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Clean Hydrogen Is a Challenge for Enterprises in the Era of Low-Emission and Zero-Emission Economy

Piotr F. Borowski * and Barbara Karlikowska

Faculty of Business and International Relations, Vistula University, 3 Stokłosy Str., 02-787 Warsaw, Poland
* Correspondence: p.borowski@vistula.edu.pl or pborowski@autograf.pl

Abstract: Hydrogen can be considered an innovative fuel that will revolutionize the energy sector and enable even more complete use of the potential of renewable sources. The aim of the paper is to present the challenges faced by companies and economies that will produce and use hydrogen. Thanks to the use of hydrogen in the energy, transport and construction sectors, it will be possible to achieve climate neutrality by 2050. By 2050, global demand for hydrogen will increase to 614 million metric tons a year, and thanks to the use of hydrogen in energy, transport and construction, it will be possible to achieve climate neutrality. Depending on the method of hydrogen production, the processes used and the final effects, several groups can be distinguished, marked with different colors. It is in this area of obtaining friendly hydrogen that innovative possibilities for its production open up. The costs of hydrogen production are also affected by network fees, national tax systems, availability and prices of carbon capture, utilization, and storage installations, energy consumption rates by electrolyzers and transport methods. It is planned that 1 kg of hydrogen will cost USD 1. The study used the desk research method, which made it possible to analyze a huge amount of descriptive data and numerical data.

Keywords: hydrogen; energy transformation; energy sector; construction sector; transport sector; decarbonization; zero-emission industry

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1. Introduction

Clean production and energy saving is one of the key issues of all developing and developed economies around the world. These actions are taken not only from the point of view of resource availability, but also the current effects of global climate change. The research problem is how countries are moving towards a low- or zero-carbon economy. The issue of hydrogen is currently widely discussed as the fuel of the future, but the most important question is how hydrogen is produced, because it is crucial that its production does not produce carbon monoxide, carbon dioxide, and other greenhouse gases. Another issue related to the production of pure hydrogen is the production of electricity that is then needed for electrolysis in the hydrogen production process. The growing, constantly developing industry around the world, on the one hand, is responsible for increasing pollution, and on the other hand, it definitely puts pressure on decision-makers to look for better, more effective and ecological ways to generate electricity. Companies undertake intensive actions aimed at mitigating their harmful impact on climate change. The activities of enterprises consist mainly in decarbonization, reduction of greenhouse gas emissions, protection of water and green areas [1]. According to various scenarios, the share of fossil fuels will be systematically reduced and the share of renewable sources and nuclear energy will increase. Three scenarios for the development of the energy sector until 2050 are presented in Figure 1.

Each of presented net-zero scenarios describes major transformations in primary energy production. Reducing the negative impact on the environment and implementing planned activities is carried out by implementing innovative solutions in companies from the energy, transport and construction sectors. Changes implemented in these three sectors can significantly reduce the negative impact on the environment. The current discussion on energy policy is strongly shaped and dominated by the subject of hydrogen used as a universal source of energy for energy transformation.

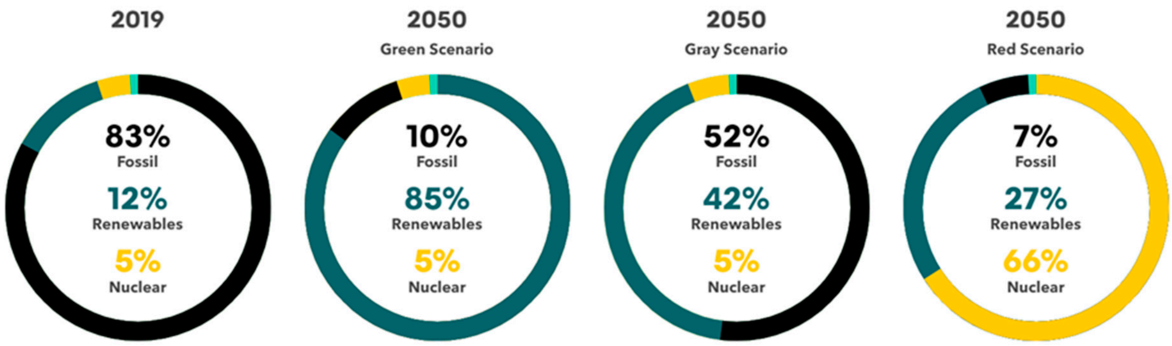

Figure 1. Scenarios for the development of the energy sector until 2050. Source: [2].

The current energy system faces serious technological challenges resulting from, among others, regulations, laws, and directives. In energy companies, the goals should primarily concern technology, ecology, and society [3]. Energy companies also require significant structural and organizational transformations and face the need to implement innovative solutions in order to meet environmental requirements. Over the last few decades, the use of renewable energy sources (RES) has been steadily increasing around the world. Energy companies implement solutions consisting in combining renewable energy with energy-saving technologies. Such solutions should make it possible to reduce greenhouse gas emissions and reduce air pollution [4].

In the transport sector, companies are also implementing technological innovations to increase performance, increase energy efficiency, and enable the use of new alternative fuels. Changing traditional polluting transport technologies requires the adoption of environmentally friendly, innovative technologies [5].

In the construction sector, the issue of energy efficiency and the environmental impact of buildings is also important. According to the EU directive [6], almost zero-energy buildings should be built, which are buildings with almost zero energy consumption. The near-zero or very low amount of energy required should be provided to a very high degree by energy from renewable sources, including renewable energy produced on-site or nearby. Low-cost hydrogen production will be possible thanks to strategically located hydrogen production plants, i.e., in areas with favorable conditions for the production of energy from wind and solar. Thanks to a good location, the cost of hydrogen production can be reduced by as much as 16–17% [7]. Generation of energy near the place of its use is possible thanks to the use of photovoltaics, wind energy, or energy from small hydropower [8]. The use of many distributed energy sources requires advanced billing systems that can be provided by the digitization of the energy sector [9,10].

In the public debate among policy-makers, entrepreneurs, and scientists, it is now recognized that renewable or low-carbon hydrogen is an important element that can be used in the construction sector to produce energy and heat buildings. The use of green hydrogen will contribute to the achievement of climate goals.

Hydrogen, which is capable of storing, transporting, and transforming energy in various ways, can be a versatile tool to fully exploit the potential of renewable energy sources. In the literature, renewable energy is widely recognized as a valuable option for the decarbonization of various sectors, including those areas of the energy system where it is currently difficult to make a deep reduction of emissions, such as long-distance transport, the chemical industry, and heavy industry [11].

The authors undertook research to analyze whether hydrogen can actually contribute to reducing the emission of harmful gases and what conditions should be met to achieve the assumed goal of a zero-emission economy.

2. Materials and Methods

The study was carried out using the desk research method, which boils down to the analysis of available data sources. In desk research, existing research materials obtained from various sources, such as repositories, libraries and archives, and the internet, are analyzed. All of the identified sources provide access to various types of scientific materials, such as articles, books, conference materials, reports, and doctoral theses. When using the desk research method, the authors remembered to use proven, verified, scientifically valuable data, characterized by scientific evidence. The use of the method of secondary data sources made it possible to answer the posed research problems. Desk research studies were the main source of information and obtained data used in the completed study. In the study, thanks to literature studies, thematic publications, articles published in scientific journals, reports, analyses, and statistical yearbooks were analyzed. Thanks to the use of the desk research method, it was possible to analyze a large amount of information related to the ongoing work on hydrogen, problems arising in its production and its implementation in various sectors of the economy. From the information obtained, after the analysis, scientific knowledge was created. The diagram of the research method used is shown in Figure 2.

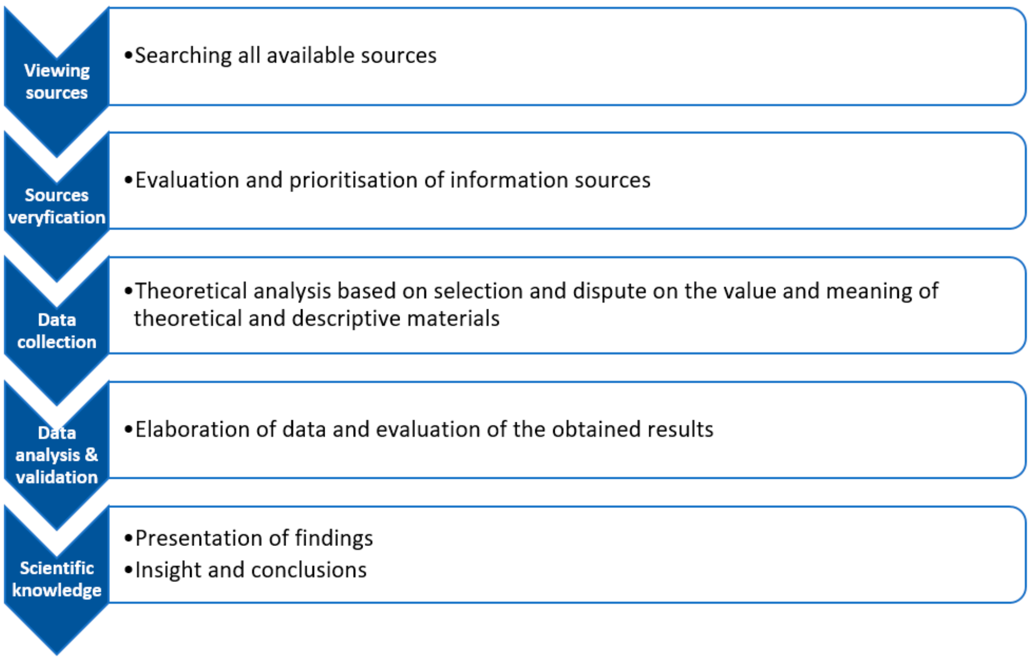

Figure 2. Scheme of the research method. Source: authors' own elaboration.

The desk research method is commonly used in scientific research, but care should be taken with the proper selection of sources. Not all published sources are valuable and not all have the same credibility, so skill should be used find those that carry cognitive value. Therefore, the authors paid special attention to the validation of sources. It is a contribution to the proper application of the research method based on desk research.

3. Literature Review

The literature review cited researchers who dealt with the discussed topic and conducted similar research. This review highlights the three main industries where hydrogen is used. Among others, scientific papers dedicated to hydrogen used by companies belonging to the energy sector, the transport sector, and the construction sector were analyzed. The choice of these three sectors was based on two complementary premises. The first premise concerns the broadly understood strategy related to the zero-emission economy, which is related to the aforementioned sectors as the most responsible for greenhouse gas emissions. The second premise is based on "A European Strategy for Hydrogen" of July 2020, developed by the European Commission. The Polish equivalent of this document, the Polish Hydrogen Strategy to 2030, identifies the following as the most important specific goals: deployment of hydrogen technologies in energy and heating as well as use of hydrogen as an alternative fuel in transportation [12].

The most interesting aspects related to hydrogen used in these three industry sectors are presented in Table 1.

Table 1. The use of hydrogen in various sectors of the economy.

Title of the Paper	The Most Important Issues Discussed in the Article
Hydrogen in Energy Sector	
Hydrogen production for energy: An overview.	Hydrogen energy is a solution with great potential for storing variable renewable energy. The hydrogen-based energy system includes subsystems: production, storage, safety, and disposal. The emissivity of hydrogen depends on the purity of the production path and the energy used to produce it [13].
Hydrogen as energy carrier: Techno-economic assessment of decentralized hydrogen production in Germany	The energy transformation will be based on energy storage. Energy storage is essential to unleash the power of renewable energy sources. Hydrogen can be one of the solutions of the future energy transformation, if it is produced economically and ecologically, i.e., using renewable energy sources [14].
Global hydrogen development—A technological and geopolitical overview	Hydrogen is an energy carrier that in the coming years will make a significant and decisive contribution to the global energy transformation and will lead to a significant reduction in greenhouse gas (GHG) emissions [15].
Green hydrogen: A new flexibility source for security constrained scheduling of power systems with renewable energies	The possibility of introducing green hydrogen as a new source of flexibility in power systems [16].
Role of hydrogen-based energy carriers as an alternative option to reduce residual emissions associated with mid-century decarbonization goals.	Energy carriers that will be produced on the basis of hydrogen will eliminate harmful emissions, assuming that these carriers come from low-emission sources, such as electricity produced from renewable sources. Alternatively, it can be derived from fossil fuels using carbon capture and sequestration (CCS). Hydrogen will reduce emissions where electrification cannot be easily implemented, such as in heavy industry and long-distance transport [17].
Hydrogen energy demand growth prediction and assessment (2021–2050) using a system thinking and system dynamics approach.	The adoption of hydrogen as a fuel for combustion is also associated with the possibility of generating NOx, which is a key air pollutant causing environmental degradation. This may limit the use of the combustion path if no measures are taken to implement solutions to reduce harmful emissions [18].
A low-cost power management system design for residential hydrogen and solar-energy-based power plants.	Implementation of a low-cost energy management system for home solar-hydrogen power plants. Control and management of the local hybrid power plant monitors the hybrid system and controls it to select the appropriate energy source for the local load [19].
A review on hydrogen production and utilization: Challenges and opportunities.	Hydrogen can be used for many purposes, combining the role of an energy carrier and, in a way, allowing for energy storage. In issues related to hydrogen, its use, storage and transport, distribution as well as key challenges and opportunities in the commercial implementation of hydrogen systems are important [20].

Table 1. *Cont.*

Title of the Paper	The Most Important Issues Discussed in the Article
Hydrogen in Transportation Sector	
An overview of using hydrogen in transportation sector as fuel	Hydrogen as a substitute for fossil fuels produced in fuel cells to produce electricity to drive the car engine. The use of hydrogen to drive cars affects the protection of the environment [21].
A green hydrogen economy for a renewable energy society	Creating a hydrogen economy and using hydrogen primarily for decarbonization, especially where there is no alternative. Deployment of hydrogen in the industrial sector as a chemical raw material, in the long-haul truck transport sector, in the construction sector for heating buildings and in the energy sector [22].
Hydrogen fuel cell heavy-duty trucks: Review of main research topics	Road transport is a significant source of CO2 emissions; therefore, initiatives are being developed and promoted to reduce emissions by developing common green macro-policies focused on hydrogen heavy-duty trucks [23].
Economic prospects and policy framework for hydrogen as fuel in the transport sector	The competitive use of hydrogen in the transport and electromobility sectors depends on the possibility of reducing fuel cell costs and implementing innovative technological solutions. In addition, economies of scale and the political will of decision-makers play an important role. Hydrogen can be used as an energy storage medium. This is an important aspect, especially due to the growing need to solve the problem of long-term storage of excess electricity [24].
Hydrogen technology towards the solution of environment-friendly new energy vehicles	In order to reduce emissions caused by transport, vehicles based on ecological, sustainable hydrogen technologies, such as batteries or fuel cells, are produced. The issues of the hydrogen economy include the production, distribution and use of hydrogen, the continuous development of fuel cell and battery technologies that affect the user of technology in the transport sector [25].
Hydrogen in Construction Sector	
Evaluation of zero-energy building and use of renewable energy in renovated buildings: A case study in Japan	Buildings equipped with a solar power generation system and using solar and geothermal heat can also produce hydrogen from surplus electricity on site and use hydrogen fuel cells [26].
Review and evaluation of hydrogen production options for better environment	Hydrogen can be utilized in buildings using existing natural gas infrastructure to provide heating, cooling and power supply. In addition, hydrogen can also minimize noise problems by replacing fossil fuel combustion processes in buildings, industry and the transport sector [27].
The role of hydrogen in German residential buildings	Climate-neutral heating options for buildings can be based on energy from renewable sources or zero-emission hydrogen. However, from the economic point of view, the supply and use of green hydrogen may prove too expensive [28].
Exergetic analysis of hydrogen utilization pathways–Part 1: Energy supply in buildings	Hydrogen can be used in all sectors of the economy, especially in construction, in the transport sector (electromobility) and in industry, e.g., in the production of steel or the synthesis of ammonia [29].
Zero-energy building by multicarrier energy systems including hydro, wind, solar, and hydrogen	Hydrogen storage system and methanation process as energy carriers at the interface between the electrical and thermal sectors supplying buildings [30].
Homes of the future: Unpacking public perceptions to power the domestic hydrogen transition	Making hydrogen technology socially acceptable is essential for the energy transition. The most common barriers to renewable or low-carbon energy adoption are financial concerns, lack of information about the technology, and socio-structural factors [31].

Source: authors' own elaboration.

4. Results

4.1. Production and Producers of Hydrogen

The production of hydrogen has been steadily increasing in recent years. In 2020, the demand for hydrogen amounted to about 90 Mt, which was basically entirely produced from fossil fuels, resulting in the emission of about 900 million tons of CO_2 [32]. The global demand in 2050 will increase to 614 million metric tons, which translates to about 25 EJ, although according to some forecasts it is estimated up to 78 EJ (1 EJ = 277.8 TWh) [33]. The environmental impact and energy efficiency of hydrogen depends on how it is produced. While hydrogen can be obtained from fossil fuels, biomass or other renewable energy sources, water or a combination of both, natural gas and coal are still the primary sources of hydrogen production [34]. A very popular method is coal gasification. It is a technological process based on the chemical reaction of coal with steam, as a result of which the final product is a mixture of hydrogen (black hydrogen), carbon monoxide and methane. When producing hydrogen from hard coal (coal gasification method), the amount of carbon dioxide emitted is 157 kg CO_2/GJ, while from lignite there of carbon dioxide is 170 kg CO_2/GJ [35].

Another popular method of hydrogen production, which is also one of the cheapest, is steam reforming of natural gas. In the process of steam reforming, hydrogen (grey hydrogen) is produced from methane and steam. In this process, syngas composed of carbon monoxide and hydrogen is produced. The use of both methods on a large scale is associated with relatively low hydrogen production costs. Some green solutions are used on a small scale, while innovative solutions that are much more expensive are still in the research phase. There is also a whole group of methods of obtaining hydrogen called thermochemical cycles. There are over 200 such thermochemical cycles that can be used to split water into oxygen and hydrogen. Hope for the widespread and environmentally safe use of thermochemical cycles is given by the fact that many scientists have developed and presented their versions of cycles using RES [36].

In the European Union, research is carried out in individual countries, but there are also joint research projects carried out together by several countries. An example is the IPCEI Hy2Use project, which was jointly developed and submitted by thirteen member states: Austria, Belgium, Denmark, Finland, France, Greece, Italy, Netherlands, Poland, Portugal, Slovakia, Spain, and Sweden. This project is to support scientific research and the development of innovative technological solutions. In addition, the first application of the developed solutions on an industrial scale and the construction of appropriate infrastructure in the value chain of hydrogen technologies are to be implemented [37]. The production of hydrogen has a huge potential, but it requires taking appropriate actions, mainly towards making hydrogen green or white, i.e., not having a negative impact on the environment. Large infrastructural investments and the involvement of an increasing number of economic entities in the development of this technology are also necessary. The main source of currently produced hydrogen in all countries is mostly fossil fuels, from which black or gray hydrogen is produced. In percentage terms, for approximately 60% of all hydrogen production installations, fossil fuels are the primary product. Only a small amount of currently produced hydrogen comes from the electrolysis of water using energy produced from RES (green hydrogen), hence the price of this hydrogen is many times higher than other types of hydrogen. Therefore, the production of hydrogen in environmentally friendly processes is a challenge for companies involved in its production using biomass and by-products (white hydrogen), nuclear energy (pink hydrogen) or renewable sources (green hydrogen). Depending on the method of its production, the processes used, and the final effects, several groups can be distinguished, marked with different colors. Innovative solutions for the production of hydrogen from renewable electricity (green hydrogen) have recently been a very popular topic, and more and more companies are announcing spectacular projects in this area, but green hydrogen technology is still mainly in the field of research and piloting [38]. The different types of hydrogen are shown in Table 2.

Table 2. Different hydrogen colors based on various manufacturing processes.

The Hydrogen Color	Production Process
Green	The electrolysis process that separates water components into oxygen and hydrogen using electricity is powered by renewable energy, green hydrogen is produced.
Turquoise	In the case of the production of turquoise hydrogen, methane, a component of natural gas, is used. Electricity from RES is used to produce turquoise hydrogen. This makes the process low-emission or even zero-emission or negative. The latter case would condition the use of biogas or biomethane instead of natural gas.
Yellow	Yellow hydrogen is the term used to mean hydrogen produced by the electrolysis of water using solar energy, although some people use it to mean hydrogen produced by the electrolysis of water using mixed sources, depending on what is available.
Aqua	Aqua hydrogen produced from oil sands (bituminous) and oil fields is a new method developed and commercialized in the west of Canada. Aqua Hydrogen represents a form of hydrogen production that does not emit CO_2 like green hydrogen but instead is produced from fossil fuel energy like blue hydrogen.
White	White hydrogen is naturally occurring geological hydrogen found in underground deposits and created by fracturing. White hydrogen is found in its natural form as a free gas, either in layers of the continental crust, deep in the oceanic crust, in volcanic gases, in geysers or in hydrothermal systems.
Pink/Purple	Purple/pink hydrogen is produced by the electrolysis of water, the production process of which is powered by nuclear energy. In addition, the very high temperatures from nuclear reactors can be used in the production of other hydrogen by using heated steam for the electrolysis or steam reforming of fossil gas-based methane.
Blue	Blue hydrogen is produced using fossil fuels, using carbon capture methods to reduce the level of impurities in the process. The most commonly used technologies are CCS (carbon capture storage) and CCU (carbon capture utilization).
Brown	Brown hydrogen is produced as a result of lignite gasification, which during combustion emits carbon dioxide into the atmosphere.
Black/Grey	Black hydrogen is hydrogen obtained from synthetic gas in methods that exploit hard coal.

Source: authors' own elaboration based on [39–42].

When analyzing the use of hydrogen by enterprises, it is worth taking into account the price differentiation of hydrogen depending on its color. Hydrogen prices from 2020 were as follows: high-carbon gray hydrogen USD 1–1.80 per 1 kg, turquoise USD 1.40–2.40 per 1 kg, green hydrogen USD 2.50–6.80 per 1 kg (sometimes even USD 12 per 1 kg), blue USD 1.40–2.40 per 1 kg [43]. The price of blue and green hydrogen is projected to decline in the future. It is worth noting that with rising prices on the world gas markets, the costs of producing hydrogen from natural gas are at the level of USD 4.8–7.8/kg H_2. The cost of hydrogen from natural gas with the carbon capture, utilization, and storage (CCUS) option is in the range of USD 5.3–8.6/kg H_2, of which roughly USD 4.1–7.4/kg H_2 comes from the cost of natural gas. At such prices for hydrogen from renewable sources, it could become a very advantageous solution, provided that production capacity was available. However, it is not known how long this price trend will continue in the gas markets [44]. The hydrogen price forecast in 2030 and 2050 is presented in the Figure 3.

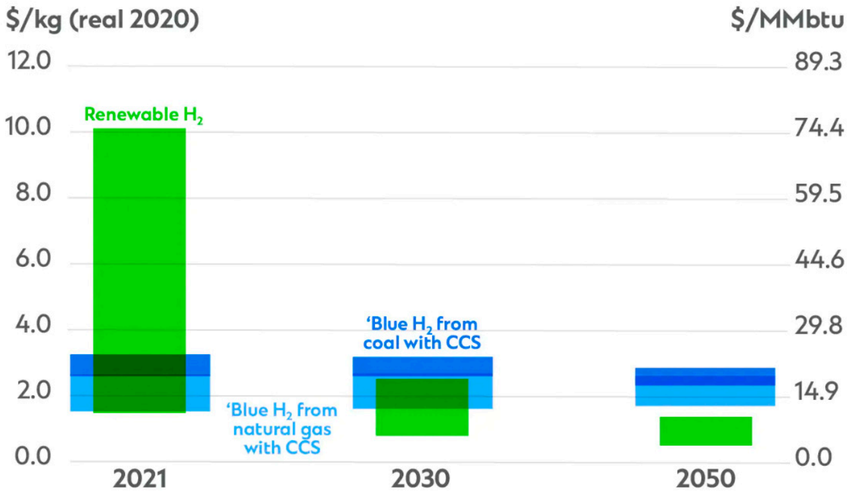

Figure 3. Projected blue and green hydrogen prices in 2030 and 2050. Source: [45,46].

From Figure 3, we can see that renewable energy and electrolyzer prices are projected to decline gradually until 2030. Projections indicate that green hydrogen will be cheaper than blue hydrogen produced from coal or natural gas with carbon capture or produced from gas alone [46].

The following paragraphs describes the importance of China and the US as the largest producers and users of hydrogen fuels. China, despite having a huge demand for hydrogen fuel, still uses gray hydrogen production technologies. The US, on the other hand, is betting on green, blue and pink hydrogen—two economic superpowers with huge potential and with very different, so far, approaches to that issue.

4.1.1. Hydrogen Production in China

China, like many countries, continues to produce and consume grey hydrogen, which is the least green form of hydrogen [47]. The biggest problem is large carbon emissions that do not meet China's "carbon peak and carbon neutrality" development plan [48]

Currently, China is the largest producer of hydrogen in the world with about 25 million tonnes (Mt) which is estimated to be one third to one quarter of global production. Most of the volume is produced from fossil fuels (60 percent from coal and 25 percent from natural gas) as raw materials used in refineries or chemical plants. Hydrogen produced from coal is cheaper than other methods of its production. The cost of producing carbon-based hydrogen remains very low in China—it is three times lower than the production of hydrogen by water electrolysis. However, China is increasingly exploring the possibility of producing and using lower-emission hydrogen to meet climate-related requirements and meet increasing energy needs with a clean raw material and stimulate industrial development [49]. In particular, China's 2060 commitment to carbon neutrality, undertaken in 2020, is an important climate-policy-oriented achievement that can help shift hydrogen production from fossil fuels to renewables [50]. The scale of potential hydrogen production in China, but also consumption, makes it very important for China to move away from grey hydrogen production. Hydrogen production methods are associated with varying levels of greenhouse gas emissions, depending on the technology used and energy source, and have different cost implications and different material requirements. The origin of hydrogen, therefore, determines its competitiveness and emissivity in the life cycle [51].

4.1.2. Hydrogen Production in the United States of America (USA)

The production of hydrogen in the USA in recent years has been about 10–11 million tonnes (MMT) per year, and the main recipients of hydrogen are currently oil refining and ammonia production companies. However, hydrogen can be used in many sectors to enable zero or near-zero emissions in other chemical and industrial processes, integrated clean energy systems and transport. Emerging markets for hydrogen in these sectors include data centers, ports, steel manufacturing, and medium- and heavy-duty trucks [52]. The United States is accelerating the construction of an economy based on hydrogen and according to the hydrogen strategy, the demand of the American economy for hydrogen fuel in 2030 will amount to 17 million tons, while in 2050 it will amount to over 63 million tons. Achieving these values would make the USA one of the leaders of the hydrogen economy in the world [53]. The Americans want to bet on hydrogen in three colors: green (from renewable energy sources), blue (from fossil fuels, but with the use of carbon dioxide capture and storage technology, i.e., CCS), and pink (from nuclear energy). The program also aims to reduce the price of hydrogen production to USD 2 per kilogram. Currently, the price of hydrogen is over USD 5 per kilogram. In addition, the USA is introducing a law that, among other things, will define "clean hydrogen"—i.e., that no more than 2 kg of CO_2 can be produced during the production of one kilogram. For comparison, the production of 1 kg of so-called of gray hydrogen emits 9–12 kg of CO_2 [54].

4.2. Hydrogen Recipients

Currently, about 120 million tons of hydrogen are used annually on a global scale. Hydrogen consumption varies from country to country. The world's largest consumer of hydrogen is China. In 2020, China's hydrogen consumption was approximately 23.9 million metric tons. Hydrogen production, which is predominantly coal-based, accounts for 3–5% of China's coal consumption. As of 2019, more than 30 green hydrogen projects are underway in China, which is still insufficient from the point of view of the pursuit of a zero-emission economy [55].

The second place in hydrogen consumption is taken by the United States, which is responsible for 11.3 million metric tons, while India with 7.2 is in third place in the world consumption of hydrogen. Countries with the highest hydrogen consumption are shown in Figure 4.

The US is not only the world's second-largest consumer but also producer of hydrogen, accounting for 13 percent of global demand. The November 2021 Infrastructure and Jobs Investment Act allocated $9.5 billion to accelerate the development of clean hydrogen-generation technologies. The US has also launched the Hydrogen Earthshot program to support the development of projects in this area. It has set an ambitious "111 goal" to bring the cost of clean hydrogen down to USD 1 per 1 kg in 1 decade [56].

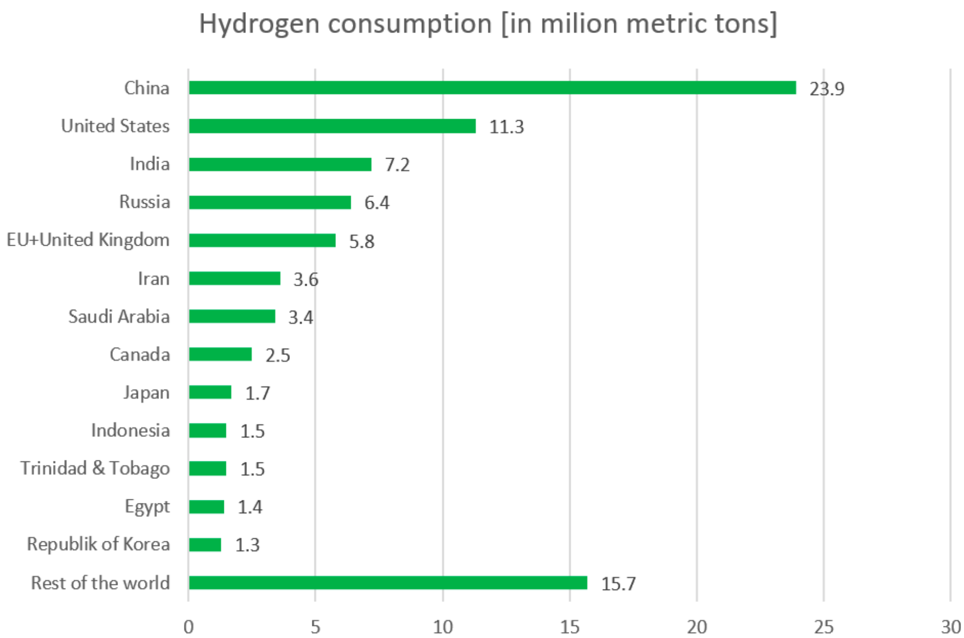

Figure 4. World hydrogen consumption. Source: authors' own elaboration based on [57].

Oil refining is currently the largest consumer of hydrogen (nearly 40 million tonnes in 2020) and will remain so in the short and medium term [58]. In refining, hydrogen is used to remove nitrogen and sulfur compounds and to saturate unsaturated hydrocarbons with hydrogen [59]. Two other major recipients of hydrogen are the chemical and food industries. It is expected that the demand for hydrogen will steadily increase [17], and according to IEA forecasts, the demand will be as follows: in 2030 it will amount to over 210 Mt, broken down by sectors: refining 26 Mt, industry 75 Mt, transport 9 Mt, power 18 Mt, ammonia-fuel 18 Mt, synfuels 7 Mt, buildings 6 Mt, and grid injection 52 Mt [58].

Hydrogen can be used as a fuel, energy carrier, or raw material, and can reduce emissions in sectors in which they are difficult to reduce, especially in industry and transport. The use of hydrogen in heavy road, rail, sea, river, air, and intermodal transport is to be developed. For several years, research and consideration have been devoted to the use of hydrogen as an alternative fuel in transport. In order to address this issue, the paper shows, based on the data collected by the authors, the performance of vehicles using hydrogen and the time needed for a full refueling. For the transport sector, an example of the range of hydrogen vehicles and refueling time is presented in Table 3.

Table 3. Selected hydrogen vehicles, their range and refueling time.

	Range for One Refueling [km]	Refueling Time [Minutes]
City bus (NesoBus) [60]	450	15
Truck (Kenworth) [61]	560	15
Car (Toyota Mirai) [62]	650	5

Source: own elaboration.

The information contained in Table 3 is based on data from manufacturers of hydrogen-powered vehicles. Two parameters were taken into account as factors, which allow drivers to quickly assess the usefulness of this fuel, namely, refueling time and range for one refueling.

In the case of city buses and trucks, the refueling time does not exceed 15 min and the range is sufficient for the tasks performed by these vehicles. In the case of passenger cars, the refueling time is also acceptable and the range allows you to move freely over long distances. The data presented in the table show that hydrogen can actually be used in transport as an alternative fuel. The results of 450–650 km (depending on the vehicle) driven on one tank are satisfactory. Refueling time is similarly satisfactory (acceptable).

Currently, the transport sector ensuring the mobility of passengers and goods is responsible for about 25% of total CO_2 emissions, so the use of green hydrogen by transport companies will reduce the negative impact of this sector on the environment.

Hydrogen can be used in many industries, from the energy sector, where it is a highly efficient energy carrier, to the food industry, where it is used, among other things, to protect food against oxidation in tightly closed packaging. The detailed use of hydrogen in the economy is presented in Table 4.

Table 4. Hydrogen in a different branch of economy.

Sector	The Way to Use Hydrogen
Energy	Hydrogen is a highly efficient energy carrier that can lead to zero or near-zero emissions at the point of use [63]. Hydrogen can speed up the energy transition by allowing the storage of clean energy and transporting large amounts of energy over long distances via pipelines and ships. Hydrogen can support the transition to green energy and balance forms of renewable energy. If we are able to produce cheap energy based on wind or sun, it is worth using it to produce hydrogen, which, with the increase in energy prices, can be converted back into energy [64].

Table 4. *Cont.*

Sector	The Way to Use Hydrogen
Transport	Hydrogen has long been known as a potentially low-emission transport fuel. Hydrogen-powered cars will play an increasingly important role in future mobility solutions. The use of ecological hydrogen technology in transport will significantly contribute to improving air quality and reducing the noise level in cities [65]. Hydrogen can serve as a fuel directly suitable for use in fuel cells used in mobility. Fuel cell technologies in vehicles guarantee high efficiency and are now at the stage of mass production and commercialization. However, an insufficient hydrogen fuel distribution infrastructure is a barrier to the development of zero-emission transport [66].
Construction	In addition to the direct use of hydrogen for heating in the built environment, it can also be used indirectly. It can be used as a fuel to replace natural gas to produce heat for district heating systems during periods of peak demand and as a reserve. In addition, the construction industry is highly dependent on fossil fuels, which makes it one of the most environmentally damaging sectors. Therefore, it uses renewable energy sources, including hydrogen, to power production plants to reduce the harmful impact on the environment [67].
Chemical	In the chemical industry, hydrogen is primarily needed for the production of ammonia. This chemical compound is of great importance in the production of fertilizers crucial for plant growth. Hydrogen is also used in various methods of chemical analysis. These methods include atomic absorption spectroscopy [68].
Food	In the food industry, hydrogen is approved as a food additive and its symbol is E949. It is used here to protect food from oxidation in tightly closed packages. Hydrogen is also used in the hardening of fats, especially in the production of margarine. Partially hydrogenated oils are one of the basic ingredients of margarine. Hydrogen is a raw material that increases the saturation of oil and fats, typically vegetable cooking oil, so that the oil will have enough viscosity to prevent damage [69].

Source: authors' own elaboration.

A graphical summary of the use of hydrogen in various branches of the economy is shown in Figure 5.

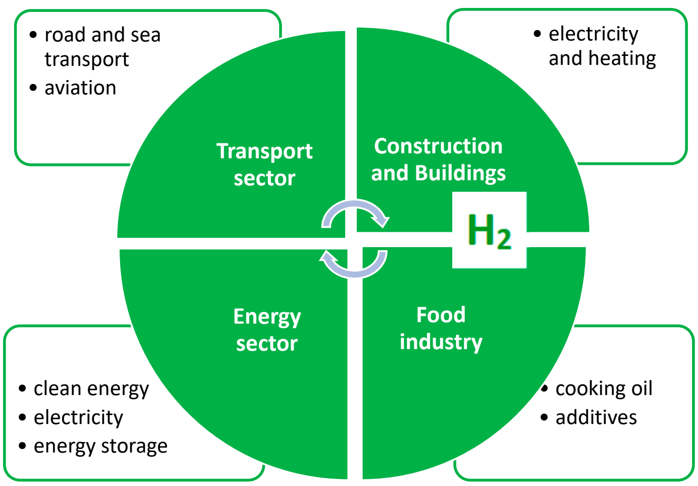

Figure 5. Hydrogen demand by sectors. Source: authors' own elaboration.

5. Discussion

Hydrogen has dominated the attention of politicians and entrepreneurs; therefore, in the coming years specific steps will be taken to develop the global hydrogen market and reduce its production costs [70]. Enterprises will look for innovative structural and technical solutions and will also be based on a new organizational culture focused on economy and industry 4.0 [71]. Prospects for the development of hydrogen technologies are seen by specialists mainly in energy-intensive sectors of industry that use high-temperature processes, such as steel production, in the chemical industry, and in energy storage. Hydrogen is an energy carrier that can play a complementary and protective role. It will be used in areas where it is significantly difficult or impossible to directly use electricity collected from RES installations, from the grid or stored in batteries [72]. For most applications, hydrogen competes directly with electricity, and electricity is simply more efficient. The only area unsuitable for decarbonization with electricity is aviation because a battery-powered aircraft can only fly short distances, where it will be difficult to compete with rail anyway [51]. A wider use of hydrogen may also be envisaged for unmanned aerial transport. These types of vehicles constitute a new path of specialized (small-size) transport services that can be used as logistic support in other sectors of the economy.

The use of hydrogen as an energy carrier in aircraft has several advantages, burning hydrogen in jet engines would produce steam, which will eliminate carbon-related emissions. However, it also comes with constraints, such as new designs and larger hydrogen storage tanks [73].

Hydrogen production processes are required to be economically sound and environmentally efficient. Efficiently produced hydrogen can play a key role in the decarbonization process [74,75]. There are several different ways to produce hydrogen with varying levels of carbon intensity. One is to run an electric current through water, splitting the water molecules into their component hydrogen and oxygen atoms. With this method, the source used to generate electricity is key. If the electricity comes from renewable sources, the entire process will be virtually carbon-free. If electricity generated by burning fossil fuels is used, hydrogen will be very emissive [76]. Thus, decarbonization cannot be achieved by using grey and brown hydrogen.

6. Conclusions

The large-scale use of hydrogen will help reduce the negative impact of many sectors of the economy on the environment. First of all, in order to reduce greenhouse gas emissions, especially carbon dioxide, it is necessary to produce green, white or blue, yellow or pink hydrogen. However, the production of gray and brown hydrogen should be stopped.

Another contribution of the authors is to present the possibilities related to the production of pure hydrogen and the price of hydrogen that must be achieved to make it a competitive fuel. The use of green hydrogen by 2050 will cover about 24% of the entire economy's energy demand and thanks to innovative solutions it will be possible to achieve a price of about USD 1 per kilogram of green hydrogen.

Between 2015 and 2050, annual demand for hydrogen energy is expected to increase about tenfold, from 8 to 78 EJ, with the most serious increase projected for 2040 and 2050 from 28 to 78 EJ.

The technological structure of hydrogen use in 2050 includes consumption of 11 EJ in the municipal and residential economy, 16 EJ in the industrial energy industry, and 22 EJ in transportation. This indicates the great potential of hydrogen technology in decarbonizing transportation and improving industrial processes.

The energy sector will implement the global energy transformation, which will be based on energy storage. Hydrogen, which is an energy carrier, can be used to store energy.

In order to reduce emissions in the construction sector, it is necessary to move towards the construction of nearly zero-energy buildings, which are buildings with almost zero energy consumption. The energy used in these buildings should come from renewable sources.

Decarbonization of the transport sector can be achieved through the use of hydrogen. Buses can travel 450 km on one refueling, trucks 560 km, and passenger cars as much as 650 km. The time for a full refueling is 15 minutes, 15 minutes, and 5 minutes, respectively.

Hydrogen is an opportunity for companies to move away from classic fossil fuels, which will contribute to the further energy transformation of their operations. Many enterprises are already investing in hydrogen and planning to build large-scale hydrogen projects.

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