2021 3rd International Academic Exchange Conference on Science and Technology Innovation (IAECST)

2021 3rd International Academic Exchange Conference on Science and Technology Innovation (IAECST) | 978-1-6654-0267-5/21/$31.00 ©2021 IEEE | DOI: 10.1109/IAECST54258.2021.9695812

From Hydrogen Production to Storage: A Process for Sustainable Development of Underground Hydrogen Storage in Caverns

Yutong Zhu
Department of Geography,
University of British Columbia,
Vancouver, Canada
guanghua.ren@gecacademy.cn

Abstract—**With the increasing trend of energy demand, it has brought a huge burden to the environment. Since sustainable development is a dominant agenda or top priority for nearly every country, there is a pressing need to find clean and sustainable alternatives to replace existing non-renewable sources (e.g., fossil fuels). Hydrogen, as a clean, safe, and efficient energy source has a wide range of applications, in which it can meet energy demands while eliminating greenhouse gas emissions. In the past decades, there was a rapid development of hydrogen-related technologies, especially hydrogen energy storage technology. Therefore, this paper will mainly examine hydrogen storage in geological formations as well as its related hydrogen production process in order to explore how it helps solve energy-related environmental issues. Besides, this paper will also employ qualitative and quantitative studies to analyze and compare different hydrogen storage methods in order to determine a feasible approach that can be widely used in the industrial sector. Overall, the results will shed light on guiding future research of underground hydrogen storage (UHS) that will be contributed to the way of sustainability.**

Keywords-sustainable development; low-carbon hydrogen; hydrogen energy storage; underground hydrogen storage (UHS);

I. INTRODUCTION

Since the last century, the overall energy consumption of various nations has significantly risen as shown in Fig. 1 [1]. It is notable that the energy consumption of some parts of the world in 2018 and 2019 reached its peak, with greater electricity demand accounting for more than half of the increase in energy needs [2]. Along with the higher energy consumption, the environmental issues have loomed large, in which the global energy-related CO_2 emissions rose to 33.1 Gt CO_2 as illustrated in Fig. 2 [2]. Besides, one notices that coal-fired power generation remains the single largest source of CO_2 emissions, accounting for 30% of all energy-related CO_2 emissions. As a result, energy-related CO_2 emissions are undoubtedly a major obstacle to achieving sustainable development, which also urgently facilitates energy transitions. Although the fossil fuels, as conventional energy sources, have versatile applications, the pollutants emission exacerbates the environmental damaging.

In order to reduce CO_2 emissions and its associated greenhouse effect, i.e., climate change, restructuring the energy system is highly required. Hydrogen, as a safe, efficient, and clean energy carrier is a viable and long-term option to reduce and eliminate greenhouse gas emissions [3]. Hydrogen and energy have shared a long history together, from powering the earliest internal combustion engines over 200 years ago to being a crucial component of the contemporary refining industry. Despite hydrogen having many advantageous properties (e.g., energy-dense, light, and storable), it has to be adopted in some sectors, e.g., electrical power generation in order to make a substantial contribution to clean energy transitions [4]. Hence, hydrogen energy-related storage technologies are one of the key solutions to the energy challenge. Plenty of scholars have stated that hydrogen energy storage is one of the promising technologies to accommodate energy demand fluctuations and will play a leading role in future power grids [3, 5, 6].

Hydrogen storage technology can be categorized into 3 typical approaches: physical storage as compressed gas, physical storage as cryogenic liquid hydrogen, and solid-state storage. Thereinto, recent research of many countries has a great interest in above-ground hydrogen storage as compressed gas or liquefied hydrogen, whereas a few studies have focused on underground hydrogen storage (UHS), as well as its applications in industrial areas. More specifically, UHS in salt caverns is not as popular as above-ground hydrogen storage methods. In addition, more emphasis should be paid to the hydrogen production process, in terms of low-carbon hydrogen, which can help to address environmental issues. Contemporarily, hydrogen is mostly derived from fossil fuels and biomass-natural gas reforming and coal gasification processes. Therefore, the generation of hydrogen results in CO_2 emissions of about 830 Mt [4, 7]. On this basis, producing hydrogen through the water electrolysis process is a key measure towards the low-carbon hydrogen pathway. Although low carbon hydrogen generation via water electrolysis is ramping up and receiving a lot of attention among policymakers, environmentalists, and scientists, water electrolysis accounts for less than 0.1% of global hydrogen generation [8]. Thus, this paper will investigate UHS in caverns, from hydrogen production to storage process, and will utilize several different metrics to evaluate this technology. At last, this paper will compare the hydrogen storage of salt caverns with the above-ground hydrogen storage methods and other types of UHS in order to identify an actionable, practical, and feasible strategy for the long-term growth of the globe.

978-1-6654-0267-5/21/$31.00 ©2021 IEEE

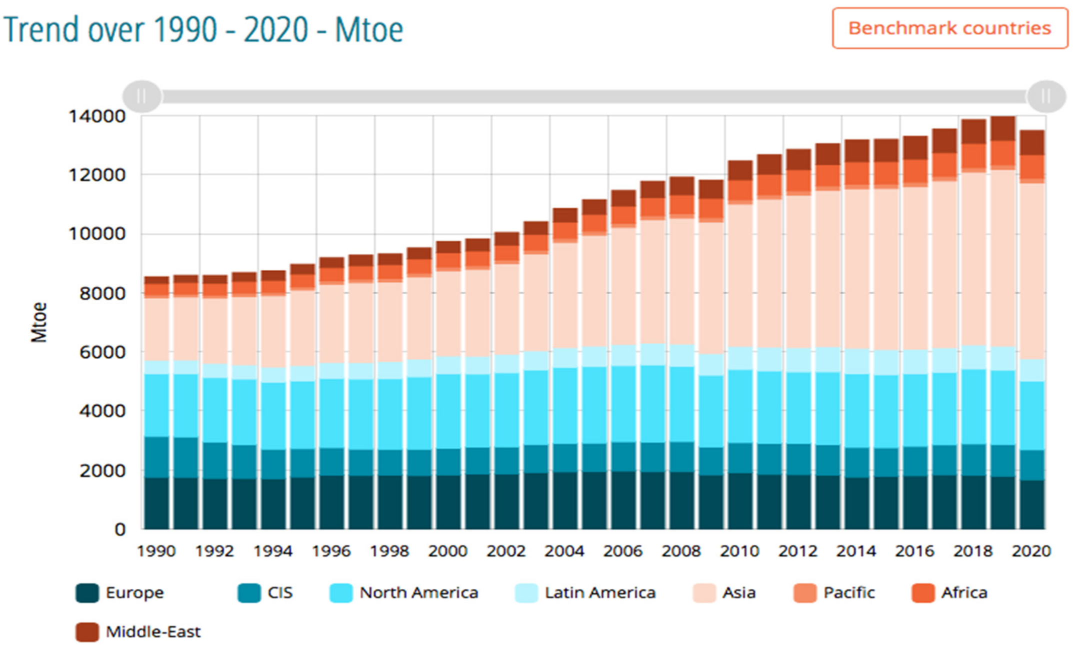

Figure 1. The general trend of energy consumption in different nations from 1990 to 2020 [1].

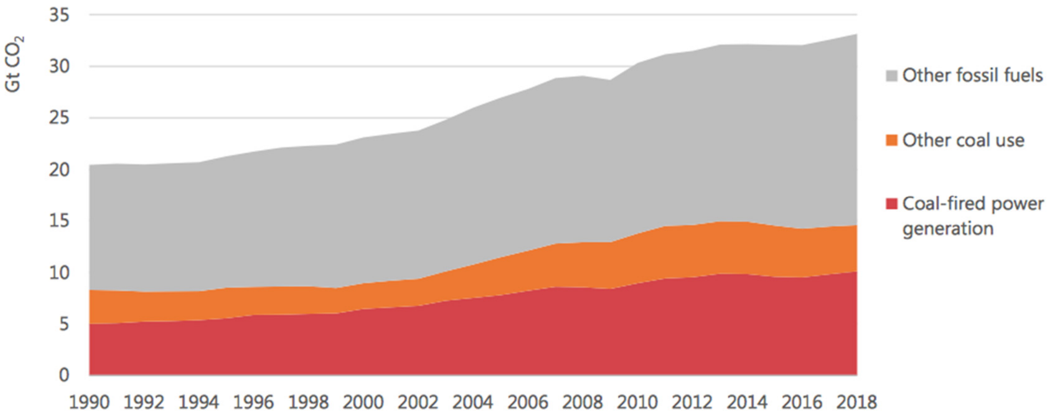

Figure 2. The CO_2 emissions of fossil fuel combustions from 1990 to 2018 [2].

II. QUANTITATIVE ANALYSIS

A. UHS in Salt Caverns

According to the European Union's (EU) proposed 2030 climate and energy framework, the 2030 greenhouse gas reduction target, in particular, emissions must be at least 40% below 1990 levels, with a minimum 32% share of renewable energy [9]. As the climate and energy targets gradually come into practice, the utilization of hydrogen energy storage comes to the front. Unlike above-ground hydrogen storage, storage of hydrogen gas in geological formations, namely underground, is the most dominant approach that is considered in connection with large-scale hydrogen use and might become a cost-effective solution for utilizing excess electric energy supplied from renewable sources [10, 11]. In the process of UHS of caverns, electricity from wind power and solar photovoltaic (as illustrated in Fig. 3) had been used for the water electrolysis to produce hydrogen, in which this type of hydrogen deemed as "green hydrogen" since there were zero greenhouse emissions to the atmosphere. Afterward, hydrogen gas had been compressed and stored in salt caverns for later use to generate electricity. The whole process of UHS in salt caverns can be explained as surplus electrical power supplied from wind and solar energy has been used to make hydrogen via water electrolysis process, which is stored as compressed gas in salt caverns. Then, when electrical power is required, the stored hydrogen gas can be used as fuel in power plants.

Based on the statistical research, the UHS of salt caverns has incredible storing capacity since it allows up to 500,000 m^3 of hydrogen to be kept at 2,900 psi in constructed salt caverns [12]. Furthermore, this technology has relatively high energy efficiency; some scholars have discussed that underground compressed air storage had an energy efficiency of 70~89% [13]. Drawing on recent research, the energy efficiency of UHS in caverns can reach as high as 60% [11]. Aside from that, its energy density can reach 300 $kWh \cdot m^{-3}$, which almost equals to the Li-ion battery [11]. It is not surprising that UHS of salt caverns has such high energy density since a single cavity is able to store thousands of tons of hydrogen. In fact, a dozen of the caverns have even more capacity and the entire storage capacity is 1700 GWh of electric power, which translates to a massive output of 14 GW [11]. Therefore, UHS in salt caverns may even become a sole technology that qualifies large-scale energy storage of renewable sources in the future. Besides the advantages of high energy efficiency and density, the storage of hydrogen in salt caverns has a longer duration time period. In other words, its lifetime can range from 20 to 40 years [13]. The International Energy Agency (IEA) had released a report in June 2019 to identify that geological storage, namely salt caverns, has become the best option for long-term storage [14]. In the meantime, it has a fast response time [13, 14], which means the time that the UHS system requires to ramp up supply is fast. However, due to the limitation of data, there is no exact number associated with it. At last, the cost is another essential metric or component to examine; it must be noted that the cost of UHS in salt caves is cheap, at just 1.61 USD/kg [15]. The lower cost of UHS in salt caverns becomes even more apparent when compared to liquid hydrogen storage (3.66 USD/kg) [16] and hydrogen stored in metal hydrides (about 9.01 to 19.67 USD/kg) [17]. The summary of detailed data has been listed in Table I.

TABLE I. SUMMARY OF THE UHS OF SALT CAVERNS BASED ON 6 METRICS [11-15]

Hydrogen storage method	Underground Hydrogen Storage (UHS)
Energy efficiency	More than 60%
Energy density	Can reach about 300 $kWh \cdot m^{-3}$
Lifetime	20 – 40 yrs
Response time	Fast
Cost	1.61 USD/kg

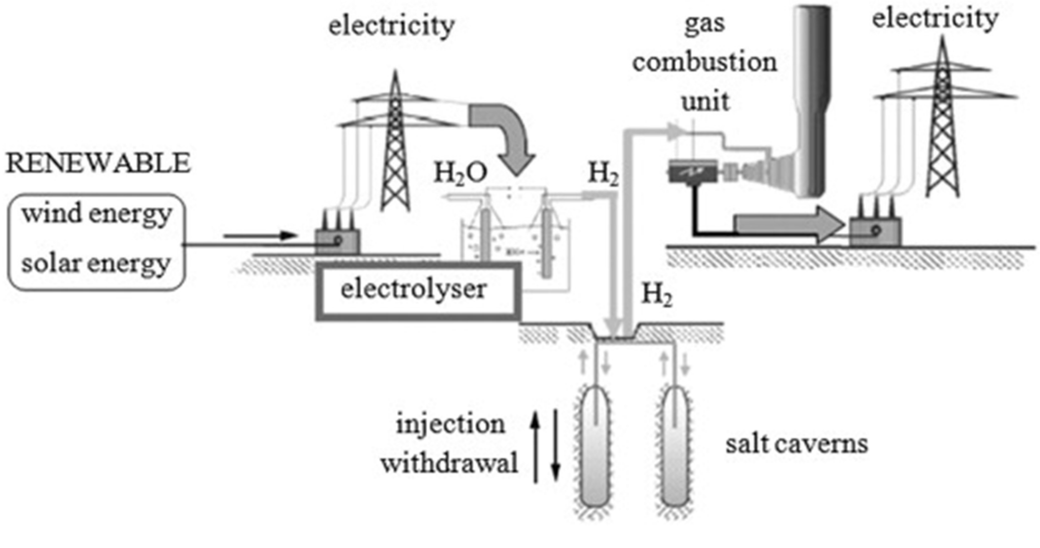

Figure 3. Schematic view of hydrogen storage in a salt cavern facility [11].

B. Limitations

For the quantitative study, there are numerous limitations of UHS in salt caverns. Because this technology has not been extensively used throughout the world, the lack of data can bring some uncertainties and might make this technology unappealing or unconvincing. For example, there are rare studies to indicate the exact response time of UHS in salt caverns, even though some scholars have stated that it has a fast response time. Nevertheless, this will cause many people to question what fast implies, and if it means that the response time will be seconds, minutes, or hours. Consequently, ambiguous data might indicate the insufficiency of data, which could impact the technology's viability. Even though UHS is a promising technology, a full detailed critical review of such parameters is still lacking. Therefore, this knowledge gap is very likely to pose some difficulties for the research and future practical application process. Another issue might be the inconsistency of data for the UHS in salt caves. Since underground rock formations vary by area, underground hydrogen storage capacity, lifespan, energy efficiency, and energy density will be somewhat or significantly different. In consequence, during the implementation of this technology, it may not be as effective as planned or as viable as previous existing projects.

III. FEASIBILITY STUDY

A. The theory & governing equations of UHS

The operation theory behind the geological storage is to inject underground hydrogen gas and store it under pressure, where it may be retrieved as needed. Normally, the process of processing gaseous fuels entails compressing it to a high pressure in order to achieve lower volume [19]. The equation of state (EOS) for ideal gas law (the Eq. (1)), as the most straightforward approach with a good approximation of many gases' behaviors can be taken when considering the underground stored hydrogen gas.

$$PV = nRT \tag{1}$$

where P is pressure (Pa); V is volume (m^3); n denotes for amount of substance; R is gas constant ($\text{kg} \cdot \text{K}^{-1}$); and T represents for temperature (K) [20]. However, unlike other gases that act mostly in line with the ideal gas law, hydrogen deviates substantially from the laws' predictions, where hydrogen covers a bigger space than anticipated by the ideal gas law. This deviation can be compensated for through using the compressibility factor (Z), as shown follows in Eq. 2 [14].

$$PV = nZRT \tag{2}$$

with

$$Z = n_{ideal} / n_{real} = m_{ideal} / m_{ideal} \tag{3}$$

In fact, this Eq. (2) is more precise to indicate the behavior of underground stored hydrogen gas. It has already been proved that the compressibility factor is 1.2 at ambient temperature and a pressure of about 300 bar, and therefore this implies that a mass of hydrogen gas within a container computed using the equation of ideal gas law will be 20% higher than the actual mass [21]. Since the aim of this paper is to explore whether UHS of salt caverns is feasible or not, a detailed numerical analysis will not be provided.

B. Comparison between above-ground and subterranean hydrogen storage

Hydrogen based storage systems have already become a research frontier, with the great potential to address energy-related environmental concerns. The compressed gaseous form of hydrogen storage is the most frequently used and simplest option among the different types of hydrogen storage technologies [3]. It can be divided into two big baskets: above-ground and subterranean compressed hydrogen gas storage, as depicted in the Fig. 4.

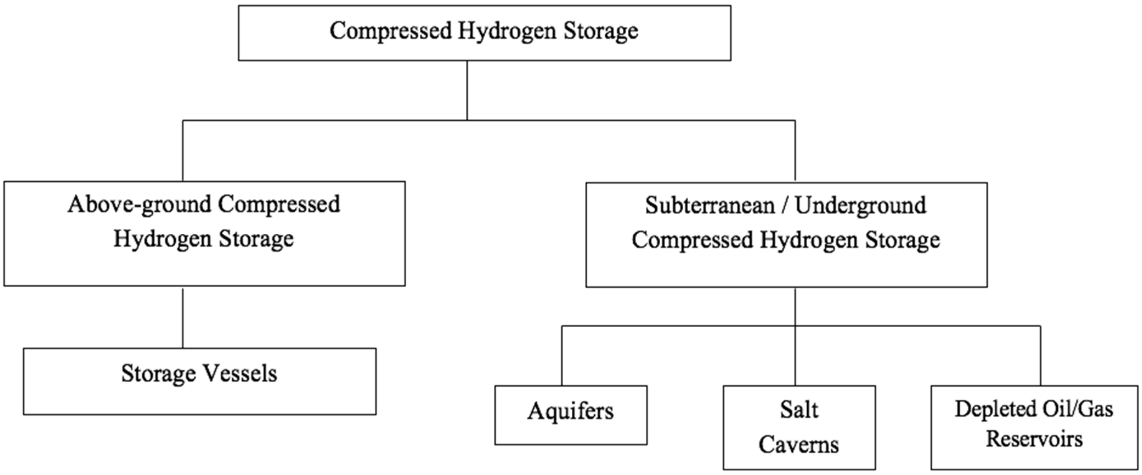

Figure 4. A schematic view of compressed hydrogen storage in different types.

Considering the several different factors of compressed hydrogen gas storage, UHS will be the best option compared to the above-ground hydrogen storage. Firstly, it is obvious that UHS, as a viable and advantageous option, has higher energy efficiency, a longer lifetime period, and a lower cost, as demonstrated in Table. I. In addition, hydrogen that has been stored in geological formations is safer compared to above-ground storage due to the absence of contact with oxygen to avoid any explosions. It has to be admitted that underground storage facilities are less susceptible to fire, terrorist assaults or any military activities [15]. Secondly, regarding the space management issue, typical surface tanks would have to cover large areas to store the same quantity of hydrogen gas as underground facilities. Besides, with an eye to the aesthetic component, subterranean facilities' need comparatively small surface installations, which are simpler to blend with the environment and existing infrastructure without modified the urban plan of cities too much [14, 15]. Furthermore, there are a lot of suitable geological structures available for hydrogen gas storage around the world, e.g., the location of Teesside in the UK and the location of Chevron in Texas in the US [11]. Those underground storage facilities are very common in many countries and over large areas. Lastly, UHS is the most cost-effective alternative; for a given comparable capacity, the costs of underground hydrogen gas storage construction are much lower than those of surface facilities.

C. Comparison of different types of subterranean hydrogen storage

There are a few types of underground gas storage facilities including: aquifers, salt caverns, depleted gas or oil reservoirs, rock caverns, and abandoned mines [14]. According to the research, some scholars have identified that there are two preferred underground facilities for hydrogen gas storage: salt caverns and "deep porous formations such as saline aquifers and depleted oil fields" [22]. Therefore, this section will mainly focus on comparison of those underground facilities, a brief diagram illustrated in Fig. 4.

Among different types of UHS, salt cavern is the most feasible approach with some special advantages. Although saline aquifers also possess great potential of storage capacity and are distributed widely around the world, there are no pure hydrogen storage exists to date [22]. The stability of stored hydrogen gas has become a big problem; biotic reactions with minerals within saline aquifers are able to result in hydrogen gas loss. Furthermore, because of the low density and viscosity of hydrogen, it has a high mobility, which will result in hydrogen losses owing to significant displacements [22]. This situation applies to the depleted gas and oil fields as well when storing hydrogen gas. The potential risks of it include microbial activity and chemical reactions of hydrogen with the minerals within depleted oil or gas reservoirs. First, microbial activity causes the conversion of hydrogen to CH_4 and H_2S, in which "hydrogen is microbially catalyzed by bacteria" under the process of bacterial sulfate reduction [23]. The danger associated with bacterial sulfate reduction is the H2S generated, which is corrosive to storage facilities, poisonous if breathed, and potentially harmful to the environment. Moreover, as recognized from carbon capture and storage, the interaction of hydrogen with the minerals of the reservoir rock and cap rock can result in mineral dissolution and precipitation, as well as porosity changes [24]. In a brief summary, hydrogen storage in saline aquifers and depleted gas or oil fields offers the possibility for seasonal storage of intrinsically variable renewable energy via the water electrolysis during the period of energy surplus [22, 23]. Whereas, low purity of stored hydrogen gas as well as gas contaminations are of great concerns.

Apart from the benefits of huge amounts and long-term storage of hydrogen in salt caverns, there are a few more reasons why salt caverns have been shown to be the most viable underground storage sites. First of all, caverns are typically formed in impermeable salt domes, which can minimize gas loss. Furthermore, rock salt has a dense matrix, low porosity, extremely low permeability, and self-healing capacity, i.e., salt caverns are already extensively used to store hydrogen gas [12]. Lastly, the engineering conditions of a salt cavern are more suitable than other reservoirs since a salt cavern usually has a space of 10^5~10^6 m^3 and a depth range of 600-2000 m, which is very suited and economical to store highly pressurized hydrogen [12]. Thus, salt caverns are the sole reservoir that has been successful for underground hydrogen storage until now. A brief summary has been presented in Table II.

TABLE II.BRIEF SUMMARY OF ADVANTAGES AND DISADVANTAGES OF 3 FOCUSED UNDERGROUND FACILITIES

Types of UHS	Advantages	Disadvantages
Salt caverns	- Large storage capacity - Storing pure hydrogen - Cost-effective - geographically widespread	- Legal and social obstacles regarding caverns construction regulations and public acceptance [14]
Saline aquifers	- Large potential storage capacity - Widely distributed	- Cannot store pure hydrogen due to chemical reactions [22] - More feasible to seasonal hydrogen storage instead of long-term period
Depleted gas/oil fields	- Presents the possibility for seasonal storage of intrinsically variable renewable energy	- Can not store pure hydrogen - Gas contamination

IV. UTURE OUTLOOK

UHS in salt caverns is not yet widely operated, lowering the cost of hydrogen generation by electrolysis will be a critical element in implementing this form of energy storage on a large industrial scale in the future. From the economic perspective, the cost of hydrogen that has been produced by alkaline electrolyzers is high [24]. Thus, this has become a limiting factor for the use of the water electrolysis method of hydrogen generation on a large scale. In views of economical requirements, water electrolysis does not have a significant commercial impact since it has a high level of electricity consumption and it has not been cost-effective [24]. Even though it is technologically simple and delivers very clean hydrogen gases, electricity is known to be the most expensive form of energy. Given that the fact of electricity has an average efficiency of about 30 to 40% when compared to primary energy, the electrolyzer's total efficiency is often less than 40% [24]. As a result, lowering the price of hydrogen generation as much as possible is important for the future hydrogen economy when meeting the sustainable development goal. Besides, plenty of scholars have stated that hydrogen could become an important energy commodity in the future market of global scale, this entails that significant cost and performance improvements in production, storage, and conversion are highly required [25]. In this case, investing in hydrogen-based technologies plays an essential role, in which only a well-balanced mix of research, development, and demonstration efforts, as well as commercial deployment, can result in the required technological advancements and cost savings.

V. CONCLUSION

In summary, governments around the world are dedicated to seeking and exploring green energy sources, as the public awareness of energy-related environmental concerns grows.

Hydrogen, as a promising and appealing energy carrier, may become a strong candidate to replace fossil fuels and capture the future energy market. Hydrogen-based storage technologies are even more effective and feasible to meet energy demands while reducing greenhouse gas emissions. It is easy to discover that the global hydrogen production system has been progressively shifted from initial fossil fuels based to renewable sources, e.g., wind turbines, solar photovoltaic, geothermal, and etc. This transition is crucial for promoting low carbon development and environmental conservation, which accelerates the pace to achieve sustainable development. This study is based on energy-related environmental issues to investigate possible green energy alternatives: hydrogen, with an emphasis on subterranean hydrogen storage in salt caverns through quantitative analysis. Finally, this paper concludes that the salt cavern is the best and feasible underground storage site through assessing other types of underground facilities, i.e., saline aquifers and depleted gas and oil fields. These results offer a guideline for the future development of hydrogen storage.

REFERENCES

[1] Enerdata (2021). Total Energy Consumption. Global Energy Statistical Yearbook 2021. Avaliable at: https://yearbook.enerdata.net/total-energy/world-consumption-statistics.html

[2] IEA (2019). Global Energy & CO2 Status Report 2019. Avaliable at: https://www.iea.org/reports/global-energy-co2-status-report-2019

[3] Zhang, Y. H., Jia, Z. C., Yuan, Z. M., Yang, T., Qi, Y., & Zhao, D. L. (2015). Development and application of hydrogen storage. Journal of Iron and Steel Research International, 22(9), 757-770.

[4] IEA (2019). The Future of Hydrogen. Avaliable at: https://www.iea.org/reports/the-future-of-hydrogen

[5] Colbertaldo, P., Agustin, S. B., Campanari, S., & Brouwer, J. (2019). Impact of hydrogen energy storage on California electric power system: Towards 100% renewable electricity. International Journal of Hydrogen Energy, 44(19), 9558-9576.

[6] Momirlan, M., & Veziroglu, T. N. (2002). Current status of hydrogen energy. Renewable and sustainable energy reviews, 6(1-2), 141-179.

[7] Dincer, I., & Acar, C. (2015). Review and evaluation of hydrogen production methods for better sustainability. International journal of hydrogen energy, 40(34), 11094-11111.

[8] IEA (2020). Hydrogen, IEA, Paris. Avaliable at: https://www.iea.org/reports/hydrogen

[9] ES2020, 2010. Energy 2020. A strategy for competitive, sustainable and secure energy (ES2020). European Commission, COM(2010) 639 final, 2010. Avaliable at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2010:0639:FIN:EN:PDF. https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2030-climate-energy-framework_en

[10] Bünger, U., Michalski, J., Crotogino, F., & Kruck, O. (2016). Large-scale underground storage of hydrogen for the grid integration of renewable energy and other applications. In Compendium of hydrogen energy (pp. 133-163). Woodhead Publishing.

[11] Ozarslan, A. (2012). Large-scale hydrogen energy storage in salt caverns. International journal of hydrogen energy, 37(19), 14265-14277.

[12] Liu, W., Zhang, Z., Chen, J., Jiang, D., Wu, F., Fan, J., & Li, Y. (2020). Feasibility evaluation of large-scale underground hydrogen storage in bedded salt rocks of China: A case study in Jiangsu province. Energy, 198, 117348.

[13] Evans, A., Strezov, V., & Evans, T. J. (2012). Assessment of utility energy storage options for increased renewable energy penetration. Renewable and Sustainable Energy Reviews, 16(6), 4141-4147.

[14] Elberry, A. M., Thakur, J., Santasalo-Aarnio, A., & Larmi, M. (2021). Large-scale compressed hydrogen storage as part of renewable electricity storage systems. International Journal of Hydrogen Energy.

[15] Tarkowski, R. (2019). Underground hydrogen storage: Characteristics and prospects. Renewable and Sustainable Energy Reviews, 105, 86-94.

[16] Agung Tri Wijayanta, Takuya Oda, Chandra Wahyu Purnomo, Takao Kashiwagi, Muhammad Aziz, Liquid hydrogen, methylcyclohexane, and ammonia as potential hydrogen storage: Comparison review, International Journal of Hydrogen Energy, Volume 44, Issue 29, 2019, Pages 15026-15044, ISSN 0360-3199.

[17] El-Eskandarany, M. S., Saeed, M., Al-Nasrallah, E., Al-Ajmi, F., & Banyan, M. (2019). Effect of LaNi3 Amorphous Alloy Nanopowders on the Performance and Hydrogen Storage Properties of MgH2. Energies, 12(6), 1005.

[18] Zivar, D., Kumar, S., & Foroozesh, J. (2021). Underground hydrogen storage: A comprehensive review. International Journal of Hydrogen Energy, 46(45), 23436-23462.

[19] Elberry, A. M., Thakur, J., Santasalo-Aarnio, A., & Larmi, M. (2021). Large-scale compressed hydrogen storage as part of renewable electricity storage systems. International Journal of Hydrogen Energy.

[20] Lindblom, U. E. 1985. A conceptual design for compressed hydrogen storage in mined caverns. International Journal of Hydrogen Energy, 10, 667–675.

[21] Hirscher, M., Züttel, A., Borgschulte, A., & Schlapbach, L. (2009). Handbook of hydrogen storage. Ceramic Transactions, 202.

[22] Sáinz-García, A., Abarca, E., Rubí, V., & Grandia, F. (2017). Assessment of feasible strategies for seasonal underground hydrogen storage in a saline aquifer. International Journal of Hydrogen Energy, 42(26), 16657-16666.

[23] Hemme, C., & Van Berk, W. (2018). Hydrogeochemical modeling to identify potential risks of underground hydrogen storage in depleted gas fields. Applied Sciences, 8(11), 2282.

[24] Stojić, D. L., Marčeta, M. P., Sovilj, S. P., & Miljanić, Š. S. (2003). Hydrogen generation from water electrolysis—possibilities of energy saving. Journal of power sources, 118(1-2), 315-319.

[25] Barreto, L., Makihira, A., & Riahi, K. (2003). The hydrogen economy in the 21st century: a sustainable development scenario. International Journal of Hydrogen Energy, 28(3), 267-284.