveness. Such works include a long-term subsidization scheme for the rollout of green hydrogen [175]. The proposed mechanisms depend on the degree of centralization of economic policy, as well as on the possible set of political tools in individual countries.

Scientists' recommendations regarding mechanisms for building a hydrogen market include the following:

- Clean hydrogen portfolio standards and clean hydrogen certificates are needed to promote green hydrogen [88]. So far, neither a definition of green hydrogen nor its stan-

dards have been clearly defined. Differences in individual countries include whether such hydrogen must be produced from renewable energy. There are different limits for the allowed carbon dioxide emissions, the emission thresholds at which hydrogen is considered ecological and which raw materials and production technologies are covered by the system [176].
- There is a lack of system-wide assessments of the impact of the hydrogen economy on sustainable development goals. Policymakers should move beyond a one-size-fits-all approach to achieving the SDGs [177].
- Cradle-to-gate social life cycle assessment (S-LCA) results show that green hydrogen production in South Africa poses the highest risk for most social indicators, especially child labor, fair wages, unemployment, rights of association and bargaining and disparities in the wages of women and men. However, in other countries, the risk for most social indicators is dramatically reduced when key equipment is produced within the country itself, rather than when it is imported from other countries [178].
- Hydrogen economy policy should be based on a mission-oriented approach [177].
- The link between the use of green hydrogen and direct and indirect sustainable development goals is undeniable. The use of green hydrogen in many industries, including the shipping industry [179], as well as transport and infrastructure, leads to the economic and social development of countries joining the hydrogen economy [180]. Understanding the role of green hydrogen in achieving the different SDGs is vital for policymakers and decision-makers [181].
- The policy framework should be adapted to public perception. Therefore, discourse on the EU's approach to hydrogen in a complex environment is focused on, with divergent interests of EU and non-EU stakeholders [182]. The sociological aspects are important because it seems that the EU will not be able to meet its needs in the field of renewable energy on its own and will have to rely on imports [183].
- Research and development activities and demonstration projects will reduce the cost of hydrogen production [88].
- Hydrogen production must overcome many serious challenges in implementing a circular economy, including waste management issues, infrastructure constraints, costs, safety, environmental issues, etc. [184]. Green hydrogen and biohydrogen are key enablers of a sustainable circular economy [59]. A low-carbon energy system needs optimal integration [1].
- It is important to ensure that hydrogen enables the integration of traditionally independent sectors, namely electricity, heat and transport, while contributing to their decarbonization [185].
- The widespread use of hydrogen as an energy carrier and vector is limited by obstacles related to its storage, distribution and transport [186]. These elements of the value chain require further research and implementation works.
- Policymakers should design tariffs and taxes for hydrogen and electricity so that they do not unduly distort the wholesale price signal at all stages of the hydrogen supply chain, while allowing for a fair sharing of benefits between hydrogen and electricity [187].
- A proper hydrogen economy requires a balance between centralized and distributed production. A compromise must be found between global environmental interests and local social interests [188].

One of the biggest questions is whether enough green hydrogen can be ready fast enough to be effective against climate change [6]. The development of the hydrogen market may be disrupted by an imbalance between demand and supply. The increase in green hydrogen production will initially be exponential, but by 2030, its share in final energy will be less than 1% in the European Union and even lower globally. Because there are no clear predictions regarding the development of water electrolysis and as the long-term trends in the development of the hydrogen economy are unknown, investors are delaying decisions on investment both in the production capacity of green hydrogen and in the infrastructure for the use of hydrogen. This is not conducive to achieving climate goals [189]. Emergency policy measures are needed to accelerate this development. Energy prices change depending on many factors, including the geopolitical situation [190]. The mutual costs of green, blue and gray hydrogen changed after Russia invaded Ukraine, following a sharp increase in natural gas prices [191]. Energy carrier price relationships will influence the pace of building the hydrogen market.

Looking further into the future (beyond 2050), it can be shown that the era of industrialization should be followed by an era of "hydrogenization", which will change the world as we know it. For this to happen, the hydrogen era is in extreme need of three elements—technology, innovation and digitalization—which need to be properly combined and synchronized [192].

8. Concluding Remarks

The task facing Europeans in achieving a zero-emission economy by 2050 is extremely difficult. The transformation of the economy towards replacing fossil fuels with hydrogen is a direction that gives hope that this will be possible. However, scenarios for using the hydrogen economy to achieve the zero-emission goal often suggest that such a result will not be achieved within the set deadline [193]. The basis for such results is the current state of hydrogen technologies and their costs, as well as the need to deal with difficult issues surrounding the safety of hydrogen's use. The chance to meet these challenges exists if governments become involved in developing methods and principles for supporting the entire value chain of hydrogen's use. Environmentally friendly development of the hydrogen economy requires a detailed definition of clean hydrogen so that only non-emission sources of electricity are used for its production. The use of green hydrogen at a large scale also becomes problematic due to the need for a significant amount of renewable energy and the associated energy, land and material impacts [193].

There are also other explanations for the pessimistic results of many hydrogen economy development models. While many models have shown that hydrogen can play a significant role in the energy transition in sectors that are difficult to electrify, in many of them, the features necessary to accurately assess its role have not been taken into account. Some have not considered all relevant sectors that could be supplied with hydrogen. Some researchers have ignored the temporal variability in the system or underestimated the dynamics of learning outcomes.

Some work [194] has shown that over the next 10 years, the increase in electrolysis power and renewable energy sources may be faster than other studies predict. Consequently, the costs of green hydrogen technology will decrease faster. As a result, hydrogen production may switch from gray to green, bypassing the blue hydrogen option. If electrolysis costs are modeled without dynamic learning by action, then the scale-up of electrolysis will be significantly delayed, while the total system costs are overestimated by up to 13% and the levelized cost of hydrogen is overestimated by 67%.

There is an undeniable link between green hydrogen and renewable energy [2]. With the implementation of innovative solutions in the field of energy production from renewable sources and hydrogen production, as well as the development of storage technologies and investments in energy transport technologies, a gradual improvement in the efficiency and profitability of hydrogen production and use is expected. This will drive the development of the hydrogen economy. Optimization strategies should be used when designing and operating green hydrogen production systems. The principal elements are maximizing efficiency, minimizing costs and reducing environmental impact [195].

Current energy systems based on fossil fuels are indeed undergoing a transformation to a "hydrogen economy". However, in this transformation, the most important primary energy carrier is renewable electricity, which can be converted into hydrogen or another gas (methane) but also into liquid fuels, chemicals (ammonia, methanol), heat, desalinated products water, and materials (steel, carbon fibers, silicon carbide, etc.). This provides the basis for further extension of the future hydrogen system to the P2X system through various conversion paths [196].

It should therefore be assumed that the hydrogen revolution, which has begun, will bring positive effects and contribute to improving the well-being of humanity while maximizing environmental protection.

Observing the extraordinary acceleration in administrative and legislative activities (especially in Europe), as well as the pace of work on the development of hydrogen-related technologies and the scale of interest in technological improvements and cost reductions at every stage of the hydrogen value chain, we must hope that they will be possible and will lead to the achievement of the climatic goals set for 2050. However, this will only be possible if all countries follow this specified direction. This will also mean dedicating the appropriate financial resources to research and development and the implementation of projects constituting the basis of the future green hydrogen economy.

Author Contributions: Conceptualization: E.M. and L.G.; methodology: E.M. and L.G.; formal analysis: E.M. and L.G.; writing: E.M. and L.G. All authors have read and agreed to the published version of the manuscript.

Funding: The work was carried out as part of the Mineral and Energy Economy Research Institute of the Polish Academy of Sciences statutory activities. It has received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are very grateful to the anonymous referees for their helpful comments and constructive suggestions.

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

References

1. Khaligh, V.; Ghezelbash, A.; Akhtar, M.S.; Zarei, M.; Liu, J.; Won, W. Optimal integration of a low-carbon energy system–A circular hydrogen economy perspective. *Energy Convers. Manag.* **2023**, *292*, 117354. [CrossRef]
2. Li, X.; Raorane, C.J.; Xia, C.; Wu, Y.; Tran, T.K.N.; Khademi, T. Latest approaches on green hydrogen as a potential source of renewable energy towards sustainable energy: Spotlighting of recent innovations, challenges, and future insights. *Fuel* **2023**, *334*, 126684. [CrossRef]
3. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A Hydrogen Strategy for a Climate-Neutral Europe. European Commission. Brussels. COM(2020) 301 Final. 8 July 2020. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301 (accessed on 13 July 2023).
4. Nuñez-Jimenez, A.; De Blasio, N. The Future of Renewable Hydrogen in the European Union: Market and Geopolitical Implications. Environment and Natural Resource Program. 2022. Available online: https://www.belfercenter.org/publication/future-renewable-hydrogen-european-union-market-and-geopolitical-implications-0 (accessed on 12 February 2024).
5. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions the European Green Deal. European Commission. Brussels. COM(2019) 640 Final. 11 December 2019. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2019:640:FIN (accessed on 30 June 2023).
6. van Renssen, S. The hydrogen solution? *Nat. Clim. Chang.* **2020**, *10*, 799–801. [CrossRef]
7. Bockris, J.O. Bockris 1923–2013. Infinite Energy Magazine September/October 30. Available online: http://www.infinite-energy.com/images/pdfs/BockrisObit.pdf (accessed on 8 August 2023).
8. Chen, Y.-T.; Hsu, C.-W. The key factors affecting the strategy planning of Taiwan's hydrogen economy. *Int. J. Hydrogen Energy* **2019**, *44*, 3290–3305. [CrossRef]
9. Brandon, N.P.; Kurban, Z. Clean energy and the hydrogen economy. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2017**, *375*, 20160400. [CrossRef] [PubMed]
10. Bockeris, J.O.M. The hydrogen economy: Its history. *Int. J. Hydrogen Energy* **2013**, *38*, 2579–2588. [CrossRef]
11. Yusaf, T.; Laimon, M.; Alrefae, W.; Kadirgama, K.; Dhahad, H.A.; Ramasamy, D.; Kamarulzaman, M.K.; Yousif, B. Hydrogen energy demand growth prediction and assessment (2021–2050) using a system thinking and system dynamics approach. *Appl. Sci.* **2022**, *12*, 781. [CrossRef]
12. Ball, M.; Wietschel, M. *The Hydrogen Economy: Opportunities and Challenges*; Cambridge University Press: Cambridge, UK, 2010.
13. Ministry of Economy, Trade and Industry—Japan. *Compilation of the Revised Version of the Strategic Roadmap for Hydrogen and Fuel Cells*; Ministry of Economy, Trade and Industry—Japan: Tokyo, Japan, 2015.

14. Committee on Climate Change. *Sectoral Scenarios for the Fifth Carbon Budget*; UK Committee on Climate Change: London, UK, 2015.
15. *Technology Roadmap: Hydrogen and Fuel Cells*; International Energy Agency: Paris, France, 2015; Available online: https://iea.blob.core.windows.net/assets/e669e0b6-148c-4d5c-816b-a7661301fa96/TechnologyRoadmapHydrogenandFuelCells.pdf (accessed on 8 August 2023).
16. The UK Gas Networks Role in a 2050 Whole Energy System. 2050 Energy Scenarios. KPMG 2016. Available online: https://www.kiwa.com/48cf07/globalassets/uk/reports/kpmg-future-of-gas-report.pdf (accessed on 8 August 2023).
17. Sunny, N.; Mac Dowell, N.; Shah, N. What is needed to deliver carbon-neutral heat using hydrogen and CCS. *Energy Environ. Sci.* **2020**, *13*, 4204–4224. [CrossRef]
18. Wang, Y.; Huang, R.; Liu, Z. The relationship between structural intensity and sound field characteristics of cylindrical shells. *Procedia Eng.* **2017**, *214*, 41–49. [CrossRef]
19. Alzoubi, A. Renewable Green hydrogen energy impact on sustainability performance. *Int. J. Comput. Inf. Manuf.* **2021**, *1*, 1. [CrossRef]
20. Eftekhari, A.; Fang, B. Electrochemical hydrogen storage: Opportunities for fuel storage, batteries, fuel cells, and supercapacitors. *Int. J. Hydrogen Energy* **2017**, *42*, 25143–25165. [CrossRef]
21. Sadhasivam, T.; Kim, H.T.; Jung, S.; Roh, S.H.; Park, J.H.; Jung, H.Y. Dimensional effects of nanostructured Mg/MgH_2 for hydrogen storage applications: A review. *Renew. Sustain. Energy Rev.* **2017**, *72*, 523–534. [CrossRef]
22. Vezzoni, R. Green growth for whom, how and why? The REPowerEU Plan and the inconsistencies of European Union energy policy. *Energy Res. Soc. Sci.* **2023**, *101*, 103134. [CrossRef]
23. Aslam, S.; Rani, S.; Lal, K.; Fatima, M.; Hardwick, T.; Shirinfar, B.; Ahmed, N. Electrochemical hydrogen production: Sustainable hydrogen economy. *Green Chem.* **2023**, *25*, 9543–9573. [CrossRef]
24. Robinson, M. *Hydrogen Fuel—Advantages, Disadvantages and Uses for Heating*; BoilerCentral: Wakefield, UK, 2023; Available online: https://www.boilercentral.com/guides/hydrogen-fuel-advantages-and-disadvantages/ (accessed on 5 August 2023).
25. Azadnia, A.H.; McDaid, C.; Andwari, A.M.; Hosseini, S.E. Green hydrogen supply chain risk analysis: A European hard-to-abate sectors perspective. *Renew. Sustain. Energy Rev.* **2023**, *182*, 113371. [CrossRef]
26. Hamacher, T. Hydrogen as a Strategic Secondary Energy Carrier. In *Hydrogen and Fuel Cell*; Töpler, J., Lehmann, J., Eds.; Springer: Berlin/Heidelberg, Germany, 2016.
27. Felseghi, R.A.; Carcadea, R.; Raboaca, M.S.; Trufin, C.N.; Filote, C. Hydrogen fuel cell technology for the sustainable future of stationary applications. *Energies* **2019**, *12*, 4593. [CrossRef]
28. Pötzinger, C.; Preißinger, M.; Brüggemann, D. Influence of Hydrogen-Based Storage Systems on Self-Consumption and Self-Sufficiency of Residential Photovoltaic Systems. *Energies* **2015**, *8*, 8887–8907. [CrossRef]
29. Abohamzeh, E.; Salehi, F.; Sheikholeslami, M.; Abbassi, R.; Khan, F. Review of hydrogen safety during storage, transmission, and applications processes. *J. Loss Prev. Process Ind.* **2021**, *72*, 104569. [CrossRef]
30. Miller, B. 11 Big Advantages and Disadvantages of Hydrogen Fuel Cells. GreenGarage. 2015. Available online: https://greengarageblog.org/11-big-advantages-and-disadvantages-of-hydrogen-fuel-cells (accessed on 5 August 2023).
31. Advantages & Disadvantages of Hydrogen Energy. Conserve Energy Future. Available online: https://www.conserve-energy-future.com/advantages_disadvantages_hydrogenenergy.php (accessed on 5 August 2023).
32. Geary, N. *Advantages and Disadvantages of Hydrogen Energy*; Boilerguide: Harborough, UK, 2023; Available online: https://www.boilerguide.co.uk/articles/advantages-disadvantages-hydrogen-energy (accessed on 5 August 2023).
33. Veziroglu, T.N. *21st Century's Energy: Hydrogen Energy System*; Sheffield, J.W., Sheffield, Ç., Eds.; Assessment of Hydrogen Energy for Sustainable Development; NATO Science for Peace and Security Series C: Environmental Security; Springer: Dordrecht, The Netherlands, 2007. [CrossRef]
34. Hydrogen Energy Center Website. The Benefits of Hydrogen Will Help Move Us to a Sustainable Energy Economy. Available online: https://www.hydrogenenergycenter.org/benefits-of-the-hydrogen-economy (accessed on 16 January 2024).
35. Guy, P.; Julien, C. Risks Associated with the Use of Hydrogen as an Energy Carrier or Source. *J. Energy Power Technol.* **2022**, *4*, 3. [CrossRef]
36. Pirelli Website. Hydrogen as a Fuel: The Pros and Cons. Available online: https://www.pirelli.com/global/en-ww/road/hydrogen-as-a-fuel-the-pros-and-cons (accessed on 5 August 2023).
37. Barreto, L.L.; Makihira, A.; Riahi, K. The hydrogen economy in the 21st century: A sustainable development scenario. *Int. J. Hydrogen Energy* **2003**, *3*, 267–284. [CrossRef]
38. Dillman, K.J.; Heinonen, J. A 'just' hydrogen economy: A normative energy justice assessment of the hydrogen economy. *Renew. Sustain. Energy Rev.* **2022**, *167*, 112648. [CrossRef]
39. Vallejos-Romero, A.; Cordoves-Sánchez, M.; Cisternas, C.; Saez-Ardura, F.; Rodrigues, I.; Aledo, A.; Boso, A.; Prades, J.; Alvares, B. Green Hydrogen and Social Sciences: Issues, Problems, and Future Challenges. *Sustainability* **2022**, *15*, 303. [CrossRef]
40. Lazarczyk, C.E.; Pickford, K.; Nyga-Łukaszewska, H. Green hydrogen and an evolving concept of energy security: Challenges and comparisons. *Renew. Energy* **2023**, *19*, 119410. [CrossRef]
41. Clarke, M.C. Can the hydrogen economy concept be the solution to the future energy crisis? *Aust. J. Multi-Discip. Eng.* **2022**, *18*, 70–84. [CrossRef]

42. Ashcroft, N.; Di Zanno, P. Hydropower: A Cost-Effective Source of Energy for Hydrogen Production. Power. Available online: https://www.powermag.com/hydropower-a-cost-effective-source-of-energy-for-hydrogen-production/ (accessed on 7 August 2023).
43. Rzeszotarska, M. Mechanosynteza, Struktura i Właściwości Kompleksowego Wodorku Typu $Mg_2Fe_XH_6$ Wytwarzanego z Proszkowych Substratów MgH_2 i 316L. (Mechanosynthesis, Structure and Properties of $Mg_2Fe_XH_6$ Complex Hydride Produced from MgH_2 and 316L Powder Substrates). Ph.D. Thesis, Faculty of New Technologies and Chemistry, Military University of Technology Jarosław Dąbrowski, Warsaw, Poland, 2021.
44. Molnarne, M.; Schroeder, V. Hazardous properties of hydrogen and hydrogen containing fuel gases. *Process Saf. Environ. Prot.* **2019**, *130*, 1–5. [CrossRef]
45. Guo, L.; Su, J.; Wang, Z.; Shi, J.; Guan, X.; Cao, W.; Ou, Z. Hydrogen safety: An obstacle that must be overcome on the road towards future hydrogen economy. *Int. J. Hydrogen Energy* **2024**, *51*, 1055–1078. [CrossRef]
46. Salehi, F.; Abbassi, R.; Asadnia, M.; Chan, B.; Chen, L. Overview of safety practices in sustainable hydrogen economy—An Australian perspective. *Int. J. Hydrogen Energy* **2022**, *47*, 34689–34703. [CrossRef]
47. Yang, F.; Wang, T.; Deng, X.; Dang, J.; Huang, Z.; Hu, S.; Li, Y.; Ouyang, M. Exploring future promising technologies in hydrogen fuel cell transportation. Review on hydrogen safety issues: Incident statistics, hydrogen diffusion, and detonation process. *Int. J. Hydrogen Energy* **2021**, *46*, 31467–31488. [CrossRef]
48. Bertagni, B.M.; Pacala, S.W.; Paulot, W.; Porporato, A. Risk of the hydrogen economy for atmospheric methane. *Nat. Commun.* **2022**, *13*, 7706. [CrossRef]
49. *Towards Hydrogen Definitions Based on Their Emissions Intensity*; International Energy Agency (IEA): Paris, France, 2023; Available online: https://www.iea.org/reports/towards-hydrogen-definitions-based-on-their-emissions-intensity (accessed on 22 February 2024).
50. Catuti, M.; Righetti, E.; Egenhofer, C.; Kustova, I. Is Renewable Hydrogen a Silver Bullet for Decarbonisation? A Critical Analysis of Hydrogen Pathways in the EU. CEPS Research Reports, Brussels. 2021. Available online: https://www.ceps.eu/wp-content/uploads/2021/12/CEPS-RR2021-02_Is-renewable-hydrogen-a-silver-bullet-for-decarbonisation.pdf (accessed on 7 August 2023).
51. Global Hydrogen Review 2023. International Energy Agency, Clean Energy Ministerial, Hydrogen Initiative: Paris, France. 2023. Available online: https://iea.blob.core.windows.net/assets/ecdfc3bb-d212-4a4c-9ff7-6ce5b1e19cef/GlobalHydrogenReview2023.pdf (accessed on 21 February 2024).
52. Cheng, W.; Lee, S. How green are the national hydrogen strategies? *Sustainability* **2022**, *14*, 1930. [CrossRef]
53. Press Release 15 February 2023 Maritime Safety: Council Parliament Strike a Deal to Ensure Cleaner Shipping in the EU. Available online: https://www.consilium.europa.eu/en/press/press-releases/2024/02/15/maritime-safety-council-and-parliament-strike-a-deal-to-ensure-cleaner-shipping-in-the-eu/ (accessed on 14 March 2024).
54. Press Release. Alternative Fuels Infrastructure: Council Adopts New Law for More Recharging and Refueling Stations across Europe. 25 April 2023. Available online: https://www.consilium.europa.eu/en/press/press-releases/2023/07/25/alternative-fuels-infrastructure-council-adopts-new-law-for-more-recharging-and-refuelling-stations-across-europe/ (accessed on 14 October 2023).
55. Press Release. Council and Parliament Agree to Decarbonise the Aviation Sector. 25 April 2023. Available online: https://www.consilium.europa.eu/en/press/press-releases/2023/04/25/council-and-parliament-agree-to-decarbonise-the-aviation-sector/ (accessed on 24 May 2024).
56. Karmaker, S.C.; Chapman, A.; Sen, K.K.; Hosan, S.; Saha, B.B. Renewable Energy Pathways toward Accelerating Hydrogen Fuel Production: Evidence from Global Hydrogen Modeling. *Sustainability* **2022**, *15*, 588. [CrossRef]
57. Farrell, N. Policy design for green hydrogen. *Renew. Sustain. Energy Rev.* **2023**, *178*, 113216. [CrossRef]
58. van der Spek, M.; Banet, C.; Bauer, C.; Gabrielli, P.; Goldthorpe, W.; Mazzoti, M.; Minkejord, S.T.; Rokke, N.A.; Shah, N.; Sunny, N.; et al. Perspective on the hydrogen economy as a pathway to reach net-zero CO2 emissions in Europe. *Energy Environ. Sci.* **2022**, *15*, 1034–1077. [CrossRef]
59. Kannaiyan, K.; Lekshmi, G.S.; Ramakrishna, S.; Kang, M.; Kumaravel, V. Perspectives for the green hydrogen energy-based economy. *Energy* **2023**, *284*, 129358. [CrossRef]
60. Vivanco-Martín, B.; Iranzo, A. Analysis of the European Strategy for Hydrogen: A Comprehensive Review. *Energies* **2023**, *16*, 3866. [CrossRef]
61. Klöckner, K.; Letmathe, P. Is the coherence of coal phase-out and electrolytic hydrogen production the golden path to 0effective decarbonisation? *Appl. Energy* **2020**, *279*, 115779. [CrossRef]
62. Tholen, L.; Leipprand, A.; Kiyar, D.; Maier, S.; Küper, M.; Adisorn, T.; Fischer, A. The Green Hydrogen Puzzle: Towards a German Policy Framework for Industry. *Sustainability* **2021**, *13*, 12626. [CrossRef]
63. Ashari, P.A.; Oh, H.; Koch, C. Pathways to the hydrogen economy: A multidimensional analysis of the technological innovation systems of Germany and South Korea. *Int. J. Hydrogen Energy* **2024**, *49*, 405–421. [CrossRef]
64. Bairrão, D.; Soares, J.; Almeida, J.; Franco, J.F.; Vale, Z. Green Hydrogen and Energy Transition: Current State and Prospects in Portugal. *Energies* **2023**, *16*, 551. [CrossRef]
65. Gawlik, L.; Mokrzycki, E. Analysis of the Polish Hydrogen Strategy in the Context of the EU's Strategic Documents on Hydrogen. *Energies* **2021**, *14*, 6382. [CrossRef]

66. Benalcazar, P.; Komorowska, A. Prospects of green hydrogen in Poland: A techno-economic analysis using a Monte Carlo approach. *Int. J. Hydrogen Energy* **2022**, *9*, 5779–5796. [CrossRef]
67. Komorowska, A.; Mokrzycki, E.; Gawlik, L. Hydrogen production in Poland – the current state and directions of development. *Polityka Energetyczna—Energy Policy J.* **2023**, *26*, 81–98. [CrossRef]
68. Giuli, M. *Italy in the International Hydrogen Economy*; IAI—Instituto Affari Internazionali: Rome, Italy, 2022; ISBN 978-88-9368-237-4. Available online: https://www.iai.it/sites/default/files/9788893682374.pdf (accessed on 7 August 2023).
69. The Transition to Low-Carbon Hydrogen in France. Opportunities and Challenges for the Power System by 2030–2035. Main Results. RTE. January 2020. Available online: https://assets.rte-france.com/prod/public/2021-03/Hydrogen%20report_0.pdf (accessed on 7 August 2023).
70. Mukelabai, M.D.; Wijayantha, U.K.G.; Blanchard, N.E. Renewable hydrogen economy outlook in Africa. *Renew. Sustain. Energy Rev.* **2022**, *167*, 112705. [CrossRef]
71. Cardinale, R. From natural gas to green hydrogen: Developing and repurposing transnational energy infrastructure connecting North Africa to Europe. *Energy Policy* **2023**, *181*, 113623. [CrossRef]
72. Bhandari, R. Green hydrogen production potential in West Africa–Case of Niger. *Renew. Energy* **2022**, *196*, 800–811. [CrossRef]
73. Lebrouhi, B.E.; Lamrani, B.; Zeraouli, Y.; Kousksou, T. Key challenges to ensure Morocco's sustainable transition to a green hydrogen economy. *Int. J. Hydrogen Energy* **2023**, *49*, 488–508. [CrossRef]
74. Ayodele, T.R.; Munda, J.L. The potential role of green hydrogen production in the South Africa energy mix. *J. Renew. Sustain. Energy* **2019**, *11*, 044301. [CrossRef]
75. Ballo, A.; Valentin, K.K.; Korgo, B.; Ogunjobi, K.O.; Agbo, S.N.; Kone, D.; Sawadogo, M. Law and policy review on green hydrogen potential in ECOWAS countries. *Energies* **2022**, *15*, 2304. [CrossRef]
76. Elmanakhly, F.; DaCosta, A.; Berry, B.; Stasko, R.; Fowler, M.; Wu, X.-Y. Hydrogen economy transition plan: A case study on Ontario. *AIMS Energy* **2021**, *9*, 775–811. [CrossRef]
77. Bridgeland, R.; Chapman, A.; McLellan, B.; Sofronis, P.; Fujii, Y. Challenges toward achieving a successful hydrogen economy in the US: Potential end-use and infrastructure analysis to the year 2100. *Clean. Prod. Lett.* **2022**, *3*, 100012. [CrossRef]
78. Beasy, K.; Emery, S.; Pryor, K.; Vo, T.A. Skilling the green hydrogen economy: A case study from Australia. *Int. J. Hydrogen Energy* **2023**, *48*, 19811–19820. [CrossRef]
79. Kar, S.K.; Sinha, A.S.K.; Bansal, R.; Shabani, B.; Harichandan, S. *Overview of Hydrogen Economy in Australia*; Wiley Interdisciplinary Reviews: Energy and Environment, Wiley Blackwell: Hoboken, NJ, USA, 2023; Volume 12.
80. Chantre, C.; Eliziário, S.A.; Pradelle, F.; Católico, A.F.; Das Dores, A.M.B.; Serra, E.T.; Tucunduva, R.C.; Cantarino, V.B.P.; Braga, S.L. Hydrogen economy development in Brazil: An analysis of stakeholders' perception. *Sustain. Prod. Consum.* **2022**, *34*, 26–41. [CrossRef]
81. Hunt, J.D.; Nascimento, A.; Nascimento, N.; Vieira, L.W.; Romero, O.J. Possible pathways for oil and gas companies in a sustainable future: From the perspective of a hydrogen economy. *Renew. Sustain. Energy Rev.* **2022**, *160*, 112291. [CrossRef]
82. Rodríguez-Fontalvo, D.; Quiroga, E.; Cantillo, N.M.; Sánchez, N.; Figueredo, M.; Cobo, M. Green hydrogen potential in tropical countries: The Colombian case. *Int. J. Hydrogen Energy* **2024**, *54*, 344–360. [CrossRef]
83. Harichandan, S.; Kar, S.K.; Rai, P.K. A systematic and critical review of green hydrogen economy in India. *Int. J. Hydrogen Energy* **2023**, *48*, 31425–31442. [CrossRef]
84. Huang, Y.S.; Liu, S.J. Chinese green hydrogen production potential development: A provincial case study. *IEEE Access* **2020**, *8*, 171968–171976. [CrossRef]
85. Liu RANDSolangi, Y.A. An Analysis of Renewable Energy Sources for Developing a Sustainable and Low-Carbon Hydrogen Economy in China. *Processes* **2023**, *11*, 1225. [CrossRef]
86. Hoang, A.T.; Pandey, A.; Lichtfouse, E.; Bui, V.G.; Veza, I.; Nguyen, H.L.; Nguyen, X.P. Green hydrogen economy: Prospects and policies in Vietnam. *Int. J. Hydrogen Energy* **2023**, *48*, 31049–31062. [CrossRef]
87. Stangarone, T. South Korean efforts to transition to a hydrogen economy. *Clean Technol. Environ. Policy* **2021**, *53*, 509–516. [CrossRef]
88. Hong, S.; Kim, E.; Jeong, S. Evaluating the sustainability of the hydrogen economy using multi-criteria decision-making analysis in Korea. *Renew. Energy* **2023**, *204*, 485–492. [CrossRef]
89. Lee, D.H.; Hsu, S.S.; Tso, C.T.; Su, A.; Lee, D.J. An economy-wide analysis of hydrogen economy in Taiwan. *Renew. Energy* **2009**, *34*, 1947–1954. [CrossRef]
90. Mah, A.X.Y.; Ho, W.S.; Bong, C.P.C.; Hassim, M.H.; Liew, P.Y.; Asli, U.A.; Kamaruddin, M.J.; Chemmangattuvalappil, N.G. Review of hydrogen economy in Malaysia and its way forward. *Int. J. Hydrogen Energy* **2019**, *44*, 5661–5675. [CrossRef]
91. Shah, S.A.A. Feasibility study of renewable energy sources for developing the hydrogen economy in Pakistan. *Int. J. Hydrogen Energy* **2020**, *45*, 15841–15854. [CrossRef]
92. Thapa, B.S.; Neupane, B.; Yang, H.; Lee, Y.H. Green hydrogen potentials from surplus hydro energy in Nepal. *Int. J. Hydrogen Energy* **2021**, *46*, 22256–22267. [CrossRef]
93. Tleubergenova, A.; Han, B.C.; Meng, X.Z. Assessment of biomass-based green hydrogen production potential in Kazakhstan. *Int. J. Hydrogen Energy* **2024**, *49*, 349–355. [CrossRef]
94. Li, Y.; Suryadi, B.; Yan, J.; Feng, J.; Bhaskoro, A.G.; Suwanto. A strategic roadmap for ASEAN to develop hydrogen energy: Economic prospects and carbon emission reduction. *Int. J. Hydrogen Energy* **2023**, *448*, 11113–11130. [CrossRef]

95. Razi, F.; Dincer, I. Renewable energy development and hydrogen economy in MENA region: A review. *Renew. Sustain. Energy Rev.* **2022**, *168*, 112763. [CrossRef]
96. Gado, M.G.; Hassan, H. Potential of prospective plans in MENA countries for green hydrogen generation driven by solar and wind power sources. *Sol. Energy* **2023**, *263*, 111942. [CrossRef]
97. Global Wind Atlas. DTU Wind Energy. Available online: https://globalwindatlas.info/en (accessed on 6 August 2023).
98. Global Solar Atlas. Solargis Website. Available online: https://globalsolaratlas.info/map (accessed on 1 March 2024).
99. EU Reference Scenario 2020—Energy, Transport and GHG Emissions—Trends to 2050. European Commission. Brussels, Luxembourg Publication Office for of European Union. 2021. Available online: https://op.europa.eu/en/publication-detail/-/publication/96c2ca82-e85e-11eb-93a8-01aa75ed71a1/language-en (accessed on 6 August 2023).
100. Regulation (EU) 2018/842 of the European Parliament and of the Council of 30 May 2018 on Binding Annual Greenhouse Gas Emission Reductions by Member States from 2021 to 2030 Contributing to Climate Action to Meet Commitments under the Paris Agreement and Amending Regulation (EU) No 525/2013 PE/3/2018/REV/2; OJ L 156, 19.6.2018. pp. 26–42. Available online: https://eur-lex.europa.eu/eli/reg/2018/842/oj (accessed on 20 June 2024).
101. Opportunities for Hydrogen Energy Technologies Considering the National Energy & Climate Plans. Final Report. Prepared by Trinomics & LBST for Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU). Rotterdam. July 2020. Available online: https://www.lei.lt/wp-content/uploads/2020/09/Final-Report-Hydrogen-in-NECPs-28-8-2020-ID-9474232.pdf (accessed on 6 August 2023).
102. Wolf, A.; Zander, N. Green hydrogen in Europe: Do strategies meet expectations? *Intereconomics* **2021**, *56*, 316–323. [CrossRef]
103. Ajanovic, A.; Sayer, M.; Haas, R. On the future relevance of green hydrogen in Europe. *Appl. Energy* **2024**, *358*, 122586. [CrossRef]
104. Zuttel, A.; Schlapbach, L.; Borgschulte, A. *History of Hydrogen. Hydrogen as a Future Energy Carrier*; Wiley-VCH Verlag GmbH & Co. KGaA: Weinheim, Germany, 2008; pp. 7–21.
105. Beswick, R.R.; Oliveira, A.M.; Yan, Y. Does the green hydrogen economy have a water problem? *ACS Energy Lett.* **2021**, *6*, 3167–3169. [CrossRef]
106. Oliveira, A.M.; Beswick, R.R.; Yan, Y. A green hydrogen economy for a renewable energy society. *Curr. Opin. Chem. Eng.* **2021**, *33*, 100701. [CrossRef]
107. Water-Energy Nexus. *Excerpt from the World Energy Outlook*; International Energy Agency (IEA): Paris, France, 2016; Available online: https://iea.blob.core.windows.net/assets/e4a7e1a5-b6ed-4f36-911f-b0111e49aab9/WorldEnergyOutlook2016ExcerptWaterEnergyNexus.pdf (accessed on 6 August 2023).
108. Dieter, C.A.; Maupin, M.A.; Caldwell, R.R.; Harris, M.A.; Ivahnenko, T.I.; Lovelace, J.K.; Barber, N.L.; Linsey, K.S. *Estimated Use of Water in the United States in 2015. Water Availability and Use Science Program*; Circular 1441 U.S. Geological Survey: Reston, VA, USA, 2018. [CrossRef]
109. Morrison, J.; Morikawa, M.; Murphy, M.; Schulte, P. *Water Scarcity & Climate Change: Growing Risks for Businesses and Investors*; Ceres: Boston, MA, USA, 2009; Available online: https://pacinst.org/wp-content/uploads/2009/02/growing-risk-for-business-investors-2.pdf (accessed on 6 August 2023).
110. Simoes, S.G.; Catarino, J.; Picado, A.; Lopes, T.F.; di Berardino, S.; Amorim, F.; Girio, F.; Rangel, C.M.; de Leão, T.P. Water availability and water usage solutions for electrolysis in hydrogen production. *J. Clean. Prod.* **2021**, *315*, 128124. [CrossRef]
111. Winter, L.R.; Cooper, N.J.; Lee, B.; Patel, S.K.; Wang, L.; Elimelech, M. Mining Nontraditional Water Sources for a Distributed Hydrogen Economy. *Environ. Sci. Technol.* **2022**, *56*, 10577–10585. [CrossRef] [PubMed]
112. Woods, P.; Bustamante, H.; Aguey-Zinsou, K.F. The hydrogen economy-Where is the water? *Energy Nexus* **2022**, *77*, 100123. [CrossRef]
113. Greenlee, L.F.; Lawler, D.F.; Freeman, B.D.; Marrot, B.; Moulin, P. Reverse osmosis desalination: Water sources, technology, and today's challenges. *Water Res.* **2009**, *43*, 2317–2348. [CrossRef] [PubMed]
114. Miller, J.E. *Review of Water Resources and Desalination Technologies*; SAND 2003-0800; Sandia National Laboratories: Albuquerque, NM, USA, 2003. Available online: https://www.osti.gov/servlets/purl/809106 (accessed on 5 August 2023).
115. Peterson, D.; Vickers, J.; Desantis, D. Hydrogen Production Cost from PEM Electrolysis—2019. U.S. Department of Energy, Record 19009. 3 February 2020. Available online: https://www.hydrogen.energy.gov/pdfs/19009_h2_production_cost_pem_electrolysis_2019.pdf (accessed on 5 August 2023).
116. Shi, X.; Liao, X.; Li, Y. Quantification of freshwater Consumption and Scarcity Footprint of Hydrogen from Water Electrolysis: A Methodology Framework. *Renew. Energy* **2020**, *154*, 786–796. [CrossRef]
117. Amirthan, T.; Perera, M.S.A. The role of storage systems in hydrogen economy: A review. *J. Nat. Gas Sci. Eng.* **2022**, *108*, 104843. [CrossRef]
118. Bouwman, P. Electrochemical Hydrogen Compression (EHC) solutions for hydrogen infrastructure. *Fuel Cells Bull.* **2014**, *5*, 12–16. [CrossRef]
119. Garcia, D.A.; Barbanera, F.; Cumo, F.; Di Matteo, U.; Nastasi, B. Expert opinion analysis on renewable hydrogen storage systems potential in Europe. *Energies* **2016**, *9*, 963. [CrossRef]
120. Ma, N.; Zhao, W.; Wang, W.; Li, X.; Zhou, H. Large scale of green hydrogen storage: Opportunities and challenges. *Int. J. Hydrogen Energy* **2024**, *50*, 379–396. [CrossRef]
121. Komorowska, A.; Olczak, P.; Hanc, E.; Kamiński, J. An analysis of the competitiveness of hydrogen storage and Li-ion batteries based on price arbitrage in the day-ahead market. *Int. J. Hydrogen Energy* **2022**, *47*, 28556–28572. [CrossRef]

122. Dias, V.; Pochet, M.; Contino, F.; Jeanmart, H. Energy and economic costs of chemical storage. *Front. Mech. Eng.* **2020**, *6*, 21. [CrossRef]
123. Le, S.T.; Nguyen, N.; Linforth, S.; Ngo, T.D. Safety investigation of hydrogen energy storage systems using quantitative risk assessment. *Int. J. Hydrogen Energy* **2023**, *48*, 2861–2875. [CrossRef]
124. Chmielniak, T. Wind and solar energy technologies of hydrogen production—A review of issues. *Polityka Energetyczna—Energy Policy J.* **2019**, *22*, 5–20. [CrossRef]
125. Farghali, M.; Osman, A.I.; Umetsu, K.; Rooney, D.W. Integration of biogas systems into a carbon zero and hydrogen economy: A review. *Environ. Chem. Lett.* **2022**, *20*, 2853–2927. [CrossRef]
126. Wang, M.; Wang, G.; Sun, Z.; Zhang, Y.; Xu, D. Review of renewable energy-based hydrogen production processes for sustainable energy innovation. *Glob. Energy Interconnect* **2019**, *2*, 436–443. [CrossRef]
127. Li, S.; Tabatabaei, M.; Li, F.; Ho, S.H. A review of green biohydrogen production using anoxygenic photosynthetic bacteria for hydrogen economy: Challenges and opportunities. *Int. J. Hydrogen Energy* **2024**, *54*, 218–238. [CrossRef]
128. Sharma, S.; Basu, S.; Shetti, N.P.; Aminabhavi, T.M. Waste-to-energy nexus for circular economy and environmental protection: Recent trends in hydrogen energy. *Sci. Total Environ.* **2020**, *713*, 136633. [CrossRef]
129. Gondal, I.A. Offshore renewable energy resources and their potential in a green hydrogen supply chain through power-to-gas. *Sustain. Energy Fuels* **2019**, *3*, 1468–1489. [CrossRef]
130. Hosseini, S.E.; Wahid, M.A. Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development. *Renew. Sustain. Energy Rev.* **2016**, *57*, 850–866. [CrossRef]
131. Hermesmann, M.; Grübel; Scherotzki, L.; Müller, T.E. Promising pathways: The geographic and energetic potential of power-to-x technologies based on regeneratively obtained hydrogen. *Renew. Sustain. Energy Rev.* **2021**, *138*, 110644. [CrossRef]
132. Miller, H.A.; Bouzek, K.; Hnat, J.; Loos, S.; Bernacker, C.I.; Wiessgarber, T.; Rontzsch, L.; Meier-Haack, J. Green hydrogen from anion exchange membrane water electrolysis: A review of recent developments in critical materials and operating conditions. *Sustain. Energy Fuels* **2020**, *4*, 2114–2133. [CrossRef]
133. Chen, Z.; Yun, S.; Wu, L.; Zhang, J.; Shi, X.; Wei, W.; Liu y Zheng, R.; Han, N.; Ni, B.-J. Waste-derived catalysts for water electrolysis: Circular economy-driven sustainable green hydrogen energy. *Nano-Micro Lett.* **2023**, *15*, 4. [CrossRef] [PubMed]
134. Bolzonella, D.; Battista, F.; Cavinato, C.; Gottardo, M.; Miccoluci, F.; Paolo, F. Chapter 13—Biohythane Production from Food Wastes. In *Biomass, Biofuels, Biochemicals, Biohydrogen*, 2nd ed.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 347–368. [CrossRef]
135. Mahant, B.; Linga, P.; Kumar, R. Hydrogen economy and role of Hythane as a bridging solution: A perspective review. *Energy Fuels* **2021**, *35*, 15424–15454. [CrossRef]
136. Messaoudani, Z.L.; Rigas, F.; Hamid, M.D.B.; Hassan, C.R. Hazards, safety and knowledge gaps on hydrogen transmission via natural gas grid: A critical review. *Int. J. Hydrogen Energy* **2016**, *41*, 17511–17525. [CrossRef]
137. El-Shafie, M. Hydrogen production by water electrolysis technologies: A review. *Results Eng.* **2023**, *20*, 101426. [CrossRef]
138. *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 °C Climate Goal*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2020; Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf (accessed on 8 March 2023).
139. Patonia, A.; Poudineh, R. *Cost-Competitive Green Hydrogen: How to Lower the Cost of Electrolysers?* OIES Paper: EL47; The Oxford Institute for Energy Studies: Oxford, UK, 2022; Available online: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2022/01/Cost-competitive-green-hydrogen-how-to-lower-the-cost-of-electrolysers-EL47.pdf (accessed on 3 March 2024).
140. Holm, T.; Borsboom-Hanson, T.; Herrera, O.E.; Mérida, W. Hydrogen costs from water electrolysis at high temperature and pressure. *Energy Convers. Manag.* **2021**, *237*, 14106. [CrossRef]
141. Kumar, S.S.; Lim, H. An overview of water electrolysis technologies for green hydrogen production. *Energy Rep.* **2022**, *8*, 13793–13813. [CrossRef]
142. Aravindan, M.; Kumar, P. Hydrogen towards sustainable transition: A review of production, economic, environmental impact and scaling factors. *Results Eng.* **2023**, *20*, 101456. [CrossRef]
143. Basheer, A.A.; Alii, I. Water photo splitting for green hydrogen energy by green nanoparticles. *Int. J. Hydrogen Energy* **2019**, *44*, 11564–11573. [CrossRef]
144. Reddy, S.N.; Nanda, S.; Vo, D.-V.N.; Nguyen, T.D.; Nguyen, V.-H.; Abdullah, B.; Nguyen-Tri, P. Hydrogen: Fuel of the near future. In *New Dimensions in Production and Utilization of Hydrogen*; Nanda, S., Vo, D.-V.N., Nguyen-Tri, P., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 1–20.
145. Schimmel, M.; Kerres, P.; Jörling, K.; Klessmann, C.; Schröder, J.; Altrock, M.; Kliem, C.; Maiworm, C.; Hillmann, S.; Deutsch, M.; et al. Making Renewable Hydrogen Cost-Competitive. Policy Instruments for Supporting Green H_2. STUDY. Agora Energiewende and Guidehouse. 2021. Available online: https://static.agora-energiewende.de/fileadmin/Projekte/2020/2020_11_EU_H2-Instruments/A-EW_223_H2-Instruments_WEB.pdf (accessed on 7 August 2023).
146. Zhuang, W.; Pan, G.; Gu, W.; Zhou, S.; Hu, Q.; Gu, Z.; Wu, Z.; Lu, S.; Qiu, F. Hydrogen economy driven by offshore wind in regional comprehensive economic partnership members. *Energy Environ. Sci.* **2023**, *16*, 2014. [CrossRef]
147. Akdağ, O. The operation and applicability to hydrogen fuel technology of green hydrogen production by water electrolysis using offshore wind power. *J. Clean. Prod.* **2023**, *425*, 138863. [CrossRef]

148. Minutillo, M.; Perna, A.; Forcina, A.; Di Micco, S.; Jannelli, E. Analyzing the levelized cost of hydrogen in refueling stations with on-site hydrogen production via water electrolysis in the Italian scenario. *Int. J. Hydrogen Energy* **2021**, *46*, 13667–13677. [CrossRef]
149. Fragiacomo, P.; Genovese, M.; Piraino, F.; Massari, F.; Boroomandnia, M. Analysis of a distributed green hydrogen infrastructure designed to support the sustainable mobility of a heavy-duty fleet. *Int. J. Hydrogen Energy* **2024**, *51*, 576–594. [CrossRef]
150. Forbes, J. Hydrogen Fuel Cell Advantages and Disadvantages in Material Handling. Flux Power. 2021. Available online: https://www.fluxpower.com/blog/hydrogen-fuel-cell-advantages-and-disadvantages-in-material-handling (accessed on 5 August 2023).
151. Jamal, T.; Shafiullah, G.M.; Dawood, F.; Kaur, A.; Arif, M.T.; Pugazhendhi, R.; Elavarasan, R.M.; Ahmed, S.F. Fuelling the future: An in-depth review of recent trends, challenges and opportunities of hydrogen fuel cell for a sustainable hydrogen economy. *Energy Rep.* **2023**, *10*, 2103–2127. [CrossRef]
152. Yang, H.; Han, Y.J.; Yu, J.; Kim, S.; Lee, S.; Kim, G.; Lee, C. Exploring future promising technologies in hydrogen fuel cell transportation. *Sustainability* **2022**, *14*, 917. [CrossRef]
153. Zainal, B.S.; Ker, P.J.; Mohamed, H.; Ong, H.C.; Fattah, I.M.R.; Rahman, S.M.A.; Nghiem, L.D.; Mahlia, T.M.I. Recent advancement and assessment of green hydrogen production technologies. *Renew. Sustain. Energy Rev.* **2024**, *189*, 113941. [CrossRef]
154. Manoharan, Y.; Hosseini, S.E.; Butler, B.; Alzhahrani, H.; Senior, B.T.F.; Ashuri, T.; Krohn, J. Hydrogen fuel cell vehicles; current status and future prospect. *Appl. Sci.* **2019**, *9*, 2296. [CrossRef]
155. Jastrzębski, K.; Kula, P. Emerging technology for a green, sustainable energy-promising materials for hydrogen storage, from nanotubes to graphene—A review. *Materials* **2021**, *14*, 2499. [CrossRef]
156. Coleman, D.; Kopp, M.; Wagner, T.; Scheppat, B. The value chain of green hydrogen for fuel cell buses–A case study for the Rhine-Main area in Germany. *Int. J. Hydrogen Energy* **2020**, *45*, 5122–5133. [CrossRef]
157. Shirizadeh, B.; Ailleret, A.; Guillon, A.; Bovari, E.; El Khatib, N.; Douguet, S.; Issa, C.B.; Brauera, J.; Trübya, J. Towards a resilient and cost-competitive clean hydrogen economy: The future is green. *Energy Environ. Sci.* **2023**, *16*, 6094–6109. [CrossRef]
158. Laguna, J.C.; Duerinck, J.; Meinke-Hubeny, F.; Valee, J. Carbon-Free Steel Production: Cost Reduction Options and Usage of Existing Gas Infrastructure. STUDY: Panel for the Future of Science and Technology, EPRS (European Parliamentary Research Service), Scientific Foresight Unit (STOA). Brussels. 2021. Available online: https://op.europa.eu/s/vJTc (accessed on 7 August 2023).
159. Barrett, M.; Cassarino, T.G. *Heating with Steam Methane-Reformed Hydrogen—A Survey of the Emissions, Security and Cost Implications of Heating with Hydrogen Produced with Natural Gas*; Centre for Research into Energy Demand Solutions: Oxford, UK, 2021; Available online: https://www.creds.ac.uk/?p=7029 (accessed on 7 August 2023).
160. Lagioia, G.; Spinelli, M.P.; Amicarelli, V. Blue and green hydrogen energy to meet European Union decarbonisation objectives. An overview of perspectives and the current state of affairs. *Int. J. Hydrogen Energy* **2023**, *48*, 1304–1322. [CrossRef]
161. Tetteh, D.A.; Salehi, S. The Blue Hydrogen Economy: A Promising Option for the Near-to-Mid-Term Energy Transition. *J. Energy Resour. Technol.* **2023**, *145*, 042701. [CrossRef]
162. Ueckerdt, F.; Verpoort, P.C.; Anantharaman, R.; Bauer, C.; Beck, F.; Longden, T.; Roussanaly, S. On the cost competitiveness of blue and green hydrogen. *Joule* **2024**, *8*, 104–128. [CrossRef]
163. Al-Kuwari, O.; Schönfisch, M. The emerging hydrogen economy and its impact on LNG. *Int. J. Hydrogen Energy* **2022**, *47*, 2080–2092. [CrossRef]
164. Kumar, S.; Baalisampang, T.; Arzaghi, E.; Garaniya, V.; Abbasi, R. Synergy of green hydrogen sector with offshore industries: Opportunities and challenges for a safe and sustainable hydrogen economy. *J. Clean. Prod.* **2023**, *384*, 135545. [CrossRef]
165. Boretti, A. There are hydrogen production pathways with better than green hydrogen economic and environmental costs. *Int. J. Hydrogen Energy* **2021**, *46*, 23988–23995. [CrossRef]
166. Franzmann, D.; Heinrichs, H.; Lippkau, F.; Addanki, T.; Winkler, C.; Buchenberg, P.; Hamacher, T.; Blesl, M.; Linßen, J.; Stolten, D. Green hydrogen cost-potentials for global trade. *Int. J. Hydrogen Energy* **2023**, *84*, 33062–33076. [CrossRef]
167. Abdelsalam, E.; Almomani, F.; Alnawafah, H.; Habash, D.; Jamjoum, M. Sustainable production of green hydrogen, electricity, and desalinated water via a Hybrid Solar Chimney Power Plant (HSCPP) water-splitting process. *Int. J. Hydrogen Energy* **2024**, *52*, 1356–1369. [CrossRef]
168. Komorowska, A.; Benalcazar, P.; Kamiński, J. Evaluating the competitiveness and uncertainty of offshore wind-to-hydrogen production: A case study of Poland. *Int. J. Hydrogen Energy* **2023**, *48*, 14577–14590. [CrossRef]
169. Boudellal, M. *Power-to-Gas: Renewable Hydrogen Economy for the Energy Transition*, 2nd ed.; De Gruyter: Berlin, Germany, 2023. [CrossRef]
170. Acar, C.; Dincer, I. Review and evaluation of hydrogen production options for better environment. *J. Clean. Prod.* **2019**, *218*, 835–849. [CrossRef]
171. Choi, W.; Kang, S. Greenhouse gas reduction and economic cost of technologies using green hydrogen in the steel industry. *J. Environ. Manag.* **2023**, *335*, 117569. [CrossRef]
172. *Geopolitics of the Energy Transformation: The Hydrogen Factor*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2022; Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jan/IRENA_Geopolitics_Hydrogen_2022.pdf (accessed on 12 February 2024).
173. Eicke, L.; De Blasio, N. Green hydrogen value chains in the industrial sector—Geopolitical and market implications. *Energy Res. Soc. Sci.* **2022**, *93*, 102847. [CrossRef]

174. Hjeij, D.; Bicer, Y.; Al-Sada, M.S.; Koç, M. Hydrogen export competitiveness index for a sustainable hydrogen economy. *Energy Rep.* **2023**, *9*, 5843–5856. [CrossRef]
175. Gatto, A.; Sadik-Zada, E.R.; Lohoff, T.; Aldieri, L. An exemplary subsidization path for the green hydrogen economy uptake: Rollout policies in the United States and the European Union. *J. Clean. Prod.* **2024**, *440*, 140757. [CrossRef]
176. Abad, A.V.; Dodds, P.E. Green hydrogen characterisation initiatives: Definitions, standards, guarantees of origin, and challenges. *Energy Policy* **2020**, *138*, 111300. [CrossRef]
177. Falcone, P.M.; Hiete, M.; Sapio, A. Hydrogen economy and sustainable development goals: Review and policy insights. *Curr. Opin. Green Sustain. Chem.* **2021**, *31*, 100506. [CrossRef]
178. Akhtar, M.S.; Khan, H.; Liu, J.J.; Na, J. Green hydrogen and sustainable development—A social LCA perspective highlighting social hotspots and geopolitical implications of the future hydrogen economy. *J. Clean. Prod.* **2023**, *395*, 136438. [CrossRef]
179. Atilhan, S.; Park, S.; El-Halwagi, M.W.; Atilhan, M.; Moore, M.; Nielsen, R.B. Green hydrogen as an alternative fuel for the shipping industry. *Curr. Opin. Chem. Eng.* **2021**, *31*, 100668. [CrossRef]
180. Mneimneh, F.; Ghazzawi, H.; Abu Hejjeh, M.; Manganelli, D.; Ramakrishna, S. Roadmap to achieving sustainable development via green hydrogen. *Energies* **2023**, *16*, 1368. [CrossRef]
181. Olabi, A.G.; Abdelkareem, M.A.; Mahmoud, M.S.; Elsaid, K.; Obaideen, K.; Rezk, H.; Wilberforce, T.; Eisa, T.; Chae, K.-J.; Sayed, E.T. Green hydrogen: Pathways, roadmap, and role in achieving sustainable development goals. *Process Saf. Environ. Prot.* **2023**, *177*, 664–687. [CrossRef]
182. Plank, F.; Muntschick, J.; Niemann, A.; Knodt, M. External Hydrogen Relations of the European Union: Framing Processes in the Public Discourse towards and within Partner Countries. *Sustainability* **2023**, *15*, 14757. [CrossRef]
183. Kakoulaki, G.; Kougias, I.; Taylor, N.; Dolci, F.; Moya, J.; Jäger-Waldau, A. Green hydrogen in Europe—A regional assessment: Substituting existing production with electrolysis powered by renewables. *Energy Convers. Manag.* **2021**, *228*, 113649. [CrossRef]
184. Eh, C.L.M.; Tiong, A.N.T.; Kansedo, J.; Lim, C.H.; How, B.S.; Ng, W.P.Q. Circular Hydrogen Economy and Its Challenges. *Chem. Eng. Trans.* **2022**, *94*, 1273–1278. [CrossRef]
185. Parra, D.; Valverde, L.; Pino, F.J.; Patel, M.K. A review on the role, cost, and value of hydrogen energy systems for deep decarbonisation. *Renew. Sustain. Energy Rev.* **2019**, *101*, 279–294. [CrossRef]
186. Qazi, U.Y. Future of Hydrogen as an Alternative Fuel for Next-Generation Industrial Applications; Challenges and Expected Opportunities. *Energies* **2022**, *15*, 4741. [CrossRef]
187. Stöckl, F.; Schill, W.-P.; Zerrahn, A. Optimal supply chains and power sector benefits of green hydrogen. *Sci. Rep.* **2021**, *11*, 14191. [CrossRef] [PubMed]
188. Squadrito, G.; Maggio, G.; Nicita, A. The green hydrogen revolution. *Renew. Energy* **2023**, *2216*, 119041. [CrossRef]
189. Odenweller, A.; Ueckerdt, F.; Nemet, G.F.; Jensterle, M.; Luderer, G. Probabilistic feasibility space of scaling up green hydrogen supply. *Nat. Energy* **2022**, *7*, 854–865. [CrossRef]
190. Scita, R.; Raimondi, P.P.; Noussan, M. Green Hydrogen: The Holy Grail of Decarbonisation? An Analysis of the Technical and Geopolitical Implications of the Future Hydrogen Economy. Fondacione Eni Enrico Mattei. 2000. Available online: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3709789# (accessed on 23 February 2024).
191. Radowitz, B. Russia's War Pushes Blue and Grey Hydrogen Costs Way above Those of Green H2: Rystad. Recharge: Global News and Intelligence for the Energy Transition. 2022. Available online: https://www.rechargenews.com/energy-transition/russias-war-pushes-blue-and-grey-hydrogen-costs-way-above-those-of-green-h2-rystad/2-1-1189003 (accessed on 12 March 2024).
192. Dincer, I. Hydrogen 1.0: A new age. *Int. J. Hydrogen Energy* **2023**, *48*, 6143–16147. [CrossRef]
193. Dillman, K.; Heinonen, J. Towards a Safe Hydrogen Economy: An Absolute Climate Sustainability Assessment of Hydrogen Production. *Climate* **2023**, *11*, 1010025. [CrossRef]
194. Zeyen, E.; Victoria, M.; Brown, T. Endogenous learning for green hydrogen in a sector-coupled energy model for Europe. *Nat. Commun.* **2023**, *14*, 3743. [CrossRef]
195. Marouani, I.; Guesmi, T.; Alshammari, B.M.; Alqunun, K.; Alzamil, A.; Alturki, M.; Abdallah, H.H. Integration of Renewable-Energy-Based Green Hydrogen into the Energy Future. *Processes* **2023**, *11*, 2685. [CrossRef]
196. Breyer, C.; Lopez, G.; Bogdanov, D.; Laaksonen, P. The role of electricity-based hydrogen in the emerging power-to-X economy. *Int. J. Hydrogen Energy* **2024**, *49*, 351–359. [CrossRef]