Trends in using hydrogen for large-scale green energy storage

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Abstract: An increasing supply of energy from renewable sources is expected soon, demanding more energy storage alternatives in the short and long-term. The short-term deals with short duration ranging from instantaneous operation (load generation balance) to satisfactory daily and weekly load curve. In the long-term, the stored energy comes from seasonal periods of excess generation that can extend over considerable time intervals. When considering the interconnection of large-scale electrical systems, the volume of surplus energy can reach hundreds of GW. The use of this surplus energy to generate hydrogen appears as a great opportunity to store clean energy, contributing to the efficient exploitation of the installed renewable capacity and contributing to the system's decarbonization. On the other hand, areas with little economic interest or isolated areas with good potential for renewable energy are becoming attractive to produce the so-called green hydrogen, contributing to an important step towards establishing a green economy. This paper presents a brief review and discussion of expectations regarding hydrogen as an alternative for large-scale energy storage.

Keywords: Renewable energy, storage, hydrogen.

1. INTRODUCTION

Hydrogen is a flexible energy storage technology. It may be produced from different energy sources, such as natural gas, waste, coal, oil, solar, tidal, and other renewables. Once produced, hydrogen can be applied in different applications, particularly to generate electrical power using fuel cells. It is also possible to transport gaseous hydrogen in pipelines or liquid hydrogen in ships. Due to it, hydrogen is considered a promising alternative to low-carbon development. However, such a process demands modifications in power systems and the society, impacting energy infrastructure, costs increase, and changes in way-of-life and consumption patterns (Glanz and Schönauer, 2021).

Within the perspectives of innovative business in a future low-carbon society, Chile has presented, in November 2020, the national strategy of green hydrogen produced from renewables (of Energy, 2020). The intention is to reach 5GW of electrolysis capacity by 2025, producing the cheapest clean hydrogen in the world by 2030 and turning the country one of the biggest exporters by 2040, when the country expects to become emission-free. To accomplish it, Chile plans to take advantage of the world's biggest solar radiation in the Atacama desert and constant fast winds in the southern region. On the other hand, Brazil announced a new climate target, to reduce carbon emissions, from 43% to 50% by 2030; and carbon neutrality until 2050, which was formalized during COP26. In Europe, on the other side, there are different opportunities to produce and store hydrogen according to decarbonization goals. The consequences from such a process are not clear yet, but evidences show that the hydrogen has a big role in it (IEA, 2019).

In the Brazilian scenario, hydrogen is part of the energy strategy in the National Energy Plan 2050 (PNE 2050). This plan pointed out hydrogen as an element of interest in the context of decarbonization of the energy matrix, listing different uses and applications (EPE, 2020). In February 2021, the research "Bases for the Consolidation of the Brazilian Hydrogen Strategy" was published, addressing the market panorama, technological routes, costs, challenges, the role of hydrogen in the energy transition and finally, the implications for public policies (EPE, 2021a). As a result, in July 2021, the proposals and guidelines of the National Hydrogen Program (PNH2) were presented, with the main objective of making hydrogen a contributing element to net carbon neutrality by 2050 (EPE, 2021b).

This paper presents an analytical review of the current situation and trends in using hydrogen to store green energy toward a low-carbon society development.The use of hydrogen contributes to mitigating greenhouse gas emissions because it is clean energy when it is produced from a renewable source. Section II presents the ways to produce hydrogen from renewable sources. In Section III the principle of fuel cells is presented. In Section IV, viable alternatives for hydrogen storage are presented. Section V presents perspectives and challenges. Finally, Section VI gives the conclusions of this paper.

2. HYDROGEN PRODUCTION

The hydrogen can be produced from renewable sources considering two trends: a) seasonal production and storage; b) green hydrogen production.

In the first option, hydrogen production uses excess of renewable energy from mid-term and long-term to mitigate mid and long-term fluctuations as well. In the second alternative, renewable-based plants are installed exclusively to produce hydrogen, creating a production chain around it, motivating surprising business models and opportunities in the coming years. Fig. 1 summarizes the process from the production of hydrogen to its final use.

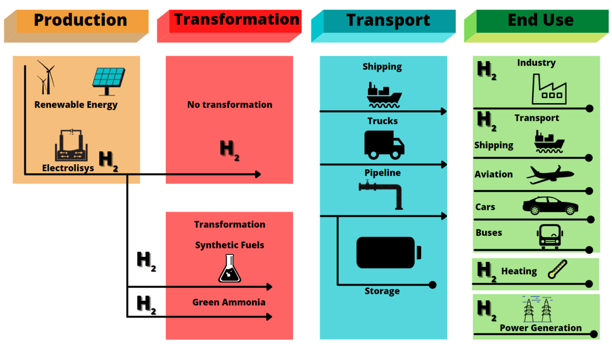

Figure 1. Green hydrogen cycle.

2.1 Seasonal Storage

While short-term variations are adequately faced with "fast" technologies, e.g., electrochemical batteries, annual fluctuations demand different solutions due to longer storage periods and limited annual cycles. Solutions for long-term energy fluctuations are only required every two years. They can be considered as measures of adequacy - a measure that is collectively financed, for example, through a system operator (ESA, 2021; Guerra et al., 2020). Hydrogen storage is a key element in hydrogen energy systems, especially when it comes to large-scale hydrogen (Moradi and Groth, 2019). Authors in Van Gerwen et al. (2020) investigate the commercial viability of seasonal energy storage in The Netherlands. Daily, weekly and annual patterns are analyzed over a period of 58 years using historical climate data. Over this period, they identify when seasonal energy storage can have an important role. The main conclusions presented are:

- Seasonal energy storage must compete with other alternatives observing the lotwest costs;
- Compressed hydrogen is a viable option to seasonal storage;
- The demand variability and the intermittent renewable generation in the period hinder the distinction between seasonal storage and capacity adequacy;
- A single company can not provide seasonal storage alone. Therefore, an initial investment in synthetic fuels is necessary (for instance, to apply in mobility or industry); and
- Seasonal storage is both an opportunity and a necessity. If the need to provide carbon-free electrical power is sufficiently high, it will reflect higher carbon costs, making seasonal storage a viable option. When the need is sufficiently large, seasonal storage becomes a business opportunity.

The viability of seasonal energy storage depends on the availability of low-cost, high-volume storage alternatives. In terms of Levelized cost, underground storage of compressed hydrogen (salt caves or depleted hydrocarbon fields) seems the most viable option for seasonal storage.

2.2 Green Hydrogen

Hydrogen is classified into three categories associated with the process and the fuel used to produce it.

- Gray hydrogen: it is produced from fossil fuels (Atilhan et al., 2021). Currently, this kind of hydrogen represents more than 90% of all globally produced hydrogen;
- Blue hydrogen: it is also produced from fossil fuel, but the carbon emissions are captured, stored, and used in other processes;
- Green Hydrogen: it is produced from renewable sources.

Green Hydrogen use must impact the economy and industry. The decarbonization goals of the Paris Agreement impose a 40% of clean energy share by 2050 (Rabiee et al., 2021). The increasing Green Hydrogen share must contribute to decreasing carbon production in industry and energy systems (Jiao et al., 2020).

The Green Hydrogen production must change the role of renewables making economically attractive far regions with high solar, wind and oceanic potential. Plants based on renewables may produce Green Hydrogen in such regions, which could be transported and sold in markets adapted to its use (of Energy, 2020).

The Green Hydrogen is produced through electrolysis from renewables, and it is almost carbon-free, with a production cost of USD 6,00 per kilogram by 2020 (Council, 2020). This cost may cheapen to USD 2,50 per kilogram by 2030. The increasing competitiveness of wind power brings new perspectives on green hydrogen costs decrease. Other production costs include the electrolyzer, which may decrease by half by 2050 due to improvements in efficiency, and utilization factor (IRENA, 2019; FHC, 2021; Glenk and Reichelstein, 2019).

The consortium formed by VNG, Uniper, Terrawatt and DBI plans to build a 40 MW wind farm by 2030 with electrolyzers, 50 billion cubic meters of storage and a dedicated hydrogen pipeline (Kakoulaki et al., 2021). Similar initiatives are in progress in other countries. In a future perspective, International Renewable Energy Agency (IRENA) reports a share of 5,277 TWh of hydrogen and renewables in energy consumption by 2050 (IRENA, 2019).

2.3 Hydrogen production by electrolysis

Hydrogen can be produced by Electrolysis. This one is a promising option for carbon-free hydrogen production from renewable and nuclear resources. Electrolysis is the process of using energy to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyzer. Electrolyzers can range in size from small, appliance-size equipment (well-suited for small-scale distributed hydrogen production to large-scale), central production facilities that could be coupled directly to renewable or other non-greenhouse-gas-emitting forms of electricity production (EERE, 2021).

Alkaline water electrolysis is a mature technology and one of the simplest methods used for hydrogen production. It has the advantage of being able to produce hydrogen using only renewable energy. The conversion efficiency for this technology is about 65% 70% (lower heating value) (ESA, 2021). In an alkaline water electrolysis cell, electricity is used to split water molecules into gaseous hydrogen and oxygen. Water splitting occurs according to the following half-cell reactions:

anode:

$$H_2O_{(liq)} \rightarrow^{1/2} O_{2(g)} + 2H^+ + 2e^- \tag{1}$$

cathode:

$$2H^+ + 2e^- \rightarrow H_{2(g)} \tag{2}$$

full reaction:

$$H_2O_(liq) \rightarrow H_{2(g)} +^{1/2} O_{2(g)} \tag{3}$$

Water molecules are reduced to molecular hydrogen and hydroxyl ions at the cathode of the alkaline cell. Solvated hydroxyl ions migrate through the electrolyte to the anode where they are oxidized into molecular oxygen (EERE, 2021).

Hydrogen production using proton exchange membrane water electrolysis (PEMWE) technology is still at an early stage of commercialization, but it shows the most promise (Song et al., 2021). It does not produce heat, vibration and has no moving parts, reducing maintenance and risks of accidents. There are several types of PEMWE; however, the basic components present in all of them are the anode, cathode, and electrolytic membrane, as illustrated in Fig. 2. The anode has the responsibility to conduct the electrons released from the hydrogen molecules for use in the external circuit. The cathode has the function of directing the electrons coming from the external catalyst circuit to be recombined with the hydrogen and oxygen ions to form water. The electrolytic membrane is a system that transports protons from the anode to the cathode. It is a special material, capable of allowing only the transfer of positively charged ions (Breeze, 2018)

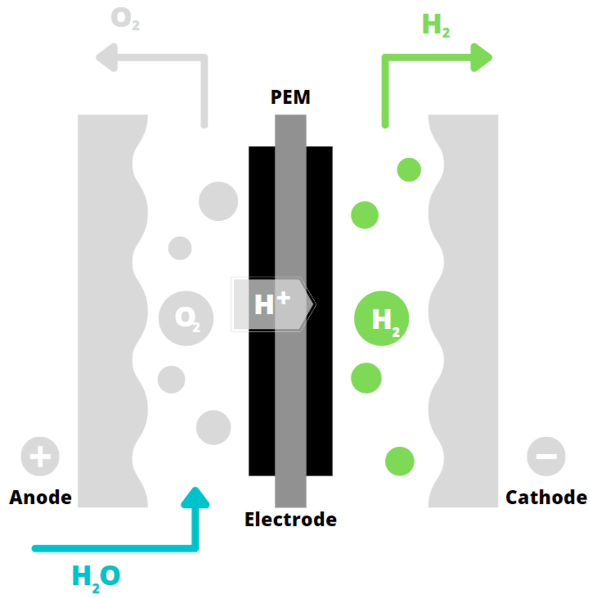

Figure 2. Proton Exchange Membrane Water Electrolysis

3. POWER GENERATION USING HYDROGEN

The power generation using hydrogen may be performed by direct burn injecting it in engines or using fuel cells, which is dominant due to higher efficiency and fewer emissions. The operating principle of a fuel cell is simple. The hydrogen comes into contact with the anode and, from there, the gas separates into two ions: H+ and e-. Positive ions cross the electrolytic membrane. The negative ions move towards the charge in a continuous electric current. At the cathode, negative and positive ions captures oxygen in the air and turn into water (Moldrik and Chvalek, 2011). The Fig. 3 depicts the process.

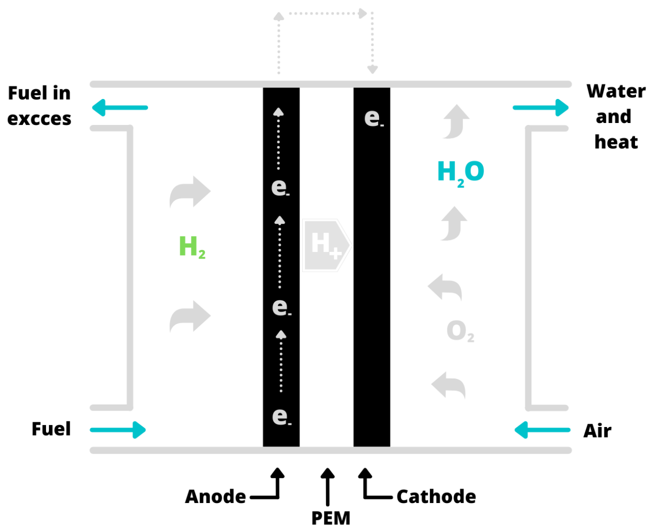

Figure 3. Proton Exchange Membrane Fuel Cell

The fuel cell power generation still a heavy burden on initial investment and operating costs when compared to traditional plants. It is a technology little known and used in the industry and with a small amount of qualified labor to maintain this system. The electrical efficiency of hydrogen-based storage is from 30% to 50 %. It is relatively low compared to other storage technologies, both on a small scale (batteries) and on a larger scale (Compressed-air energy storage - CAES). However, due to the high scale of storage, interest in this option is gradually increasing (Breeze, 2018).

4. HYDROGEN STORAGE ALTERNATIVES

The hydrogen can be stored in a gaseous state or in a liquid state (BloombergNEF, 2020). In gaseous state, the following alternatives are suitable:

- Salt caverns: allows for large-scale storage. However, the geographical availability of this alternative is limited.
- Depleted gas fields: the availability of extinct gas fields is also geographically limited. In this option it is also possible to store hydrogen on a large scale.
- Rock caverns: This option allows storage of H2 on an intermediate scale. The availability of caverns is limited.
- Pressurized containers: allows the storage of H2 for short-term use (hours, days). Containers are manufactured, with no availability restriction.

In liquid state, the most popular alternatives are:

- Liquid hydrogen: Allows storage of small-medium volumes, for use on the days-week scale.
- Ammonia: It is used for storage in large volumes, for applications on the scale of months-weeks.
- LOHC (liquid organic hydrogen carrier): As in the previous case, this option allows storage in large volumes, for use on a scale of weeks to months.

Several studies have focused on the available alternatives for the hydrogen transport by sea (Wulf et al., 2018). It is a consensus that to avoid excessive costs, the sea transport of hydrogen requires the highest possible energy density per unit volume. Since hydrogen cannot be transported in ships in its gaseous forms, other alternatives must be considered. For long distance hydrogen transport the alternatives include liquid hydrogen, ammonia or LOHC. LOHC are organic compounds that can absorb and release hydrogen through chemical reactions. All alternatives imply additional energy costs, need improvement for technical and economic feasibility(Noussan et al., 2020). After being transported over a long distance, hydrogen needs to be distributed safely and efficiently to end users. At this level, the options available are broader, including gaseous transport of H2 through pipelines or liquid or compressed hydrogen by trucks.

5. DISCUSSION

This section summarizes energy storage discussion using hydrogen, raising several key aspects frequently referred to in the technical literature. Besides, perspectives and challenges to develop such technology are presented.

- Efficiency: the efficiency of hydrogen-based energy storage is relatively low compared to other storage technologies, both on a low and large scale. However, due to the possibility of large-scale applications, the interest in hydrogen is increasing. According to a 2019 International Energy Agency (IEA) report (IEA, 2019), hydrogen has a big potential in the future economy. It may help to face several critical challenges, giving alternatives decarbonize many sectors which are facing problems in evolving towards a greener operation, e.g., transportation, chemical, and steel industries. It also may help to improve air quality and to strengthen energy security. Air pollution kills an estimated seven million, people worldwide every year (WHO, 2021). The IEA reports that global energy-related CO2 emissions in 2019 have stabilized at the level of 33 gigatonnes after two years of increasing. This reflects the growing role of renewable sources (mainly wind and photovoltaic solar energy), as well as the replacement of coal with natural gas, among other initiatives(IEA, 2020).
- Energy density: the hydrogen energy density ranges from 33 to 39 kWh/kg. One kg of gaseous hydrogen has the same energy content as $2.8kg$ of gasoline. However, the hydrogen has a low volumetric density, $0.53kWh/L$. Thus, for applications in transportation, it may be compressed to become competitive.
- Storage costs: producing hydrogen from low carbon energy is expensive now. The IEA (IEA, 2019) predicts this cost will fall at least 30% by 2030 as a result of the decaying costs of renewables and increasing of hydrogen production. Fuel cells, refueling equipment and electrolyzers (which produce hydrogen from electricity and water) can benefit from mass manufacturing. The development of hydrogen infrastructure is slow and prevents its widespread adoption. Hydrogen prices for consumers are highly dependent on how many refueling stations there are, how often they are used and how much hydrogen is delivered per day. Solving it requires planning and coordination that brings together national and local governments, industry, and investors. Underground hydrogen storage in salt caves is technically a viable option for large-scale storage of electricity, but it requires adequate geology and also public acceptance (IEA, 2020). The specific costs of building the salt caves decrease significantly with size, with investments in caves $> 500,000m^3$ in brownfield areas ranging from 47 to 71 USD/m^3 (HyUnder, 2014).
- Availability: Currently, hydrogen is usually produced from natural gas and coal (IEA, 2020). Its application on an industrial scale is a reality, but producing it releases annual CO_2 emissions equivalent to Indonesia and United Kingdom together. Harnessing that scale on the road to a clean energy future requires capturing CO_2 of hydrogen production from fossil fuels and an increased supply of hydrogen from clean sources. Hydrogen storage as a way to store renewable-based energy via electrolysis and underground storage is economically challenging (Noussan et al., 2020). In the short-term, according to the assumptions adopted, the transport sector is the only market expected to allow a hydrogen selling price that can allow the commercial operation of an integrated hydrogen electrolysis and storage plant. As a result,

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availability is strongly linked to the form of storage and transportation, aspects that limit the growth in the term cost of this type of storage.

- Standardization: Hydrogen generation has standardized technologies; however, they need improvement to make this process more efficient. For transportation, natural gas pipelines can be used with appropriate adaptations. However, standardization for the entire hydrogen production chain will be achieved as costs make this technology feasible.
- Technology Readiness Level (TRL): Technology maturity still has a TRL between 6 and 7. According to expectations, hydrogen will reach an appropriate relation between technology and the market by 2030.
- Safety: hydrogen is highly flammable and easy ignition. Therefore, technologies and procedures that standardize the security of storage and transportation must be followed.
- Viability for microgrids: Microgrids can benefit from hydrogen in different ways to generate energy, heat and drive industrial processes. Hydrogen can be distributed with pipelines similar to natural gas ones with some adaptations. As far the hydrogen production chain reaches maturity and competitiveness in future decades, such a vision of the future will become a reality.

5.1 Perspectives

The growing need for flexibility options to facilitate the continuous deployment of electricity from intermittent renewable energy sources should not drive the deployment of hydrogen energy storage on a structural basis in the short term. But hydrogen definitely has a long-term role to play as a low-zero CO_2 energy vector toward to a decarbonized energy system. To accomplish its full potential, hydrogen needs to become an integral part of the energy system as a universal energy carrier, with its additional energy storage capacity.

An example of such a role is already seen in the automotive industry, where hydrogen developments have entered a new phase. The German H2Mobility initiative, for instance, announced plans to install 400 hydrogen refueling stations by 2023, and similar market preparation and initial market development initiatives are being developed in other European countries such as the United Kingdom or France, as well as in Japan, the USA, and South Korea. In addition, several OEM - Original Equipment Manufacturer intends to introduce Fuel Cell Electric Vehicles (FCEV) in market. Electric mobility based on fuel cells in combination with hydrogen from water electrolysis, ideally using renewable electricity, is also one of the few options capable of meeting future emissions reduction targets of CO_2 for the transportation sector. Hydrogen Europe, an association representing European industries, research centers, and associations in the hydrogen and fuel cell sector, maintains a website with up-to-date information on closed and ongoing hydrogen projects (Noussan et al., 2020) describing the research and investment initiatives related to the theme.

5.2 Challenges

The widespread and clean use of hydrogen in the global energy transition faces several challenges. The efforts and resources spent in Europe to develop technologies around hydrogen are considerable. The European Economic Community financed one project, HyUnder, to assess the long-term underground large-scale hydrogen storage potential from renewable sources for a total amount of USD 2,099,619.09 (HyUnder, 2014). In the Project report, the following conclusions on the storage potential of the evaluated countries are highlighted (BloombergNEF, 2020; Noussan et al., 2020; IEA, 2020; HyUnder, 2014):

- There is geological potential for underground hydrogen storage in salt caves in all countries examined. In particular, Germany and the Netherlands appear to offer good geological conditions in their northern region. Initially, there will be a preference for existing natural gas storage locations due to the necessary infrastructure availability.
- The electrolysis dominates the total costs of an integrated underground hydrogen production and storage facility, with more than 80% (with the utilization of around 50 %), of which electricity costs have an important share. Although a cave requires a significant initial investment, it makes a relatively small contribution to the total specific costs of hydrogen ($< 0.59\ USD/kg$).
- Despite the higher specific costs of a smaller cave of around $50,000m^3$ compared to a large cave, the investment impact is still relatively small and may initially justify the development of smaller caves.
- In addition to the capital expenditure (CAPEX) of the electrolyzer and the purchase prices for electricity, the hydrogen costs of electrolysis depend heavily on the electrolyzer's use. With less than 2,000 hours of continuous use, capital costs begin to dominate production costs, making hydrogen from electrolysis increasingly expensive. As scenarios with more than 2,000 hours of excess energy are not common to be achieved, the storage of electricity in the form of hydrogen still remains expensive.

6. CONCLUSION

Green Hydrogen is the driving force behind the new low-carbon society. As the technologies linked to their production, storage and distribution are improved, competitive prices and concrete indicators of the decarbonization process of the grid will become evident. Hydrogen has the potential to help with the intermittent production of renewables, such as solar photovoltaic (PV) and wind energy, increasing their contribution to the decarbonization process. Hydrogen is one of the main options for storing energy from renewable sources. It looks promising as a lower-cost option to store electricity in days, weeks, or even months. Hydrogen and hydrogen-based fuels can transport energy from renewable sources over long distances - from regions with abundant solar and wind resources, to cities in need of energy thousands of kilometers away.

Many regions with low economic attractiveness (e.g. infertile or low productivity land, inhospitable areas, etc.) can be used to explore renewable sources to produce hydrogen. This can be exported to large consumption centers or other countries, generating new productive and economic chains In a preliminary analysis, the offshore wind potential of Brazil, especially in the Brazilian equatorial margin, presents itself as an excellent opportunity (Pimenta et al., 2019). Additionally, the north coast of Brazil presents attractive indicators of potential in oceanic energies, with significant tidal levels and tidal streams (Czizeweski et al., 2020). For example, the Varador Channel in the State of Amapá, presents good energy density in oceanic energy. However, this extensive area is not inhabited and is far from the large centers of electrical energy consumption.

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