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Hydrogen Supply Chains – New Perspective for Stabilizing Power Grid

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Abstract: Today's energy systems increasingly rely on renewable energy sources. However, the energy potential of these solutions is not stable. This means that there will always be a supply and demand imbalance in this respect. Therefore, it becomes extremely important to create a hydrogen supply chain system that stabilizes the operation of the electricity network in the long term. The article shows the possibility of converting energy into hydrogen, which has many potential utility properties, including the possibility of changing it back into electricity. The assumptions for the integration of renewable energy sources with the power grid through hydrogen supply chain have been presented.

Keywords: energy storage, energy system stabilization, hydrogen production, hydrogen supply chain, power grid, renewable energy sources

1. INTRODUCTION

Hydrogen has great potential for general modernization and supporting the potential of electricity, heat and industrial technologies. This is due to the use of renewable energies in hydrogen production technologies, many proven methods of storing energy in hydrogen, as well as the possibility of using hydrogen without emissions in various energy and industrial installations and in transport.

From the point of view of using energy from hydrogen to stabilize the power grid, there are three basic utility functions of hydrogen:

- hydrogen as a fuel resulting from conversion from electricity,
- hydrogen as a form of electricity storage,
- hydrogen as a carrier of electricity (alternative form).

Along with the rapid development of renewable power generation, the impact of their inherent intermittency, fluctuation and difficulty in prediction on the existing electric grid attracts more and more concern. There is a need for flexibility within the system. Electricity storage is seem to be a solution for eliminate the curtailment, increase the penetration of renewable power generation, and provide better connection between demand and supply as well as other economic and technical benefits. Electricity storage is not a new technology. Currently, there are dozens of different storage methods in existence, from capacitor/super capacitors, batteries, pumped-hydro, compressed air, flywheels, to superconducting magnetic energy storage, hydrogen and so on. Among them, hydrogen is believed to be a promising candidate not only for energy storage but also leads to a new hydrogen economy [1]. An open question and an important research question is the issue of including the hydrogen storage system in the existing power grids, developing technical, legal, economic and social assumptions that will form the basis for building the model, and then the system itself.

A cover must be made for the potential of hydrogen as a fuel that can be used in transport. Zero emission vehicles like battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV) fuelled by renewably-produced hydrogen have the potential to reduce both CO2 emissions and locally active pollutants at the same time. Moreover, hydrogen facilitates the coupling of electricity with the mobility sector: producing hydrogen via electrolysis during periods when high renewable power generation exceeds grid load would offer an emission-free fuel for FCEVs [2]. In such a case, the issue of energy distribution is extended to the issue of fuel distribution, and thus the creation of hydrogen supply chains.

2. ENERGY PRODUCTION BASED ON THE HYDROGEN CONCEPT

Hydrogen plays a minor role today in the electricity sector: it is responsible for less than 0.2% of electricity production. It is mainly related to the use of gases from metallurgy, petrochemical plants and refineries. This may change in the future. Ammonia co-firing could reduce the carbon dioxide intensity of existing conventional coal-fired power plants, and hydrogen-fired and combined cycle gas turbines could provide flexibility in electricity systems with an increased share of variable renewables. In the form of compressed gas, ammonia or synthetic methane, hydrogen can also become a long-term storage option to compensate for seasonal changes in electricity demand or its generation from renewable sources [3].

Hydrogen can be produced from a large number of different feed stocks such as water, coal, natural gas, biomass, hydrogen sulfide, boron hydrides, and others, through thermal, electrolytic or photolytic processes. Currently, over 50 million tons of hydrogen is produced worldwide annually. However, an estimated 95% or more is from fossil fuels [2]. Hydrogen production methods are presented in Table 1.

Table I: General hydrogen production methods

Method	Description	Material	Energy
Water electrolysis	Water decomposition into oxygen and hydrogen by passing a direct current that drives electrochemical reactions	Water	Electrical
Hightemperature steam electrolysis	Steam decomposition by using direct current assisted by thermal energy to drive electrochemical reactions to split water molecule	Steam	Electrical, Thermal
Photo electrochemical water splitting	Uses electric and photonic energy to electrolyse water and generate H2 and O2	Water	Photonic, Electric
Photocatalysis	Uses photonic energy and catalysts to decompose water molecule	Water	Photonic
Biophotolysis	Uses a reversible reducible cofactor and photometabolically active microbes to generate hydrogen from water	Water	Photonic, Biochemical
Anaerobic digestion	Uses biological energy manipulated by microbes to extract hydrogen from biodegradable materials in the absence of oxygen	Biomass	Biochemical
Thermolysis	Uses thermal energy to decompose water molecule at very high temperature (2500◦C)	Water	Thermal
Thermochemical water splitting	Thermally driven chemical reactions performed in a loop with the overall result of water splitting	Water	Thermal
Thermocatalytic cracking	Uses thermal energy to break the carbon-hydrogen bonds of hydrocarbons and eventually generate hydrogen	Fossil fuels	Thermal
Gasification	Converts solid carbonaceous materials into carbon monoxide and hydrogen by reacting them with O2 and/or steam	Water, fossil fuels, biomass	Thermal
Reforming	Reacts carbon-based liquid or gaseous fuels with steam at high temperature to produce carbon dioxide and hydrogen	Water, fossil fuel or biofuels	Thermal

Source: [4].

When hydrogen is used to store green energy, electrolysis is the primary production system. Electrolysis uses electrical energy to split apart water molecules to produce hydrogen and oxygen. With respect to decarbonising, the source of electricity is important. There is no environmental benefit in generating hydrogen from an electrolyser powered by electricity from fossil fuels. Electrolysers provide significant added benefit to renewable generation that is constrained. When there is ample resource but insufficient demand or export infrastructure then electrolysers provide a solution where excess power can be stored and/or exported in the form of hydrogen [5].

3. HYDROGEN STORAGE AS A KEY ELEMENT OF THE POWER GRID STABILIZING SYSTEM

Hydrogen and hydrogen fuels, such as ammonia and synthetic natural gas, can be fuels for energy production and also are options for large-scale and long-term energy storage to counterbalance seasonal changes in electricity demand or its fluctuating generation from renewable energy sources. Hydrogen has a very high energy content by weight (about three times more than gasoline), but it has a very low energy content by volume (liquid hydrogen is about four times less than gasoline). This makes hydrogen a challenge to store.

Gas compression to low volume and high pressure is a commonly used storage method for gaseous fuels. The apparent difference between compression of hydrogen and compression of other conventional fuel gases, such as natural gas and town gas, is the energy requirement. As hydrogen has a lower specific gravity than other fuel gases, it takes more energy to compress hydrogen for given mass and compression ratio [6]. The efficiency of energy storage by compressed hydrogen gas is about 94%. This efficiency can compare with the efficiency of battery storage around 75%. It is noted that increasing the hydrogen storage pressure increases the volumetric storage density (H2-kg/m3), but the overall energy efficiency will decrease [7].

Liquefied hydrogen is denser than gaseous hydrogen and thus it contains more energy in a given volume. Similar sized liquid hydrogen tanks can store more hydrogen than compressed gas tanks, but it takes energy to liquefy hydrogen. However, the tank insulation required to prevent hydrogen loss adds to the weight, volume, and costs of liquid hydrogen tanks [8].

Many commercially available technologies are used to store hydrogen. The most common method is to use high-pressure tanks that come in different sizes and used in different pressure ranges. Hydrogen can be stored underground in caves, aquifers and spaces left over from oil and gas production. Underground hydrogen storage systems are similar to natural gas storage systems, but are approximately three times more expensive. Underground hydrogen storage systems pose minimal technical problems.Pure hydrogen is, in most cases, stored in pressurized tanks. Few materials of construction are available for the manufacture of tanks suitable for hydrogen storage as it increases their fragility considerably. Currently, the best solution is ultra-light composite materials that can withstand pressures above 20 bar. They are used in prototypes of cars and buses. Among them are [9]:

- metal tanks made of steel, with a pressure of 200 bar, or of aluminum, with a maximum pressure of 175 bar,
- aluminum tanks reinforced with glass, aramid or carbon fibers with a maximum pressure of over 250 bar,
- cylinders made of fiberglass / aramid or carbon fiber composites with a metal insert, withstanding maximum pressures of 305 and 438 bar respectively,
- the cylinders are made of typical carbon fiber covered with a polymeric layer that can withstand pressures above 661 bar.

Carbon nanofibers, such as carbon nanotubes - structures with unique electrical and mechanical properties, resembling a mat woven of carbon ropes under an electron microscope, may become the material of the future for the construction of hydrogen tanks. They conduct heat well and show high strength, which makes them one of the strongest and stiffest materials discovered today [9].

Compressed and liquid hydrogen are the current state of the art in hydrogen storage. All alternative hydrogen carriers substances like metal organic frameworks (MOFs), metal hydrides, chemical hydrides or liquid organic hydrogen carrier (LOHCs) were initially investigated for on-board hydrogen storage in a fuel cell vehicle [10]. While storage systems for mobile storage allow higher capital investments, the use of carrier systems for the supply infrastructure requires a cheap carrier compound with easy handling and a high hydrogen share. Solid carriers like MOFs or metal alloys do not fulfil these requirements. Chemical and metal hydrides still lack regenerable carriers, which are not dismantled during unloading, with scalable loading and unloading reactions, and offering easy transportation of the loaded and unloaded carrier compound. LOHCs are thereby promising candidates for hydrogen infrastructure, since the loaded as well as unloaded carrier exist naturally in a liquid state [11].

High-pressure storage tanks remain cost-intensive while the liquefaction of hydrogen is energy-intensive (30% of the LHV of hydrogen) [12]. The Nexant Report [13] included alternative carrier systems like LOHCs and metal hydrides in its calculations. Thereby, it was determined that using alternative carriers in a pathway that discharges hydrogen at the fuelling station and supplies compressed hydrogen to vehicles will offer little or no benefit for fuelling station costs. Another studies shows that the main benefit of an LOHC system lies in the ease and low cost of storage and transportation [11].

4. INTEGRATION OF THE HYDROGEN ENERGY SYSTEMS WITH EXISTING POWER NETWORKS

Currently, many initiatives are taken in the field of building power plants, fuel cells or energy storage systems using hydrogen. Examples include Australia, the USA, Japan and many others. The most significant projects undertaken in recent years in this area include [14,15,16]:

1. Renewable Hydrogen Production Plants, California, USA (120-MWe). The complex will process 40,000 tons of waste annually, the hydrogen will be used to supply California’s 42 hydrogen fueling

stations. The goal is to immediately get that to 100 and then eventually to 1,000. Construction will begin in 2021 and it is expected to be fully operational in the first quarter of 2023.

2. Crystal Brook Energy Park, Australia (50-MWe). Along with hydrogen production, Neoen Australia's "super-hub" facility will have 110-MW of wind, 100-MW of PV, and 100-MW of lithium-ion battery storage when it comes online in 2021.
3. Port Lincoln project, Eyre Peninsula, Australia (15 MWe). Australian firm Hydrogen Utility in February 2019 picked Baker Hughes GE to develop its novaLT gas turbine generator for the green hydrogen power plant that could be online in 2021.
4. Fukushima Power-to-gas Hydrogen Project, Japan (10 MWe). Slated to start in 2020, this power-to-gas project spearheaded by Japan's government, Toshiba, Tohuku Electric, and Iwatani Corp. will house a hydrogen production facility alongside solar power generation facilities.
5. Hebei, China (4 MWe). French hydrogen equipment firm McPhy completed this power-to-gas project, which stores surplus power from a 200-MW wind farm, in 2017 for Hebei Construction and Investment Group Co.
6. ELYGRID, Spain (3.5 MW). Between 2011 and 2014, this research project studied efficiency improvements at high pressure alkaline electrolysers that produced hydrogen from wind power.
7. Markham Energy Storage, Canada (2.5 MWe). Hydrogenics Corp. and Enbridge Gas Distribution began operating this power-to-gas/energy storage facility in July 2018. It features a "next-generation" proton exchange membrane (PEM) electrolyzer technology to provide Ontario's independent grid operator with a fast-responding resource to support reliability.
8. HAEOLUS, Norway (2.5 MWe). The European Union (EU)-backed hydrogen system installed in Berlevåg at the end of 2019. It is Hydrogenics project that use advanced PEM electrolysers.
9. Hassfurt, Germany (1.25 MWe). Wind power is converted to hydrogen and stored, and then combusted at an innovative cogeneration unit manufactured by 2G and owned by German utility Stadtwerke Hassfurt. The unit began operation in July 2019.
10. Lam Takhong Wind Hydrogen Hybrid Project - EGAT, Thailand (1.2 MWe). The Electricity Generating Authority of Thailand (EGAT) is a "wind-hydrogen hybrid" that went online in 2018—uses a 1-MW Hydrogenics PEM electrolyzer to use up curtailed power from a 24-MW wind farm and a 300-kW PEM fuel cell to repower the hydrogen.
11. INGRID, Italy (1.15 MWe). Inaugurated in 2016, this EU-backed project in Troia showcases solid-state hydrogen storage technology that can be applied for energy storage and power-to-gas.

The emerging initiatives and supporting projects show how important a problem we are dealing with. Meanwhile, integrating new hydrogen storage systems into the existing grid is not straightforward. It requires mapping and measuring the parameters of the distribution network, including the determination of external (exogenous) conditions taking into account the adopted assumptions for the efficiency of the network and apparatus and the possibility of collecting hydrogen. In this case, data on, inter alia, the spatial layout of the network (including the number of renewable energy sources if we assume this variant of the system construction and supply and demand aspects), parameters describing / evaluating the operation of the network, functional and organizational conditions.

This will allow not only to properly prepare the infrastructure, but also to develop an automatic control system for the operation of the installation in terms of autonomous operation, cooperation with the power and heating network. There must also be developed procedures for monitoring the condition of the installation - sensory systems - aimed at the dangers of a potential uncontrolled leak of hydrogen from the installation between the places of its processing, storage and use. It is also extremely important to assess the installation in terms of diagnostics, so that the control system and the control layers allow for current detection of defects, and the control allows for operation in a fault tolerant regime. All acquired information should be exchanged with supervisory systems of the power grid.

The hydrogen energy storage system integrated with renewable energy sources should, as part of the algorithm controlling the developed device, use data on current and forecast weather conditions, as well as information closely related to the cyclicality of energy consumption (weekly cycle, time of day, etc.). This will allow the optimization of the operation of such a system.

5. THE CHALLENGES OF HYDROGEN SUPPLY CHAINS DESIGN

Hydrogen supply chains can have a different structure depending on the purpose of their operation. They have a significant impact on the sustainable development of energy systems [17]. Figure 1 shows the hydrogen supply chain stabilizing the points of obtaining renewable energy, in which hydrogen is converted into fuel and distributed to the end user.

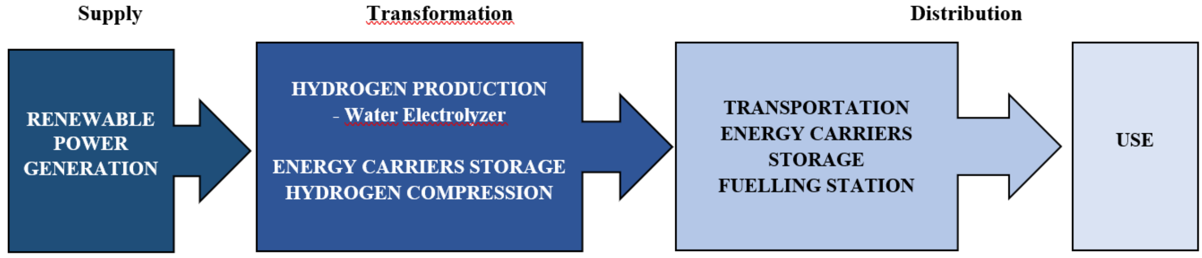

Figure 1: Hydrogen supply chain powered by renewable energy sources
Source: own elaboration.

When talking about hydrogen supply chains, we think about the supply chain of hazardous materials, which requires a special approach, including compliance with regulations and social pressure related to the location of nodes. Hydrogen is perceived by society as one of the most dangerous fuels. Contrary to appearances, it is less flammable than gasoline or other fossil fuels. Like any other fuel, hazards arise when stored and transported improperly. These risks can be minimized by using appropriate control systems. These include [18]:

- leakage prevention by highly accurate tank tightness testing,
- installing multiple shutoff valves,
- designing devices resistant to shock, vibration and high temperatures,
- use of hydrogen sensors for leak detection,
- prevention of ignition by locating all hazards that create an electric spark,
- separation of fuel cells from other electrical devices.

Due to safety problems, the most commonly referred to as hydrogen fuel supply chains with centralized production, at an appropriate distance from inhabited places. However, hydrogen can be produced in a distributed system close to collection points. In the case of hydrogen refueling stations, hydrogen can even be produced at the station [19]. In such a case, the production costs will be higher, but they will reduce the costs related to transport. The cost of producing hydrogen depends strongly on the technology used and using the technology of centralized production of hydrogen using SMR technology, the cost of producing 1 kg of this gas is estimated at EUR 2 and is strongly dependent on the price of natural gas. In the case of distributed production, the cost is estimated at EUR 4 without taking into account the cost of CO2 emissions. In the case of hydrogen production from water in the EC process, the cost of centralized production is € 6 / kg, and in the case of distributed production, the cost is estimated at € 8 / kg [20].

Many different transportation modes can be used to deliver hydrogen from production facilities to storage sites and finally to the fuelling stations. Hydrogen can be transported by cylinders, road tankers, pipelines, bulk ships or ferry. Each of these solutions entails additional risks related to transport safety as well as social and environmental effects, such as air pollution or the land consumption of infrastructure. Establishing hydrogen as a fuel for transportation requires also a detailed cost analysis of the entire supply chain. This includes how hydrogen is to be produced, its large-scale storage that takes the seasonal intermittency of renewable power generation into account, its transportation and distribution from a central production plant to fuelling stations as well as the fuelling stations themselves [11]. Numerous studies investigate the most cost-efficient supply structure between production and transportation. Yang and Ogden [21] investigate a method for comparing the different transport possibilities of tube or liquid trailer truck vs. pipeline delivery. They show that each technology has a maximally cost-efficient niche and there is no single perfect solution for the entire system. Another studies [22] develop an Excel tool for calculating the cost of hydrogen supply while varying different input parameters like FCEV market penetration, refuelling station capacity, transmission mode or production volume for different delivery scenarios. Although, hydrogen production is not calculated inside either model and is instead assumed to be an input. As such, the influence of hydrogen production on storage demand was not investigated.

Crucial for the design of the supply chain has a hydrogen fuel station location and distance from their places of production and storage. The key factors in the installation of fuelling stations are characterizing the required demand and the form of product to dispense. These two factors will determine the size and type of fuelling stations [23]. The costs of building hydrogen stations are high and the return on investment is negligible due to the low popularity of such vehicles. Meanwhile, sales of hydrogen-powered cars are negligible, mainly due to high purchase costs and the lack of a charging network. It is easier for electric cars to win the market, because even without an extensive network of chargers, they can still be charged from a home socket. There is no way to deal with the problem of the lack of infrastructure with hydrogen cars.

6. DISCUSSION AND CONLUSION

Hydrogen can be obtained from various sources, often completely renewable. The main source, the most abundant, is water, but it can also be other sources of renewable energy. Hydrogen can be stored in liquid, gaseous or solid form. It can also be stored bound in substances such as methanol, ethanol or metal hydrides. It can be produced and transformed into energy with high efficiency, and also safely transported and stored like other conventional fuels. This causes the growing popularity of this medium in terms of using it to store surplus energy and stabilize power grids. However, the validity of assessing the using hydrogen to stabilize the power grid profitability should be comprehensive, and therefore made in the context of the functioning of the entire supply chain.

The implementation of such solutions requires appropriate preparation. The presented considerations constitute a conceptual framework for the authors that should be taken into account in the analytical model assessing the possibilities of implementing investments in the field of hydrogen storage and its conversion into electricity. In a model that allows to determine the demand for electricity obtained from a hydrogen fuel cell on the basis of current calendar data, the state of the power grid, and weather conditions. A model that allows to determine the production of hydrogen in the developed installation depending on weather conditions and the type of connected RES sources, as well as taking into account a predictive algorithm controlling the operation of a hydrogen energy buffer that would perform production tasks, i.e. conversion of electricity from RES into hydrogen and work as a fuel cell, ie putting stored energy back into the power grid. The model should also include the development of diagnostics of the hydrogen energy buffer, determination of potential defects and methods of their detection, and the potential implementation of a fault tolerant control system, as well as the method of information exchange with master systems of the power grid along with a set of critical variables that will ensure the proper system functioning.

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