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Prospects for a large-scale green hydrogen storage methods development in Poland – a review

Perspektywy rozwoju metod wielkoskalowego magazynowania zielonego wodoru w Polsce – przegląd

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Keywords: *hydrogen, underground storage, salt cavern, ammonia, liquid hydrogen, gas grids, Power to Gas*

Abstract
Hydrogen is predicted to play a significant role in the economy and in the process of reaching climate neutrality by 2050. Optimizing its utilization in the economy necessitates first and foremost the development of a storage system. The core of storing energy in a form of hydrogen, created from renewable energy sources during periods of energy surplus, is its reuse during times of high demand for it. In addition, the stored hydrogen can be used in many industries, such as chemicals, refining, and transportation. This article discusses the possibility for large-scale green hydrogen storage in Poland. The potential of subsurface hydrogen storage, liquid hydrogen storage, ammonia storage, and the utilization of gas networks for storage are investigated.

Słowa kluczowe: *wodór, podziemne magazynowanie, kawerna solna, amoniak, ciekły wodór, sieci gazowe, Power to Gas*

Streszczenie
Przewiduje się, że wodór będzie odgrywał znaczącą rolę w gospodarce oraz w procesie osiągnięcia neutralności klimatycznej do 2050 roku. Optymalizacja jego wykorzystania wymaga przede wszystkim opracowania wydajnego systemu magazynowania. Istotą magazynowania energii w postaci wodoru, wytworzonego z odnawialnych źródeł energii, w okresach produkcji jej nadwyżek, jest ponowne wykorzystanie zmagazynowanej energii w okresach wysokiego zapotrzebowania na nią. Zmagazynowany wodór może być ponadto wykorzystany w wielu gałęziach gospodarki, takich jak przemysł chemiczny, rafineryjny, czy transport. Niniejszy artykuł omawia możliwości wielkoskalowego magazynowania zielonego wodoru w Polsce. Zbadano potencjał podpowierzchniowego magazynowania wodoru, magazynowania ciekłego wodoru, magazynowania amoniaku oraz wykorzystania sieci gazowych do magazynowania.

1. Introduction

The transformation from a carbon-based to a carbon-free energy system necessitates the development of new technologies capable of storing and using renewable energy. One of the most promising alternatives is hydrogen [1], [44]. Storage system and interface standards are essential to assist hydrogen technology adoption, as well as safety and acceptance by the public. The success of hydrogen storage development is critical for the future of the energy systems [2]. Green hydrogen, generated by electrolysis of water and using renewable energy sources, will play an increasingly important role in the coming years [42], [43]. Hydrogen will be a crucial pillar of industry decarbonization, acting not only as a vector for green energy and fuel, but also as a means to energy independence if fossil fuel supplies are depleted [28], [39], [30]. The growing supply of hydrogen to local industry and the mobility sector implies that demand for large-scale underground storage of renewable hydrogen is projected to expand dramatically [46], [5]. Energy storage methods must be developed in order to deal with the expected growth in big renewable energy source installations and the challenges they bring [26]. The storage technique is chosen based on a number of factors, including the quantity of energy to be stored, the storage duration, the reaction time, round-trip efficiency, energy density, and cost [42]. Hydrogen storage in underground geological formations (salt caverns), storage of liquid hydrogen, hydrogen injected into natural gas distribution and transmission networks, and hydrogen in the form of ammonia are common used large-scale storage methods [25]. Underground storage is the most cost-effective and efficient option [5]. Ammonia as an intermediate hydrogen carrier will only be a viable option to fossil hydrogen carriers such as natural gas (NG) if the synthesis is accomplished by green sustainable synthesis processes [14], [31], [47]. The Haber-Bosch process has been the primary method for producing ammonia [8], [13], [38]. Ammonia storage has significant benefits over alternative hydrogen storage medium since it may be held as a liquid under moderate circumstances, contains 17.6 weight percent hydrogen, has a greater volumetric energy density than hydrogen, and can be used as a fuel directly or broken back into hydrogen [2],[27]. A vast and rapidly growing number of initiatives propose to manufacture green ammonia for export as an international energy vector [35], [37], [50]. Furthermore, LNG terminals will play an important role in the safe and efficient transport of liquid ammonia, assisting in the expansion of ammonia usage for cleaner, more sustainable energy source and accelerating our low-carbon future [18]. The viability of repurposing an existing LNG terminal is determined by whether it will eventually receive hydrogen or ammonia [20]. This extensive review focuses on the most recent research and initiatives in

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the field of large-scale green hydrogen storage, investigating the potential of individual large-scale storage systems in determining Poland's energy industry's future. The article is divided into the following sections: Section 2 reviews the current technology and prospects for hydrogen storage in geological structures, with a focus on depleted hydrocarbon deposits and salt caverns. Section 3 presents liquid hydrogen storage systems, with an emphasis on the potential for converting existing LNG terminals for LH2 storage. Section 4 presents methods for storing hydrogen in the form of ammonia, with an emphasis on the possibility of converting existing LNG terminals for NH3 storage. Section 5 discusses opportunities and projects for hydrogen storage in gas networks. Section 6 of the article discusses Power to Gas technology.

2. Hydrogen storage in geological structures

The storage of hydrogen in geological formations is seen to be a viable approach for better using its potential. It allows for long-term, safe storage of this gas, with energy storage capacity in the terawatt hour range and comparatively cheap prices [42]. Furthermore, the availability of geological structures suitable for underground storage, as well as Poland's experience with underground gas storage, make this system an appealing option for large-scale hydrogen storage, with relatively low investment costs when compared to other storage technologies [28], [41], [42]. Underground geological formations allow for the safe storage of huge amounts of hydrogen at high pressure and energy density with minimizing environmental damage. Countries across the world, including the United Kingdom (Teesside, Yorkshire) and the United States (Clemens, Moss Bluff, and Spindletop), have previous experience with hydrogen storage in salt caverns. In Poland, the primary prospects for deep underground hydrogen storage in geological formations are primarily the salt caverns, depleted natural gas and oil reservoirs and porous aquifer formations [28], [39]. The distribution of currently utilized cavernous and underground gas storage facilities in Poland is given below:

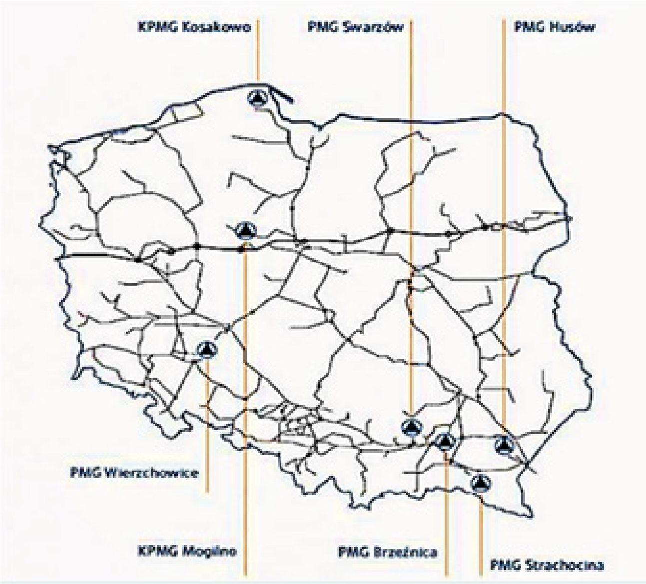


Fig. 1. The cavernous and underground gas storage facilities in depleted reservoirs currently in use in Poland. Source: [51]

Rys. 1. Kawernowe i podziemne magazyny gazu w szczerpanych złożach eksploatowane obecnie w Polsce. Źródło: [51]

In Poland, a potential strategy for storing hydrogen is to exploit existing gas storage facilities, which are located, among other places, in the Pre-Carpathian collapse area, and to store natural gas in autochthonous Miocene sandstone strata [30]. During the ongoing investigation, 27 natural gas and 12 oil fields were chosen for under-ground hydrogen storage [51].

2.1. Salt caverns

Underground salt caverns, which are artificial chambers formed by the leaching of salt in its seam deposits or in salt domes, are suitable for underground hydrogen storage due to the physical properties of the salt. The walls of a salt cavern are impenetrable to this gas, and the flexible qualities of salt protect them from the formation and spread of fissures, which compromise tank integrity [10], [41]. The number of "turns" of injected gas per year is conceivable depending on the demands and functioning of sub-terranean storage [10], [29]. Salt caverns for storage must be properly built based on the individual qualities of the salt and the exact operating conditions. The caverns' design must assure their stability, tightness for the stored gas, tolerable surface settlement, and environmental safety [46]. Figure 2 depicts an example of a method for creating hydrogen from renewable energy sources and injecting and withdrawing it from a salt cavern:

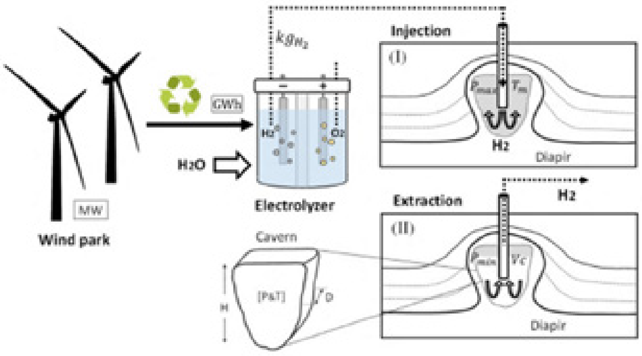


Fig. 2. The process of hydrogen production and then injecting and withdrawing it from a salt cavern. Source: [46]

Rys. 2. Proces produkcji wodoru oraz zatłaczania i odbioru z kawerny solnej. Źródło: [46]

Caverns can be developed at depths of up to 2.000 m, with geometric volumes of up to 1.000.000 m^3, heights of 300 – 500 m, and widths of 50 – 100 m, depending on requirements and technological capabilities. They may work at pressures as high as 20 MPa depending on their depth, allowing them to store very large amounts of gas [46]. They are extremely resistant to external impacts [23], [29]. Cavern storage facilities feature substantially cheaper construction costs, a theoretically infinite lifespan, and a relatively small surface area for above-ground development as compared to surface gas reserves [29]. The storage capacity is affected by the depth of the caves. A deeper cavern allows for more compressed hydrogen storage (higher pressure) [42]. The country's geological and mining structure makes it ideal for drilling large-scale salt caverns in halite deposits, with the Zechstein (Upper Permian) deposits being the most suitable for cavern building [28]. The geographic location of salt domes on the country's territory clearly determines the locations for such storage facilities, but these locations may not be optimal in terms of transporting the stored hydrogen [14]. Storage facilities located in salt caverns have been operational in Poland for many years, holding natural gas (KPMG Mogilno and KPMG Kosakowo storage facility) and fuels (PMRiP Góra) [25]. An evaluation of the possibility of converting Kosakowo's cavern storage facilities for hydrogen storage reveals a capacity of 160.000 MWh, while Mogilno has a potential of up to 260.000 MWh [5]. Furthermore, Gas Storage Poland has proposed a concept to build the first hydrogen cavern in Damasławek around 2030. The location and geological features allow for the building of a vital storage facility for Poland's energy security and the development of the hydrogen clusters [45]. Several locations have been investigated for the possibility of subsurface hydrogen storage. The potential of rock salt deposits in the northern part of the Pomeranian Voivodeship was investigate, where proximity to the Baltic Sea

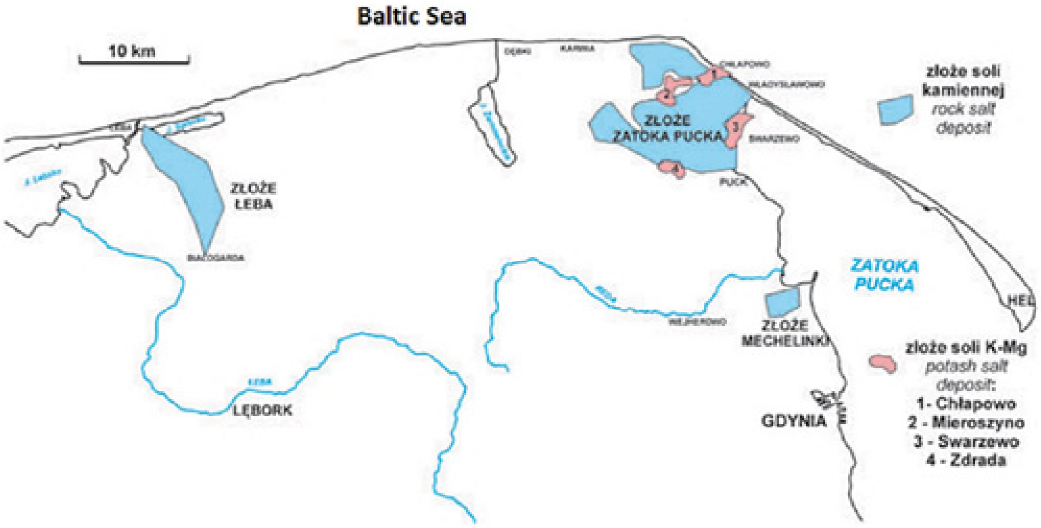


Fig. 3. The salt deposits for possible hydrogen storage caverns in the Łeba, Mechelinki and Puck Bay region. Source: [9]

Rys. 3. Złoża soli pod ewentualne kawerny do magazynowania wodoru w rejonie Łeby, Mechelinek i Zatoki Puckiej. Źródło: [9]

enables the release of leached brine [10]. The Łeba Elevation, Łeba, Mechelinki and the Bay of Puck have been well studied. The older halite (Na1) deposits are considered the most suitable for caverns, which in the , Łeba, Mechelinki and Puck Bay deposits occur at depths of 490 – 800 m, 950 – 1000 m and 730 – 790 m, respectively. The map below shows the probable location of hydrogen storage caverns in the Łeba, Mechelinki and Puck Bay region [9]:

Another region take under consideration was Legnica-Głogów, located in the pre-Sudetic monocline [28]. Only seven of the 27 analyzed salt diapirs (fully or partially penetrating Mesozoic sediments) in the Polish Lowlands in Zechstein formations meet the requirements for the building of hydrogen storage caverns. The Rogóźno salt diapir provides the best circumstances for the installation of storage caverns (big area, shallow salt and substantial salt deposits, reasonably thick diapir top, and prior recognition of the structure) [10]. The next structure is the large Damasławek outcrop. The pair of Łanięta and Lubień islets were evaluated as the third and fourth structures in the assessment of appropriateness. Potential structures (rating IV) are the comparatively small Goleniów and Izbica Kujawska islets [10].

3. Storage of liquefied hydrogen

During storing hydrogen as a cryogenic liquid, it has various benefits over compressed gas (CGH2). The liquefaction process necessitates highly pure hydrogen, multiple cycles of compression, liquid nitrogen or helium cooling, and expansion via the Joule-Thomson (JT) effect [4], [20]. Liquid hydrogen needs cryogenic storage and boils at – 253°C. The utilization of LNG (liquefied natural gas) terminals for long-term hydrogen storage is a viable option by expanding its usage to other possible energy carriers. Because there is no worldwide market for liquid hydrogen, the technology is deemed marketable, but there are no large-scale demonstration programs. So yet, just one prototype liquid hydrogen terminal in Kobe, Japan, has been created [34]. The use of LH2 in LNG terminals is regarded extremely demanding due to its lower boiling point, which necessitates considerable changes to the thermal insulation of the components. The regularly used steels cannot be utilized in LNG tanks due to the risk of hydrogen embrittlement. Some high-alloy stainless steels appropriate for very low temperatures (e.g., 304L or 316L) or specialist aluminum alloys can be used. If LH2 compatible steel is utilized in the storage tank's construction and a greater boiling coefficient is appropriate, nearly half of the LNG investment expenses can be reused using LH2 [25], [34]. Using hydrogen instead of natural gas necessitates additional safeguards. At normal temperature, liquid hydrogen held in cryogenic tanks evaporates at a rate of several percent each day [33], [16], [3]. Specialized constructions are required to keep the tank at extremely low temperatures [20]. Spherical tanks are used because their design decreases daily hydrogen leakage owing to decreased heat influx [34]. Because most LNG terminals today have flat-bottomed tanks, evaporation may be greater when LH2 is utilized, due not only to the insulation, but also to the tank design (unfavorable surface to volume ratio) [34]. There are currently just several liquid hydrogen tanks, and their capacity are smaller than that of LNG (e.g., 600 m3). They have not been scaled up to date since larger hydrogen tanks have not been required [34]. The present LNG terminal at Świnoujście in Poland, contains two LNG tanks each with a capacity of 160.000 m3 of LNG, and a third tank with a capacity of 180.000 m3 is has been installed in 2022 [25]. Repurposing current or proposed LNG infrastructure to accept liquid hydrogen is technically a challenge. Most of the equipment must be replaced or drastically modified. Commercially accessible large liquid hydrogen storage tanks are not yet available [20]. A possible alternative for a new or proposed terminal may be to construct it for liquefied hydrogen but utilize it first for LNG. Material selections and insulation must be compatible with liquefied hydrogen in the design, even if this means overdesigning for usage as an LNG terminal in the early phase [20].

4. Ammonia as a carrier for hydrogen storage

Ammonia is an alkaline, colorless gas with a strong stench. It has a far greater combustion heat, 11.2 MJ/l, than liquid hydrogen (8.58 MJ/l). Due to its lower density than air, gaseous ammonia dissipates fast in the air under atmospheric conditions, reducing the risk of explosion and fire in the event of a leak. Nowadays, the Haber-Bosch Process is used to produce 90% of the ammonia produced on industrial sizes. Because the industrial production of this commodity is well-known, along with a highly established pre-existing infrastructure, ammonia has significant potential to become a carbon-free energy vector in the future, as it is more conveniently stored and transported than hydrogen [1], [35]. Ammonia-ready distribution and storage facilities will be a driving force in making ammonia a prominent participant in the zero--carbon energy environment [18]. First, ammonia may be liquefied in moderate circumstances. Secondly, ammonia has a higher energy density than hydrogen. The volumetric hydrogen density of liquid ammonia is approximately 45% greater than that of liquid hydrogen, implying that more hydrogen may be held in liquid ammonia with the same volume [18]. The benefits of ammonia include its constant usage requirement, being an even more effective hydrogen transporter than hydrogen itself, and emitting no carbon dioxide as a fuel [2]. Ammonia is stored under pressure in spherical or cylindrical containers at an ambient temperature. These containers can hold up to 2000 tons of NH3 and are normally pressured to 1.6 – 1.8MPa. Vertically orientated cylindrical storage tanks are used in low-temperature ammonia storage. These tanks are preserved at 240 K temperatures by two-stage refrigeration compressors and have a maximum storage capacity of 50.000 tons of NH3 [15]. Transforming existing LNG terminals to ammonia storing is widely regarded as one possibility for long-term ammonia hydrogen storage. There are now 88 ammonia import facilities in operation across the world [41]. Amonia transport has negligible losses, and its liquefaction temperature is greater than LNG (-33°C against – 162°C for LNG) [25], [34]. It is predicted that adapting an existing LNG terminal to handle ammonia will cost 11-20% of the capital expenditure of an LNG regasification operation. There is no need to raise the level of insulation because the temperature of ammonia liquefaction is higher than that of LNG [20]. The conversion from LNG to ammonia necessitates an evaluation of the safety and environmental implications, which may restrict the number of eligible locations. Although some components, such as pumps, would need to be changed, the additional expenditures for an ammonia-ready terminal might be half those of retrofitting an old terminal [20]. When planning to transform an LNG storage tank to an ammonia storage tank, the chemical characteristics of both LNG and anhydrous ammonia must be examined. They are shown in Table 1:

Table 1. The characteristics of liquefied natural gas and ammonia. Source [18]

Tabela 1. Charakterystyka skroplonego gazu ziemnego i amoniaku. Źródło: [18]

Parameter	Ammonia	LNG
Boiling point at 1 atm (°F)	-28,0	-259,0
Liquid density at 1 atm boiling point (kg/m3)	673,59	423,54
Heat of vaporization at 1 atm boiling point (kJ/kg)	1376,8	509,16

Full-containment and single-containment LNG containers are often compatible with chilled ammonia tanks. Based on the LNG density against liquid ammonia density ratio, the maximum liquid level permitted for ammonia storage is projected to be around 2/3 of the original design, implying that the nominal tank capacity when utilized for ammonia will be roughly 2/3 of the original design [34]. The insulation system for a typical LNG tank with a size of 100.000 m3 to 200.000 m^3 is designed to satisfy the BOG rate of less than 0.05 % per day [18]. In order to import and store ammonia in the future, the following items must be considered in the original design of an LNG import plant [34], [18]:

- Pre-investment planning of import plant design consideration for ammonia application to reduce the cost effect of converting the LNG facility to ammonia.
- Redesign the LNG storage tank for ammonia.
- Liquid pumps: For ammonia operation, the liquid LNG transfer pumps (sub-merged pump and HP pumps) must be changed.
- Piping: Due of the greater density, piping supports must be built specially for ammonia.
- Boil-off Gas (BOG) system: Due to the higher vaporization rate, the LNG regasification plant need a substantially larger BOG system capacity. The LNG/ammonia design flare stack must run at a reduced BOG rate to accommodate ammonia import and storage.
- Instrument and safety devices: Instrument and safety devices must be created for the controlling case for LNG and ammonia services.

The plan for an ammonia-ready LNG import terminal is shown below:

Liquid ammonia is known to produce stress corrosion cracking (SCC) in steel under specific situations. Extensive study and examinations into ammonia SCC have resulted in preventive measures being implemented on low-temperature carbon steel used in refrigerated ammonia tanks [18], [34]. More research and analysis will be necessary to guarantee that the tank's structural integrity is maintained during the design life. Because of ammonia's toxicity and high solubility in water, it is inappropriate for use as a fuel in natural subterranean caves [26], [40].

5. Hydrogen storage in gas grids

When combining hydrogen with natural gas, the energy density of hydrogen is 1/3 that of natural gas, therefore the energy content per unit volume of the combination is less than that of pure natural gas [5]. The amount of transported gas will need to be increased, which will result in an increase in operating expenses and the burden on the transmission and distribution network. As a consequence, the capacity reserves of gas pipes designed for mixed transmission will be reduced. However, if it is decided to transport hydrogen via pipes over large distances (even tens of kilometers), transportation and distribution expenses might exceed three times the cost of production [19]. The figure below depicts the cost-effectiveness of hydrogen transportation techniques based on the volume of hydrogen produced and the distance from the outlet market [49]:

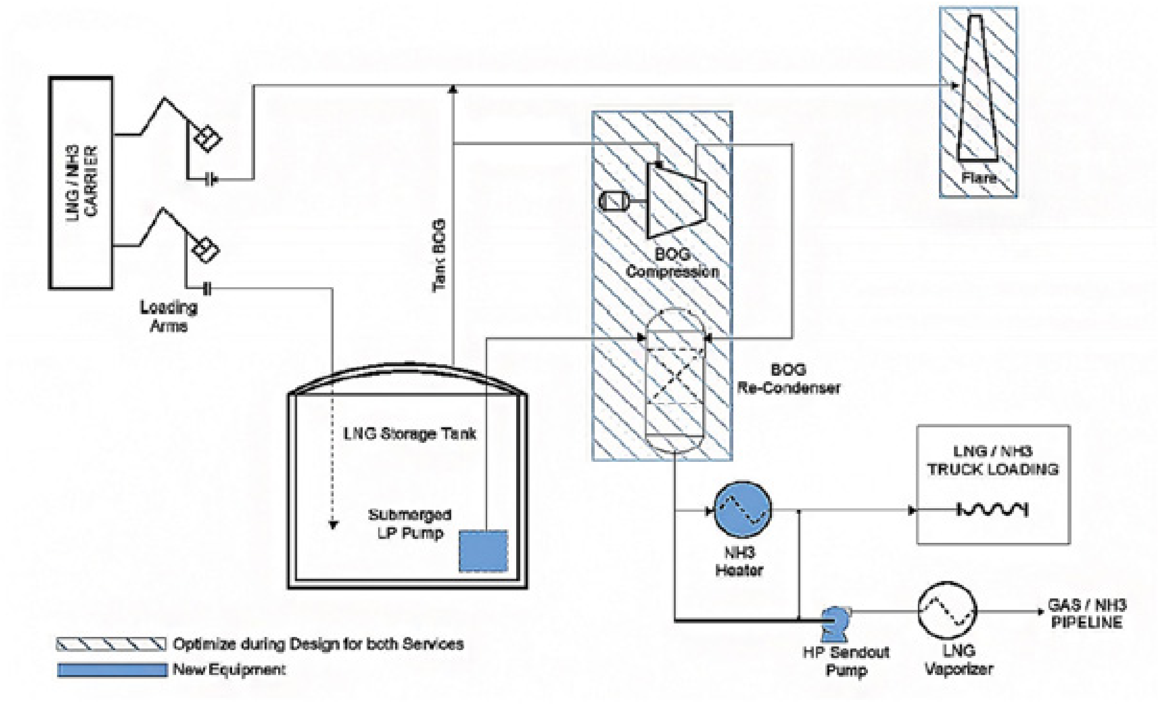
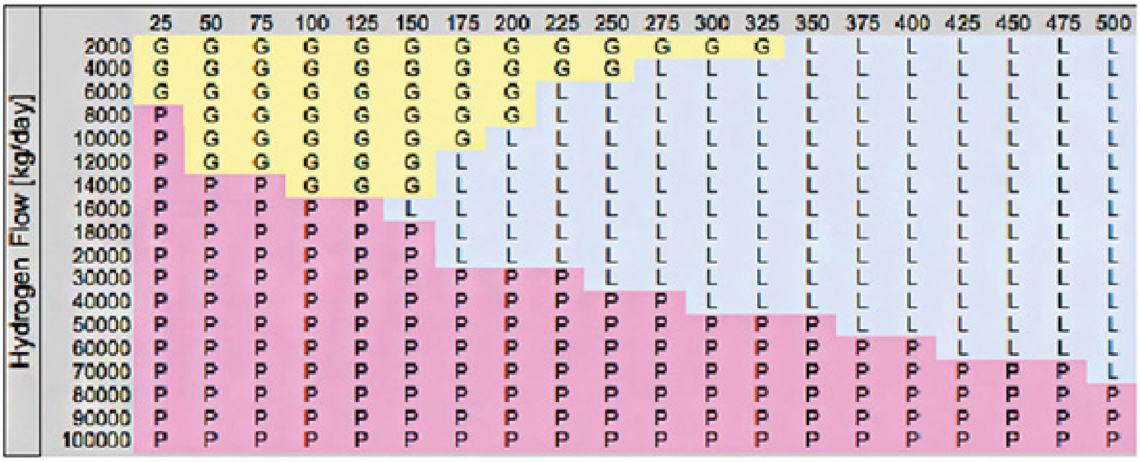


Fig. 4. The plan for an ammonia-ready LNG import terminal. Source: [18]

Rys. 4. Plan terminalu importowego LNG przystosowanego do magazynowania amoniaku. Źródło: [18]



Hydrogen Flow [kg/day]	25	50	75	100	125	150	175	200	225	250	275	300	325	350	375	400	425	450	475	500
2000	G	G	G	G	G	G	G	G	G	G	G	G	G	L	L	L	L	L	L	L
4000	G	G	G	G	G	G	G	G	G	G	L	L	L	L	L	L	L	L	L	L
6000	G	G	G	G	G	G	G	G	L	L	L	L	L	L	L	L	L	L	L	L
8000	P	G	G	G	G	G	G	G	L	L	L	L	L	L	L	L	L	L	L	L
10000	P	G	G	G	G	G	G	L	L	L	L	L	L	L	L	L	L	L	L	L
12000	P	G	G	G	G	G	L	L	L	L	L	L	L	L	L	L	L	L	L	L
14000	P	P	P	G	G	G	L	L	L	L	L	L	L	L	L	L	L	L	L	L
16000	P	P	P	P	P	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
18000	P	P	P	P	P	P	L	L	L	L	L	L	L	L	L	L	L	L	L	L
20000	P	P	P	P	P	P	L	L	L	L	L	L	L	L	L	L	L	L	L	L
30000	P	P	P	P	P	P	P	P	P	L	L	L	L	L	L	L	L	L	L	L
40000	P	P	P	P	P	P	P	P	P	P	P	L	L	L	L	L	L	L	L	L
50000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	L	L	L	L	L	L
60000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	L	L	L	L
70000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	L
80000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
90000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
100000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P

Fig. 5. Diagram of the cost-effectiveness of hydrogen transportation techniques based on the volume of hydrogen produced and the distance. Source: [49]

Rys. 5. Wykres opłacalności metod transportu wodoru w oparciu o ilość wyprodukowanego wodoru i odległość. Źródło: [49]

It is estimated that the globe now has around 4.500 km of dedicated hydrogen pipelines. The longest hydrogen pipes in Europe are in Belgium (app. 600 km) and in Germany (about 400 km). There hydrogen pipes in Europe are mostly used in industrial operations connected to the chemical and fuel industries. The demand for hydrogen from industrial clients is consistent, while the availability of renewable energy for hydrogen generation fluctuates dramatically. As a result, these pipelines are frequently local and transport hydrogen for internal consumption. However, because of safety and transportation costs, long-distance transport of doped hydrogen will be done via gas pipes, which will need the construction and expansion of a large-scale hydrogen transportation infrastructure. One of the primary aims and problems of the future hydrogen economy will be to achieve this goal. Given the cost of this sort of expenditure, one must question the project's practicality, magnitude, and purpose. The presence of hydrogen in metals and alloys has a negative impact on their physical and chemical characteristics, resulting in lower strength and increased brittleness. Hydrogen also hastens the rusting process. Even at ambient temperature, it quickly diffuses into the crystalline structures of iron. Other issues include the increased sensitivity of present control and measurement equipment, such as volume converters or gas chromatographs, to the higher amount of hydrogen in the natural gas mixture. It should be noted that a greater proportion of hydrogen necessitates the modification of industrial and municipal equipment. Because hydrogen belongs to the group of gases that explode the most easily, attempts are being undertaken for safety concerns to store and transport mixes of hydrogen, such as with nitrogen. In Europe, two approaches will be used to build a networked hydrogen storage and transit infrastructure. First, based on new specialized gas pipes. Second, by adapting existing gas transmission infrastructure to new conditions. The development of hydrogen storage and transportation systems via gas networks will confront two key technological challenges [48], firstly the requirement to maintain the appropriate purity of the feedstock throughout the whole transmission route and the process's energy efficiency – the power necessary to accomplish the requisite compression to convey the lightest gas [48]. However, because to the high expense of creating network infrastructure specialized to the transmission and storage of pure H2, the reach of this option is now restricted. Furthermore, it is important to assess

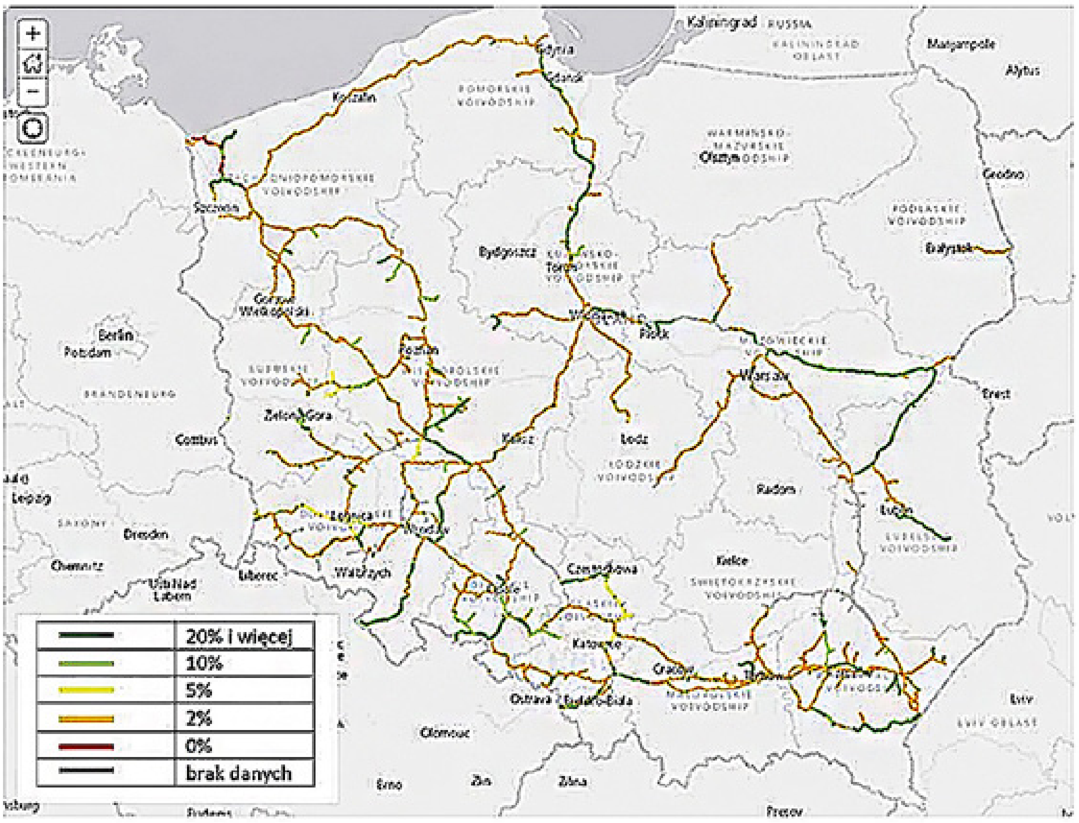


Fig. 6. The permissible hydrogen content of each section of the transmission system in Poland. Source: [24]

Rys. 6. Dopuszczalna zawartość wodoru na poszczególnych odcinkach sieci przesyłowej w Polsce. Źródło: [24]

the feasibility of carrying pure hydrogen over longer distances via new proposed gas pipelines, which would necessitate substantial expenditures. Such decisions must be both ecologically and economically justifiable. End users will also play a role in determining the hydrogen-natural gas blending ceiling. The mixture composition's upper limit must be properly determined and suited to the technical capabilities of the installed equipment. A number of initiatives are presently ongoing in Poland and other EU countries to investigate the functioning and design of equipment and gas infrastructure components. In the Netherlands, a research project found that a gas mixture containing 30% hydrogen poses no problems for domestic appliances such as boilers or gas hobs. Industry will have the most difficulties. Most equipment is not doped gas certified. Furthermore, most gas turbines are built for gas with a maximum H2 level of 3 – 5 %. According to current research, most existing gas system components can withstand a 5 – 10 % of doped hydrogen in natural gas. According to the Energy Safety Research Institute, up to 30% hydrogen addition is achievable [21], [22]. The RES Industry Development and Benefits to the Polish Economy Team has prepared recommendations, indicating that the hydrogen transportation and distribution system on selected sections of the gas network can be adjusted and demonstrated to 2% in the short term (2025) and above 2 % in the long term (2027/2030) [24]. The allowable proportion of H2 was determined using the HYREADY project, which defined the permissible hydrogen content for the various grades of steel used in the transmission system. The permissible hydrogen content of each section of the transmission system is shown in the figure below:

To prevent the risk of exceeding natural gas's allowable hydrogen content, the answer is to add synthetic natural gas (SNG) to the gas network, which is the outcome of the hydrogen methanation process, provided, of course, that we have a network with appropriate capacity reserves.

5.1. Construction and reclassification costs for gas pipelines

The network is planned to evolve spontaneously between 2030 and 2040 as hydrogen demand and supply rise. By 2040, a significant European hydrogen network with a total length of 53.000 kilometers is envisaged, with approximately 60 % of that length being re-trained pipes. The European Hydrogen Backbone (EHB) [12] will initially serve primarily industrial demand, but between 2030 and 2040, hydrogen will become a significant energy carrier in heavy transport, e-fuel production, construction, and long-term storage of energy with the ongoing conversion of LNG terminals to hydrogen terminals [7]. A map of networked hydrogen infrastructure in Europe is shown in the figure below [11]:

According to the research, prices would vary from €80 billion to €143 billion by 2040, including the complete construction expenses of new pipes and the repurposing of existing pipelines. This will entail a number of research and development projects as well as expert studies by gas system

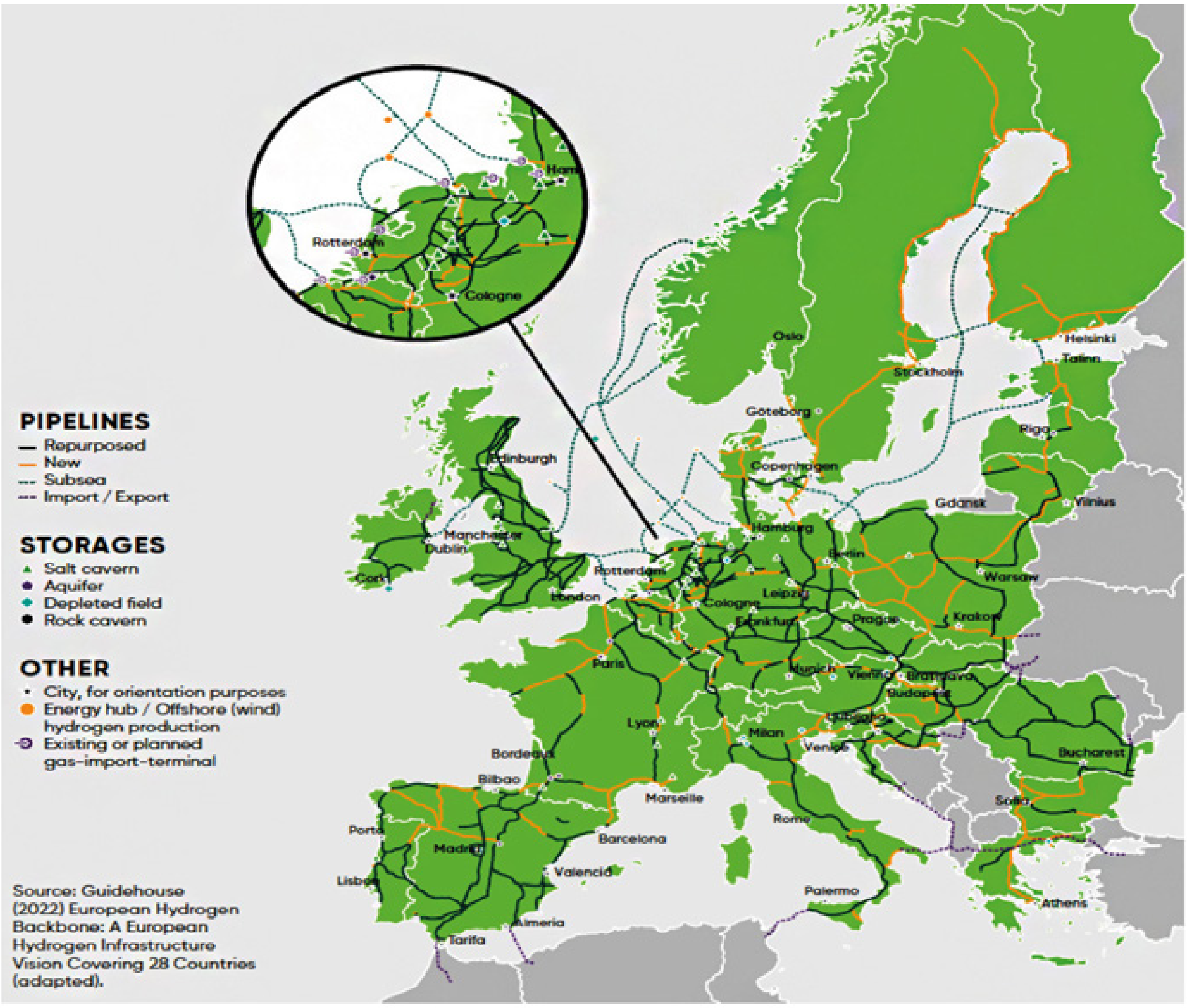


Fig. 7. The map of networked hydrogen infrastructure according to EHB in 2040. Source: [11]

Rys.7. Mapa sieciowej infrastruktury wodorowej według EHB w 2040 r. Źródło: [11]

operators. This will allow us to determine if the condition, materials, and technology utilized in the building of gas pipelines provide safe hydrogen storage and transit. Gas pipeline diagnostic studies made on metal alloys will be critical. The development of networks for the storage and transport of doped gas will be significantly influenced by the adaptation of existing transmission and distribution infrastructure. The cost of building and running hydrogen networks varies depending on the length, technology employed, and technical condition of the gas pipes used. According to estimates, the cost of upgrading existing gas transmission pipelines will range between $0.6 and $1.2 million, while the cost of building new pipelines would range between $2.2 and $4.5 million. Because of the more onerous investment circumstances, the cost of building offshore gas pipelines rises by 1.3 to 2.3 times. This is also owing to the difference in working circumstances; ordinary high-pressure pipes run at a pressure of around 8.4 MPa, whereas a subsea pipeline operates at a pressure of 15 MPa or more. According to the German organization of gas transmission pipeline operators, the cost of building new pipes to carry pure hydrogen will be about 9 times that of retraining them [17]. By 2050, infrastructure devoted to carrying clean hydrogen will coexist alongside natural gas networks delivering growing volumes of biomethane in a decarbonized Europe. It should be noted, however, that all choices and expenditures relating to the building or alteration of existing gas infrastructure should always be made with the principles of cost-effectiveness and economic efficiency in mind, for the benefit of both customers and the operator. As a result, investment decisions should be made responsibly after conducting extensive market evaluations, and laws for the development and subsidization of clean hydrogen networks should be implemented progressively as the hydrogen market grows. The expenses of adjusting or developing a distribution network are proportionally lower, owing to lower pressure and smaller diameters. However, in the event of natural gas transportation with 20% hydrogen, they will begin to play an important role. There is a reason why distribution gas network operators are waiting for government assistance. The Polish gas grid national operator, Polska Spółka Gazownictwa (PSG), operates a vast and diversified network across Poland, with over 200.000 km of gas pipes developed over time and with various technology. It will be able to transport hydrogen in a combination with natural gas in some of them, but this will require responsibility and validation in future research. PSG also highlights two essential aspects. First, there is currently a scarcity of organizations capable of supplying hydrogen for transmission via distribution networks. Second, all indicators point to hydrogen producers using gas pipelines to transport pure hydrogen, or finding another means to transport or consume hydrogen near to where it is generated (ideally from RES). Despite significant technological challenges, hydrogen transmission through gas networks is not ruled out in Europe, if only because such pipes already exist and a slew of hydrogen infrastructure projects are being undertaken. Local gas distribution networks in Europe have been able to provide cost-effective, dependable, and safe pipeline gas distribution and delivery for decades. The Ready4H2 alliance, which comprises 90 European gas distribution operators (DSOs), is one initiative worth highlighting since it brings together knowledge and experience in hydrogen storage and transport. The Ready4H2 Alliance believes that local gas distribution networks, working in tandem with gas trans-mission and storage infrastructure, are critical to realizing hydrogen's massive growth and carbon-reduction possibilities. This partnership allows for a speedier energy transition and is likely to fund larger emission reductions, boosting Europe's decarbonization goals.

6. Power to Gas technology in hydrogen storage

Power to Gas (P2G) technologies, coupled with hydrogen injection into the gas grid, enable the use of existing gas infrastructure to store power generated by renewable sources in the form of gaseous fuels pumped into the gas grid. These technologies include, among other things, the conversion of energy to gas for onward distribution or storage. By design, they are potential solutions that provide improved energy system balance since surplus power may be utilized to make green hydrogen that is pumped into grid infrastructure. One of the primary benefits of this technology is the integration of the electrical and gas networks for surplus electricity storage. The importance of gas networks as critical to Europe's future decarbonization will grow as the energy and gas sectors become more intimately intertwined. The transportation of hydrogen with natural gas has more ad-vantages than just lower transportation costs. It's also possible to store large volumes of hydrogen in existing natural gas storage facilities. Furthermore, the storage and mixing of hydrogen with natural gas might be a significant barrier to large-scale market development. That is the reason it is so critical for implementing new tools and technologies in the gas sector that enable, among other things, infrastructure diagnostics or optimization and simulation of gas network operation in the context of technological pipeline capacity analysis, determination of capacity and transmission possibilities under boundary conditions for various natural gas or biogas with hydrogen mixtures. The security of supply to existing and prospective clients is a critical duty for a gas fuel distributor. As a result, any endeavor to inject the combination into operational gas pipelines for transmission and storage should be preceded by thorough economic, technical, and modeling assessments. This should be based on reliable gas network models that account for the mixing of heterogeneous natural gas distributions in conjunction with hydrogen. An increase in the pro-portion of hydrogen in the mixture reduces the calorific value and increases the gas flow rate, resulting in an increase in the velocity of the flowing medium, which involves an in-crease in flow resistance, a change in the turbulence characteristics of the flow, and higher pressure drops in the pipelines, all to deliver an equal amount of energy. In a distribution network, for example, a combination of natural gas and hydrogen with a ratio of 85 – 15 % will have a flow velocity 1.7 times greater than pure methane, assuming an equal stream of energy provided [6].

7. Conclusions

Underground hydrogen storage is an effective method of energy storage that involves injecting hydrogen, for example, into geological formations in times of energy surplus and then releasing and utilizing it when demand for energy rises [32]. The placement of geological structures ideal for hydrogen storage in salt deposits, hydrocarbon reservoirs, and aquifers imposed by natural circumstances. Underground storage locations must be carefully chosen and evaluated for integrity, and also the H2 storage process must be monitored and confirmed [42]. Surface installations will be able to store smaller quantities of hydrogen. The selection of hydrogen storage form (e.g., compressed gas, liquid, or ammonia) is extremely complex and is influenced by a variety of practical factors such as geographic limitations, safety standards, installation costs and obstacles, volume, logistics and transport method, and end use, with each form of storage having its own set of benefits and drawbacks [32], [36]. The viability of converting LNG terminals to liquid hydrogen (LH2) is dependent not only on the terminal components, but also on the function of LH2 as an energy carrier [34]. Ammonia is seen as a potential choice for storing huge amounts of energy over extended periods of time, however it has limits due to the fact that dynamic operation could damage ammonia synthesis catalysts. However, it offers a lot of room for substantial technical advancements, which might lead to better storage efficiency along with lower capital costs. It is generally thought that converting existing LNG facilities to use ammonia is technically viable. The storage tank is the terminal's most expensive component, however it may be reused with simple changes. Material compatibility, as with hydrogen, must be evaluated during the terminal design process, because other elements may not be acceptable for conversion to ammonia [34]. Power to Gas technologies, which allow power generated from renewable sources to be stored as gaseous fuels in gas networks, provide an opportunity to capitalize on current and planned gas infrastructure. The storage and transportation of hydrogen in constructed and deployable gas transmission and distribution pipes involves a number of concerns that must be ad-dressed by the EU and state governments. These will include not only factors of investment funding, but also the selection of the best storage technique, taking into account, among other things, free gas transportation, local circumstances, and, most importantly, safety concerns. The cost of hydrogen transportation and storage will undoubtedly be one of the primary aims and problems of the Polish hydrogen economy.

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