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Prospects for the Implementation of Underground Hydrogen Storage in the EU

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Abstract: The hydrogen economy is one of the possible directions of development for the European Union economy, which in the perspective of 2050, can ensure climate neutrality for the member states. The use of hydrogen in the economy on a larger scale requires the creation of a storage system. Due to the necessary volumes, the best sites for storage are geological structures (salt caverns, oil and gas deposits or aquifers). This article presents an analysis of prospects for large-scale underground hydrogen storage in geological structures. The political conditions for the implementation of the hydrogen economy in the EU Member States were analysed. The European Commission in its documents (e.g., Green Deal) indicates hydrogen as one of the important elements enabling the implementation of a climate-neutral economy. From the perspective of 2050, the analysis of changes and the forecast of energy consumption in the EU indicate an increase in electricity consumption. The expected increase in the production of energy from renewable sources may contribute to an increase in the production of hydrogen and its role in the economy. From the perspective of 2050, discussed gas should replace natural gas in the chemical, metallurgical and transport industries. In the longer term, the same process will also be observed in the aviation and maritime sectors. Growing charges for CO_2 emissions will also contribute to the development of underground hydrogen storage technology. Geological conditions, especially wide-spread aquifers and salt deposits allow the development of underground hydrogen storage in Europe.

Keywords: hydrogen; underground storage; prospects; European Union

Citation: Uliasz-Misiak, B.; Lewandowska-Śmierzchalska, J.; Matuła, R.; Tarkowski, R. Prospects for the Implementation of Underground Hydrogen Storage in the EU. *Energies* **2022**, *15*, 9535. https://doi.org/10.3390/en15249535

Academic Editor: Muhammad Aziz

Received: 17 November 2022
Accepted: 14 December 2022
Published: 15 December 2022

1. Introduction

Today's environmental and geopolitical conditions encourage the governments of individual countries to develop an industry based on renewable energy sources and use other types of energy carriers, such as hydrogen. Hydrogen can be used as a raw material, fuel, or energy carrier [1–10]. In the future, hydrogen may enable a partial reduction of fossil fuel use (Figure 1) [6–8,11–18].

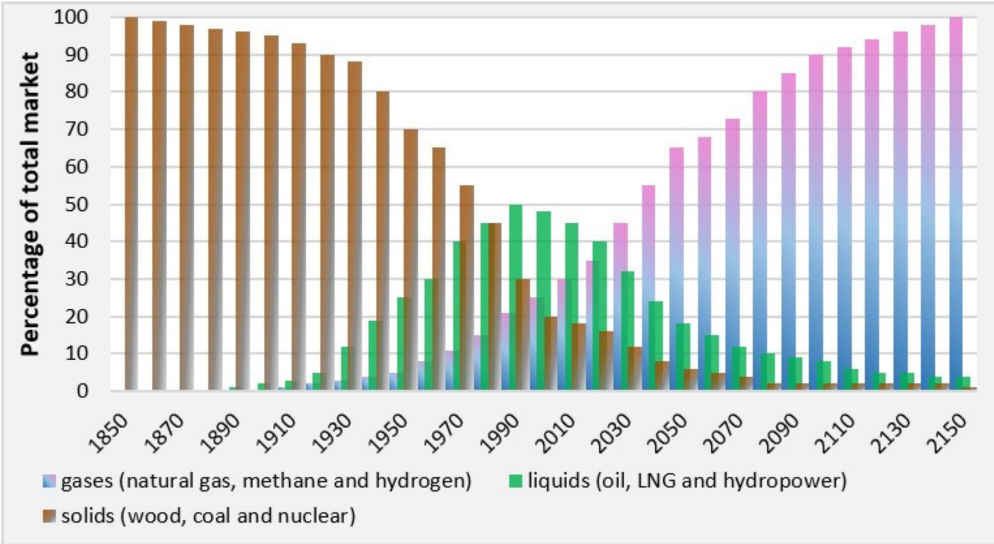

Figure 1. Global primary energy consumption since 1850 (data after [19]).

The hydrogen economy is a priority of the EU economic recovery package after COVID-19, as part of the European Green Deal, which obliges EU countries to transform their economies. This would allow Europe to become the world's first climate-neutral continent by 2050 [20]. A necessary condition for achieving this goal is greater use of hydrogen produced in the process of water electrolysis, based on energy from renewable sources, as renewable hydrogen (so-called "green" hydrogen) (Figure 2). Temporarily, it will also be low-emission hydrogen produced from natural gas (so-called "grey" hydrogen) or based on fossil fuels, with carbon dioxide emitted in the process of its production being neutralized using Carbon Capture and Storage (CCS) or Carbon Capture Utilization and Storage (CCUS) technology "blue" hydrogen [21]. Today, most of the hydrogen used in industry comes from natural gas ("grey" hydrogen), where the process of its production is associated with the emission of significant amounts of CO_2 [11].

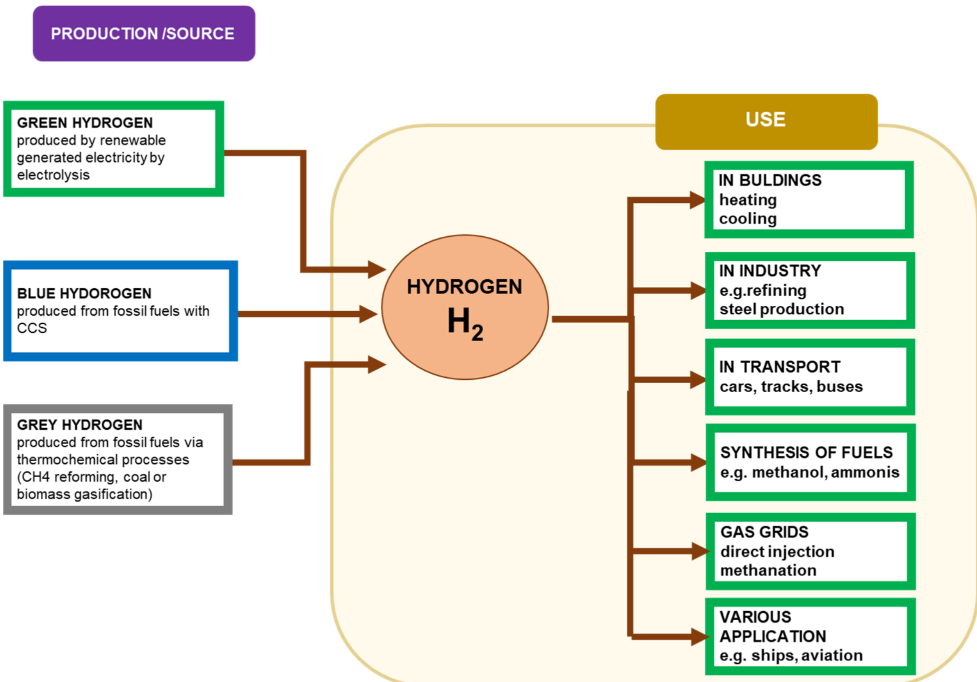

Figure 2. Production technologies and ways to use hydrogen.

The use of hydrogen is part of the low-carbon economy [6,8,22,23]. The production of this gas, depending on the technology and energy source used, is associated with a varied amount of CO_2 emissions [6–8,13,24–28]. On the other hand, hydrogen combustion itself does not emit CO_2 [13,26,27,29,30]. The increased use of hydrogen will enable the decarbonisation of those sectors of the economy where reducing CO_2 emissions is difficult to achieve [31–33]. It is expected that in the future (2050 perspective), hydrogen may completely replace natural gas in the chemical, metallurgical, and transport industries, and in the long term, also in the aviation and maritime sectors [3,31,34–36].

In a future situation where renewable energy will provide most of the energy, multi-megawatt storage systems will be necessary. "Green" hydrogen can store surplus energy from intermittent supplies from renewable sources. Hydrogen can be stored in tanks on the surface, can be mixed with natural gas in gas networks (so-called Power-to-Gas–P2G technology) [28,37,38], or stored underground in deep geological structures (UHS) [5,18,29,39–43].

Long-term storage of GWh/TWh of energy as hydrogen in geological structures requires sites with high-volumetric capacity (salt caverns, deep aquifers and depleted hydrocarbon reservoirs) [5,8,18,29,43–46]. It is expected that in the next several years, underground hydrogen storage may become an economically interesting solution for using excess amounts of electricity from renewable sources [7,8,12,13,29,47].

Underground hydrogen storage is of increasing interest to governments, industry and the scientific community [48,49]. This interest has translated into an increasing number of scientific publications [8,15,17,29,50] as well as reports and forecasts prepared for government administrations and companies. There is a question about the prospects for the implementation of UHS technology on an industrial scale, and the factors that will affect the rapid use of this technology. According to the authors, the UHS technology has prospects for its implementation. Before this, however, numerous barriers must be overcome: legal, economic and social [51].

In the present article, the authors have attempted to present the prospects for the implementation of underground hydrogen storage and the aspects affecting the introduction of this technology on an industrial scale. The great interest in hydrogen in Europe is due to the EU's policy of transition to a low-carbon economy. This is evidenced by the forecasts of energy production and consumption, the structure of energy production in the EU, the increase in energy production from RES, the increase in CO_2 emission fees, and the existing positive geological conditions for underground hydrogen storage in Europe. The latter of these is discussed in this article.

2. EU Policy of Transition to a Low-Emission Economy

Hydrogen is important for reducing carbon dioxide emissions until 2030 and achieving neutrality in terms of carbon dioxide emissions by 2050. Hydrogen consumption is projected to increase, from the current level of less than 2% to 13–14% [31]. Renewable ("green" hydrogen–produced from the electrolysis of water powered by solar energy or from wind turbines), is necessary to achieve the goal of climate neutrality and is present in all eight of the European Commission's scenarios for achieving net-zero emissions by 2050 (*A Clean Planet for All: A European Long-Term Strategic Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy*) [52].

The European Commission (EC) has published three communications in which it presents the strategy for the EU's transition to a climate-neutral economy from the perspective of 2030 and 2050. These are: the *European Green Deal* [53], the *Boosting a Climate-Neutral Economy: EU Strategy on Energy System Integration* [54], and the *Hydrogen Strategy for a Climate-Neutral Europe* [31]. Hydrogen is an important element in the implementation of these strategies. The *Hydrogen Strategy for a Climate-Neutral Europe* [31], published in July 2020, assumes that renewable hydrogen (a priority in the 2050 perspective) and low-emission hydrogen (in the short and medium term) can contribute significantly to the reduction of greenhouse gas emissions, even before 2030. Hydrogen is indicated as a key element to achieving the goals of a climate-neutral economy with zero pollutant emissions by 2050. This is because it can replace fossil fuels and raw materials in sectors where it is difficult to decarbonise. The communication also states that renewable hydrogen offers unique opportunities for research and innovation that will establish Europe's leadership in renewable hydrogen technologies [31].

Among the reasons why the development of the hydrogen economy is crucial for achieving the goals of the European Green Deal, the following facts are indicated:

- Hydrogen allows for the storage of excess electricity from RES.
- The possibility of supporting seasonal fluctuations in the production of electricity from RES by enabling the connection of production sites with more distant centres of demand [31].

In scenarios for the implementation of climate policy in highly industrialized countries, the development of the hydrogen economy is considered. The considered scenarios assume a reduction of CO_2 emissions in transport, large-scale use of renewable energies and/or CCS, and high prices of oil and natural gas in the medium and long term [2].

In 2022, the European Commission published the *REPowerEU* plan to make Europe independent of Russian fossil fuels by 2030. The plan includes energy saving, the production of green energy, and the diversification of energy supplies. The plan provides for accelerating the ecological transformation and large investments in energy from renewable sources. Among the medium-term goals, until 2027, the following are indicated: raising the European target for renewable energy sources by 2030 from 40–45%, accelerating the use of hydrogen – increasing the capacity of electrolysers to 17.5 GW by 2025, which can produce 10 million tonnes of renewable hydrogen, and the introduction of a modern regulatory framework for the use of hydrogen [55].

Prospects:

- The need to replace fossil fuels with low-emission energy sources;
- Renewable and low-carbon hydrogen is a key element of the EU's energy transition by 2050;
- Impact of hydrogen on greater use of renewable energy sources.

3. Forecasts of Energy and Hydrogen Production and Consumption

3.1. Energy Production

Primary energy production (extraction of energy products in a usable form from natural sources) has been on a downward trend in recent years. Similar relationships have been observed in energy consumption in the EU. In 2020, energy demand was 17.5% lower than in 2010 (Figure 3). This was related to the global financial and economic crisis, the depletion of fossil fuel resources, the cessation of exploitation of some deposits of energy resources due to their unprofitability, and the greater use of RES [56].

Primary energy produced in the EU comes from a variety of sources. This is energy from the combustion of fossil fuels, nuclear energy and energy from renewable sources. The data published on the EUROSTAT website shows that in 2020, the share of renewable energy in the total production of primary energy in EU countries was 40.8%. In second place was nuclear energy with a 30.5% share of the total primary energy production [56].

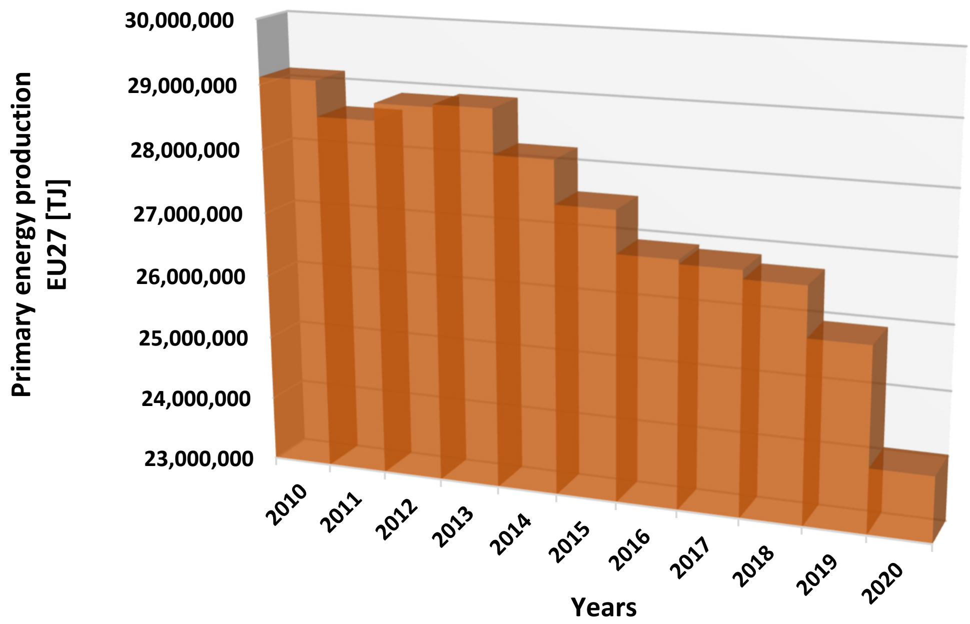

Figure 3. Primary energy production, EU-27, 2010–2020 (data after [56]).

The production of energy from renewable sources and biofuels in the EU Member States has been steadily increasing, from 1.8 PJ in 2010 to 7.8 PJ in 2020 (Figure 4).

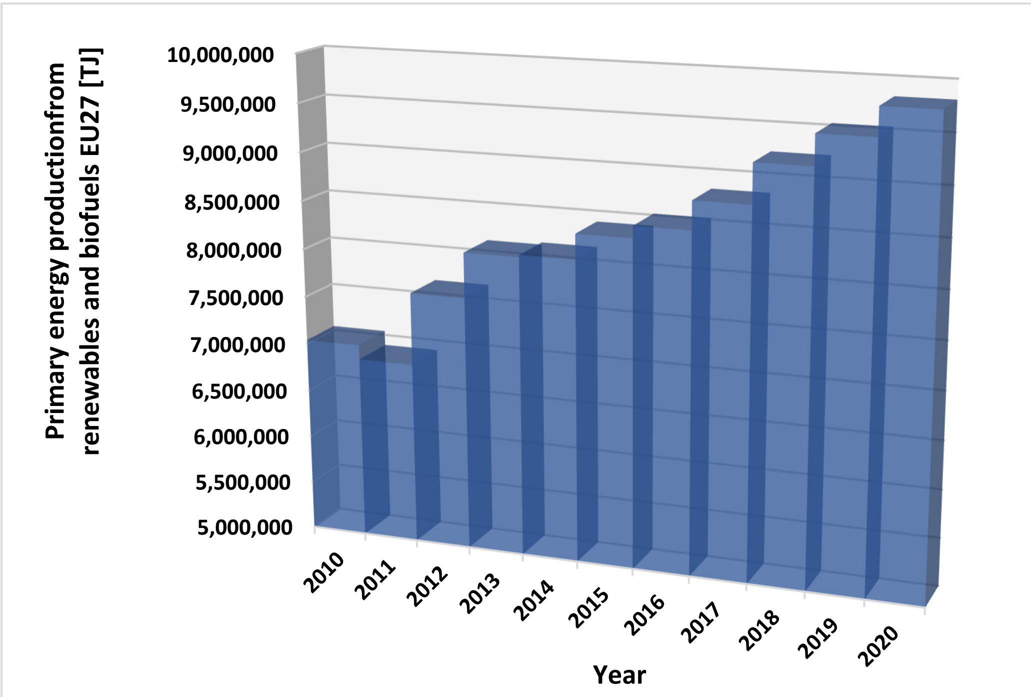

Figure 4. Primary energy production from renewables and biofuels in the EU, 2010–2020 (data after [56]).

According to EUROSTAT data for 2020, the production of energy from renewable sources and biofuels in the 27 EU countries amounted to 239.7 Mtoe. The largest amounts of energy came from renewable waste and biofuels—58.8% of total energy production from renewable sources, from wind—14.3%, from water—12.4%, heat pumps—5.5%, solar energy (photovoltaics)—5%, geothermal energy 2.9%, and solar thermal energy—1.9% (Figure 5).

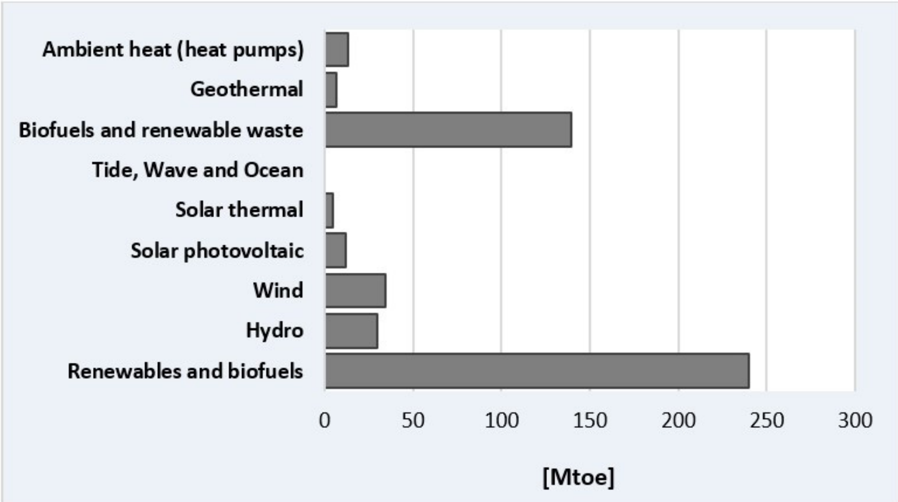

Figure 5. Gross inland consumption from renewables and biofuels in EU27 in 2020 [57].

In the future, the production and consumption of energy in EU countries will be conditioned by the introduction of the European New Deal and the pursuit of climate neutrality by 2050. A significant reduction in CO_2 emissions will be associated with energy transformation and greater energy efficiency. Hydrogen plays a significant role in all energy consumption projections until 2050 [3,6,13,17,34,35,58,59]. As Europe moves towards climate neutrality by 2050, interest in clean hydrogen is growing in sectors such as the steel and chemical industries (more than half of all hydrogen in the world is used in the production of fertilizers and oil refining) [11].

Analyses of energy demand in the EU indicate that the total final energy demand will remain constant until 2050. The energy transformation, and in particular, changes in the fuel mix, will make it possible to decouple CO_2 emissions from energy consumption. It is expected that the largest decrease in the amount of fuel consumed in 2050, compared to 2015, will concern solid and liquid fuels. Consumption of solid fuels may be reduced by 189 Mtoe, and of petroleum products by 122 Mtoe. In 2050, total electricity demand may exceed 3500 Twh/year [60].

Prospects:

- Projected decrease in the consumption of solid fuels;
- Changes in the fuel mix–gradual elimination of fossil fuels in favour of RES;
- Increasing the production of low-emission hydrogen by 2030, replacing it with renewable hydrogen by 2050;
- Increased demand for electricity related to electromobility.

3.2. Increase in Energy Production from Renewable Energy Sources

The final energy consumption forecasts prepared by IRENA [61] indicate that in the case of continuation of the European Commission's policy, EU countries will reach a 24% share of renewable energy in final energy consumption by 2030 (*Reference Case scenario*). If the entire potential of renewable sources will be used, this will reach 34% (*REmap scenario*). In 2050, renewables will become the second most important energy carrier, exceeding 39% of the gross final energy consumption by 2050. The Reference Case scenario predicts significant changes in the renewable energy mix by 2030. Wind energy has the largest increase over this period (three-fold increase) and photovoltaic (eight-fold increase). Despite the expected increase in bioenergy in absolute terms, its share in the total final consumption of renewable energy will decrease to 60%. Similarly, the share of hydropower will fall to 12% of total renewable energy consumption. In the *REmap* scenario, the increase in renewable energy consumption will come from wind energy, biofuels for transport, solar energy in industry and buildings, biomass in industry and construction, and photovoltaics. The share of wind and photovoltaic energy combined will account for

21% of the gross final consumption of renewable energy, while the share of bioenergy will fall to 55%. In the *REmap* scenario, the share of biofuels in transport increases to 13% of total renewable energy consumption, while the share in the heating and cooling sector decreases to 42%. The share of renewable energy in the energy sector is expected to increase to 50% by 2030, while in end-use sectors it will be 42% in construction, 36% in industry, and 17% in transport [62]. The increase in energy production from RES (wind and solar energy) will translate into the use of surpluses for hydrogen production.

The biggest challenge in producing renewable hydrogen is that it will require huge amounts of renewable energy. The International Energy Agency estimates that meeting current hydrogen demand through water electrolysis would require 3600 TWh per year, more than the EU's entire annual electricity production. Conversion to hydrogen is a type of security for investors in renewable energy. "Blue" hydrogen – with the right climate safeguards – is believed to have a transitional role to play. It can help launch different sectoral applications and lower prices through economies of scale. "Blue" hydrogen could accelerate industrial transformation.

Prospects:

- Projected significant increase in the share of energy from intermittent RES supplies, which will contribute to increasing the production of renewable hydrogen;
- EU energy transition assuming the decoupling of CO_2 emissions from energy consumption.

3.3. Increased Demand for Hydrogen

Most hydrogen today is produced from natural gas and consumed in industrial plants [1,4,8,9,25,28,63]. Hydrogen is used in many industries (Figure 6). In the chemical industry, it is mainly used for the production of ammonia, in the refining industry, it is necessary for the refining process. It is also used in the textile, pharmaceutical, and confectionery industries [1,8,13,19,26].

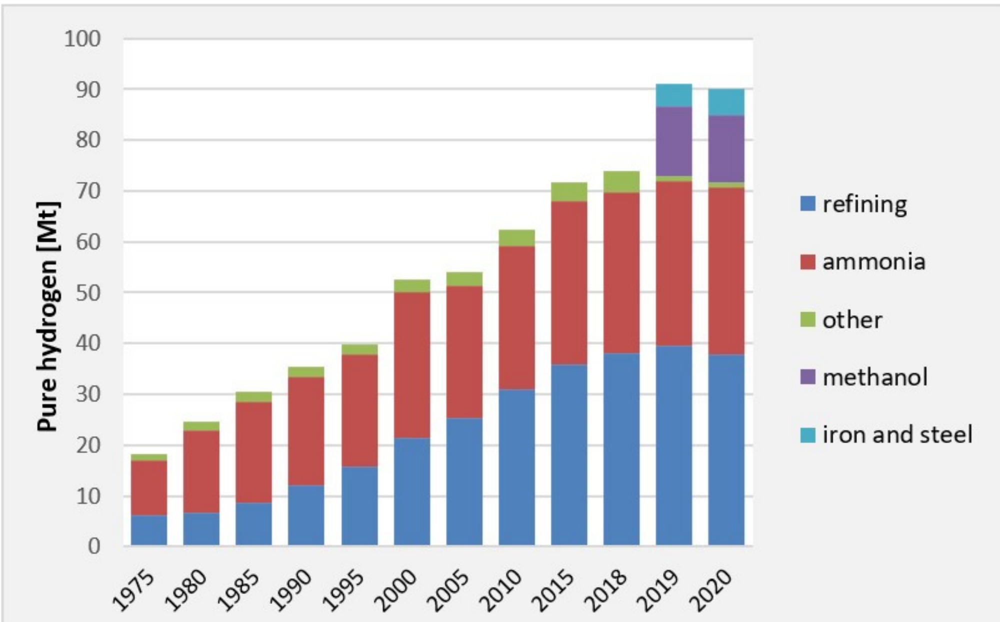

Figure 6. Global demand for pure hydrogen, 1975–2020 [64,65].

In the EU, the annual consumption of hydrogen in 2020 was 8.7 Mt. The most hydrogen was used in refineries (4.4 Mt) (45% of total hydrogen consumption) and the chemical industry (ammonia production 2.5 Mt, methanol and other chemicals 1.09 Mt). Energy uses are 0.3 Mt. Currently, mainly "grey" hydrogen is produced in EU countries; its production capacity in 2020 was at the level of 11.4 Mt. The production capacity of "green" hydrogen is less than 0.5% of the total production capacity [66].

The two main pioneer markets for hydrogen are industrial and mobility. An important sector where the use of hydrogen has great potential is steel production. According to the International Energy Agency, up to 90 Mt of hydrogen can be used in the global economy to produce steel (current global hydrogen production is 120 Mt [67]. Hydrogen can be used in autonomous vehicles (forklifts, vans, city buses, taxis), which due to the short refuelling time and greater range, is competitive with electric cars [68].

Hydrogen offers a solution for those segments of the transport system where emission reductions are difficult to achieve. The use of hydrogen fuel cells will develop in heavy road vehicles and trains, where electrification is difficult or unprofitable. Hydrogen could become an alternative fuel for inland and short-sea shipping. In the long term, hydrogen is the solution to decarbonising the aviation and maritime sectors [31].

It is expected that the demand for hydrogen in the EU Member States will increase from 338 TWh in 2030, to 1350 TWh in 2040, and 2260 TWh in 2050 (Figure 7). This corresponds to 20–25% of final energy consumption in the EU and the UK by 2050. From 2030 to 2050, the largest increase in hydrogen demand is expected in aviation, energy production, ammonia, heating, and heavy road transport (from around 68 times to around 10 times). A much smaller increase in the demand for hydrogen (several times) is forecast in fuel production, heat, and steel and iron production [34].

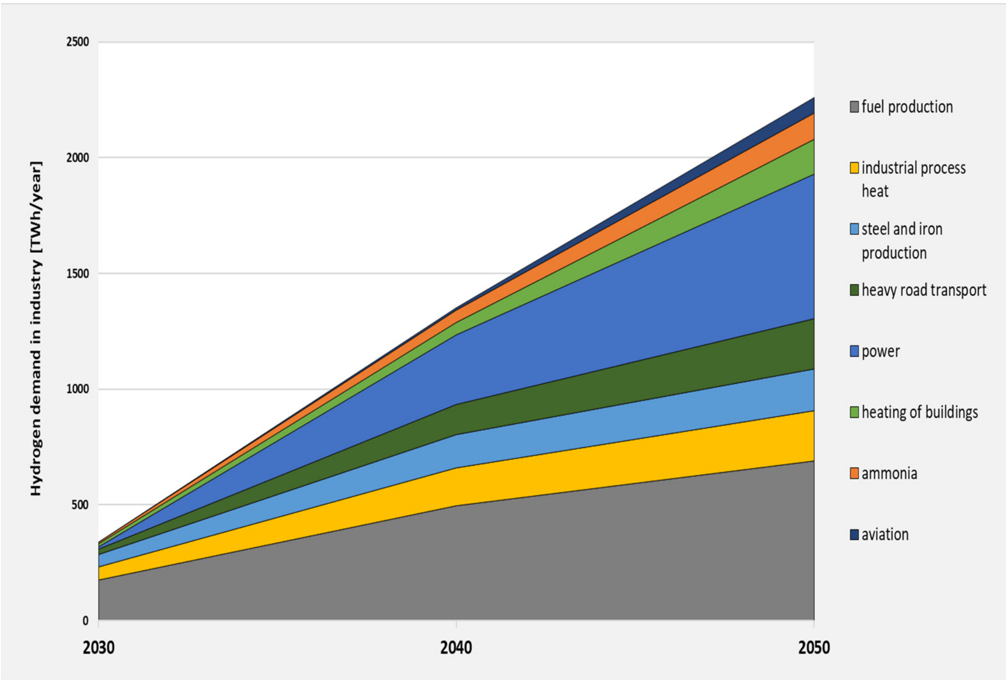

Figure 7. Future hydrogen demand in EU countries (data after [34]).

In 2021, the estimated costs of hydrogen production from renewable sources in EU countries, as well as Great Britain and Norway, range from EUR 3.3/kg to EUR 6.5/kg. In favourable locations with the best insolation or the best wind conditions, it will be possible to reduce these costs up to EUR 2.2–2.9/kg. In this way, hydrogen from renewable sources becomes cost-competitive with "grey" hydrogen, for which the average production costs for 2021 have been estimated at EUR 2.65 per kg. In 2022, due to high natural gas prices, these costs increased to around EUR 10 per kg of hydrogen [66].

Currently, "grey" hydrogen costs around EUR 1.50/kg, "blue" hydrogen EUR 2–3/kg and "green" hydrogen EUR 3.50–6/kg. It is estimated that a price of EUR 50–60 per tonne of carbon dioxide (CO_2) could make blue hydrogen competitive in Europe [11].

It is estimated that by 2050 almost all renewable hydrogen potential can be produced for less than EUR 2.0/kg. Production costs for blue hydrogen are expected to be EUR 1.4–2.0/kg with moderate natural gas and CO_2 prices [34].

Prospects:

- Increase in the demand of EU countries for hydrogen from the perspective of 2050, which corresponds to 20–25% of energy consumption;
- Hydrogen is to completely replace natural gas in the chemical, metallurgical, and transport industries by 2050, and in the long term, also in the aviation and maritime sectors;
- Hydrogen provides a solution for those segments of the transport system where emission reductions are difficult to achieve.

4. Increase in Prices of Allowances for Carbon Emissions

The EU Emissions Trading System (EU ETS) is an EU incentive for cost-effective decarbonisation, in all sectors covered by this system, by setting fees for greenhouse gas emissions. Almost all existing hydrogen production from fossil fuels is covered by the EU ETS [31].

According to the data of the European Environment Agency, in the years 2013 to 2020, the prices of allowances (EUA) fluctuated, from below EUR 3 to approximately EUR 41 [69]. The fourth phase of carbon trading began in 2021 and will run until 2030. According to forecasts, the price of allowances may increase to USD 100/1 tonne of CO_2 at that time [70].

The analyses carried out under the LIFE Climate CAKE PL project used two scenarios: 50% of the GHG reduction target for the EU (*GHG50 scenario*) and 55% (*GHG55 scenario*). These showed an increase in the price of allowances to EUR 34/EUA in 2025 and EUR 52/EUA in 2030, respectively.

However, the consequence of increasing the emission reduction target to 55% (GHG55 scenario) will be an increase in the price of allowances to EUR 41/EUA in 2025 and EUR 76/EUA in 2030. According to the *GHG55 scenario*, the price of allowances may reach EUR 76/EUA [71]. The mentioned scenarios did not fully meet expectations, because as of mid-November 2022, the price of CO_2 emission allowances for one tonne is approximately EUR 76. In 2022, the prices of CO_2 emission allowances reached as much as EUR 100, with an average of approximately EUR 84 per ton.

The projected increase in the cost of CO_2 emission allowances (Figure 8) will increase the profitability of the CCS technology, which will translate into the profitability of low-emission hydrogen production. New technological innovations should indicate more possibilities for the use of CO_2 in industry, which will further reduce the cost of CCS/CCUS. These changes will bring the price of low-emission hydrogen closer to the price of hydrogen produced from fossil fuels.

Figure 8. Price of European Emission Allowance for EU ETS (data after [72]).

Prospects:

- Projected increase in fees for CO_2 emissions;
- Development and increase in profitability of CCUS/CCS technology;
- Increased possibilities of industrial use of CO_2.

5. Geological Conditions of Underground Hydrogen Storage

The use of geological structures in porous rocks (aquifers, hydrocarbon reservoirs) and caverns leached in rock salt deposits have been considered for hydrogen storage. The first occurs in naturally–anticlinal structures in aquifers or in the form of traps in which crude oil or natural gas accumulates. The second is created artificially by leaching caverns in a rock salt deposit [60,73–76].

The possibilities for underground storage in porous rocks are conditioned by the properties of the storage formation. Rocks in which hydrogen is stored should have appropriate reservoir properties (high porosity and permeability) and have a tight overburden to ensure the safety of hydrogen storage.

The most advantageous for storing hydrogen are thick rock salt beds and salt domes. Unfavourable conditions for hydrogen storage are the insoluble interlayers of non-salt rocks and highly soluble salts of potassium and magnesium.

Experience with hydrogen storage in geological structures is limited and concerns mainly storage in salt caverns. H_2 cavern storage has been operating since the 1970s in Great Britain (Teesside). Hydrogen is also stored in salt caverns in Texas (Clemens, Moss Bluff and Spindletop) [43,48,77–79]. Several underground storage facilities for pure hydrogen have been established in Russia [80,81]. Experience with underground storage of hydrogen in porous rocks is limited to hydrogen-containing gas mixtures (town gas) [43,82]. Town gas has been stored in aquifers in France (Beynes), the Czech Republic (Lobodice), and Germany (Engelborstel, Bad Lauchstaedt, Kiel) [78,79,82–84]. The injection of hydrogen-containing gas into depleted gas fields is carried out as part of a pilot project in Argentina (Diadema field), and in Austria [43].

In the EU Member States, there are favourable conditions for underground hydrogen storage resulting from the presence of sedimentary basins with salt deposits and numerous aquifers and hydrocarbon reservoirs in their area.

In Europe, salt-bearing formations cover large areas (Figure 9). Territorially, the Permian salt-bearing formation has the largest range, stretching from NW to Central Europe, covering large areas of such countries as Great Britain, the Netherlands, Denmark, Germany, Poland, and Lithuania. In Triassic Europe, salt-bearing basins occupied the Iberian Peninsula, Aquitaine, the Apennines Mountains, in Sicily, the Balkans, north-western Europe, and part of western Poland. In the Tertiary period, rock salts were deposited in the Paris Basin, the Rhine Trench, the Iberian Basins, Sicily, Transylvania (Romania), the Balkans, and the Carpathian Basin [85]. Recognition of salt structures in Europe is quite good.

Salt deposits occur as the rock salt beds and salt domes. Rock salt beds occupy large areas (up to several thousand km^2), and their depth may reach several hundred or even several thousand meters. Most of the European Triassic and Tertiary salt deposits lie at a depth of up to 1000 m [76]. Restrictions on the occurrence of salt formations in the UE, the depth of salt formations and the occurrence of salt domes will affect the possibilities for underground hydrogen storage.

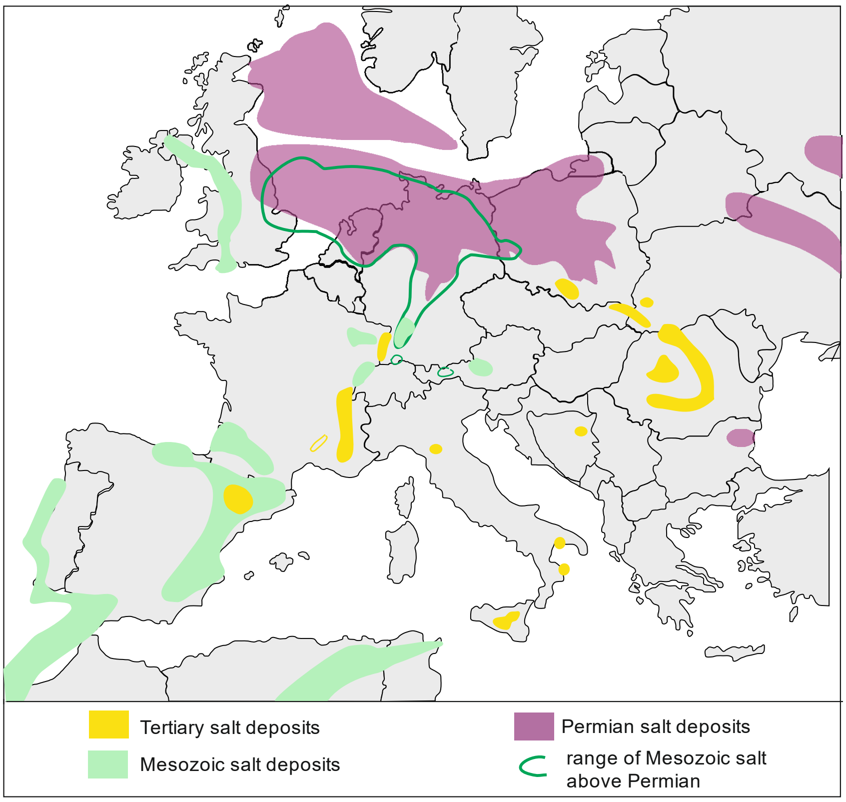

Figure 9. Salt deposits in Europe (based on [86]).

In Europe, sedimentary basins are widespread (Figure 10). Due to the complex geological development of Europe, sedimentary basins vary in structure and size. One of the largest sedimentary basins in Europe is the Permian Basin of Northern and Central Europe. This basin stretches from the southern part of the North Sea to England and Poland. Other examples are the Paris Basin and the Aquitaine Basin in France, the Alpine Foothills Basin, north of the Alps, and the Pannonian Basin in Central and Eastern Europe [87]. The presence or absence of sedimentary basins in the individual countries of the European Union will determine the possibility of storing hydrogen in aquifers. Aquifers in sedimentary basins are poorly explored. Formations for underground storage of gases (carbon dioxide and hydrogen) are currently being studied to assess their potential.

Hydrocarbon deposits are located in several sedimentary basins. In particular, the North Sea area has numerous significant hydrocarbon deposits (mainly in the Norwegian and British sectors). There are also numerous hydrocarbon deposits in the Netherlands, Germany, Hungary, and Romania [87]. The possibilities of storing hydrogen in these structures are related to their resources and the degree of depletion.

Prospects:

- The presence in Europe of large sedimentary basins containing numerous complexes of porous rocks suitable for hydrogen storage;
- Widely distributed and thicker salt-bearing formations suitable for leaching of hydrogen storage caverns.

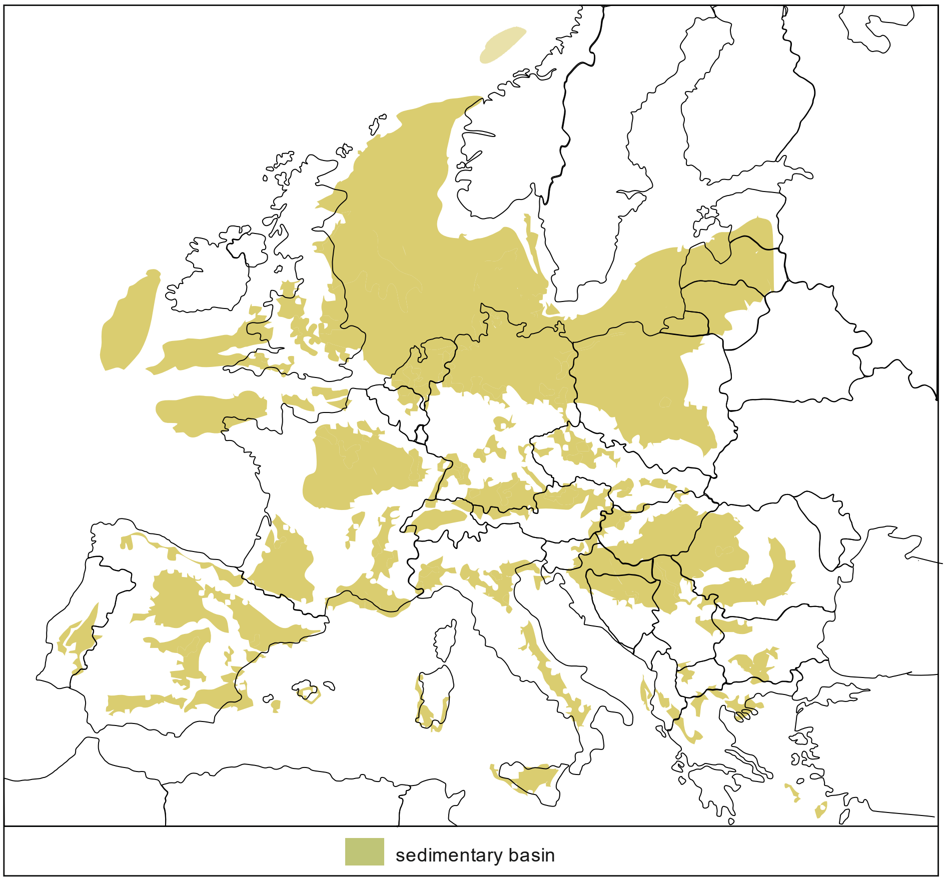

Figure 10. Sedimentary basins in Europe (based on [88]).

6. Discussion

Hydrogen is a universal energy carrier. It can be used in the power industry, in various industries, or in transport. It is produced in industrial processes with varied CO_2 emissions, depending on the technology used. Its combustion does not emit CO_2. An important problem is the reduction of fossil fuels in its production, in favour of the use of RES. Regarding the production of hydrogen from renewable energy sources, the problem of hydrogen storage arises. Underground hydrogen storage in salt caverns, deep aquifers and depleted hydrocarbon deposits for strategic or seasonal purposes is being considered today. The prospects for the implementation of underground hydrogen storage technology in the EU result from the EU policy of transition to a low-emission economy, energy production forecasts, increase in energy production from RES, increase in hydrogen demand and CO_2 emission fees, and geological conditions in individual EU Members.

Hydrogen is important for significantly reducing the level of carbon dioxide emissions by 2030, and achieving CO_2 neutrality by 2050. This gas is considered an important element for achieving the goals of the European Green Deal and clean energy transformation. Communicates of the European Commission (COM/2019/640; COM/2020/299; COM/2020/301) present the strategy of the EU transition to a climate-neutral economy, where a crucial element is hydrogen. In the short and medium term, a greater role is assigned to low-emission hydrogen, using CCS technology.

From the perspective of 2050, the priority is renewable hydrogen produced by the electrolysis of water, using energy from RES. To achieve the goal of climate neutrality, hydrogen plays a significant, differentiated role in all eight of the European Commission's scenarios for net-zero emissions by 2050 (European Commission, 2018). Furthermore, the *REPowerEU* plan, published by the European Commission in 2022 (European Commission, 2022), is extremely topical in light of the conflict between Russia and Ukraine and assumes EU independence from Russian fossil fuels before 2030.

From the perspective of 2050, in the EU, with unchanged demand for electricity, a significant decrease in the consumption of fossil fuels is assumed in favour of RES. There is growing interest in renewable hydrogen in CO_2-intensive sectors such as the heavy, chemical industries and transport. The use of hydrogen will contribute to the decarbonisation of these sectors.

In the forecasts for 2050, renewable energy sources will become an important energy carrier, exceeding even 39% of gross final energy consumption. This will translate into the use of "surplus" energy from RES for the production of renewable hydrogen.

Due to its diverse applications, hydrogen is of increasing interest to the energy sector. Analyses show that by 2050, the demand for hydrogen in the EU and Great Britain will amount to 2300 TWh (2150–2750 TWh), which corresponds to 20–25% of final energy consumption.

A sufficient supply of renewable hydrogen will be possible subject to public acceptance of the accelerated implementation of the installed renewable capacity. This will allow the EU countries to meet the projected European demand for hydrogen in all sectors, at lower costs compared to low-emission hydrogen and other alternative fossil fuels, taking into account the costs resulting from the prices of CO_2 emission allowances.

Until hydrogen production becomes cost-competitive, support schemes will be required. Almost all existing hydrogen production from fossil fuels is covered by the EU ETS. The projected increase in fees for CO_2 emissions will increase the profitability of the CCS technology, which will translate into the profitability of low-emission hydrogen production.

In the EU Member States, there are favourable conditions for underground hydrogen storage. They result from the presence of sedimentary basins containing deep aquifers, depleted hydrocarbon deposits and salt deposits. Hydrogen storage in geological structures is still limited today and concerns salt caverns. However, underground hydrogen storage poses new challenges related to the physicochemical characteristics of this gas. Its use will be possible if safe hydrogen storage is ensured in quantities of the order of terawatt hours, at relatively low costs. The research results so far show that geological structures or caverns in salt deposits are capable of storing hydrogen in the amount of several GWh to several TWh, depending on the structure under consideration. The subject of underground hydrogen storage is today the subject of great interest for the scientific community, governments and industry, which also bodes well for the development of underground storage of this gas.

7. Conclusions

Hydrogen produced today mainly from fossil fuels, from the perspective of 2050, will be produced with an increasing share of renewable energy sources (renewable hydrogen), using water electrolysis. With large centres producing energy from RES, during periods of its "overproduction", there will be a need to store energy. The solution may be underground storage of this gas (UHS).

Caverns located in salt deposits and structures in deep aquifers and depleted hydrocarbon deposits seem to be suitable for medium or long-term safe storage of this gas, in quantities ranging from several GWh to several TWh. In order to implement the technology of underground hydrogen storage, there are still numerous obstacles to overcome, coming from the physicochemical properties of this gas and the geological exploration of the underground environment.

The EU transition policy to a low-emission economy, forecasts of energy production and consumption until 2050, increase in energy production from renewable energy sources, and CO_2 emission fees, are the reasons for the growing interest in hydrogen production and storage of its surpluses in underground geological structures. The prospect of a quick implementation of underground hydrogen storage in the EU will depend on the appropriate geological conditions and the acceptance of this technology by the governments of individual countries. In the next years, intensive researches on UHS will contribute to demonstrating the safety of long-term underground hydrogen storage.

Author Contributions: Conceptualization, B.U.-M., J.L.-Ś. and R.T.; methodology, B.U.-M., J.L.-Ś., R.T. and R.M.; writing—original draft preparation, B.U.-M. and R.T.; writing—review and editing, J.L.-Ś. and R.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by AGH University of Science and Technology (Subsidy No. 16.16.190.779).

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

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