sciendo

LATVIAN JOURNAL OF PHYSICS
AND TECHNICAL SCIENCES
2022, N 4

DOI: 10.2478/lpts-2022-0033

THE GREEN HYDROGEN AND THE EU GASEOUS FUEL DIVERSIFICATION RISKS

L. Jansons[1,2], L. Zemite[1]*, N. Zeltins[1], I. Bode[1], I. Geipele[2], K. Kiesners[1]

[1]Riga Technical University,
Faculty of Electrical and Environmental Engineering,
Institute of Power Engineering
12-1 Azenes Str., Riga, LV-1048, LATVIA
[2]Riga Technical University,
Faculty of Engineering Economics and Management,
Institute of the Civil Engineering and Real Estate Economics,
6 Kalnciema Str. 210, Riga, LV1048, LATVIA
*e-mail: laila.zemite@rtu.lv

Hydrogen is the most abundant chemical element on the Earth, and it has really a wide variety of applications, starting from use in refining, petrochemical industry, steel manufacturing, and ending with use in energy production and renewable gas (*hereinafter* – RG) blending for gradual replacement of natural gas in all sectors of the national economy. Being practically emission-free, if produced in sustainable way or from renewable energy sources (*hereinafter* – RES), hydrogen is regarded as one of the most promising energy sources for decarbonisation of practically the entire segment of industrial and energy production. Growing pressure of the European climate neutrality targets has triggered special interest in production, use, storage and transportation of hydrogen – especially the green one, which can be used in at least four fundamental ways: as a basic material, a fuel, an energy carrier and an energy storage medium. In the context of sector coupling, however, hydrogen facilitates decarbonisation of those industrial processes and economic sectors in which carbon dioxide (*hereinafter* – CO_2) emissions can either not be reduced by electrification or this reduction would be minimal and linked to very high implementation costs. At the same time, development of an extensive hydrogen economy is the key to the achievement of the European climate protection targets, with the European Commission's (*hereinafter* – EC) Hydrogen Strategy, a framework created in 2020 to develop and promote sustainable hydrogen economy in the European Union (*hereinafter* – EU), in its centre.

Green hydrogen also will take its legitimate place in the gaseous fuel diversification risk management strategy, as this gaseous fuel is not only one of the most perspective future energy sources, but also one of the most volatile and demanding sources. In the process of gaseous fuel diversification in the EU and worldwide, new logistical chains and supply – demand networks of green hydrogen will emerge. Therefore, adequate addressing of potential challenges of this new regional and global production, delivery and consumption framework will be of utmost importance for secure, safe and predictable functioning of future energy systems.

Key words: *Diversification risks, gaseous fuels, green hydrogen, hydrogen technologies.*

1. INTRODUCTION

Hydrogen is the most abundant chemical element on the Earth, and it has really a wide variety of applications, starting from use in refining, petrochemical industry, steel manufacturing, and ending with use in energy production and renewable gas (*hereinafter* – RG) blending for gradual replacement of natural gas in all sectors of the national economy. It is also a rich source of energy, far more efficient than other fuels [1]–[3].

To be used in industry and energy production, however, hydrogen needs to be compressed to occupy the smallest possible volume. In comparison with other gases, it has the lowest molecular weight, low density, very low solubility in water and low dynamic viscosity. Also, hydrogen has high mass-energy density with very low volumetric energy density [4]. Other main characteristics of hydrogen are listed in Table 1.

Table 1. The Main Characteristics of Hydrogen

Molecular weight	g/mol	2.016
Density	kg/m^3	0.083
Higher calorific value	MJ/kg MJ/m^3	141.9 11.89
Lower calorific value	MJ/kg MJ/m^3	119.9 10.05
Boiling point	^0C	294
Density as liquid	kg/m^3	70.8
Critical point Temperature Pressure Density	 ^0C Bar kg/m^3	 306 12.84 31.40
Flame temperature	^0C	585
Diffusion coefficient	cm^2/s	0.61
Specific heat	KJ/kg K	14.89

Being a colourless and odourless gas, over time hydrogen has been given many colour markers, which describe sources and sometimes technology used in its production [5], rather than its actual chemical or physical properties. The colour marker of hydrogen, known as green one, is produced by using RES to power electrolysis that splits water molecules into hydrogen and oxygen. Green hydrogen formed through

this process is a clean energy source that can be effectively stored and transported over long distances.

The environmental challenges arising from the climate change have sparked particular interest in green hydrogen, which can be used as a fuel, an energy carrier and an energy storage option. In context of sector coupling, hydrogen facilitates the decarbonisation of those industrial processes and economic sectors in which CO_2 emissions can either not be reduced at all by electrification or only at considerable cost.

The experts are almost unanimous that development of an extensive hydrogen economy, based on sustainable forms of hydrogen – primarily, green hydrogen and blue hydrogen with carbon capture, utilization and storage (*hereinafter* – CCUS) is the key to the achievement of the European energy sector decarbonisation targets [6].

However, production of green hydrogen and sustainable forms of hydrogen using CCUS at the moment is at its infancy. In 2020, global hydrogen demand was 90 Mt, practically all produced almost exclusively from fossil fuels – natural gas and coal, resulting in close to 900 Mt of CO_2 emissions. The average global percentage of hydrogen produced from natural gas stands in more than 70 % [7]. At the same time, by mid-2021, a global capacity of electrolysers, which are needed to produce green hydrogen, doubled over the last five years to reach just over 300 megawatts (*hereinafter* – MW). Around 350 projects currently under development could bring global capacity up to 54 giga-watts (*hereinafter* – GW) by the end of this decade. Another 40 projects accounting for more than 35 GW of electrolyser capacity are at the early stages of development. The main green hydrogen source technologies are alkaline water electrolysis, proton-exchange membrane electrolysis, and solid oxide electrolysis, with the latter being in the research and first-trial phase [8]. If all planned projects are completed, global green hydrogen supply could reach more than 8 Mt by 2030, but this is still well below the 80 Mt required in the way to net zero CO_2 emissions by 2050 set out in the IEA Roadmap for the Global Energy Sector, or 70Mt short of the most conservative EU energy decarbonisation target for the same date [9].

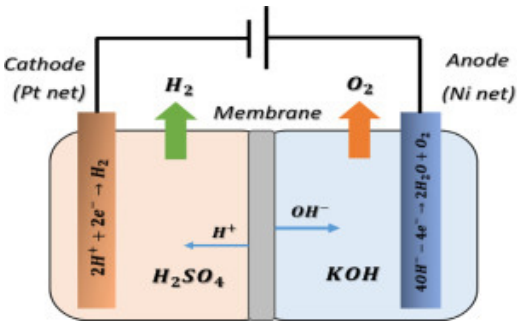


Fig. 1. The general principle of water electrolysis.

2. THE GLOBAL HYDROGEN DEVELOPMENT TRENDS

At present, Europe is a leading green hydrogen producer and electrolyser capacity deployer, with 40 % of global installed capacity, and is set to remain the largest market for this resource in the near term, as ambitious hydrogen strategies of the EU [10] and the United Kingdom [11] have been reviled in recent years. Moreover, supranational hydrogen strategies like one deployed by the EU is also strongly backed by Member States' commitment for hydrogen initiatives, with provision of financial support and necessary sector regulations. As of 2021, over thirty countries worldwide have produced hydrogen related framework documents, such as hydrogen strategies and

road maps, and have committed more than $70 billion in public funding to support the practical action. The German federal government alone is planning to provide up to 9 billion euros (*hereinafter* – EUR) by 2040 to implement its national targets and to build hydrogen-related international partnerships not only at the regional, but also at the global scale. The EC expects that cumulative investment in hydrogen in Europe will make up to 480 billion EUR by 2050.

In Europe, the first ever continent-wide initiative to unify hydrogen transportation and storage infrastructure is deployed, known as the European Hydrogen Backbone (*hereinafter* – EHB) [12]. This initiative consists of a group of thirty-one energy infrastructure operators. The EHB aims to accelerate Europe's decarbonisation journey by defining the critical role of hydrogen infrastructure – based on existing and new pipelines – in enabling the development of a competitive, liquid, pan-European green and sustainable hydrogen market [13].

Also in the United States, movement towards strong promotion of green hydrogen economy shift is seen not only on the federal, but also on the state level. More than thirty states have already adopted plans to promote sustainable hydrogen production and consumption technologies. The goal is to build a broad-based hydrogen industry that in 2030 will generate $140 billion in annual income and employ more than half a million people. The United States is stepping up ambitions with the Energy Hydrogen Program Plan [14], which is one of the most detailed and ambitious hydrogen strategical document to date.

China, one of the biggest consumers and producer of fossil hydrogen, is also planning to invest in the promotion of green and sustainable technology over the next years, which should result in innovative hydrogen production facilities throughout the country. On 23 March 2022, China released a plan on the development of hydrogen energy for the 2021–2035 period, as the country would strive toward its carbon peaking and neutrality goals. By 2025, China will put in place a relatively complete hydrogen energy industry development system, with the innovation capability significantly improved and the core technologies and manufacturing processes basically mastered, according to the plan jointly released by the National Development and Reform Commission and the National Energy Administration. Annual hydrogen production from renewable energy is expected to reach 100 000 t to 200 000 t to become an important part of new hydrogen energy consumption by 2025, and enable CO_2 emission reduction of one million to two million t per year [15].

Also, Australia's National Hydrogen Strategy [16] suggests that it could catch up with Europe in a few years. In context of this document, Australia is about not only to produce and use green and sustainable hydrogen domestically, but also to build up international partnerships, establish well-balanced and transparent guarantee of origin scheme, and create hydrogen industrial hubs in different regions of the country [17].

Bearing in mind that not only production of green hydrogen alone can help radically decarbonize the energy production and industry, but also production of hydrogen from fossil fuels with CCUS could help the matter in short and mid-time perspective, CCUS technologies are also strongly backed and promoted. As for early 2021, sixteen projects for producing hydrogen from fossil fuels with CCUS were operational, producing 0.7 Mt of hydrogen annually. Another fifty projects are under development and, if realized, could increase the annual sustainable hydrogen production to more than 9 Mt by 2030. Canada and the United States lead in the production of

hydrogen from fossil fuels with CCUS, with more than 80 % of global capacity production, although the United Kingdom and the Netherlands are pushing to become leaders in the field and account for a major part of the projects under development [12].

While hydrogen, from a technological point of view, can be used for diverse purposes, the development of a sustainable hydrogen economy is still controversial, because major challenges are presented by the production, storage and transport of hydrogen.

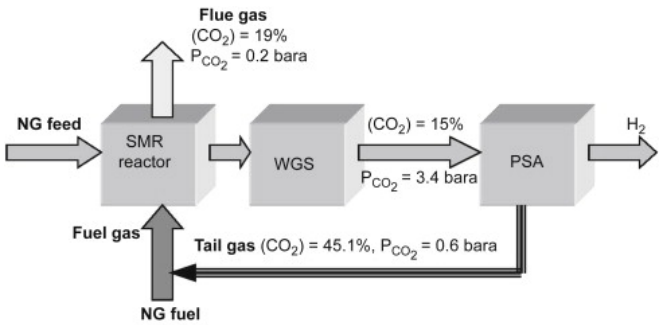


Fig. 2. The principle of methane steam reforming.

A crucial element of a sustainable hydrogen economy is cost-efficient production of green hydrogen. Currently, only about 5 % of hydrogen worldwide is produced via electrolysis, but, at the same time, by 2021, 76 % of all global hydrogen came from the natural gas produced via methane steam reforming cycle [7]. In comparison with electrolysis, steam reforming requires half as much water and significantly less energy. As this process is more cost-effective, natural gas could theoretically remain the predominant energy source for hydrogen production in the short and mid-time perspective. Moreover, the storage and transport of hydrogen present particular technical challenges: hydrogen is usually cooled to minus 253 ^{0}C or stored under very high pressure [18]. Possible alternatives, which make it easier to transport and store hydrogen, include conversion to ammonia, binding to liquid organic hydrogen carriers (*hereinafter* – LOHC) and the production of renewable fuels, such as methanol [19]. However, the conversion and reconversion processes result in energy losses, and some of these processes are not currently ready for the industrial scale usage.

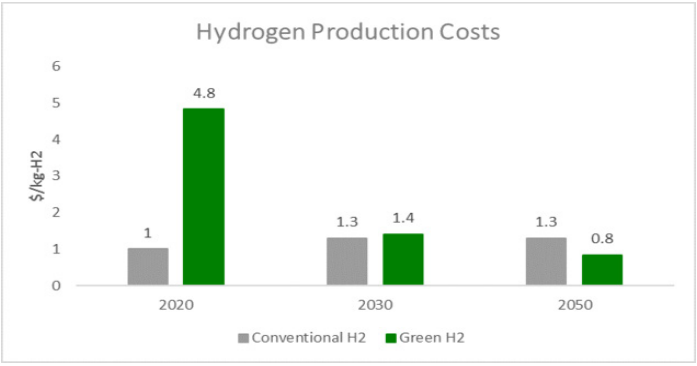
3. ADVANTAGES AND CHALLENGES OF WIDER HYDROGEN USE

In a long-term energy sector transformation perspective, sustainable and in particular green hydrogen can help tackle various critical energy and industrial challenges. First of all, this resource offers ways to decarbonize a wide range of sectors of the national economy, such as freight, air and maritime transport, chemical industry, including production of fertilizers, iron and steel. In all these sectors of the national economy, it has been proven difficult to meaningfully reduce CO_2 emissions. Hydrogen can also help improve air quality and strengthen energy security [20]. Despite very ambitious international climate goals, global energy-related CO_2

emissions reached an all-time high just recently – in 2018 [21]. Outdoor air pollution also remains a pressing problem, with several million people dying prematurely each year.

The strong advantage of wider use of hydrogen is a fact of its versatility. Technologies available today enable hydrogen to produce, store, move and use energy in different ways. A wide variety of fuels are able to produce hydrogen, including RES, nuclear, natural gas, coal and oil [22]. It can be transported as a gas by pipelines or in liquid form by ships, much like liquefied natural gas. It can be transformed into electricity and methane to power households and feed industry, and into fuels for almost all kinds of transport. At the same time, hydrogen can enable RES to provide an even greater contribution to global and the European energy transition. It has the potential to help with variable output from RES, like solar photovoltaics (*hereinafter* – PV) and wind, whose availability is not always well matched with demand curves [23]. Hydrogen is one of the leading options for storing energy from RES and looks promising to be a lowest-cost option for storing electricity over a long period of time. Hydrogen and hydrogen-based fuels can transport energy from RES over long distances – from regions with abundant solar and wind resources, such as Africa and Australia, to energy-hungry industrial cities thousands of kilometres away [16]. With a global energy sector in flux, the versatility of hydrogen is attracting stronger interest from a diverse group of governments and companies. Support is coming from governments that both import and export energy as well as RES electricity suppliers, industrial gas producers, electricity and gas utilities, car industry, and oil and gas companies.

To this date, hydrogen is used mostly in oil refining and for the production of fertilizers. But, to make a significant contribution to clean energy transitions, it also needs to be adopted in sectors where it is almost completely absent at the moment, such as transport, buildings and power generation [24]. In this context, however, clean, widespread use of hydrogen in global energy transitions faces several challenges, too. It is common knowledge that producing hydrogen from RES is still costly. According to the International Energy Agency (*hereinafter* – IEA), the cost of producing hydrogen from RES electricity could fall 30 % by 2030 as a result of declining costs of RES and the scaling up of hydrogen production. Fuel cells, refuelling equipment and electrolysers can all benefit from mass manufacturing [9].



Source: NRDC

Fig. 3. Estimated conventional and green hydrogen cost (2020–2050).

The development of hydrogen infrastructure, including pipelines and large-scale on-ground and underground storage facilities, is slow. Hydrogen prices for consumers are highly dependent on how wide accessibility of resources is at the moment, and how often they are used and how much hydrogen is delivered in a specific period of time (per day, week or month). Tackling this issue is likely to require planning and coordination that bring together national and local governments, industry and investors.

As hydrogen currently is almost entirely produced from natural gas and coal, it is already used at an industrial scale, but its production is responsible for huge annual CO_2 emissions. Harnessing this existing scale on the way to a clean energy future requires both capture of CO_2 from hydrogen production from fossil fuels and greater supplies of green hydrogen. It also must be pointed out that industrial scale usage of hydrogen worldwide is sporadic in its sense – hydrogen is produced and used locally, without a need to develop an extensive logistical network and assure mobility of resources at least at a regional scale. Within the EU, Clean Hydrogen Partnership's hydrogen regional initiative has been carried out since 2016, with significant efforts to reach out to all those European regions and cities having an interest in the potential use of fuel cell and green or sustainable hydrogen-based products to help them achieve their decarbonisation goals [25].

In regulatory sense, regulations limit the development of a clean hydrogen industry, so government and industry must work together to ensure that existing regulations are not becoming unnecessary barriers to investment and subsequent market growth. The hydrogen market expansion would benefit immensely from common international standards for the safety of transportation and storage of large volumes of hydrogen, and for tracing the environmental effects of different hydrogen logistical chains.

4. HYDROGEN IN HEAT AND POWER GENERATION, AND ITS TRANSPORTATION OPTIONS

4.1. Hydrogen in Heat and Power Generation

It is believed that green and sustainable hydrogen, first and foremost, is meant to be used in decarbonisation of industry and energy generation processes, with smaller segments of energy sector not being the first priority. District and local heating are one of these sectors, where there is a great dispute on the necessity to include hydrogen in energy mix in Europe in a short and mid-term perspective. According to the IEA, globally, district heating supplies a relatively small share of heat used in buildings, at only 8.5 % of the sector's heat consumption – a share that has remained impressively constant since 2000, considering that floor area has increased by 65 % at the same time. Although the global average share is low, district heating does cover a high portion of heat delivered to buildings in some European countries, such as Denmark and Sweden (both above 45 %) [26].

As usage of natural gas in district heating is still rather widespread in the EU and the United Kingdom, the injecting of up to 10 % hydrogen (by volume) into the natural gas transportation and distribution networks would not require any major alterations to equipment and would significantly reduce

CO_2 [27] for households and small business consumers. At the same time, injection of up to 10 % hydrogen into the natural gas networks would contribute not only to district heating companies and their clients, but also to local and individual heating system users. They would also use hydrogen – natural gas – biomethane blend in their natural gas boilers and other equipment, not replacing them by new ones, and, at the same time, contributing to national and the EU emission reduction targets [28].

In the electricity sector, burning of liquid and gaseous hydrocarbons, currently represents the largest share of electricity generation around the world. Countries with limited RES and hydrocarbon resources rely significantly on expensive imported and polluting fuels. Importing electricity through transmission lines might sometimes be problematic due to high costs, system losses, and geographical barriers [29]. However, green hydrogen offers a viable alternative. Countries importing large amounts of hydrocarbons today, in the near future could switch to import of low-cost green hydrogen and convert it into electricity through large-scale fuel cells in domestic power plants [1]. Hydrogen concentrations of up to 10 % and 20 % are still permissible for the operation of turbines and compression stations, respectively, while pipelines can stand mixtures of up to 50 % (given some technical adjustments); anything above those values is currently still being researched [30]. For instance, Mitsubishi Hitachi Power Systems, Ltd. has recently disclosed the successful test of a large-scale highly efficient turbine fed with a 30 % hydrogen blend, attaining a stable combustion with a 10 % reduction in CO_2 emissions [31].

4.2. Hydrogen Transportation Options

In order to transport hydrogen, it needs to be compressed, liquefied or chemically combined. Safe and cost-efficient transport and distribution of hydrogen are critical for its large-scale deployment, as its low energy density, high diffusivity, and high flammability imply important technological and infrastructural challenges associated with the transport and large-scale adoption in such markets, as sustainable district and local heating or transport. It is likely that the initial adoption and use will be locally concentrated in hydrogen hubs or hydrogen valleys [32], while for global large-scale integrated value chains it will take longer to emerge. In terms of means of transport, hydrogen can be transported by road and rail, as gaseous or liquid, in special vessels, tubes, and containers, by sea, primarily in specialized cryogenic tankers in a liquefied form, and by pipelines, which can carry either pure methane-biomethane, pure hydrogen or a blend [12]. For distances that fall below 2000 km, transporting hydrogen through pipelines is the lowest-cost option. In case of longer distances, ammonia shipping is the most economical solution. It is estimated that investments required to meet green hydrogen export demand in 2050 are around $2.1 trillion, where $1 trillion would go to building the dedicated RES capacity, $900 billion – to setting up the hydrogen conversion and export facilities, and $200 billion – to developing the water electrolysis facilities [1].

4.3. Building up New Pipelines or Retrofitting the Existing Ones

At the same time, hydrogen blending into the existing natural gas network has multiple advantages and can be a cost-effective transitional option in the short term in regions without parallel or duplicated networks. The retrofitting and repur-

posing of existing natural gas networks can be combined and complemented with the construction of new dedicated hydrogen infrastructure. It needs to be reminded that a purely hydrogen pipeline infrastructure is not a novelty. Such networks, although strictly compact and localized, are already used to supply single consumers, for example, petrochemical and fertilizer plant. At present, a 900 km long hydrogen pipeline network is built along the Gulf coast of the United States, which is regarded as the longest high-pressure hydrogen transportation network in the world [33]. In Europe, currently the largest and longest industrial hydrogen pipeline network is located in the area of ports of Rotterdam and Antwerp, with total length around 1500 km, where the longest part consists of small diameter distribution infrastructure [12]. In line with this, there are various initiatives, EHB and the Re-Stream studies carried out [34], in order to assess the potential of the existing European oil and gas infrastructure to carry hydrogen and/or carbon monoxide.

In addition, in the EU, a well-developed and regulated network of natural gas is already in place, with the transmission grid being approximately 200 000 km long.

A distribution grid, which is double the size of the current transmission grid, implies that the natural gas infrastructure is the key enabler for the deployment of a hydrogen economy. The UNECE Group of Experts on Gas recognised the key role of the natural gas transmission and distribution operators (*hereinafter* – TSO, DSO), natural gas industry and the natural gas infrastructure in the transition to a hydrogen economy through the energy system integration [35]. Even though pipelines and the natural gas storage facilities today are being considered the most cost-competitive solution for hydrogen distribution, numerous challenges remain. One of them is an increasing difficulty of building new pipelines, as many landowners are not ready to have such objects close to their properties. Thus, it is in the best interest of actors in the hydrogen value chain to find ways to extensively reuse existing natural gas infrastructure instead of constructing an entirely new hydrogen infrastructure. It is necessary to start immediate retrofitting and repurposing of current natural gas infrastructure. Given TSO and DSO know-how in operating natural gas transmission and distribution infrastructure, the gas TSOs should be among those certified as owners and operators of future hydrogen networks [36]. Authorizing the natural gas TSOs to carry out activities related to the development, integration and operation of hydrogen infrastructure would facilitate an efficient way forward due to their experience in planning, financing, constructing, operating and maintaining gas infrastructure, since existing gas grids will be retrofitted and repurposed for hydrogen [12].

5. OUTLINING THE MAJOR HYDROGEN-RELATED RISK ASSESSMENT

Work is underway worldwide to further develop technologies in the fields of hydrogen electrolysis, storage and transportation. The vast majority of hydrogen today is produced and used on-site in industry. The production of ammonia and oil refining are the prime purposes, accounting for two-thirds of hydrogen use. Ammonia is used as nitrogen fertilizer and for the production of other chemicals. At petroleum refineries, hydrogen is added to heavier oil for transport fuel production [37].

What is new is that the type and scale of its use are changing fundamentally, with the expected rapid growth of generation capacities in close future. New companies are entering the market as planners, manufacturers and operators, but there is a steep learning curve involved. Established players size up their offers and are simultaneously required to find skilled staff and realise cost-saving potential. As such, all projects require careful risk assessment. The potential risks involved with green hydrogen production, storage and transportation include, but are not limited to: *fire and explosions, market immaturity, material embrittlement and business-related challenges.*

5.1. The Major Physical Hydrogen-Related Risks

Possibility of fire and explosion is the main risk when handling hydrogen, as it is highly explosive, when mixed with air. In addition, leaks are hard to identify without dedicated detectors because hydrogen is colourless and odourless [38]. A hydrogen flame is almost invisible in daylight. Industry loss investigation statistics show that approximately one in four hydrogen fires can be attributed to leaks, with around 40 % being undetected prior to the loss. Fire and explosion protection needs to be considered on three different levels: preventing the escape of inflammable gases as much as possible, ensuring safe design of electrical and other installations in areas where ignition sources cannot be excluded, constructing buildings and facilities to withstand an explosion with limited damage [39].

Proper handling of hydrogen is critical, and any emergency requires appropriate fire safety equipment. An AGCS analysis of more than 470 000 claims across all industry sectors over five years shows how costly the risk of fire and explosion can be. Fire and explosions caused considerable damage and destroyed values of more than €14 billion ($16.7 billion) over the period under review [40].

Material or metal embrittlement or hydrogen-assisted cracking (*hereinafter* – HAC) *is another potentially dangerous side effect of hydrogen handling.* Diffusion of hydrogen can cause metal and steel, especially high-yield steel, to become brittle, and a wide range of components could be affected, for example, piping, containers or machinery components. For the safety of hydrogen systems, it is important that problems such as the risk of embrittlement and HAC are taken into account at the design phase. This is ensured by selecting materials that are suitable under the expected loads as well as considering appropriate operating conditions (pressure, temperature, mechanical loading). High-yield strength steel is particularly at risk of hydrogen-related damage [41].

5.2. Business and Market Formation Related Risks

Business inconsistency or interruption risks are also potentially present in green and sustainable hydrogen risk management. Hydrogen production, transportation and distribution involve high-tech equipment and failure to critical elements could result in significant financial losses. For example, in case of damage to electrolysis equipment or heat exchangers in liquefaction plants, it could take very long to replace such essential equipment, resulting in production delays. In addition, such interruption costs following a fire can add significantly to the final loss

total. For example, AGCS analysis shows that, across all industry sectors, the average business loss from fire incidents is around 45 % higher than the average direct property loss – and in many cases the business interruption share of the overall claim is much higher, especially in volatile segments such as oil and natural gas [40].

Slow market development also represents a potential threat to widespread green hydrogen penetration of crucial European economy sectors, as hydrogen infrastructure development is still at an early stage. As mentioned previously, a group of the European companies and TSOs have proposed to start planning the EHB. As large supply corridors come together, a core EHB can be envisaged by 2040. This means that a pan-European hydrogen infrastructure can be created connecting twenty-eight European countries. By 2040, the proposed backbone can have a total length of almost 53 000 km, consisting of approximately 60 % repurposed existing infrastructure and 40 % of new hydrogen pipelines. Assuming that the backbone is equipped with a fit-for-purpose and technically robust compression system, the proposed network could be able to adequately meet the expected annual hydrogen demand in Europe by 2040 [42]. But, at the moment, creation of such massive infrastructure and retrofitting of existing natural gas pipelines are moving at a rather slow pace, putting a major accent to the regulatory framework of infrastructure building.

In this context, massive public investments and financing are to be committed to kick-starting the hydrogen market. The conditions for access to the transmission networks and common rules for the internal market in hydrogen need to be designed, as well as the framework for how hydrogen should compete for demand. In many respects, this is far from simple, particularly with respect to trading rules and guarantees of origin. There are many unknowns, and considerable technological development will occur in upcoming years. For example, promising new manufacturing processes for zero and even negative carbon hydrogen are emerging, such as pyrolysis powered by RES. It is important not to create market structures and support mechanisms for financing what may become stranded assets [43].

Therefore, at this stage, the best way to establish the basic future hydrogen market rules would be to follow the logic and principles established for the regulation of the natural gas market through the EU directive on gas and hydrogen networks [44]. On 15 December 2021, the EC adopted a legislative proposal to recast the 2009 EU Gas Directive [45], as part of the proposed hydrogen and decarbonised gas markets package. This reflects the EU's growing climate ambitions, set out in the European Green Deal and its "Fit for 55" package. The EC's proposal aims to support the decarbonisation of the energy sector by ramping up the production of RG and hydrogen, and facilitating their integration in the EU energy networks. The recast directive would become a central element of a new EU legislative framework for hydrogen networks, comparable to those that already exist for natural gas and electricity. The proposal would refine the principles of the existing Gas Directive and fully extend its scope to cover hydrogen networks. This includes an important set of consumer rights, provisions relating to TSOs and DSOs – especially, their unbundling, third-party access and integrated network planning, and independent regulatory authorities [46].

6. HYDROGEN AND THE GASEOUS FUEL DIVERSIFICATION RISKS

The gaseous fuel diversification, which includes, but is not limited to wider RG usage in energy generation and energy intensive industry throughout the EU, has strong national economy and climate related advantages. But, at the same time, gaseous fuel diversification, especially when carried out at a large scale, can be associated with numerous risks factors. These risks can vary from sector to sector, and apply not only to large-scale energy and industrial processes, but to a residential gas supply as well.

A risk matrix is one of the most effective assessment tools to pinpoint and generalize risks factors [47] that can be present in residential gas supply sector during a period of gaseous fuel diversification. If the main avenues of gaseous fuel diversification correspond to blending of the following RGs: biomethane and green hydrogen, into existing natural gas networks with subsequent delivery of blended resources to all consumers, including residential ones, – risks associated with it fall into two categories. The first category is methane rich fuel associated risks (the natural gas and biomethane) and the second – non-methane rich fuel associated risks (hydrogen). The first category includes the natural gas related risks, as chemically biomethane is a substance identical to it. These risks are leaks, fire, explosion and suffocation; however, natural gas alone will not burn or explode. It needs the right amount of air and an ignition source. The second category includes green hydrogen (or hydrogen of any origin) that could be blended with methane and biomethane in low proportions with minimal investments into the existing natural gas systems. The share of hydrogen in a blend may range up to 10 % by energy, although this is subject to ongoing debate. Any quantity of hydrogen exceeding a 10 % threshold may require either major network repurposing measures or a buildout of an entirely new hydrogen pipeline networks [27].

The main risk factors associated with usage of pure hydrogen or high concentration of hydrogen in hydrogen-methane blends are propensity to leaks, as hydrogen can diffuse through many materials considered airtight or impermeable to other gases, buoyancy as hydrogen is the lightest known gas that rises quickly under atmospheric conditions, flammability – when mixed with air, hydrogen can easily ignite or/and explode, hydrogen-induced cracking as reduction in the ductility of metal can occur due to absorbed hydrogen (in steel, iron, nickel, titanium, cobalt, and their alloys). Also risks of proper mechanical blending of hydrogen and methane may arise in certain situations that might, among other, result in rising gaseous fuel usage risks in the residential sector, especially, when domestic appliances that are not designed to run on a high mix of hydrogen (gas boilers, furnaces, cook stoves etc.) are concerned. To mitigate these risks in a timely manner, at least part of them have to be replaced with hydrogen-compatible alternatives, which are currently available to consumers in rather limited amounts [37].

As with any energy risk, fire and explosion is a key point. Business interruption and liability exposures are also important, as are transit, installation and mechanical failure risks. There is rightly great enthusiasm around hydrogen solutions as a key driver toward a low-carbon economy, but it should not be neglected that these projects involve complex industrial and energy risks and require high levels of engineering

expertise and insurance know-how to be able to provide coverage.

To some extent, risks related to smart gas distribution can also be listed in association with hydrogen risks, as smart gas distribution is being built upon natural gas and biomethane, bearing in mind prioritization of their chemical and physical properties. An important factor that ought to be examined is the effect of hydrogen blending in the natural gas supply chain. Considering an average lower calorific value of natural gas and hydrogen [48], injection of hydrogen into natural gas networks will inevitably translate into reduction in the calorific power of the blend. From a theoretical point of view, a blend with significantly more than 10 % of hydrogen, the calorific value of which remains within the limits currently imposed by regulation, might pose certain challenges for some smart gas distribution network elements [49].

Hydrogen underground storage associated risks are still analysed by the industry experts not only in Europe, but also in other parts of the world. Underground hydrogen storage facilities can be distinguished from other types of energy storage primarily by the large volume of gas stored, the seasonal or long storage period, and large capital expenditures related to their construction and exploitation, as their economic viability is directly affected by the cost of electricity for water electrolysis and the construction costs [50]. Some parameters affect underground storage differently, for example, low viscosity of hydrogen and the associated rate of gas movement carry a higher risk of leakage.

For underground hydrogen storage different types of storage – namely, salt caverns, deep water aquifers and depleted oil and natural gas reservoirs – have been proposed [51], which are specific environments characterised by potentially high microbial abundance and activity. Subsurface microorganisms can use hydrogen in their metabolism and thus lead to a variety of undesired side effects or risks, such as hydrogen loss, methane and acid formation, as well as clogging and corrosion [52].

In contrast to above ground storage systems, underground gas storages have several strong advantages, too: they allow gas to be stored in large quantities, thus reducing storage costs, ensure storage safety – underground storage is less vulnerable to fire or terrorist attack, optimize the land use – traditional above ground storage may occupy significant areas, which might be used for other purposes, and existing engineering and safety management experience in underground gas storage sector (regarding storage of natural gas) [53].

6. CONCLUSIONS

The EU gaseous fuel diversification risks fall into several categories and they may be mitigated in various ways. In order to mitigate the EU gaseous fuel diversification risks, it is necessary to evaluate mitigation pathways, which are close to future tasks of hydrogen sector development, and not the current situation of its development. The following pathways therefore must be addressed with particular attention.

One of the long-term risk mitigation ways is to establish a stable role for green and sustainable hydrogen in long-term energy strategies. This concerns not only supranational and the national framework documents, but also regional and city-wide initiatives that can guide and help the hydrogen economy to grow on various

levels. The businesses and other companies should also have clearly defined long-term energy goals, which, if necessary, should define their own green hydrogen adaptation agenda. Key sectors here include, but are not limited to refining, chemical industry, iron and steel production, freight, long-distance, air and maritime transport, building sector, and power generation and storage. It means that stimulation of commercial demand for green hydrogen also would follow the framework strategic initiatives, as incentives for doing so would also become more and more present in different consumption segments. At the moment, sustainable and green hydrogen technologies are available on the market; thus, their costs are rather challenging. Policies that create sustainable markets for green hydrogen and help reduce emissions from fossil fuel-based hydrogen are needed to underpin investments by suppliers, distributors and consumers. By scaling up supply chains, these investments can drive cost reductions, whether from low-carbon electricity or fossil fuels with carbon capture, utilization and storage. New applications for green and sustainable hydrogen, as well as hydrogen supply and infrastructure projects stand at the riskiest point of the deployment curve.

The other important issue to mitigate the EU gaseous fuel diversification risks regarding green hydrogen is widespread support for research and development (*hereinafter* – R&D) activities to eventually bring down green and sustainable hydrogen production costs. Alongside cost reductions from economies of production scale, R&D is crucial to lower costs and improve performance, including for fuel cells, and hydrogen-based fuels. Government actions, including the use of public funds, are critical in setting the long-time research agenda and gradually attracting private capital for innovation.

Elimination of regulatory barriers and harmonization of standards are the issues addressed in the EU gaseous fuel diversification risk mitigation. Green hydrogen project developers in the EU still face impediment, where regulations and permit requirements are unclear, unfit for new purposes, or inconsistent across sectors and countries. Sharing knowledge and harmonizing standards is a key, including for equipment, safety and certifying emissions from different sources. Enhancement of international cooperation is needed across the board but especially on standards, sharing of good practices and cross-border infrastructure. Hydrogen production and use need to be monitored and reported on a regular basis to keep track of progress towards long-term goals. By relying on current policies, infrastructure and skills, these mutually supportive opportunities can help scale up infrastructure development, enhance investor confidence and lower costs. For instance, it is possible to use the most of existing industrial ports to turn them into hubs for lower-cost, lower-carbon hydrogen, use existing gas infrastructure to spur new clean hydrogen supplies, support transport fleets, freight and corridors to make fuel-cell vehicles more competitive, and establish the first shipping routes to kick-start the international hydrogen trade.

The EU gaseous fuel diversification risks of green and sustainable hydrogen can also be minimalized and mitigated by building up and improving the planning and simulation process of the entire hydrogen production, transportation and consumption chain – green hydrogen ecosystem. Here digital twin (*hereinafter* – DT) technologies can be successfully used for the intelligent management of all types of data. By using different applications, for instance, the internet of things, software simulation, and data analytics, DT technologies

create a digital replica of a physical object or a system, in this case – even a replica of green hydrogen ecosystem. DT use is gaining momentum due to rapidly evolving simulation and modelling capabilities, better coupling between interoperability and the internet of things sensors, and increased availability of infrastructure for the use of digital devices. Furthermore, DT technologies have proven to offer advantages in accelerating technology growth, optimizing design, and improving return on capital. Despite the potential offered by DT technologies, little attention has been given to their application in green hydrogen facility design. To address these gaps, the present study proposes a DT-driven approach based on stochastic simulations for the smart design of green hydrogen facilities.

ACKNOWLEDGEMENTS

The research has been supported by the National Research Programme, project "Trends, Challenges and Solutions of Latvian Gas Infrastructure Development" (LAGAS) (No. VPP-EM-INFRA-2018/1-0003).

REFERENCES

1. PwC. (2020). *The Dawn of Green Hydrogen. Maintaining the GCC's Edge in a Decarbonized World*. Available at https://www.strategyand.pwc.com/m1/en/reports/2020/the-dawn-of-green-hydrogen/the-dawn-of-green-hydrogen.pdf
2. Kobzars, V., Zemite, L., Jasevics, A., Kleperis, J., Dimanta, I., Knoks, A., & Lesnicenoks, P. (2021). Appropriateness of hydrogen production in low-power hydropower plant. Paper presented at the *2021 IEEE 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University, RTUCON 2021 - Proceedings,* doi:10.1109/RTUCON53541.2021.9711687
3. Kleperis, J., Boss, D., Mezulis, A., Zemite, L., Lesnicenoks, P., Knoks, A., & Dimanta, I. (2021). Analysis of the Role of the Latvian Natural Gas Network for the Use of Future Energy Systems: Hydrogen from RES. *Latvian Journal of Physics and Technical Sciences, 58* (3), 214–226. doi:10.2478/lpts-2021-0027
4. Edwards, P., Kuznetsov, V., & David, B. (2007). Hydrogen Energy. Philosophical Transactions. *Series A, Mathematical, Physical, and Engineering Sciences, 365*. DOI: 10.1098/rsta.2006.1965
5. National Grid. (n.d.). *Energy Explained*. Available at https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum
6. Sadik-Zada, E.R. (2021). Political Economy of Green Hydrogen Rollout: A Global Perspective. *Sustainability, 13*, 13464. https://doi.org/ 10.3390/su132313464
7. Colombia, Sipa. (2021.) *Hydrogen Fact Sheet: Production of Low-Carbon Hydrogen*. Available at https://www.energypolicy.columbia.edu/sites/default/files/pictures/HydrogenProduction_CGEP_FactSheet_052621.pdf
8. Nnabuife, S.G., Ugbeh-Johnson, J., Evaristus Okeke, N., & Ogbonnaya, C. (2022). Present and Projected Developments in Hydrogen Production: A Technological Review. *Carbon Capture Science & Technology*, *3*. https://doi.org/10.1016/j.ccst.2022.100042
9. IEA. (2021). *Global Hydrogen Review 2021*. Available at https://www.iea.org/reports/global-hydrogen-review-2021/executive-summary

10. COM (2020) 301 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. *A Hydrogen Strategy for a Climate-Neutral Europe*. Available at https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf
11. HM Government. (2021). *UK Hydrogen Strategy*. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf
12. UNECE. (2021). *Technology Brief. Hydrogen*. Available at https://unece.org/sites/default/files/2021-10/Hydrogen%20brief_EN_final_0.pdf
13. Gasforclimate. (2020). *European Hydrogen Backbone. How a Dedicated Hydrogen Infrastructure can be Created*. Available at https://gasforclimate2050.eu/wp-content/uploads/2020/07/2020_European-Hydrogen-Backbone_Report.pdf
14. US. Department of Energy. (2020). *Department of Energy Hydrogen Program Plan*. Available at https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf
15. CSIS. (2022). *China Unveils its First Long-Term Hydrogen Plan*. Available at https://www.csis.org/analysis/china-unveils-its-first-long-term-hydrogen-plan
16. COAG Energy Council. (2019). *Australia's National Hydrogen Strategy*. Available at https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf
17. Australian Government. (2022). *Growing Australia's Hydrogen Industry.* Available at https://www.industry.gov.au/policies-and-initiatives/growing-australias-hydrogen-industry
18. Li, J-Q., Li, J-C., Park, K., Jang, S-J., & Kwon, J-T. (2021). An Analysis on the Compressed Hydrogen Storage System for the Fast-Filling Process of Hydrogen Gas at the Pressure of 82 MPa. *Energies*, *14* (9): 2635. https://doi.org/10.3390/en14092635
19. Preuster, P., Papp, C., & Wasserscheid, P. (2016). Liquid Organic Hydrogen Carriers (LOHCs): Toward a Hydrogen-free Hydrogen Economy. *Accounts of Chemical Research, 50* (1). doi: 10.1021/acs.accounts.6b00474.
20. US. Department of Energy. (n.d.). *Hydrogen Benefits and Considerations*. Available at https://afdc.energy.gov/fuels/hydrogen_benefits.html
21. Scientific American. (2018). *CO2 Emissions Reached an All-Time High in 2018*. Available at https://www.scientificamerican.com/article/co2-emissions-reached-an-all-time-high-in-2018/
22. Tholen, L., Leipprand, A., Kiyar, D., Maier, S., Küper, M., Adisorn, T., & Fischer, A. (2021). The Green Hydrogen Puzzle: Towards a German Policy Framework for Industry. *Sustainability, 13,* 12626. https://doi.org/10.3390/su132212626
23. Stamatakis E., Perwög E., Garyfallos E., Millán M.S., Zoulias E., & Chalkiadakis N. (2022). Hydrogen in Grid Balancing: The European Market Potential for Pressurized Alkaline Electrolyzers. *Energies*, *15* (2): 637. https://doi.org/10.3390/en15020637
24. Espegren, K., Damman, S., Pisciella, P., Graabak, I., & Tomasgard, A. (2021). The Role of Hydrogen in the Transition from a Petroleum Economy to a Low-Carbon Society. *International Journal of Hydrogen Energy, 46* (45). https://doi.org/10.1016/j.ijhydene.2021.04.143.
25. Clean Energy Partnership. (n.d.). *Background Info FCH Regions' Initiative*. Available at https://www.clean-hydrogen.europa.eu/get-involved/regions-hub/background-info-fch-regions-initiative_en
26. Jaribion, A., Khajavi, S., Ohman, M., Knapen, A., & Holmstrom, J. (2020). A digital twin for safety and risk management: A prototype for a hydrogen high-pressure vessel. In *15th International Conference on Design Science Research in Information Systems and Technology*, (pp. 369–375), 2–4 December 2020. Kristiansand, Norway. doi: 10.1007/978-3-030-64823-7_34

27. Savickis, J., Zemite, L., Zeltins, N., Bode, I., Jansons, L., Dzelzitis, E., & Ansone, A. (2020). The Biomethane Injection into the Natural Gas Networks: The EU's Gas Synergy Path. *Latvian Journal of Physics and Technical Sciences*, *57* (4), 34–50. doi: 10.2478/lpts-2020-0020
28. ADBA. (2021). *Biomethane & Hydrogen. Two Green Gases, One Future. Biogas Insights 2*. Available at https://www.greengastrading.co.uk/wp-content/uploads/2021/07/ADBA-Hydrogen-and-biomethane-Decarbonising-gas.pdf
29. World Nuclear Association. (2020). *Electricity Transmission Systems*. Available at https://world-nuclear.org/information-library/current-and-future-generation/electricity-transmission-grids.aspx
30. Bolobov, V.I., Latipov, I.U., Popov, G.G., Buslaev, G.V., & Martynenko, Y.V. (2021). Estimation of the Influence of Compressed Hydrogen on the Mechanical Properties of Pipeline Steels. *Energies*, 14.
31. Mitsubishi Power. (n.d.). *MHPS Successfully Tests Large-Scale High-Efficiency Gas Turbine Fuelled by 30 % Hydrogen Mix*. Available at https://power.mhi.com/news/20180119.html
32. EC. (2021). *Hydrogen Valleys. Insights into the Emerging Hydrogen Economies around the World*. doi: 10.2843/133091
33. Air Products. (2012). *Air Products' U.S. Gulf Coast Hydrogen Network Enhanced Reliability from the World's Largest Hydrogen Pipeline*. Available at https://microsites.airproducts.com/h2-pipeline/pdf/air-products-us-gulf-coast-hydrogen-network-datasheet.pdf
34. Re-Stream. (2021). *Study on the Reuse of Oil and Gas Infrastructure for Hydrogen and CCS in Europe*. Available at https://www.concawe.eu/wp-content/uploads/Re-stream-final-report_Oct2021.pdf
35. UNECE. (2020). *Report of the Group of Experts on Gas*. Available at https://unece.org/sed/documents/2022/04/reports/report-group-experts-gas
36. ENTSOG. (2021). *ENTSOG Summary of Proposals for Addressing Hydrogen Regulation in the Revision of the 3rd Energy Gas Package*. Available at https://www.entsog.eu/sites/default/files/2021-06/202106%20-%20Position%20-%20ENTSOG%20-%20Open%20PC%20Hydrogen%20Gas%20Market%20Decarbonisation%20Package.pdf
37. Van Gend, C. (2021). *Hydrogen Economy: Opportunities and Risks in the Energy Transition*. Available at https://www.propertycasualty360.com/2021/05/12/hydrogen-economy-opportunities-and-risks-in-the-energy-transition/
38. HyDeploy. (n.d.). *Hydrogen is Invisible and does not Smell. How will we Know if there is a Leak*? Available at https://hydeploy.co.uk/faqs/hydrogen-invisible-not-smell-will-know-leak/
39. EDF. (2022). *For Hydrogen to be a Climate Solution, Leaks must be Tackled*. Available at https://www.edf.org/blog/2022/03/07/hydrogen-climate-solution-leaks-must-be-tackled
40. Allianz. (2022). *Fire, Natural Catastrophes and Faulty Workmanship Top Causes of Insurance Claims for Business: Allianz.* Available at https://www.agcs.allianz.com/news-and-insights/news/claims-review-2022.html
41. Sandeep Kumar, D., & Manish, V. (2019). Effect of Hydrogen in Advanced High Strength Steel Materials. *International Journal of Hydrogen Energy,* 44 (51). doi: 10.1016/j.ijhydene.2019.08.149
42. EHB.(2022).*European Hydrogen Backbone. European Hydrogen Infrastructure Vision Covering 28 Countries*. Available at https://ehb.eu/files/downloads/ehb-report-220428-17h00-interactive-1.pdf
43. ACER. (2021). *Possible Regulation of Hydrogen Networks.* Available at https://www.acer.europa.eu/en/Gas/Documents/ACER%20H2%20Paper_%20vFinal_clean.pdf
44. EP. (2022). *EU Directive on Gas and Hydrogen Networks.* Available at https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/729303/EPRS_BRI(2022)729303_EN.pdf

45. *Directive 2009/73/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in natural gas and repealing Directive 2003/55/EC*. Available at https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32009L0073
46. EP. (2022). *EU Directive on Gas and Hydrogen Networks*. Available at https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2022)729303
47. Sandia National Laboratories. (2019). *Hydrogen Quantitative Risk Assessment.* Available at https://www.hydrogen.energy.gov/pdfs/review19/scs011_muna_2019_o.pdf
48. ToolBox. (n.d.). *Fuels—Higher and Lower Calorific Values.* Available at https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html
49. Savickis, J., Zemite, L., Bode, I., & Jansons, L. (2020). Natural Gas Metering and its Accuracy in the Smart Gas Supply Systems. *Latvian Journal of Physics and Technical Sciences*, *57* (5). https://doi.org/10.2478/lpts-2020-0026
50. Le Duigou, A., Bader, A–G., Lanoix, J.–C., & Nadau, L. (2017). Relevance and Costs of Large-Scale Underground Hydrogen Storage in France. *International Journal of Hydrogen Energy*, *42* (36). https://doi.org/10.1016/j.ijhydene.2017.06.239.
51. Storengy. (2021). *Large Scale Hydrogen Storage – the Underground Perspective.* Available at https://www.storengy.de/en/medias/news/large-scale-hydrogen-storage-underground-perspective
52. Dopffel, N., Jansen, S., & Gerritse, J. (2021). Microbial Side Effects of Underground Hydrogen Storage – Knowledge Gaps, Risks and Opportunities for Successful Implementation. *International Journal of Hydrogen Energy*, *46* (12). https://doi.org/10.1016/j.ijhydene.2020.12.058.
53. EIA. (2015). *The Basics of Underground Natural Gas Storage*. Available at https://www.eia.gov/naturalgas/storage/basics/