H2 ECOSYSTEM ROADMAP FOR OSTROBOTHNIA

Workpackage 1 Report

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research reports a3

PUBLISHER:
Vaasan ammattikorkeakoulu | Vaasa University of Applied Sciences

ISSN 2954-1158 (Vaasan ammattikorkeakoulu, University of Applied Sciences publications. A, Research reports, 3)

ISBN 978-952-5784-62-6 (online)

https://urn.fi/URN:ISBN:978-952-5784-62-6

Design: VAMK | Satu Aaltonen

Layout: Tritonia | Merja Kallio

Vaasa 2022

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Vipuvoimaa EU:lta 2014–2020

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FOREWORD FOR THE HYDROGEN REPORT

I wish you welcome to a hydrogen journey with our project report on the H2 Ecosystem for the Ostrobothnia project. In work package 1 (WP1) and this paper, we aim to strengthen the knowledge base of hydrogen technology and economy. There are separate reports for work packages 2 and 3 and these reports can be found at the address: https://www.h2ecosystem.org/. The WP2 topic is "*Regional SME´s entrance to the hydrogen value chain*" and the topic for WP3 is "*A common vision and roadmap for a hydrogen economy in Ostrobothnia*".

We are living in the middle of the fourth hydrogen wave and there are both globally and locally many things going on in the field of hydrogen. Hydrogen is a hot topic and there are many different kinds of views about the business opportunities of hydrogen. When reading recent hydrogen reports from IRENA or IEA, many of them estimate that green hydrogen will reach economical viability in the year 2030. During Spring 2022 I was attending some hydrogen seminars where some experts were postponing the hydrogen economy breakthrough first to the year 2040 due to challenges in how fast the efficiency of the electrolyzer technology is developing.

Alkaline electrolysis is a very mature technology and already in the year 1928, there was commissioned a 165 MW electrolyzer in Rjukan in Norway. Many experts are anyhow estimating that Polymer Exchange Membrane (PEM) electrolysis will be the market leader in the near future due to the improved efficiency and better capability to cope with intermittent wind and solar energy. Although both Solid Oxide Exchange Cell (SOEC) and Anion Exchange Membrane (AEM) are still in the developing stage these electrolysis technologies should neither be overlooked.

In Spring 2022 I was also attending some hydrogen seminars where people from the hydrogen industry were presenting the view that the hydrogen economy is already here and now among us – we don´t have to wait ten or fifteen years to gain economic feasibility to green hydrogen, we can do it today.

There are some viewpoints that support this view from the representatives of the industry. The first fact is that we don´t need to create any new markets or usage for hydrogen, this gas is already used widely within the petrochemical and fertilizer industries. The main challenge is just how to replace the current grey hydrogen from fossil fuels with the green hydrogen from renewables. The viewpoint by M. Liebreich (2021) regarding the hydrogen ladder model, gained support during this project, we don´t need to figure out new consumption for hydrogen, just to replace the grey hydrogen with very extensive CO_2 emissions with the green one.

Thus the view that the hydrogen economy would suffer from an egg-chicken dilemma is incorrect because there is already a huge demand for hydrogen. And it is quite likely that also the steel industry will need a huge amount of hydrogen in the near future. A second common myth regarding hydrogen was also busted during this project. It is often stated that there will be a need to curtail wind and solar power production and the electrolyzer process could be based on the curtailment (negative market prices and/or grid limitations).

The *curtailed wind/solar production* is one of the three business models regarding hydrogen production, but in this option, estimates are showing that the operation time (full-load hours, capacity factor) is too low for the electrolyzer to gain any economic viability. In the business model of *dedicated renewables*, the whole wind farm or solar power plant production is used to produce green hydrogen and this operational model offers a significantly higher capacity factor. Also, the third business model *using grid electricity* from renewables can offer a high number of annual operation hours for electrolyzers.

Something that became evident during this project was the benefit to find different kinds of hybrid solutions. This applies both to the source of electricity and also to what is to be done with the produced hydrogen. It is pretty easy to store smaller amounts of hydrogen with metal/composite vessels, but storing large amounts of hydrogen is a challenge. In Finland, there are no old salt caverns to be used for this purpose and there is often a great need for converting the produced hydrogen into some e-fuels like ammonia, methanol, or methane. Often it is stated that hydrogen is a great way to store energy, but this is not the case due to the storage problem presented here earlier and the low round-trip efficiency of an electricity-hydrogen-electricity chain. There are many sources of losses when hydrogen is produced out of the water with the electrolyzer. When storing hydrogen you can either compress it as a gas or cool it down into liquid form (–253 °C) and both these need energy and create losses. Practically almost all power-to-gas (P2G) solutions are based on hydrogen, thus Hydrogen is the cornerstone of e-fuels. Due to the storage and transport challenges, it is very attempting to create something else out of hydrogen as soon as possible.

When discussing the production costs of green hydrogen two components are vital; access to cheap wind and solar power through own production or through a long-term Power Purchase Agreement (PPA). Naturally, the price of the electrolyzer is also vital, but that is something that a local player can not much influence. You can only optimize your electrolyzer operating hours and try to get as cheap renewable energy as possible.

I want to thank all the authors of this report and a special thank you also to European Union and Ostrobothnian council to finance this project, which has been a great journey. I want also to express my gratitude to the steering group of the project and there, especially the insights we have gained from the industrial representatives.

In Vaasa 18th November 2022

Ossi Koskinen

Ph.D., the editor, and co-author of this report.

Shiva Sharma, Kaisa Penttilä and Ossi Koskinen

1. INTRODUCTION TO H2 ECOSYSTEMS IN OSTROBOTHNIA PROJECT

Background of the project

Energy systems are globally in a phase of transformation. Increasing interest in sustainable development, environmental concerns, and energy security is forcing businesses and society to look for new solutions to ensure economic growth and fight climate change. In 2019, the European Commission (2019) presented Green Deal, outlining the new growth strategy which aims to transform the European Union (EU) into a fair and prosperous society, with a modern, resource-efficient, and competitive economy where there are no net emissions of greenhouse gases (GHG) in 2050 and where economic growth is decoupled from resource use. Among many innovations, green hydrogen could play a significant role in reducing GHG and help reach no net emission of GHG by 2050. The EU Commission launched *A Hydrogen Strategy for a Climate Neutral Europe* in the summer of 2020. Since then, the Commission has promoted green hydrogen as a key technology in the transition to carbon-neutral societies and industries. Major investments are now being made at the EU level to realize this strategy and finance various types of demonstration and scale-up projects in green hydrogen.

The Vaasa region has branded itself as the Energy Hub of the Nordics and energy system solutions are key export products produced by the region's companies for global markets. Hydrogen has however not been a focus area for either the businesses or the education sector in our area. Two years ago, in the summer of 2020, green hydrogen had not yet surfaced in the everyday news media but was mostly discussed in Finland among core experts in the field of green alternatives to fossil fuels and new technological solutions for renewable energy storage. In the EU and among many other global players, analyses of green hydrogens' role in the energy transition had however been conducted for more than a decade

In light of the new strategic focus areas on the EU level, a holistic mapping and update of the green hydrogen-related knowledge and activities for the Ostrobothnia seemed timely and highly needed. Knowledge about green hydrogen, business opportunities related to the technology, and green hydrogen's role in the region's transition towards climate neutrality needed to be built up and forming a network of actors with interest in green hydrogen technology and business opportunities were deemed essential. This network was to be formed with a broad base of actors – universities, large companies, small and medium-sized enterprises, development organizations, and municipalities – to share knowledge and get together the actors that could lead the development forward.

This work has been carried out under the project "H2 Ecosystem Roadmap (for Ostrobothnia)". The project was started as a collaboration between three Universities in Vaasa namely Novia University of Applied Sciences, Vaasa University of Applied Sciences (VAMK), and Hanken School of Economics. It initially received partial funding from the Vaasa University Consortium (City of Vaasa) and was then granted REACT-EU project funding to implement the project in its entirety. Through the project members' cooperation, each party contributed with its specific expertise, regarding ecosystem orchestration and leadership, organizational and business thinking, marketing and branding, technical know-how, and systems know-how.

The guiding principle of this project has been that competence to build systems that transcend industrial boundaries requires knowledge based on multidisciplinary sciences. Only technical know-how or business know-how is not enough in the holistic system solutions that form the basis for business models that require ecosystem-level cooperation. The development of ecosystems around hydrogen requires that several actors with different types of skills and resources come together, find common goals to work for and complement each other in a way that contributes to the synergies being greater than the sum of each actor apart. The development of a regional roadmap for a green hydrogen ecosystem thus also requires multidisciplinary knowledge and cooperation.

At the core of all the activities in the project has been to collaborate with a broad base of different actors and to engage the practitioners to become involved as much as possible. For this project, it has been essential to work in close collaboration with the regional development companies and the National Hydrogen Network (Kansallinen Vetyverkosto). This has enabled the project to gain momentum for engaging a broader base of companies, municipalities, and educational institutions in our region to start working on green hydrogen-related initiatives. During the project, more than 130 individuals, including representatives from over 50 companies, have taken part in the project activities and expressed interest in exploring collaboration around hydrogen in the Ostrobothnia and Kvarken region.

Objectives of the project

Green hydrogen can be produced with many technologies, but the most common one is when electricity from renewable resources is used to split water into hydrogen and oxygen gas through a process called electrolysis (Kakoulaki et al., 2021). This hydrogen can be used in different ways such as a feedstock, a fuel, or an energy carrier, and has many applications across industries, transport, power, and building sectors. According to the EU's long-term vision for a climate-neutral economy, the role of green and low-carbon hydrogen will be essential to decarbonize the energy system effectively and efficiently (European Commission, 2018). Unlike batteries and thermal storage, hydrogen can *in theory* be stored for a long period and can also be used as a means of the energy storage system. But it is as well good to be aware that storing a large amount of hydrogen is not technically an easy task. Abroad the most promising solution to store large amounts of hydrogen is to exploit old salt caverns. These projects are mostly in a feasibility study or test phase. Hydrogen does not emit carbon dioxide (CO_2) when used and the focal question is how the hydrogen is manufactured; is it gray hydrogen from fossil fuels or green hydrogen from renewables?

The project's goal has been to build a regional network of actors with an interest in green hydrogen, create a knowledge base for the role of green hydrogen technology as part of system-level energy solutions, support the development of new business opportunities related to green hydrogen, and promote the regional transition to CO_2 neutral society.

The lodestar of all the activities and the ultimate purpose of the project has been to support the regional actors to find what niche in the future hydrogen economy they could be world-class in and proactively build up the knowledge base and networks needed to enable this development. Some of the major actors in the region have already taken a proactive position regarding the development of the hydrogen market and have hydrogen technology on their strategic agendas. For the region as a whole to be able to participate in this development, knowledge about these hydrogen-related technologies and how ecosystems around hydrogen can be organized, need to reach out to small and medium-sized companies and municipal decision-makers. Companies and municipal decision-makers in the region need a holistic view of the opportunities and challenges of becoming involved in business ecosystems around green hydrogen.

Key project activities and measures

To achieve the goals of the project, we have conducted a holistic mapping and update of the H2 knowledge and activities in the region, started a new collaboration network between a broad base of regional actors (universities, large companies, small and medium-sized enterprises, development organizations, municipalities) and together with this network created a vision for how the Ostrobothnian actors can build successful ecosystems around green hydrogen, which in turn can contribute to the region's specialization and innovation activities.

The concrete measures in the project have been:

1. Investigating the conditions for the development of the hydrogen economy in the Ostrobothnia region through a study of technical information, market status, and future forecasts regarding green hydrogen (WP 1, see Part 1 of this report).

2. Through an interview study, investigating the strengths and challenges of the export cost regarding hydrogen technology and the development of a hydrogen economy. Identify actors who could take a place in the ecosystem from producer to end user through direct contacts and meetings. In addition to the already started demonstration projects around hydrogen, identify possible pilot projects and R&D activities around hydrogen production, distribution, storage, and usage that various actors in the region have an interest in collaborating on (WP2, see a separate report).

3. Facilitating the sharing of knowledge through publishing blogs and articles, starting a hydrogen network, and developing a common vision by arranging five (5) networking seminars and workshops (WP3, see a separate report).

4. Writing a report that analyses and synthesizes the common vision and the project's results in the form of a roadmap for the development of a green hydrogen ecosystem in the Ostrobothnia region (WP 3 cont, see a separate report).

Contribution of the project to the development of the green hydrogen economy in the Ostrobothnia region

Green hydrogen is considered by the EU and other global players as a key technology in the transition to carbon-neutral societies and industries. Major players in the region are investing heavily in developing systems and solutions using hydrogen technology. However, hydrogen production, distribution, and storage had before this project not been investigated in regional EU-funded projects, and know-how within the education sector, regional development organizations, and among public decision-makers was lagging. The results of this project contribute to information about the latest knowledge in the technology and markets for green hydrogen in Europe and the Nordic countries and an increased understanding among companies, universities, and municipal and regional decision-makers of the opportunities for new business activities in the region of Ostrobothnia.

At the EU level, major investments are being made to finance various types of RDI and demonstration projects in green hydrogen and regional actors have been made more aware of these opportunities. The latest international expert reports indicate that the hydrogen economy will break through both in Europe and globally over the next 5-10 years. This project has helped the region to prepare for this and investigate the regional actors' opportunities to participate in and serve this new market. Through the project's technical and market study, interviews, and workshop seminars, a basis is created for identifying specific goals for research, development, and innovation collaboration.

Hydrogen will play a major role in sector integration energy systems and therefore knowledge is needed about the integration of hydrogen in existing systems and how different actors can develop these systems together. Starting a collaboration network among regional actors on green hydrogen and identifying roles and positions that can be taken by new actors in the future regarding the hydrogen economy (large and small companies, research and educational institutes, municipal and regional decision-makers, financiers) has been a key activity within the project.

The project has sought to answer the need to create a common picture regarding the role and function of hydrogen for the region as a whole, but also how especially small and medium-sized suppliers can use their expertise to be able to deliver components to the major players in the region and the international markets directly. Potential subcontractors, producers of renewable electricity, and municipal decision-makers have been proactively approached to take part in the information and networks built up during the project. This has been a way to ensure that key stakeholders develop their knowledge of the possibilities and challenges of green hydrogen production, storage, distribution, and use so that new hydrogen ecosystems can be developed in the Ostrobothnia region.

Knowledge and plans for cooperation to develop a hydrogen ecosystem in the region must be developed in collaboration with different actors. In addition to an updated picture of the situation, a common vision is needed that drives development forward. The project's result is a regional roadmap for a green hydrogen ecosystem in Ostrobothnia that summarizes a common vision and identifies new R&D and business opportunities around hydrogen technology that can be realized through the collaboration of different actors.

Shiva Sharma and Ossi Koskinen

2. GREEN HYDROGEN PRODUCTION COSTS (LCOH)

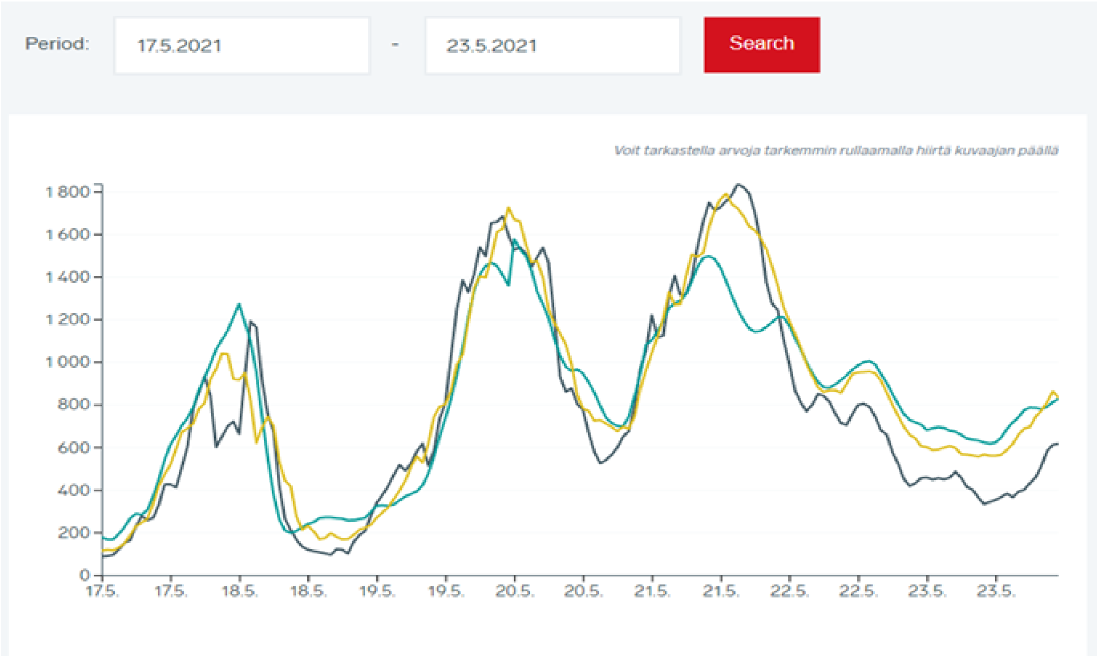
Background for green hydrogen

Green hydrogen is produced when electricity from renewable resources is used to split water into hydrogen and oxygen gas through a process called electrolysis (Kakoulaki et al., 2021). This hydrogen can be used in different ways such as a feedstock, a fuel, or an energy carrier, and has many applications across industries, transport, power, and building sectors. According to the EU's long-term vision for a climate-neutral economy, the role of green and low-carbon hydrogen will be essential to decarbonize the energy system effectively and efficiently (European Commission, 2018). Unlike batteries and thermal storage, hydrogen can be stored for a long period and can also be used as a means of energy storage system. Most importantly hydrogen does not emit carbon dioxide (CO_2) when used.

This has led to increasing interest in green hydrogen production. Hence, it requires more focus and research to be widely used. Moreover, the price of hydrogen production is an interesting topic for all actors who are involved in the energy market. There are many other reports on the topic of cost calculation but with varying degrees of transparency to cost assumptions. Thus, the focus of this work has been the current status of hydrogen technology, to identify and highlight the opportunities for green hydrogen technologies to achieve 2030 and 2050 climate targets of Finland and EU member states from a regional perspective and not only to calculate Levelized cost of hydrogen (LCOH) in different scenarios but also to explain the method of calculation so that reader can quickly calculate the LCOH with their value and assumption using the method presented in this work.

Objectives of hydrogen the production

Zero net emission of GHG by 2050 is an ambitious target. To succeed, different technologies will play a significant role. Advancement in one single solution cannot meet this target, thus we need to investigate different technologies and solutions. Renewable energy such as wind and solar has one common disadvantage, there is no sun shining all the time and the wind does not blow according to our demand. This means that in some periods we will have an energy surplus and in other times we have a deficit if our grid was 100% renewable. This is challenging because there is not yet an appropriate solution to store large quantities of energy in our surplus period and use them when we are in deficit. Figures 1 and 2 show the fluctuation of wind and solar energy production. Figure 1 shows the wind power generated in MWh/h during the period of 17.52021-23.5.2021 by Fingrid.



Name	Minimum	Maximum	Average
Wind power generation	86	1836	771 MWh/h
Day ahead wind power forecast	167	1576	825 MWh/h
Continuously updated wind power forecast	113	1789	835 MWh/h

FIGURE 1. Wind Energy production fluctuation during the period 17.05.2021 and 23.05.2021 (Fingrid, n.d.)

Figure 2 shows the production fluctuation of solar energy during the period 17.05.2021-23.05.2021 at the Meteoria Vaasa site. International Renewable Energy Agency (IRENA) estimates that if the share of use of renewable energy in the world's energy system doubles by 2030 there is a need to triple the global electricity storage capacity (IRENA, 2017). Green hydrogen could be part of the solution in this situation, needed more research on its overall perspective. Also, the cost of production of green hydrogen is an important aspect to parties that are interested in hydrogen technology and especially in green hydrogen. The measurement of LCOH is based on the formula of Levelized Cost of Energy (LCOE). There are two main ways to calculate the LCOE (real and nominal) and the difference is how you deal with the inflation rate. There are many reports on LCOH with varying degrees of transparency to cost assumption and method used. Thus, there is a need for transparent work on how LCOH is calculated, and all the assumptions made during the calculation. The LCOE is often called the "holy grail of confusion" and the same issues apply naturally as well when we are calculating the true production cost of hydrogen with the LCOH.

The research method that will be used for this work is a review of literature and reports from institutions applying, hydrogen technology and policymakers and analyzing the status and LCOH. The justification for this study is that there is a lot of ongoing research and development activities in both the scientific and industrial world in recent times and there is a need for a review of this knowledge in one condensed form where the reader gets the resent holistic view of the technology and its background.

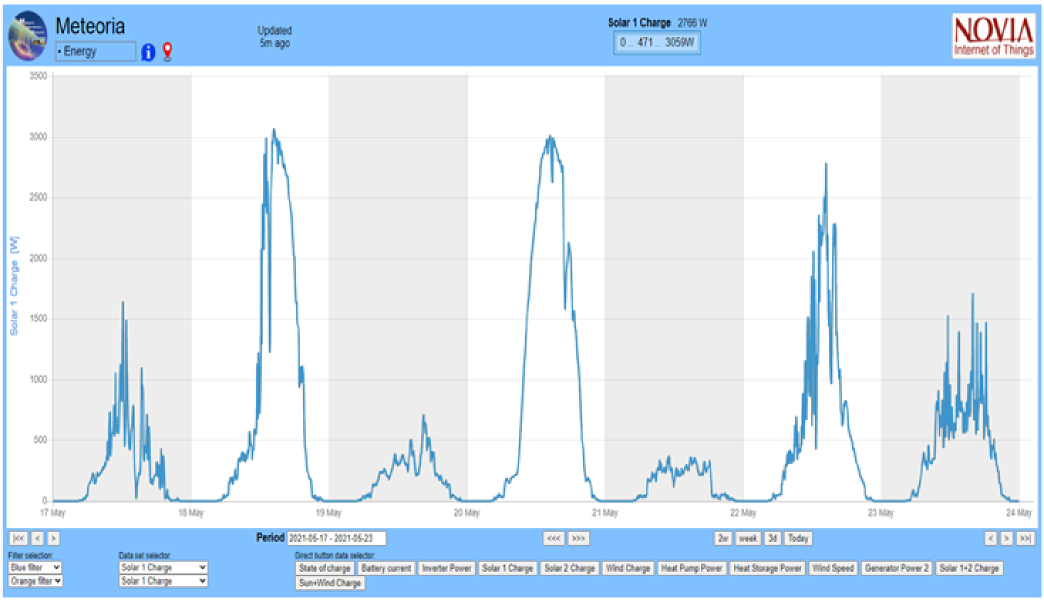


FIGURE 2. Solar Energy production fluctuation during the period 17.05.2021 and 23.05.2021 (Novia, n.d.).

LCOH was calculated using the concept of life cycle costing (LCC) and Levelized cost of energy (LCOE) for low, average, and high-cost conditions. Moreover, the methods and assumptions for calculation were presented in a transparent way. Furthermore, 3 different scenarios (see chapter 4 for different scenarios and calculation methods) for green hydrogen production were created and calculated for these scenarios to get more insights into the costs of hydrogen in euros per kg. Parameters and assumptions were taken from wide and recent literature studies that would fit real case scenarios to get a realistic cost of green hydrogen production.

3. HYDROGEN AS A CHEMICAL ELEMENT

Background of the hydrogen element

Let us start from the beginning. I mean, from the beginning of the four-dimensional space-time. Some 13.8 billion years ago, the Big Bang started the formation of our universe. During the first second of space and time, a lot happened. Then almost nothing for a very long period. Eventually, after about 379,000 years, individual protons combined with individual electrons, formed hydrogen (H) atoms. At this point, our universe consisted of almost nothing else but hydrogen atoms. Later on, individual H atoms combined with other atoms, forming diatomic hydrogen molecules, . Even today, hydrogen is the most common element in the universe, about 74 % of normal matter is in the form of hydrogen.

Hydrogen is the simplest atom ever possible to construct, it has only one proton in its nucleus and one electron is orbiting it. To be accurate, some hydrogen atoms may have also another subatomic particle in its nucleus, together with the single proton, namely a neutron. This particle has about the same mass as the proton, but it does not carry any electric charge. The number of protons in the nucleus of an atom defines the element. If there is only one proton, we have hydrogen at hand, if two protons, the element's name is helium, and so on. The number of neutrons, on the other hand, defines the so-called isotope of the element. If the atomic nucleus of hydrogen includes one neutron in addition to the proton, we call the substance hydrogen-2 or deuterium. People often use the symbol D for deuterium, to separate this heavier hydrogen from the normal hydrogen, H. In figure 3 is the periodic table and the hydrogen atom is the first one it.

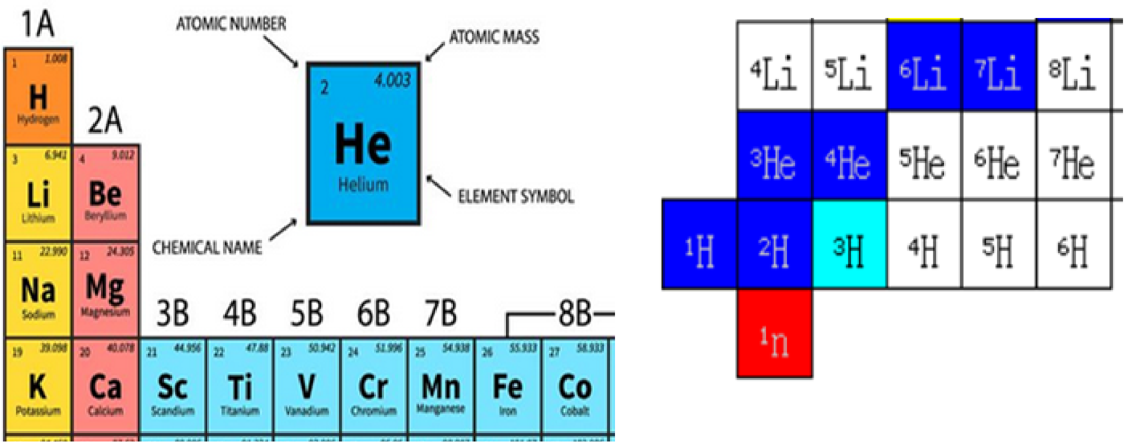


FIGURE 3. In its nucleus, a hydrogen atom has one proton and 1-3 neutrons. The number of protons dictates the element and the number of neutrons states the isotope. The periodic table of the elements (left) and the chart of nuclides (right).

It is also possible that the nucleus of a hydrogen atom includes two neutrons and one proton. Such a substance is called tritium, and the symbol T is often used for this. It is important to understand that hydrogen, deuterium, and tritium are all the same element, namely hydrogen, even though people often use different chemical symbols for them: H,D and T. If one wanted to avoid confusion, one should use symbols H, and for these Isotopes of the same element.

By heavy water we mean water made from molecules consisting of two deuterium atoms and one oxygen atom, . This is, obviously, heavier than normal water, which explains the name. Deuterium and tritium play a vital role in fusion reactor technology. At this very moment, a fusion test reactor called ITER is under construction in southern France. Altogether 35 nations are collaborating to build the world's largest tokamak-type fusion test reactor, which should be able to produce 500 MW of output power with just 50 MW of input power. The facility is designed to prove the feasibility of fusion as a large-scale and carbon-free source of energy. ITER is a crucial step toward the fusion power plants of tomorrow.

Hydrogen is hard to liquefy and the cooling process consumes electricity. One needs extremely low temperatures to make undergo phase a transition from gas to liquid, as liquids below 20 K (kelvins), which is equal to . Without saying, it is much easier to liquify natural gas than hydrogen. Therefore, one can find liquified natural gas (LNG) from any service station, but finding liquid hydrogen is another story.

Despite the liquification problem, can be used in many technical processes to generate energy. For example, one can burn high-pressure ammonia in an internal combustion engine (ICE). Obviously, it could also be possible to burn high-pressure hydrogen itself, but this would result in many technical problems, together with a high risk of dangerous explosions. So, ammonia is the best form of hydrogen for ICEs. Hence, one molecule of this gaseous substance includes 3 hydrogen atoms, chemically bonded with one nitrogen atom. This binary hydride is a stable, colorless gas with a distinctively pungent smell.

One can also use high-pressure hydrogen in a fuel cell to produce heat, electric current, and water. Because of this, fuel cells have been used for space missions already since the beginning of the 1960s. It is excellent for such a purpose because it does not only produce electric current, but also heat and water, which are both in high need in space crafts. Nowadays, fuel cells are plowing their way into the car industry. They offer an excellent alternative to Battery electrical vehicles (BEV), which are much more common cars of today. One can ask: why? One of the biggest obstacles to having more fuel cell cars in the market is the lack of a hydrogen distribution network in Finland, and, actually, in the whole of Europe.

It has been a pleasure to follow the recent political activity in Finland, striving toward a European-level hydrogen distribution network. This would enter our country most probably from the Haaparanta region, exceeding southward along the coastline of Ostrobothnia. However, building such massive infrastructure is too slow, in our opinion. We need much more rapid actions so that companies and car drivers could benefit from all the positive aspects of hydrogen as soon as ever possible.

In summary, one can say that hydrogen is number one in many ways: it is the first ever atom in the universe, it is the first element in the periodic table and, in our opinion, it is the best choice for a versatile fuel in the carbon-free future of the mankind; also in our region, precious Ostrobothnia.

Hydrogen gas is colorless, odorless, tasteless, and non-toxic. It is also non-corrosive, but it can embrittle some metals. Hydrogen is the lightest and smallest element represented by the symbol H but most expressed H2 or . It is in gaseous form under standard temperature and pressure (0 °C and 1014 hPa) (Godula-Jopek, 2015). Some of the physical properties of hydrogen are presented in Table 1.

TABLE 1. Physical properties of Hydrogen (Godula-Jopek, 2015).

PARAMETER	VALUE	UNIT
Molecular weight	2.016	Mol
Melting point	13.96	K
Boiling point	14.0	K
Density liquid	0.089	g/cm^3
Gas density (0°C, 1 atm)	0.071	g/cm^3
Gas density (25°C, 1 atm)	0.0899	g/l
Autoignition temperature	858	K
Flammability limit in oxygen	4-94	%
Flammability limit in air	4-74	%
Ignition energy in the air	0.017	MJ
Ignition energy in oxygen	0.0012	MJ

Hydrogen as a fuel is expected to play a big role in future economy and development. The combustion of Hydrogen gas provides a very clean reaction. Equation 1 shows that the product of this reaction is just pure water and energy.

$$H_2 + O_2 \rightarrow 2\ H_2O + 572\mathrm{J} \qquad 1$$

Hydrogen is one of the simplest and most abundant elements found on earth. The hydrogen atom consists of only one proton and one electron. However, hydrogen is always combined with other elements and is difficult to find in pure gas form. Hydrogen has a good energy density by weight, but poor energy density by volume compared to hydrocarbons. Table 2 shows that hydrogen produces a higher amount of energy although it has low density.

TABLE 2. Specific energy and energy density of different fuels (Edwards et al., 2007).

FUEL	SPECIFIC ENERGY (kWh/kg)	ENERGY DENSITY (kWh/dm³)
Liquid hydrogen	33.3	2.37
Hydrogen (200 bar)	33.3	0.53
Liquid natural gas	13.9	5.6
Natural gas (200 bar)	13.9	2.3
Petrol	12.8	9.5
Diesel	12.6	10.6
Coal	8.2	7.6
Methanol	5.5	4.4
Wood	4.2	3.0

Hydrogen and its different shades

Hydrogen can be produced from a variety of processes with different sources that are associated with a wide range of GHG emissions depending on the technology. Conventionally hydrogen is produced from coal gasification, steam reforming of natural gas, or by electrolysis using nonrenewable electricity. Although hydrogen is a colorless gas, it is categorized into different color codes such as Green, blue, grey, Turquoise etc., depending on GHG emissions during its production process (Enapter, 2020a). These color code naming is not universal and may differ in different countries.

IRENA (2020) describes color codes as following:

Green hydrogen (or renewable hydrogen) means hydrogen produced from renewable energy and it is a near-zero carbon production route. The most established and widely used technology for producing green hydrogen is water electrolysis by using renewable electricity.

Grey hydrogen is produced from fossil fuels such as coal and methane by processes like steam methane reforming (SMR) and coal gasification. Carbon dioxide (CO_2) produced from these processes is released into the atmosphere, which makes these technologies not suitable for net-zero emissions.

Blue hydrogen is produced from fossil fuels in a similar way to grey hydrogen, but the carbon produced in the process is captured and stored or utilized for industrial uses. Almost three-quarters of hydrogen currently produced comes from natural gas, thus carbon capture and storage (CCS) would allow a continuous flow of hydrogen with low GHG emissions while green hydrogen ramps up production and storage capacity.

Turquoise hydrogen is produced as a by-product of methane pyrolysis that splits methane into hydrogen gas and solid carbon black. Carbon black can be more easily stored than gaseous CO_2. It is considered that this makes turquoise hydrogen a low-emission hydrogen choice, but this depends on other energy-demanding thermal processes being powered with renewable energy and the carbon being permanently stored.

Beyond this, the color starts to get a bit blurred. Pink hydrogen can also be found, referring to hydrogen produced by electrolysis powered by nuclear energy. Yellow hydrogen is referred to as hydrogen produced by electrolysis with solar power. Finally, white hydrogen is naturally occurring hydrogen and can be found in underground deposits and created through fracking (Enapter, 2020a). In the Figure 4 one can see the different shades of hydrogen.

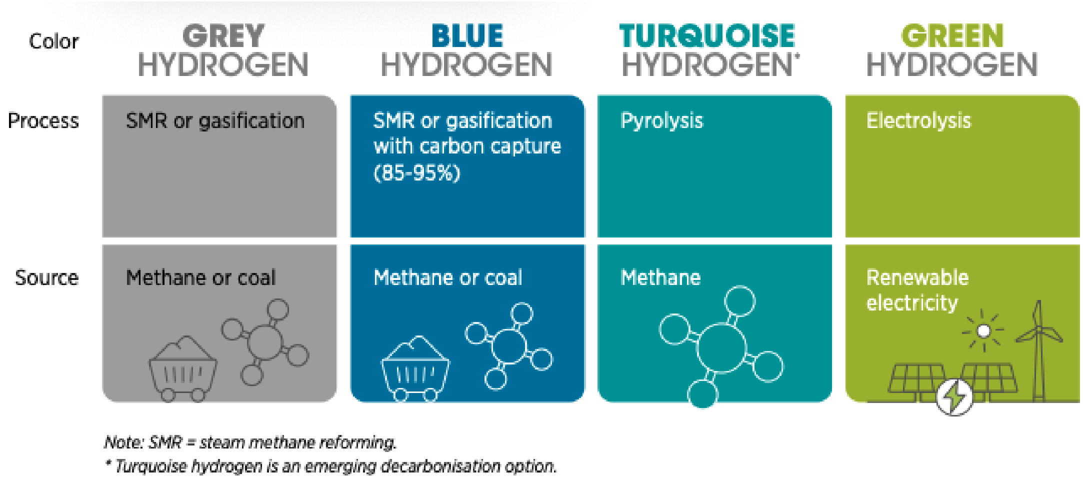


FIGURE 4. Different shades of hydrogen (IRENA, 2020).

Overview of Water Electrolysis

Water electrolysis is the process where direct current is passed between two electrodes immersed in an electrolyte. Electrolysis of water typically consists of an anode, a cathode separated by an electrolyte, and a power supply. The electrolyte can be made of an aqueous solution containing ions, proton exchange membrane (PEM) or an oxygen ion exchange ceramic membrane. Oxygen is produced at the anode (positive terminal) and hydrogen is formed at the cathode (negative terminal) (Godula-Jopek, 2015). Equation 2 shows the dissociation of liquid water into its element components that is molecular hydrogen and oxygen. Electrolysis of water is not a spontaneous reaction

$$H_2O(l) + electricity \rightarrow H_2(g) + \frac{1}{2}O_2\,(g) \qquad 2$$

In standard conditions of temperature (T = 298 K) and pressure (P = 1 bar) water is liquid and hydrogen and oxygen are gaseous (Godula-Jopek, 2015). Enthalpy, entropy, and Gibbs free energy standard changes for reaction in equation 2 are, respectively:

$$\Delta H\ (H_2O\ (l) = \ +285.840\ \mathrm{kJ\ mol^{-1}}$$

$$\Delta S\ \left(H_2O\ (l)\right) = \ +163.15\ \mathrm{J\ mol^{-1}K^{-1}}$$

$$\Delta G_d\ (H_2O\ (l) = \ \Delta H\left(H_2O\ (l)\right) - T\cdot\Delta S\left(H_2O\ (l)\right) = 237.22\ \mathrm{kJ\ mol^{-1}}$$

Despite favorable entropic contributions due to the formation of 1.5 mole of gaseous species, the enthalpy change is strongly endothermic and as a result the Gibbs free energy change is positive and thus making the reaction non-spontaneous (Godula-Japek, 2015). Water vapor can also be dissociated into gaseous hydrogen and oxygen according to:

$$H_2O(Vap) + electricity \rightarrow H_2(g) + \frac{1}{2}O_2\,(g) \qquad (2.1)$$

Enthalpy, entropy, and Gibbs free energy standard changes for reaction in equation 2.1 are, respectively:

$$\Delta H\ (H_2O\ (Vap) = \ +241.80\ \mathrm{kJ\ mol^{-1}}$$

$$\Delta S\ \left(H_2O\ (Vap)\right) = \ +44.10\ \mathrm{J\ mol^{-1}K^{-1}}$$

$$\Delta G_d\ (H_2O\ (Vap) = \ \Delta H - T\cdot\Delta S\left(H_2O\ (l)\right) = 228.66\ \mathrm{kJ\ mol^{-1}}$$

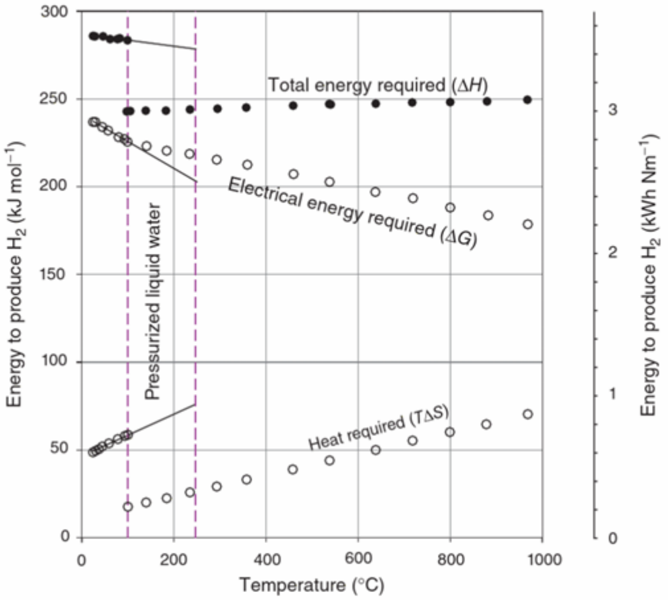


FIGURE 5. ΔG,ΔH and $T\Delta S$ of the water splitting reaction at 1 bar. Data for pressurized liquid water up to 250 °C (Godula-Jopek, 2015).

From the figure 5 we can see that a higher operating temperature facilitates the dissociation of water by decreasing the electrolysis voltage. At room temperature, 15% of the total energy required for electrolyzing water comes from heat and 85% from electricity and at 1000 °C, one-third comes from heat and two-third from electricity. Higher-temperature water electrolysis is interesting when heat is available ad electrolysis requires less electricity which is in most cases more expensive than heat. According to figure 5, water electrolysis can be performed at different temperatures. At any operating temperature T, is the total amount of energy that is required to split 1 mole of water, is the amount of electrical work needed and is the heat demand. This is given by following equation 2.2

$$\Delta H(T,1) = \Delta G_d(T,1) + T \cdot \Delta S\,(T,1) \tag{2.2}$$

The thermodynamic electrolysis voltage E in volts at temperature (T) and pressure (P) is defined as

$$E(T,P) = \frac{\Delta G_d(T,P)}{nF}$$

Thermoneutral voltage (V) in volts is defined as

$$V(T,P) = \frac{\Delta H(T,P)}{nF}$$

Under standard temperature and pressure

$$go\Delta G_d\ (H_2O\ (l) = 237.22\ \mathrm{kJ\ mol^{-1}} \rightarrow E = \frac{\Delta G_d(T,P)}{nF} = 1.229\ \approx 1.23\ V$$

$$go\Delta H\ (H_2O\ (l) = 285.840\ \mathrm{kJ\ mol^{-1}} \rightarrow E = \frac{\Delta H(T,P)}{nF} = 1.4813\ \approx 1.48\ V$$

$$ofn = 2\ (electrons\ exchanged\ during\ the\ electrochemical\ splitting\ of\ water)$$

$$F\ \approx 96485\ Cmol^{-1}\ (Faraday\ constant)$$

In other words, to split 1 mol of water in standard conditions cell voltage of 1.23 V is required and an additional voltage of 0.25 V must be added to the thermodynamic voltage E to provide the heat required by the equation (Liu et al., 2012).

Alkaline Electrolysis

Alkaline water electrolysis has a lengthy history in the chemical industry (Liu et al., 2012). Alkaline water electrolysis is a mature technology. The principle of alkaline water electrolysis is simple. Oxygen and hydrogen are separated from the water when a direct current is applied to the water. Hydrogen arises at the cathode and at the anode, oxygen arises. Alkaline electrolyzers contain caustic water solution and 25% to 30% of potassium hydroxide (KOH). Sodium hydroxide (NaOH) and sodium chloride (NaCl) are used as catalysts (Coutanceau et al., 2017). The liquidd electrolyte allows ions to be transported between the electrodes and is not consumed in the chemical reaction but is gradually replenished depending on losses in the system. The direct current density used in the alkaline electrolyzer is around 2000 A/m² - 4000 A/m², the working temperature is generally maintained at 80°C-90°C and the working pressure is maintained within 3.2 MPa (Guo et al., 2019). Alkaline electrolyzers are the most used hydrogen generators in the industry.

99% pure hydrogen is produced through this process, and of certain purification processes, higher purity can be reached which is required for hydrogen fuel cells. The operating principle of alkaline electrolysis is described in Figure 6.

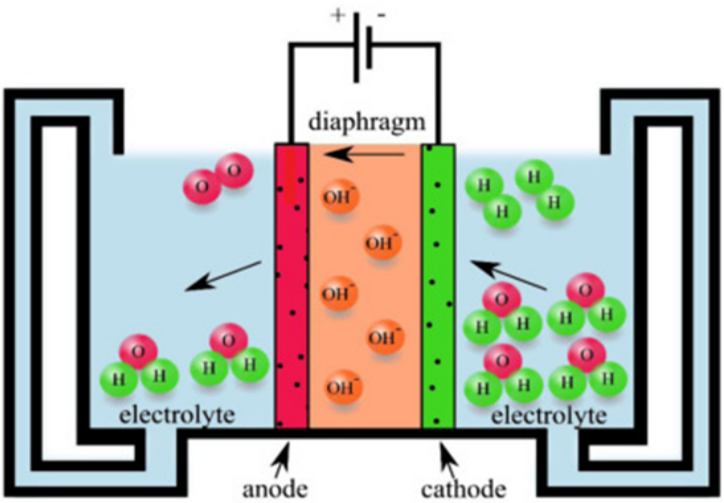


FIGURE 6. Operating principle of an alkaline electrolysis cell (Syed, 2021).

Polymer Electrolyte Membrane (PEM) Water Electrolysis

In modern electrochemical literature, solid polymer electrolyte (SPE) is referred to as proton exchange membrane or PEM cells (Godula-Jopek, 2015). In PEM cells, a thin proton-conducting membrane is used as a solid electrolyte usually 50-250µm. According to the literature PEM water electrolysis cells can reach an efficiency of 80% at 1 A cm^{-2}, a value that is commonly good practice at least at the lab scale but hard to find outside the lab (Godula-Jopek, 2015). When voltage is applied, water is oxidized at the anode to make hydrogen ions, electrons, and oxygen. The hydrogen ions move through the conductive polymer membrane to the cathode, where they are reduced to form hydrogen gas. Figure 7 describes the operating principle of PEM cells.

Compared to the alkaline electrolyzers PEM technology is more expensive, this extra cost is partly due to expansive materials (polymer electrolyte, catalyst, but also other cell components) and partly because the electrolyte is confined in the polymeric membrane, tolerance of cell component dimensions is more demanding and requires sophisticated mechanical tools (Godula-Jopek, 2015).

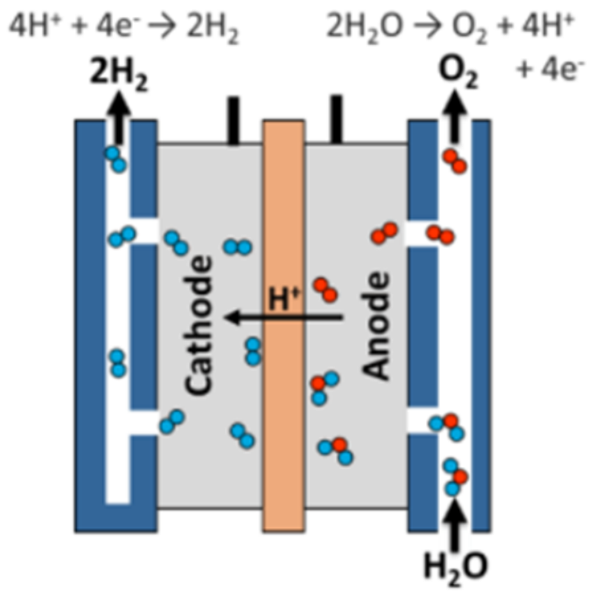


FIGURE 7. Operating principle of PEM electrolysis cell (Hydrogen and Fuel Cell Technologies Office, n.d.-a).

High-Temperature Electrolysis

A typical technology for high-temperature electrolysis is solid oxide electrolysis cells (SOEC). A SOEC is the Solid oxide fuel cell (SOFC) run in reverse. Solid oxide electrolyzers (SOE) are a less mature technology that uses a solid ceramic material as the electrolyte. SOEC technology is gaining growing interest due to its potential to increase the efficiency of water electrolysis by using high operating temperatures which are typically 700-1000°C. Therefore, in SOE water vapor is reduced to hydrogen. The main advantage is that a substantial part of the energy required for electrolysis is added in form of heat, which is much cheaper than electricity. A SOEC typically constitutes an oxygen electrode (anode) and a hydrogen electrode (cathode) separated by a dense ionic conducting electrolyte (Nechache & Hody, 2021). As shown in Figure 8, in the case of SOEC, water supplied at the cathode side is reduced into hydrogen and oxygen ions. The latter crosses the electrolyte to eventually form oxygen by oxidation at the anode side (Nechache & Hody, 2021).

SOEC appears to be a possible game-changer technology for several markets in the mid/long term (2025–2030), identified as:

i. Large-scale H2 production thanks to its high-power efficiency when external heat is available,

ii. Power-to-X by coupling SOEC with chemical reactors to produce several fuels/liquids such as ammonia, methanol, and formic acid,

iii. Power-to-Power thanks to its reversible SOFC/SOEC operation ability.

In addition, SOEC shows interesting flexibility as it can be considered for both decentralized hydrogen production close to the end user and centralized mass production in countries with high renewable potential. Furthermore, flexibility lies in the ability to produce multiple gases (syngas by H_2O + CO_2 co-electrolysis, CO by CO_2 electrolysis, etc.) (Nechache & Hody, 2021).

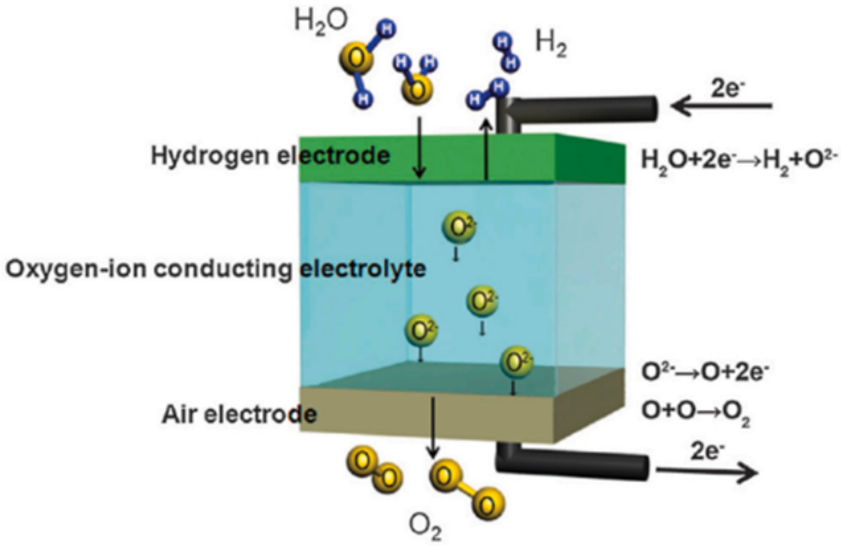


FIGURE 8. Solid oxide electrolysis cell principle for hydrogen production from water (Nechache & Hody, 2021).

However, research and development challenges remain with this technology, as this technology is currently much more limited in lifespan than PEM and alkaline electrolysis technologies, with an estimated lifespan of less than 2–3 years, whereas PEM and alkaline electrolysis are in the range of 10 and 20 years, respectively (Nechache & Hody, 2021). In table 3 one can find the characteristics of different water electrolysis technologies.

TABLE 3. Characteristics of different water electrolysis technologies (Vidas & Castro, 2021).

	CHARACTERISTICS	AEL	PEM	SOEC
OPERATION PARAMETERS	Temperature (°C)	40-90	20-100	650-1000
	Pressure (bar)	<30	<200	<20
	Current density (A/cm²)	0.20-0.40	0.60-2.00	0.30-2.00
	Voltage (V)	1.80-2.40	1.80-2.20	0.70-1.50
NOMINAL FEATURES	Cell area (m²)	<4	<1.30	<0.06
	Production rate (m³/h)	<1400	<400	<10
	Gas purity (%)	>99.50	>99.99	>99.90

	CHARACTERISTICS	AEL	PEM	SOEC
SYSTEM DETAILS	Energy consumption (kWh/ m^3)	~5.55	~5.40	~3.80
	Efficiency (%)	51-60	46-60	76-81
	Stack lifetime (kh)	60-120	60-100	8-20
	Degradation (%/y)	0.25-1.50	0.50-2.50	3-50
ECONOMIC PARAM-ETER	Capital costs (EUR/kWh)	740-1390	1300-2140	>2000
	Maintenance cost (% of investment/year)	2-3	3-5	Not available
MISCELLANEOUS	Advantages	Low capital cost; cheap catalysts; high durability; stable operation	Highest purity; compact design; high production rate	High efficiency; low pressure; low energy consumption; no need for a noble metal catalyst
	Disadvantages	Corrosive system; lowest purity; high energy consumption	High cost of rare components; acidic environment; high pressure	Large design; low durability; small cell area; high temperature
	Maturity	Commercial	Near commercial	Demonstration

Hydrogen Storage and Distribution

Once hydrogen gas is produced and processed, it needs to be distributed and stored safely. Commercially viable hydrogen storage is regarded as one of the most technically challenging key barriers to its widespread application as an effective energy carrier and feedstock (Godula-Jopek, 2015). There are many ways to store hydrogen such as:

- ✓ High-pressure gas cylinders up to 800 bar.
- ✓ Liquid hydrogen in cryogenic tanks at 21 K.
- ✓ Adsorbed hydrogen on interstitial sites in a host metal at ambient temperature and pressure.
- ✓ Chemically bonded in covalent and ionic compounds at ambient pressure.
- ✓ Through the oxidation of reactive metals such as lithium, sodium, and magnesium, with water.

Nowadays the most proven, tested, and commercially available hydrogen storage is in compressed gaseous form or liquid form. To achieve a satisfying energy density with a compressed gas storage system, the operating pressure has been raised to 700 bar. On the other hand, liquid hydrogen can exist only at temperatures that are below the critical temperature of -239.9°C, in reality, liquid hydrogen is usually stored at a lower temperature of -253°C, because at -253°C it could be stored at atmospheric pressure whereas at -239.9°C pressurized storage at 13 bar is required (Godula-Jopek, 2015).

The storage of hydrogen in metal hydrides is another technology that has several advantages concerning storage under high pressure or in liquefied form. Energy consumption may be reduced, transportation may be simplified, and storage safety can be increased. The challenges with storing hydrogen in hydrides are the high weight of the reliable carriers and the complicated process of getting hydrogen out of them.

A significant advantage of hydrogen is that it can be stored without losses for long periods as gas. In addition to this, a lot of the existing natural gas infrastructure can be used. However, hydrogen has a low volumetric energy density at atmospheric pressure compared to natural gas or oil. It is less of a problem in stationary applications, where large storage tanks with low pressure are acceptable compared to mobile applications where the size and weight of the tank are a significant concern. To store hydrogen as such without converting it to any of the e-fuels is the most mature storage technology. The current near-term storage technology for onboard automotive hydrogen storage is at 350 and 700 bar nominal working pressure compressed gas tanks (Hydrogen and Fuel Cell Technologies Office, n.d.-b). Figure 9 describes the components of a pressurized hydrogen storage tank.

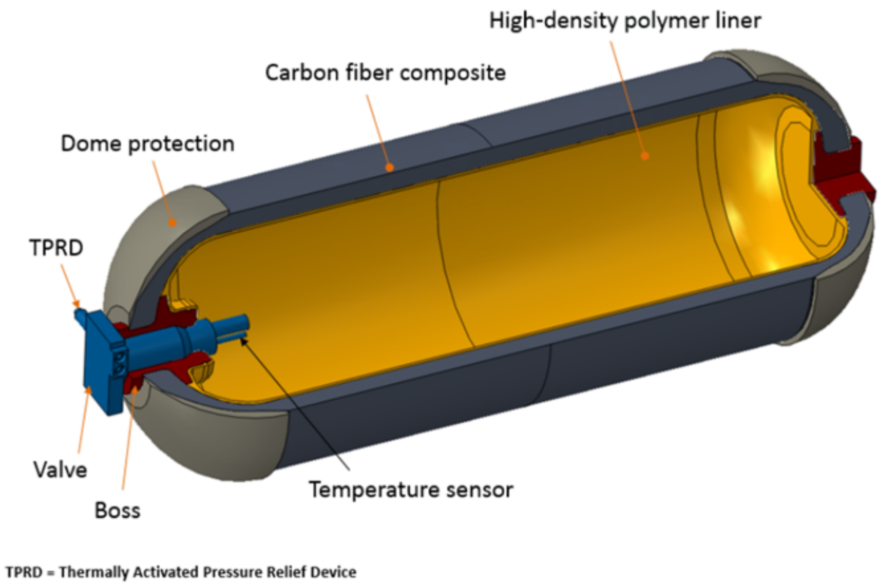


FIGURE 9. Components of a pressurized hydrogen storage tank (Hydrogen and Fuel Cell Technologies Office, n.d.-b).

Gaseous hydrogen is usually distributed to the point of use either in high-pressure containers or via pipeline. Transportation of hydrogen in high-pressure tanks faces similar challenges as the storage in high-pressure vessels can be facilitated using rail, road, or maritime transportation. This makes transportation flexible and suited to reach any destination without any need for new infrastructure.

Transmission of hydrogen via pipelines is a good solution if a large amount of hydrogen needs to be distributed. Gas pipelines usually can transport a high amount of energy at a lower cost than electricity transmission on overhead power lines. The already existing gas pipeline infrastructure in countries such as Germany can be used to transport hydrogen with few adaptions. Theoretically, a methane pipeline could transport the almost same amount of energy using hydrogen. However, this depends on the integrity of the pipeline components like fittings and pipes. It can be so that hydrogen embrittlement accelerates the formation of cracks and thus resulting in a shorter lifespan of pipelines. Factors such as dynamic stress and existing fractures need to be considered as well if one plans to transport hydrogen Mixing natural gas with hydrogen to mitigate these risks and decrease the requirements for adaptations to the existing pipelines is also possibler adaptations to the existing pipelines. However, if the share mixture percentage of hydrogen exceeds 40 %, parts like compressors and turbines likely need to be exchanged to cope with the high volume flow of hydrogen. (TÜV SÜD, n.d.).

Storage and distribution of hydrogen onsite are also feasible, but it requires a safety concept and testing before commissioning. The main challenges are mostly related to the high-pressure tanks as well as the filling station itself. Also, companies need to ensure the integrity of components as well as the training of employees for the safe handling of hydrogen.

The biggest challenges companies face with the transmission and storage of hydrogen are the costs, safety, and availability of skilled personnel. However, these challenges can be tackled with the right partners to gain an edge over competitors and mitigate risk (TÜV SÜD, n.d.). Investing in and building infrastructure and partnerships for hydrogen projects will position companies to profit from the rising demand for clean energy and e-fuels.

Hydrogen or Lithium-ion Batteries

It is very tempting to know which technology is best compared to another. This has been one of the initial questions about writing this work. The more one digs in the more it concludes that it is not apple to apple comparison. They have a similar purpose but are two different technologies with their advantages and disadvantages. There are many types of lithium-ion batteries such as lithium cobalt oxide (LCO), lithium nickel manganese cobalt oxide (NMC), lithium iron phosphate (LFP) etc. NMC is a type of lithium-ion battery commonly used in electric vehicles whereas LFP is a type of lithium-ion battery used primarily for energy storage. When we talk about energy storage systems few main scenarios come in one's mind. Number one being able to store a large amount of renewable energy for deficit periods, second, being able to be used in different transport vehicles and thirdly being able to use on a small scale either in off-grid scenarios or on grid connections. Also, economy and scalability play a significant role in technology being widely used.

One of the major advantages of batteries over hydrogen as energy storage is that fuel production efficiency and overall efficiency from production to usage are higher. Figure 10 shows a comparison of the efficiency of two types of vehicles. Even though the comparison has been done for vehicles we can still see that the losses are much greater in fuel production in hydrogen technology. One should keep in mind that some of the heat losses can be utilized in the form of heat energy which will increase the efficiency of the overall process. But more than 40 percent of the electrical energy is already lost during the production of hydrogen through electrolysis. One important question that this figure does not explain while comparing the two technology techniques is how much energy is required to produce the batteries and how sustainable is it to mass produce batteries. One should also not forget to question the sustainability of the process of making fuel cells and electrolyzers either. More in-depth research is needed on these questions if we are going to compare these two technologies as apple to apple. Figure 10 shows the comparison of the efficiency of battery electric vehicles and fuel cell vehicle

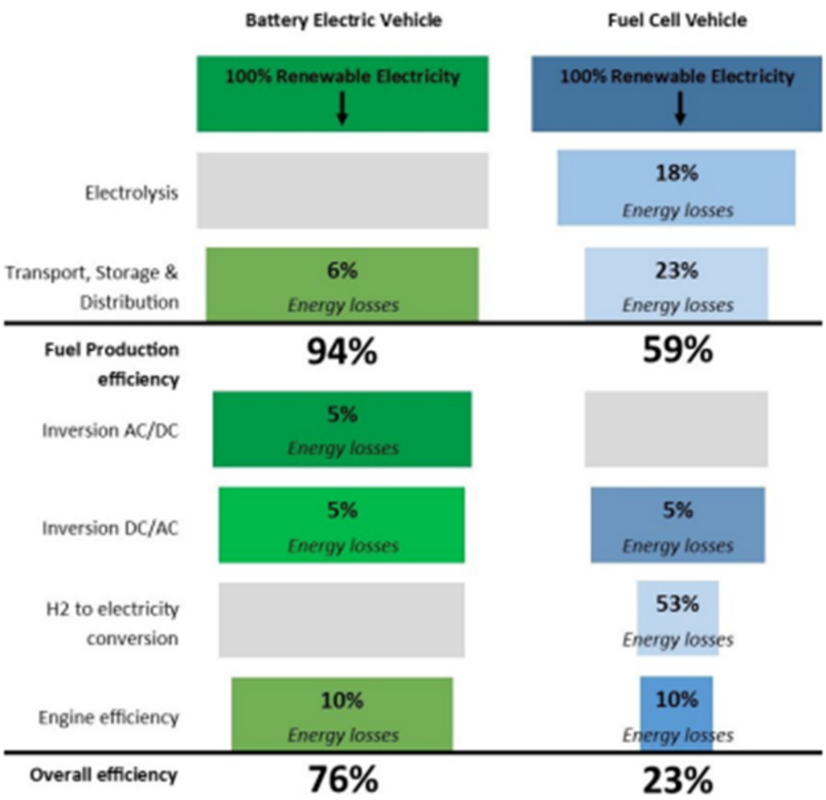


FIGURE 10. Comparison of the efficiency of battery electric vehicles and fuel cell vehicles (Tsakiris, 2019)

On the other hand, hydrogen seems to have a major advantage over batteries when it comes to energy storage for a long period and has the potential to store a large amount of energy in an already existing cavern. Salt caverns, and exhausted oil and gas fields can all provide underground hydrogen storage on an industrial scale. Storing hydrogen in the cavern is the most expensive option but also the most suitable one. Operational experiences of cavern-based hydrogen storage are limited to a few locations in Europe. Project Haystack hydrogen storage in the Netherlands by Gasunie and HyPSTER in France are some projects to demonstrate the ability of hydrogen storage on an industrial scale Storengy, 2021; Gasunie, n.d.).

Compressed hydrogen and fuel cells can provide electricity to a vehicle traction motor with weights that are much less than batteries (Thomas, 2009). From figure 11 one can see that extra battery weight to increase the range requires extra structural weight, heavier brakes, a larger traction motor, and in turn more batteries to carry around the extra mass. The data in figure 11 is to some extent outdated in the year 2022 the difference regarding weight and range is almost none-existing. This is one drawback of battery power electric vehicles. Hydrogen offers a promising solution to this problem and could be best suited for heavy-duty transport, aviation, and shipping.

It should also be noted that after 80% of the depth of discharge the voltage drops sharply for LFP as shown in Figure 12. This implies in some casies that only around 80% of battery capacity can be used. It is also generally suggested not to fully discharge LFP often to increase its life and overall health, which further suggests that we cannot use 100% capacity of batteries if installed as energy storage.

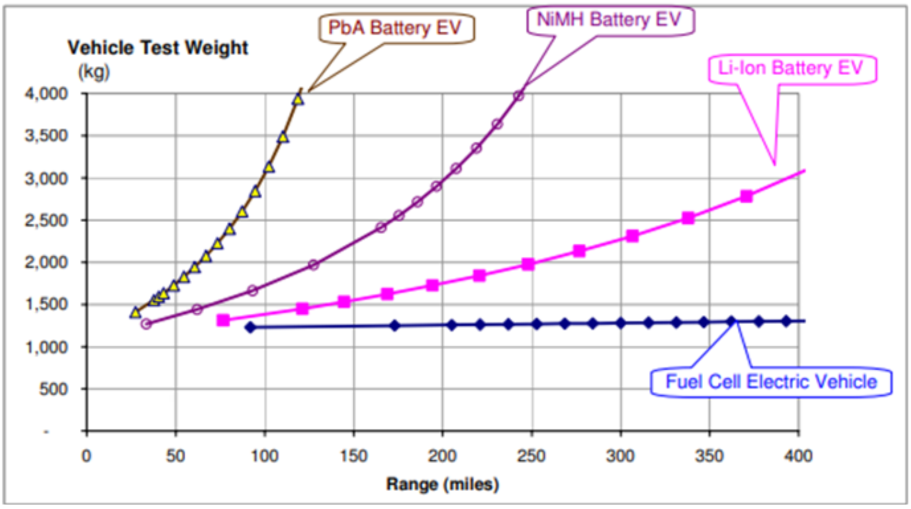


FIGURE 11. The calculated weight of fuel cell electric vehicles and battery electric vehicles (Thomas, 2009).

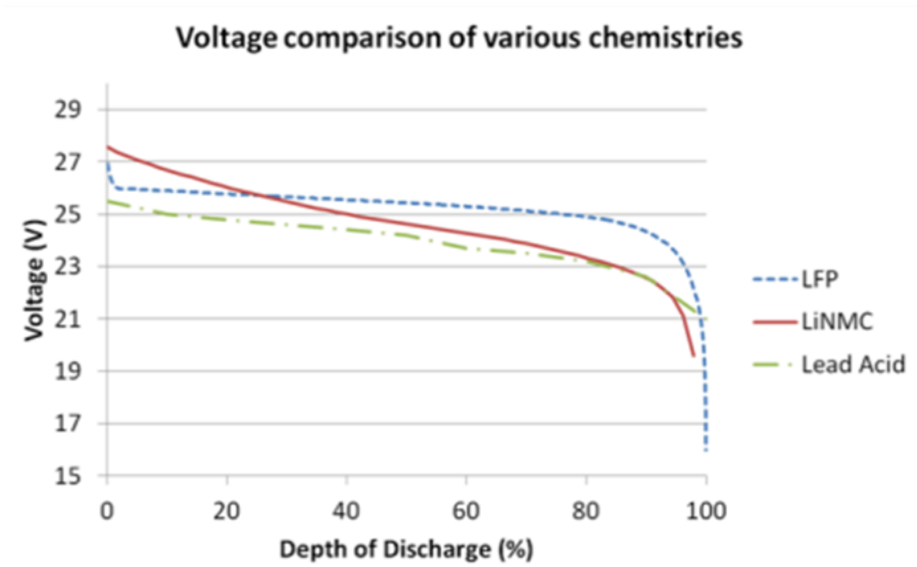


FIGURE 12. The voltage of each chemistry is relative to its capacity for various 24 V packs (Heeger et al., 2017).

Overall thoughts from the literature review are that there is no silver bullet solution to storing energy. In case of the passenger cars and small energy storage systems batteries can be declared the winner among the two. When the question comes to the storage of energy on a large industrial scale and fuel for heavy transport and aviation's hydrogen might win the battle. But still, the author wants to remind us that it is two different technologies, and they cannot be compared as apples to apples, both technologies will play vital a role in our future carbon-neutral society.

Shiva Sharma and Ossi Koskinen

4. EU STRATEGY ON ENERGY SYSTEM INTEGRATION AND HYDROGEN

Hydrogen and energy systems

Energy system integration (European Commission, 2020a) refers to the coordinated planning and operation of the energy system 'as a whole, across multiple energy carriers, infrastructures, and consumption sectors by creating strong and effective links between them to deliver low-carbon, reliable, and resource-efficient energy services with minimum cost for society. It encompasses three complementary and reinforcing concepts.

- A circular energy system, with energy efficiency at its core, where the least energy-intensive choices are emphasized, unavoidable waste streams are refused for energy purposes, and synergies are exploited across sectors.

- Greater direct electrification of end-use sectors.

- The use of renewable and low-carbon fuels, including hydrogen, for end-use applications where direct heating or electrification are not feasible, not efficient, or have higher costs.

The highly integrated system (European Commission, 2020a) will also be a multi-directional system where consumers play an active role in energy supply. This strategy proposes concrete policy and legislative measures at the EU level to slowly gradually a new integrated energy system meanwhile respecting the different starting points of different member states. The parallel vision "A hydrogen strategy for a climate-neutral Europe" complements this strategy to elaborate in detail on the opportunities and necessary measures to scale up the uptake of hydrogen in the context of an integrated energy system.

Hydrogen is enjoying rapidly growing attention in the EU and around the world due to its useability as feedstocks, an energy carrier and storage, and its different applications across many industries. Renewable electrical energy is expected to decarbonize a great share of the EU energy consumption in the future by 2050, but it cannot completely decarbonize all. Hydrogen has a strong potential to fill some of this gap, as an energy vector for renewable energy storage together with batteries, and to be used as a transport fuel, ensuring backup for seasonal variations (European Commission, 2020b). Europe is highly competitive in green hydrogen technologies manufacturing and has positioned itself to benefit from the global development of green hydrogen. Cumulative investment in green hydrogen the in EU could be up to 180-470 billion euros by 2050 (European Commission, 2020b). However, green hydrogen and low-carbon hydrogen are not cost-competitive compared to fossil-based hydrogen. To harness all opportunities with hydrogen EU has developed a strategy called "The EU hydrogen strategy", which was adopted in July 2020. In the figure 13 one can see the concept path towards a European hydrogen ecosystem step by step developed by the EU.

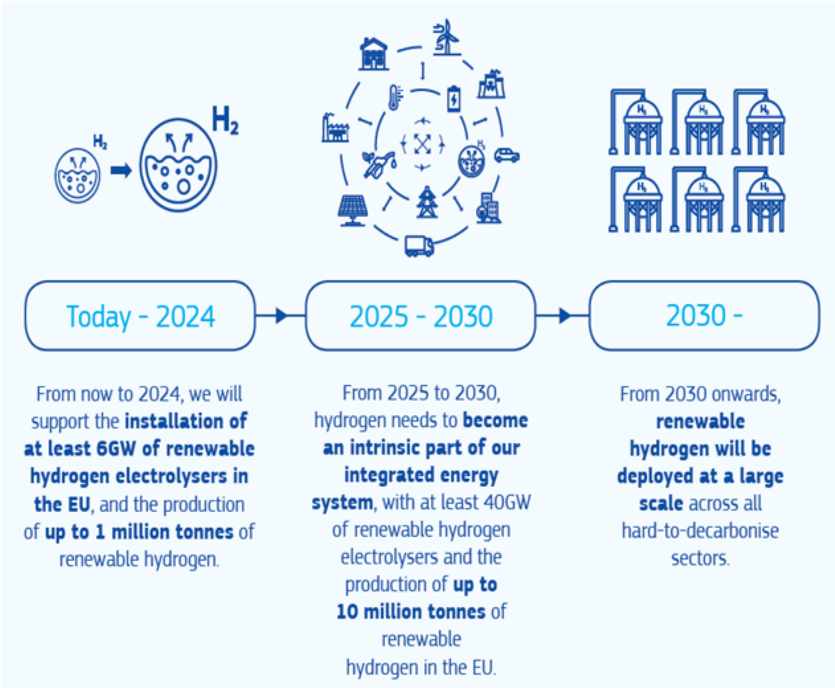


FIGURE 13. The step-by-step path toward a European hydrogen ecosystem (European Commission, 2020b).

Most EU states have put plans for green hydrogen in their National Energy and Climate agenda, 26 states have signed up to the "Hydrogen Initiative" (European Commission, 2020b) and 14 states have put hydrogen in the context of their alternative fuels infrastructure national policy framework. Furthermore, the EU has put action plans to achieve advancements in hydrogen technologies and harness all possible benefits from it, these actions are as follows:

1. An investment agenda for the EU: To support investments and the emergence of a hydrogen ecosystem, the EU commission has established The European Clean Hydrogen Alliance. It is a forum bringing together industry, public authorities, and civil society, to coordinate investments. This Alliance will play a crucial role in facilitating and implementing the actions of supporting investments to scale up production and demand for green and low-carbon hydrogen.

2. Boosting demand for and scaling up production: To help boost demand and scale up production EU has purpose measures to facilitate the use of hydrogen and its derivatives in the transport sector in the commission's Sustainable and smart Mobility Strategy and other related policy initiatives. Furthermore, additional support measures, including demand-side policies in the end-use sector, for green hydrogen building on the existing provisions of the Renewable Energy Directive. It has also worked to introduce comprehensive terminology and EU-wide criteria for the certification of green and low-carbon hydrogen. It has developed a pilot scheme for a carbon contract for different programs particularly to support the production of low-carbon and circular steel, and chemicals.

3. Designing an enabling and supportive framework: It has started the planning of hydrogen infrastructure, including in the Trans-European Networks for Energy and Transport the Ten-year Network Development plans also consider the planning of a network of fueling stations. It has a design enabling market rules to the employment of hydrogen, including removing barriers for efficient hydrogen infrastructure development and ensuring access to liquid markets for hydrogen producers and customers and the integrity of the internal gas market, through the upcoming legislative reviews. It has launched

a 100MW electrolyzer and a Green Airports and Ports call, for proposals as part of the European Green deal call under Horizon 2020. Establish the proposed clean hydrogen partnership, focusing on green hydrogen production, storage, transport, distribution, and key components for priority end-uses of clean hydrogen at a competitive price. It has also facilitated the demonstration of hydrogen-based innovations and launched a call for pilot action on interregional innovation under cohesion policy on hydrogen technologies in carbon-intensive regions.

4. The international dimension: Eu has strengthened its leadership in international technical standards, regulations, and definitions of hydrogen. It has developed a hydrogen mission within the next mandate of Mission Innovation. It has promoted cooperation with southern and eastern neighbor partners and energy community countries on renewable energy and hydrogen. [27].

One of the biggest issues regarding green hydrogen is the criteria for when the produced hydrogen can gain official green hydrogen status. In Spring 2022 there was a suggestion in the European parliament about the requirements for using grid electricity for the production of green hydrogen. This proposal had six different requirements for green hydrogen, which would have made the usage of grid electricity and the Guarantees of Origin (GoO) almost impossible to produce green hydrogen. Fortunately, this proposal was voted down and rejected in Autumn 2022, which creates a better starting point to compete in the global hydrogen markets.

Ashkan Fredström, Shiva Sharma and Seppo Mäkinen

5. HYDROGEN ECONOMY

History and the choice of energy bearer

The history of hydrogen goes back to the late 18th century when early experiments showed water can split into two distinct gases. In the year 1783, Antoine Lavoisier gave hydrogen its name: hydro (water), gen (generator, generated of). During the first 25 years after these events, a significant portion of technologies related to hydrogen was already developed. Those include fuel cells, electrolysis, and hydrogen-based internal combustion engines. These technologies initially failed commercialization. The next generation of hydrogen-based technologies happened to be between the mid-19th century and the mid-20th century. Those include advancing the prior technologies, in addition to Zeppelin and airships. Later on, until the mid-20th century, other technologies were introduced, including utilizing hydrogen's atomic energy (deuterium), liquid hydrogen, and hydrogen rocket fuel, and commercialized production of hydrogen by coal. The first envision of green hydrogen appears to be from the early 20th century, when John Haldane wrote "great power stations where during windy weather the surplus power will be used for the electrolytic decomposition of water into oxygen and hydrogen." (Haldane, 1923).

In Figure 14 we have the history of hydrogen, which did not unfold in isolation. Many other technologies, anywhere in the spectrum of absolutely complementary and competitive have been developed in parallel. Those include carbon fuels extraction and refinery, combustion engines, fuel cells, and gas distribution channels among others. Development in carbon fuel refinery technologies made it cheaper for those fuels to be used in mass, and that was a competition for investments in hydrogen technologies. On the other hand, developments in combustion engines and gas pipelines could be used for either, and thus were complementary to the hydrogen path.

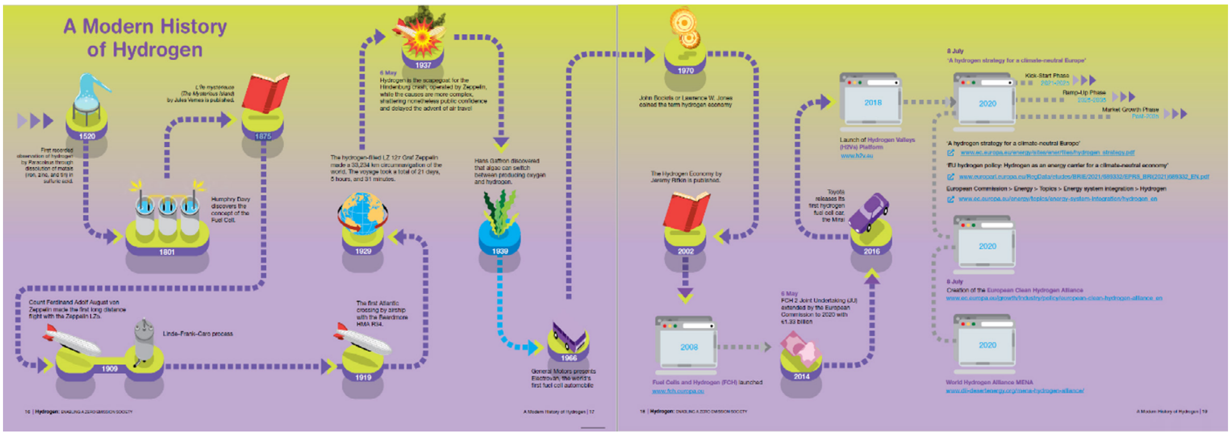


FIGURE 14. History of hydrogen (Stancell et al., 2021).

It is important to know the history of parallel technologies because they directly affect how the economy of hydrogen develops. Here is an example. At the start of the 20th century, when automobiles were coming into the market, companies, and individuals who could set a standard for fuel and sell their fuel would have had a lucrative business. How would one convince others that fuel is the best? Can the answer be the price and efficiency? Individuals such as Thomas Midgley Jr. had such an answer (Lebedev et al., 2022). He came up with a fuel addition that could be produced inexpensively and was highly efficient, tetraethyl lead. The fuel started to be used on a large scale. The problem with this fuel was, despite it being cheap and efficient, that it was lethal. After many reported death cases, including the company's workers, Midgley himself died of lead poisoning. The use of fuel was stopped, both because of its price or efficiency, but because of its side effects, the indirect costs on society.

If there was one lesson there, it would have been to consider those costs to the larger society when choosing the bearer of energy. An answer to the question of 'how would one convince others that fuel is the best' must consider this factor as well. compared to green hydrogen, carbon fuel does have a huge cost on the earth's environment and people's health. Had those costs shown themselves rapidly as in the case of tetraethyllead, the use of these fuels too would have been discarded a while ago.

In choosing future bearers of energy societal costs must be considered. Green hydrogen is a bearer of energy that has minimal costs of that sort. But what about other factors, efficiency and price? Many assert that green hydrogen lacks economic and lacks science (Morris, 2020). Is green hydrogen indeed inefficient? The answer to this question is, "not necessarily", in our view. We will discuss this matter in the next sections.

Recent Development in Hydrogen Technology

We are all living in very exciting and historically important times at the moment. Hydrogen-related technologies are pushing through, and news about these developments is seen almost daily. Recently, a LinkedIn article written by Michael Liebreich (2021) gave several interesting and relevant aspects related to the use of hydrogen in several different technologies. In his opinion, "The problem is, just like a Swiss Army Knife, you won't use hydrogen for everything you could theoretically do with it. Clean hydrogen will have to win its way into the economy, use case by use case. It could do so on its merits, or it could do so because of supportive policy (including carbon prices). But it will have to do so in competition with every other clean technology that could solve the same problem. And that is where the dreams of the hydrogen economy hit reality: in almost all use cases there is a good reason why hydrogen is not currently used - because other solutions are cheaper, simpler, safer, or more convenient." Such an attitude is realistic but unfortunate. One should see green hydrogen as a solution also to problems, which cannot be justified with economical reasoning quite yet. With time, as hydrogen technology evolves naturally, the prices will decline with increasing volumes of the technologies.

Liebreich writes also about the use of hydrogen as long-term storage of energy, and as means of providing resilience in times of crises: "In the power system, you won't routinely use hydrogen to generate power because the cycle losses – going from power to green hydrogen, storing it, moving it around and then using it to generate electricity – are simply too big. The standout use for clean hydrogen here is for long-term storage.

The economy of the future, which is going to be vastly more deeply electrified than today, needs long-term storage. It's not just about providing backup for when there is no wind or sun, it is also going to be about providing deep resilience in the case of weather disasters, cyber or physical attacks, neighboring countries shutting off interconnectors, and the like. Hydrogen can be stored in salt caverns, depleted gas fields as compressed gas, or liquified at various strategic points. It can be converted back into electricity centrally at 60% or more electrical efficiency via fuel cells, providing as high a level of grid resilience as you want to pay for."

Liebreich sees that because of natural and unavoidable reasons, it will be impossible to use battery technologies for medium- and long-haul aviation. However, he also finds hydrogen technology insufficient for such usage. This comes from hydrogen's very low density, which results in the need for high fuel volumes in practical cases. In short-range aviation, he sees battery technology as useful as the energy density of batteries is increasing at the same time their costs are coming down.

About shipping, he writes: "Local ferries, routes up to a few hundred kilometers, are most likely to go electric. However, coastal and river vessels, working routes of a few hundred to a thousand or so, look like a very promising market for hydrogen. These lengths of routes can't be served by batteries, but marine vessels don't have the energy density challenges of aviation, so hydrogen might work, either in a fuel cell or just burned in an internal combustion engine which can benefit from the existing marine engine supply chain." In internal combustion engines, it is common to use ammonia as the fuel – not pure hydrogen gas.

Liebreich does not believe in the use of hydrogen for land transportation at all. He sees that no matter which types of vehicle you consider, or how long or short distances are considered, battery technology will win over hydrogen technology in all of them. This somewhat contradicts some other opinions, which suggest the use of hydrogen for heavy transportation over long distances. He also does not believe the in use of long gas pipelines for the transportation of hydrogen from country to country.

Despite Liebreich's opinions, Toyota, BMW, Daimler, and Hyundai are examples of car manufacturers, which have invested loads of time and money in fuel-cell-driven cars. Toyota Mirai (n.d.), BMW iX5 (Vijayentrihan, 2021) and Mercedes-Benz GLC F-CELL (n.d.) are examples of working and commercially viable models. Hyundai, on the other hand, decided to suspend the development of their hydrogen fuel cell car Genesis almost immediately after the company announced an end to internal combustion engine development (Dow, 2021). This seems to indicate that Hyundai is about to invest all in battery technology.

In addition to fuel cells, batteries, and traditional internal combustion engines using benzine or diesel fuel, there is also a very rare and dangerous-looking alternative. Toyota has started to investigate the use of pure hydrogen gas as a fuel for an internal combustion engine (Segura, 2021). However, one has to admit that Toyota is perhaps the only car manufacturer in the world making such investigations at the moment. Other companies abandoned this idea already years ago.

Besides one-family cars, there are also serious attempts for using hydrogen fuel cells in driving very heavy trucks (Preyser, 2021). However, also battery technology is being used for such devices, for example very large excavators (Lambert, 2019).

A recent report reveals that shipping hydrogen in the liquid state would be five times more expensive than shipping liquid natural gas (LNG) (Barnard, 2021). This ratio has been estimated by considering costs per unit of energy in each fuel. This fact speaks for local hydrogen production rather than large-scale factories producing large volumes of hydrogen, followed by international and intercontinental transportation around the world.

In December 2021, the Finnish company *Enersense* announced its decision to invest 13-18 million euros in another company called *P2X Solutions* (Koponen, 2021). This will build Finland's first green hydrogen production factory in Harjavalta. The final decision requires significant support, about 25 M€, from the ministry of employment and the economy of Finland (TEM, 2021). The final decision is expected to be done at the beginning of the year 2022. This might be the first of several similar factories around Finland. Hopefully, one of these will be located in the region of Ostrobothnia.

One problem with battery-powered electric vehicles is related to the availability/abundance of lithium, the third element on the periodic table. In a recent discussion Simon Moores, CEO of Benchmark Mineral Intelligence, opened up on some aspects related to lithium, the most essential material in the lithium-ion batteries used for electric vehicles and energy-storage systems at the moment (Donnelly, 2021). He suggests that in 2022, there will be a lot of debate about the availability and price of lithium. "While there is plenty of lithium on the planet, it isn't being extracted and refined quickly enough to keep up with the rapidly growing demand for batteries. By 2030, there's projected to be a lithium deficit between 455,000 and 1.7 million metric tons each year." He foresees a shortage of battery-grade lithium in the electric vehicle industry, and he sees that price volatility will last for about 3 years." Even though Moores does not see this problem as very critical and long-lasting, this an evidence of the problems related to other technologies. With hydrogen technology, abundance will never be a problem.

Chinese battery manufacturers are fighting to collect as much lithium and other battery-technology-related elements as possible. They are investing in the mining other these rare elements internationally and at a national level (Kriittisetmateriaalit.fi, 2021).

One of the most fascinating sights to the future of Ostrobothnian small-size and medium-sized companies involves the possibility to not only produce green hydrogen gas but to manufacture large storages for the gas. Such storages have specific requirements from the material's point of view: their walls must be able to keep high-pressure hydrogen gas inside the container. This is not easy for most materials, including stainless steel. The most important reason for this is the extremely small size of hydrogen molecules. However, this problem can be avoided by using modern composite materials on the inner surface of the container. Ostrobothnia is one of the rare regions in Finland, which has vibrant sailing boat factories. Such an industry requires large amounts of composites, and hence the production of composite hydrogen storage would fit into our region most naturally. This idea is strongly supported by a recent press release, which tells that EKA Composite will start a new composite factory in Oravainen (Koivisto, 2022).

Green Hydrogen: Drivers and Barriers

As mentioned in the above chapters green hydrogen is an energy carrier that can be used in many ways. Figure 15 shows the production, conversion, and end uses of green hydrogen across the energy system. Around 120 million tonnes of hydrogen are produced globally and 95% of this hydrogen is produced from fossil fuels such as natural gas and coal. At this date there is no significant hydrogen production from renewable sources, green hydrogen has been limited to demonstration projects (IRENA, 2020). Approximately 70-100 million tonnes of CO_2 annually are released in the EU to produce hydrogen from fossil fuels (European Commission, 2020b). Hydrogen accounts for less than 2% of the EU's current energy consumption and is mostly used to produce chemical products, such as plastics and fertilizers. 96 % of this hydrogen is produced from fossil fuels. This fossil-based hydrogen can be replaced by green hydrogen or green hydrogen can be used to start new industrial products such as green fertilizers and steel. It can also be used in the transport sector, especially in heavy-duty and long-distance trucks, buses, ships, and planes where the weight of fuel matters.

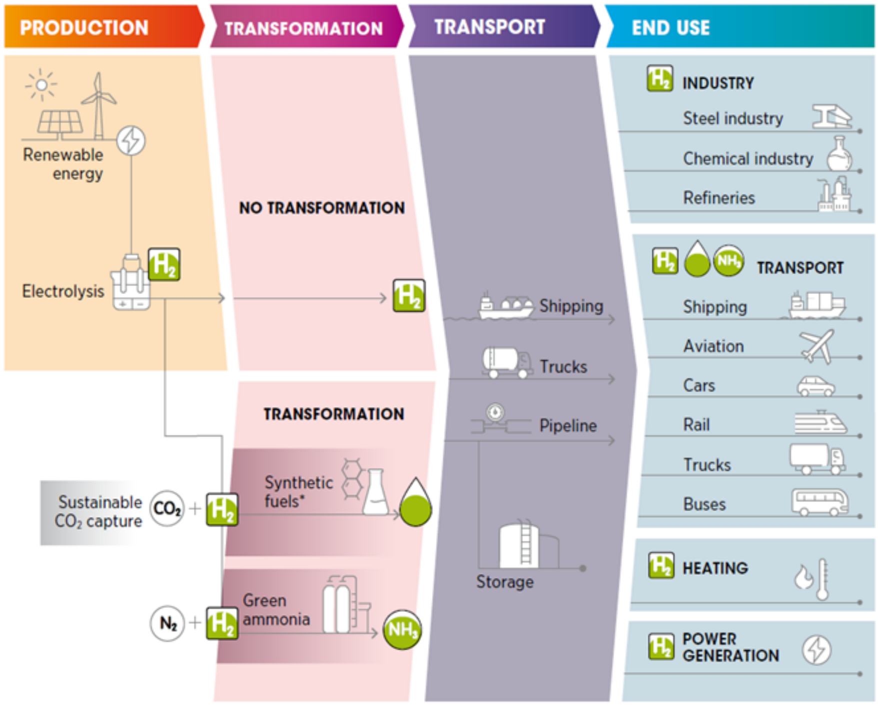


FIGURE 15. Production, transformation, transport, and end use of green hydrogen (IRENA, 2020).

This is not the first time that interest in hydrogen has begun. There have been many waves of interest in hydrogen in the past, which were mainly fueled by oil price shocks, concerns about peak oil demand and air pollution, and research on alternative fuels (IRENA, 2020). Recently there have been a few megatrends that sparked interest in green hydrogen again. First of all, the electrification of city life. According to a United Nations (2017) report by 2050, the world's urban population is expected to nearly double. This figure is estimated to reach 85% by 2100. Within 150 years the urban population will have increased from less than 1 billion in 1950 to 9 billion by 2100 (OECD, 2015). This will put huge pressure on the infrastructure in those cities. Feeding the population, electrification of mobility, and the trend of digitalization are some other megatrends that will require a large increment in energy demand and has fueled interest in green hydrogen. Fulfilling these demands with renewables will be a big challenge especially when wind and sun energy are available all the time when want. All options should be considered and storing excess renewable electricity in form of green hydrogen is another greatest driver of raising interest in green hydrogen. Electricity must be reliable, should be available all the time and above all, it must be clean. The challenge faced today is not only to cover the additional energy demand but also to cover the electricity demand that falls away from the shutdown of fossil-based power plants.

However, green hydrogen still faces many barriers which prevent its full contribution to the energy system transformation. Below are a few important barriers faced by green hydrogen are mentioned.

1. High production cost: Today green hydrogen is not cost-competitive against fossil-based hydrogen. The cost of fossil-based hydrogen is highly dependent on natural gas prices, and it is around 1.5 euro per kilogram (€/kg) whereas, the cost of green hydrogen is about 2.5-5.5 €/kg for the EU (European Commission, 2020b). On top of this adopting green hydrogen, technologies can be expensive for end

users. Vehicles with fuel cells and hydrogen tanks are almost two times the price of their fossil fuel counterparts (IRENA, 2020).

2. Lack of infrastructure: Currently hydrogen has been produced close to where it is used, with limited dedicated transport infrastructure. There are around 470 hydrogen refueling stations around the world (IEA, 2020), compared with more than 200000 gasoline and diesel stations in the United States (US) and the EU.

3. Energy Losses: Producing green hydrogen with electrolysis has around 60-70 percent efficiency rate, meaning about one-third of the electricity goes as waste heat. Using hydrogen to produce electricity again by using a fuel cell or gas turbine, the efficiency is 40-55 percent. Hence the overall efficiency from electricity to hydrogen and back to electricity is about 24-38 percent. (Vartiainen, 2020).

However, the efficiency can be improved if this waste heat is recovered and used. In this scenario, the overall efficiency from electricity to hydrogen and hydrogen to energy can be as much as 60-70 percent (Vartiainen, 2020). In figure 16, one can see the amount of hydrogen that can be produced by 55-kilowatt hours (kWh) of electricity and how much electricity and heat energy can be recovered.

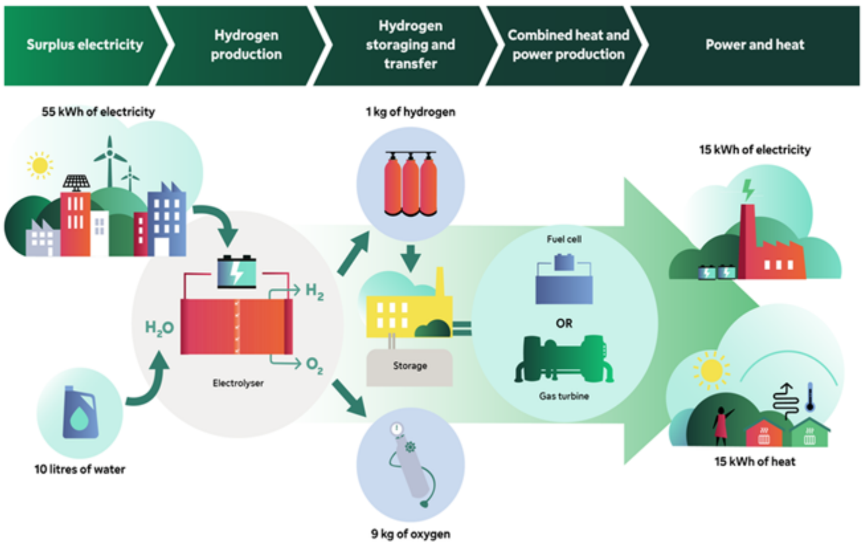


FIGURE 16. Production of green hydrogen from 55 KWh renewable energy (Vartiainen, 2020).

4. Lack of value recognition: Currently there is no market for green hydrogen, no green steel, no green shipping fuel and there is no valuation for the lower GHG emissions that green hydrogen brings. There is also no internationally recognized way to differentiate green from grey hydrogen which limits the demand for green hydrogen. (IRENA, 2020).

Hydrogen Market and supply

The market for hydrogen consists of both supply and demand for it. It is also characterized by how supply and demand are met. The currently fully formed hydrogen market applies to the supply and production of non-green hydrogen, and its demand and use for mostly non-energy-related applications. The market for green hydrogen supply and its use as energy storage is yet to be developed.

Hydrogen can be produced in various ways. Not all of them are environmentally friendly. Color codes given to hydrogen correspond to how the production process is carbon-free. Green hydrogen, for example, refers to hydrogen produced by electrolysis using renewable electricity. Carbon-based hydrogen, which can be coded as black, brown, or grey based on the process and the input materializes the most damaging to the environment. There are other color codes such as blue, turquoise, and pink that can be argued to pollute less than totally carbon-based production without carbon capture. For the sake of simplicity in this chapter, we categorize them into two groups, carbon-based hydrogen, and green hydrogen. (Yue et al., 2021).

Currently, the supply of fossil-based hydrogen is established while the production processes of green hydrogen are in the early industrial stages. Because the final product is hydrogen gas with the same properties, fossil-based hydrogen is the direct competitor of green hydrogen.

The competition is moderated when there are carbon-based taxes on fossil-based hydrogen while green hydrogen technologies receive subsidies and other funds. However, in terms of production costs and the final price green hydrogen cannot compete with fossil-based hydrogen yet.

The price efficiency of fossil-based hydrogen is partly because it is produced at scale and also as a bi-product in the petrochemical industry. That means, fossil-based hydrogen enjoys both economies of scale and economies of scope. It enjoys economies of scale, because, after years of production at scale, engineers have had enough time to make the involved processes as efficient as possible. Additionally, as in any other product, when it is produced at scale, the share of the fixed one-time costs such as initial heavy investments broken down per each unit of the produced hydrogen.

Fossil-based hydrogen additionally benefits from economies of scope. The processes and the material needed in the processes are used jointly in the production of other petrochemical products. If you are already producing those products, why not produce hydrogen as well on the side, when a lot of processes, equipment, and material could be used for both purposes.

At this early stage, green hydrogen does not have those benefits yet, and that is one reason for higher production costs and higher prices. However, if the investments in green hydrogen continue at the current pace, green hydrogen too would very soon be produced at scale, and that would lead to economies of scale for green hydrogen. That in turn means less production cost and room for reducing the prices of green hydrogen.

Green hydrogen could as well benefit from economies of scope. If for instance in the future hydrogen is at a higher scale used for storing excess renewable energy, since many of the processes and equipment would be already in place, renewable energy producers could also decide to sell green hydrogen as well.

In addition, as more investments come into the related technologies and industries, the needed equipment for the production of green hydrogen could experience more and more cost-efficient because of the engineers' learnings and innovations, and because of economies and scale and scope. For example, there are currently very large investments in producing less costly but more efficient electrolyzers. The advancement of production machinery at the current pace means the initial investments would reduce as these industries mature, and that would open space for the reduced price of green hydrogen.

The point here is that the cost efficiency of green hydrogen should not be seen as a screenshot of current market conditions. Rather, the industry and the economy are dynamic, and the prices change over time.

Especially, when an industry is new and in its early stages, it is to expect the prices and costs to reduce over time.

If we agree that green hydrogen, in comparison to carbon-based hydrogen, has the potential to gain price efficiency, the question remains if hydrogen in general could be price efficient compared to other fuels. To open this question up, we discuss another characteristic of green hydrogen: the possibility of it being decentralized and democratized.

Carbon fuels such as diesel have been in production for decades. All processes in the discovery, extraction, and production of petrochemical fuels are made efficient to a large extent. Similar to the arguments earlier, these fuels have the benefits of economies of scope and scale. There is however one issue with these fuels that makes them risky when it comes to price efficiency. That is for them being more towards monopolized, centralized products, rather than being more competitive and decentralized. That risk can be recognized when we see organizations such as OPEC whose purpose is to keep the monopoly and price manipulation of these products. That, in economic terms, imposes risk on price efficiency. We have seen the consequences of this risk a few times in recent history, including the 1972 oil crisis, the recent events of the Russian war in Ukraine, and the increased prices of carbon fuels because of that.

Although currently the prices and the production costs of green hydrogen are higher than carbon fuels, it imposes no such risks. In contrast to state-backed oil companies, green hydrogen can be produced in a decentralized manner, where smaller production units could supply the fuel to the market. In other words, green hydrogen is produced in a competitive market, and the prices will be set competitively.

In time, as the industry and technologies related to green hydrogen mature, it is completely for it possible to be price efficient in comparison to other fuel alternatives. Additionally, it imposes less price risk since the market for green hydrogen is closer to the more competitive spectrum. Green hydrogen not only has fewer negative effects on people's health and the environment, but it also has the potential to be a better economic choice. As the investments in this industry are growing at speed, there is a clear sign that mass availability of lower priced and less risky fuel of green hydrogen can happen.

Hydrogen Demand

Hydrogen is generally used for two different categories of purposes, as shown in figure 17. Either as fuel and energy storage, or as a chemical element for the production of other products. Currently and in the past, the most usage of hydrogen has been the latter. The demand for hydrogen is for example related to welding and heat-treating of metals and in the steel industry, glass purification, and production of pharmaceuticals, semiconductors, and fertilizers among other applications. Hydrogen has also been used as a bearer of energy and as fuel, especially in the aerospace industry. Hydrogen has been used as a rocket fuel by NASA since the 1950s.

Hydrogen would continue being demanded as an element in industrial processes. The challenge here is to replace fossil-based hydrogen with green hydrogen to be used in those processes. Demand for hydrogen as a fuel and bearer of energy on the other hand is growing at speed, mostly due to the efforts to decarbonize the economy. Considering the share of greenhouse gas emissions produced by the energy industry, which is 73% compared to other sectors according to Ritchie et al. (2020), we put a focus on the energy-related usage of hydrogen.

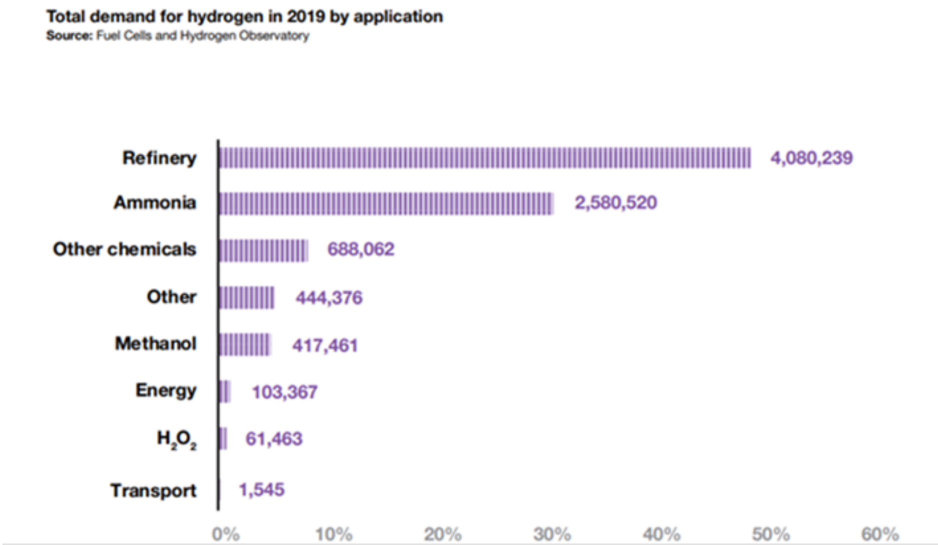


FIGURE 17. Hydrogen usage and demand (Stancell et al., 2021, p. 47)

Energy used in steel production, for example, is a very large contributor to CO_2 emissions in Europe and worldwide. Projects such as H2 Green Steel have the mission of minimizing carbon emissions in the steel industry by using green hydrogen as a source of energy. In addition to the steel industry, the air transport industry is a large emitter of CO_2 (see figure 18). In that regard, Airbus has released prototype airplanes that would be produced and put on the market if the infrastructure for delivering the fuel is in place in airports around the world.

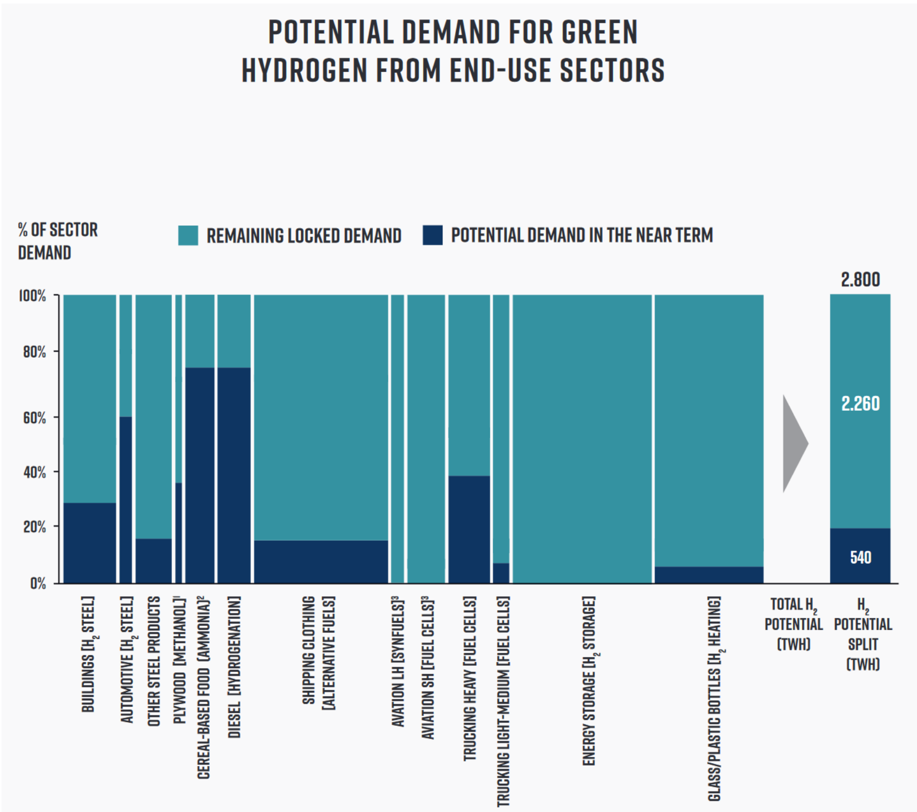


FIGURE 18. Hydrogen consumption by industries (Material Economics, 2020, p.7).

The automotive industry has not been left behind when several major car manufacturers have products or prototype fuel-cell electric vehicles. In that industry, however, battery-based electric vehicles are competitors to hydrogen-based fuel cell cars. However, the time needed for the vehicles to be charged with electricity is an issue that is an advantage to hydrogen-based fuel cell cars. That issue is especially more critical for trucks, the batteries of which would take hours to be charged. On the other hand, currently, battery-based electric vehicles have the upper hand as the infrastructure and battery charging stations are developed at a higher degree compared to hydrogen fuel stations.

The example of vehicles shows green hydrogen being the only and best solution to all fossil-free energy problems is under challenge. Generally, the more energy conversion, the less efficiency there is an alternative fossil-free solution might be more suitable in some cases. As a clear example, when trains can directly take renewable energy from the wires, it would not make sense to convert electricity to hydrogen, and then convert the hydrogen back into electricity in the fuel cells of a train. These energy conversions can be avoided for a train, but not in all applications. That sometimes makes other fossil-free energy solution to be more energy efficient. For example, if a house, because of its location, can be heated by geothermal energy, it makes less sense to burn green hydrogen for heating, and the other fossil-free solutions are more suitable.

Despite that, green hydrogen has a big role to play. In addition, for the mentioned fuel use cases, hydrogen can be used as storage of energy in renewable energy power plants. The electrical energy produced by wind or solar energy can be converted to chemical energy in hydrogen by electrolyzers. The chemical energy can be converted back to electrical energy by fuel cells. These give the potential for hydrogen to be means of storing energy at renewable power plants.

One challenge for renewable energy power plants is that weather is unpredictable and the energy received by wind and sunlight fluctuates. Sometimes there is more wind, and sometimes there is no wind. Sometimes it is sunny for weeks, and sometimes solar energy is scarcer. That leads to the energy not being enough at some points and being in excess some other times. At the excess times, energy producers might need to sell the excess at a negative price, or if the network cannot take the excess energy, waste it as heat. On the other hand, at scarce times, the price of energy would rise.

A solution to this problem is to store the excess energy, and release it at times when there is less energy available. Currently, a lot of solutions are around grids and storing energy in batteries. The issue with this solution is that the capacity is limited, and it is costly to increase the capacity, whilst a solution to convert the energy into hydrogen and back has less of that problem. Green hydrogen therefore can be both demanded and supplied at renewable energy facilities.

Hydrogen Infrastructure

There are many applications for green hydrogen, including that of industrial processes, as a fuel, and for other energy-related demands. There are alternative fossil-free solutions in numerous cases, however, green hydrogen is a significant solution that is to be a part of our quest for a carbon-free economy. Every technological advance in demand for hydrogen leads to an improvement in supply and vice versa. As renewable power plants use hydrogen-based solutions to store the excess energy, technologies for converting the energy, both for electrolyzers and fuel cells, develop. That would make the consumption and production of hydrogen in other industries to become more efficient. The green hydrogen industry involves a feedback loop that could exponentially take us closer to a carbon-free economy. Currently, hydrogen is mostly demanded other purposes than energy storage. Energy storage, at the same time, is delivered by other means than green hydrogen. Changing that would create enormous demand for green hydrogen.

The market for hydrogen consists of both supply and demand for it, as it was described above. It is also characterized by how supply and demand are met. The currently fully formed hydrogen market mostly applies to the supply and production of fossil-based hydrogen, and its demand and use for non-energy-related applications. The market for green hydrogen supply and its use as energy storage is yet to be developed further.

In addition to developing solutions for the production of green hydrogen and its use as an energy bearer, infrastructure needs to be established to make it possible for the supply and demand to meet. The infrastructure dimensions for green hydrogen include legal, physical, digital, as well as transportation and delivery related.

Legal infrastructure

The legal infrastructure is related to regulations about the production, distribution, and consumption of green hydrogen. Safety regulations, municipal regulations for distribution, and tax exemptions are some examples. A developed legal framework helps add clarity and encouragement to the formation of a system where green hydrogen is smoothly traded. Although currently, the regulations for green hydrogen are slowly being developed, the legal infrastructure is still far from being developed. Floristean (2019) lists EU-level regulations that affect the hydrogen economy in different dimensions, such as production, storage, and transport, and in specific use cases such as vehicles, electricity grids, stationary grids, and fuel cells. They find that many regulations indirectly affect the hydrogen economy, and mostly as a barrier. On the other hand, there are regulations such as the GHG intensity of hydrogen and technical requirements to be followed by refueling stations that are directed at the hydrogen economy. These are the report claims, rarely a source of unreasonable barriers.

Physical infrastructure

The physical infrastructure is the physical equipment that is in place for hydrogen to be traded easily, and for the hydrogen economy to function efficiently. Examples include liquid hydrogen fuelling facilities at airports, without which hydrogen airplanes could not operate. Other examples include fuel stations for possible future fuel cell electric vehicles. Similar to the legal infrastructure, physical infrastructure is not yet developed to the level for green hydrogen to be easily traded. Nonetheless, in recent years, there have been activities by different companies to build the infrastructure. Examples are Nilsson Energy in Sweden and Ren Gas in Finland.

Physical infrastructure includes also the facilities related to the transport and delivery of green hydrogen. This is a challenge worldwide for the hydrogen economy to function (Agaton et al., 2022). The characteristics of hydrogen gas make it difficult for it to be transferred by the means that are currently used for fossil-based fuels. For example, because of the small size of the hydrogen atom, it escapes the containers. The equipment for transporting hydrogen should be designed accordingly, especially for that purpose. The current know-how makes it expensive to transport hydrogen gas. Additionally, because it is a light gas, it takes much volume, and the amount of energy per unit of volume is low. Therefore, it makes sense to transport liquid hydrogen. However, the process of liquefying hydrogen is very costly.

There are different alternative solutions to these issues. One is, as previously stated about the production and consumption of green hydrogen, to let the technologies grow at a level for the transport of hydrogen to be cost-effective. Until then, other solutions include transporting smaller containers in shorter distances, when green hydrogen can be produced in a decentral manner. Pipelines are another solution. A network of pipelines to which different suppliers and consumers are connected could facilitate the transport of green hydrogen. Another solution is through chemical reactions to transform hydrogen into material that is easier to transport, such as ammonia which is built of nitrogen and hydrogen, and then at the destination, either use the new product or split it back into hydrogen. Although this could potentially reduce the problems of hydrogen transport, it would add to the complexity of the energy system. Either way, a clear way and infrastructure of transporting hydrogen is still lacking and need to be developed.

Digital infrastructure

Infrastructure also includes digital platforms by which transportation and delivery of the green hydrogen from the supplier to the consumer could be facilitated. Digital platforms that facilitate the trade of green hydrogen would contribute to this type of infrastructure. Especially because the green hydrogen economy could be decentralized, the need for collecting and managing data on the supply and demand of green hydrogen is of crucial importance. Data could be collected from the suppliers, the consumers, or the equipment using IoT, and using technologies such as AI, the best solutions for trading green hydrogen could be produced. Additionally, digital solutions could contribute to the efficiency of the production and consumption of green hydrogen as a bearer of energy. Here even though that companies such as Hexagon Sweden among others have invested in digital solutions for the efficiency of production-consumption, and trading of hydrogen, the infrastructure is still developing.

Future outlook

Different aspects of infrastructure and the market for trading green hydrogen are still in the very early stages of development. These need to continue being developed in parallel and together with the technologies for the production and consumption of green hydrogen, for a hydrogen economy to be functional.

Market Shaping and Competing Solutions

Due to their environmental impact, there is a serious need for changing the energy solutions currently in place. That is happening at a high pace at this moment. However, the direction towards which the changes would go is still unclear. Numerous solutions could replace the current systems across different industries.

Examples include fuel cell green hydrogen, internal combustion green hydrogen, LNG, ammonia, different kinds of batteries, etc.

Not all those solutions would necessarily reduce the negative impacts on the environment. They might improve the current systems in some ways, but hurt the environment in some other ways. The systems must be designed in a way that the risk of future new environmental crises is minimized. For example, if wind energy is a major source of renewable energy in the future, we should also make sure that all machinery and turbines used for generating the energy can be and will be recycled. Lithium can be a major element used in batteries, if we can make sure mining of lithium at a large e scale will not lead to major negative societal and environmental impacts. As another example, a very large solar panel could interrupt the local climate, and a crowded wind park, onshore or offshore could interrupt the life ecosystem. No matter which of the solutions are pursued in different industries, one should make sure that the solution will have minimum impact on the environment. Critical discussion and dialog as well as evidence-based analyses are needed, to determine the best solutions both for the environment and the society at large.

Politics, differing interests, and the role of governments and the scientific community

The transformation that is coming will significantly change currently established industries, both by threatening their current businesses and by giving them opportunities for future profit. With that, there is a potential threat that some actors might try to steer the change in a direction that minimizes their loss and maximize their profit. Some might do this by offering the cheapest and most efficient solutions to the market, without considering short- and long-term impacts on health, society, and the environment, to get as many customers as possible and establish their solution as the standard. Some might choose more offensive strategies, which happen to be an issue of this era, such as spreading untrue stories on social media in an attempt to form the populous opinion towards a solution, or against the competing solution.

Not all actors would have such intentions and attitudes, however. Corporate social responsibility, being an agenda among many industrial actors, is a factor for them to direct the changes in a way that benefits the environment and society as a whole. There are not many companies that would avoid showing a public image in which they do not care about sustainability. In Europe and the Nordics, the sustainable approach is very common. Examples include efforts in the production of sustainable batteries (such as FREYR Batteries) and steel manufacturing ventures using green hydrogen (such as SSAB and the Hybrit project).

Even though many companies pursue social responsibility, it is a significant role for the media and for research institutes to find and report loudly the future solutions that have least the minimum environmental impacts, as well as reporting those that are less sustainable. This can counter the potential malicious attempts by some investors. Examples of research include Lehmann et al. (2021). In terms of hydrogen, both research and media have shown the benefits and warned about the potential fallbacks that need to be avoided. For example, while burnished hydrogen does not release CO_2, it can emit NOx in certain conditions, and it is important to ensure the production of hydrogen itself is green and sustainable.

The role of governments in preferring any of the solutions is not that straightforward. On the one hand, governments need to keep the democratic setting in choosing the solution so that the private sector could enjoy an environment in which innovativeness could be maximized. Too many interventions in the early stages might be counterproductive (Coglianese, 1998). Once the negative impacts are established by research and public debate, however, proper tax and subsidy incentives should be introduced, and in extreme cases, certain solutions should be outlawed. Examples include the carbon tax and subsidies for solutions that contribute to carbon neutrality. This is indeed the role of the government whose job is to make them adjust for the externalities that cannot be correctly priced by the market.

The quest for carbon neutrality is not only about finding innovative solutions. Rather, it also requires spreading the message of which solutions could best contribute to the goal of carbon neutrality, and shaping the future. That is where economic and social science research, as well as media and policymakers the most important role.

Challenges

Green and carbon-neutral hydrogen have a minimum negative impact on the environment. They have added the potential to become cost-efficient once the technology evolves to a certain level. Utilizing the potential of green hydrogen in the energy ecosystem is however not challenge-free.

Another challenge for the green hydrogen economy is that it is not the only sustainable solution out there. Many of them are legitimate in being a perfect solution for certain applications when compared with the green-hydrogen solution. There are other times when there are competing less sustainable ideas, but the discourse is in favor of them. Either way, the promoted competing ideas pose a challenge to the development of the green hydrogen economy.

Cost and efficiencies

One of the challenges is the fact that the production and consumption of green hydrogen at this point are not efficient yet. Consequently, there is no demand that is ready immediately to pay more for less energy. For that reason, investors might hesitate to invest in large amounts in developing an industry around green hydrogen, for the fear of negative profitability. That means slowed development of the industry in the early stages.

Technological readiness level

Technologies also need to develop for easing the transportation of hydrogen. That is because hydrogen gas has characteristics that make it different and more challenging compared to other elements to be transported. It is challenging to transport hydrogen by currently established means. There are nevertheless various ways to overcome this challenge, but they are still in the early stages of development in the industry.

The chicken-egg problem

Lack of infrastructure is another challenge currently in place. None of the legal, physical, or digital infrastructure is developed enough yet to support a wholesome green hydrogen economy. They too get developed as the demand for them increases by an initially slowly developing green hydrogen industry. If the infrastructure and the demand are not ready, there would be less investment. If there is less investment, there would be lower infrastructural readiness. That issue is sometimes called the chicken-egg problem of sustainable energy solutions (Clark & Rifkin, 2006). It is anyhow good to remember that the global annual hydrogen demand is over 90 Mtons and thus the need and markets for hydrogen exist.

Summary of challenges

Although there are several challenges facing the development of green hydrogen, they can be overcome. The development of the technologies might be slow, but they are underway (see figure 19). Additionally, the current discourses around green hydrogen show that it might not be the only solution in the future of the energy system, but it will most probably be a major solution woven into the fabric of a colorful sustainable energy system.

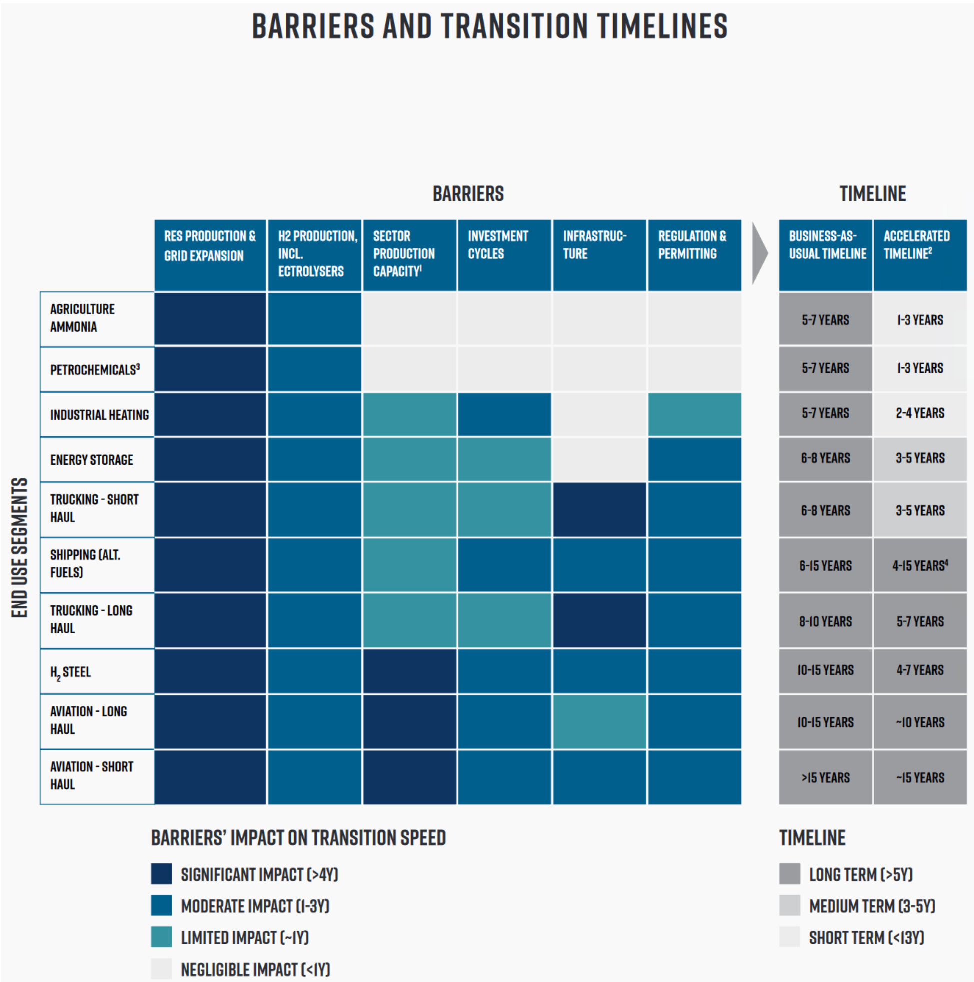


FIGURE 19. Hydrogen barriers and timeline (Material Economics, 2020, p.9)

Opportunities

The economy of green hydrogen comes with many opportunities. An economy with green hydrogen is an idea that has been around for several decades. All the essential technologies for its realization have existed for centuries. The know-how already exists, and the realization of widespread green hydrogen as an energy bearer is not a question of technological discovery, but rather an optimization and innovative combination of current technologies.

The chicken and egg challenge is one that also gives rise to opportunities. Everything is related to the value chain of the green hydrogen economy and the market for renewable energy is multi-sided. Investments in wind parks and other renewable energy production require infrastructure for storing it. Investments in storing energy as hydrogen facilitate the improvement of technologies related to electrolysis and fuel cells. Those in turn push for improving the market need and consumption technologies of hydrogen. Investments in any sector related to green hydrogen, improve the prospects of green hydrogen, which lead to further investments in developing the industry. Once the threshold is passed, the pace of development of the green hydrogen economy could ride a feedback loop and grow exponentially.

Green hydrogen moreover enjoys a strong political commitment from EU leaders. That is a major encouragement for investments in the industry, as the industry's growth is largely driven by demand. The positive attitude towards green hydrogen is manifested in public policy, internationally, at the EU level, and at Nordic and country levels. The policymakers have started to encourage a sustainable green hydrogen economy by directing large public funding for innovation and deployment of existing technologies in building new infrastructure.

The creation and development of new industries, new companies, new operations, and new infrastructure around green hydrogen would lead to new jobs and sustainable economic growth. That is an opportunity that green hydrogen offers.

What is unique about green hydrogen, in comparison to the energy systems currently in place is that, it would not only contribute to economic growth, the economic growth would be regional, local, and decentralized economic development of regional communities is an additional opportunity that comes with green-hydrogen based energy system.

That also means strengthening energy security. When the energy supply is not concentrated in a few providers, and their location is geographically spread, there is less risk, both in terms of pricing, and in terms of defense. The recent events of the Russian war in Ukraine show the importance of not relying on centralized energy providers, such as Russia. A decentralized green hydrogen economy takes reliance on many local and in-house providers. Additionally, geographically, there is a risk to have very few power plants that provide the majority of energy. In scenarios of a failure or a foreign attack, that would lead to a vulnerable situation.

Last but not the least, green hydrogen offers an opportunity to contribute to carbon neutrality. The solution is environmentally friendly and sustainable. It helps to make the earth habitable for future generations and to make it for the earth's life ecosystem to sustain.

Shiva Sharma and Ossi Koskinen

6. GREEN HYDROGEN COST AND CONLUSIONS

In the EU, green hydrogen is currently more expensive than conventional fossil fuels. The market price of hydrogen generally depends on the required parameters for example its purity. In addition, the price also depends on the customer's location, which determines how the hydrogen is delivered. Distribution, transport, and storage are important when green hydrogen is produced on a large scale that determines the final price for the customer. Currently, in the EU, most of the hydrogen is produced on-site by the team methane reforming method.

When talking about the costs of green hydrogen, its production cost is mainly influenced by capital expenditure (CAPEX), operating expenses (OPEX), Lifetime, and, efficiency (Enapter, 2020b). This chapter tries to estimate the Levelized cost of hydrogen per kilogram (kg) in different scenarios. This will help the reader get some insights into green hydrogen costs and how the Levelized cost of hydrogen production is calculated. The authors create three different cases: lowest costs case, average costs case, and high-cost case. The low costs case assumes the lowest investment and operating costs and similarly average and highest-cost case assumes the average and highest investment and operating cost respectively. Furthermore, the author creates 3 different scenarios for use of renewable electricity in how green hydrogen is produced. To make it as close to real life scenario as authors go through a wide range of resources and make assumptions that would be very reasonably applicable here in the Vaasa region. The focus of this study was set to understand the green hydrogen production cost; the scope was limited to production and short-term storage only. To make it simple the size the of green hydrogen production plant was set to be the capacity of 1 MW. A graphical representation of the system boundary is depicted in figure 20.

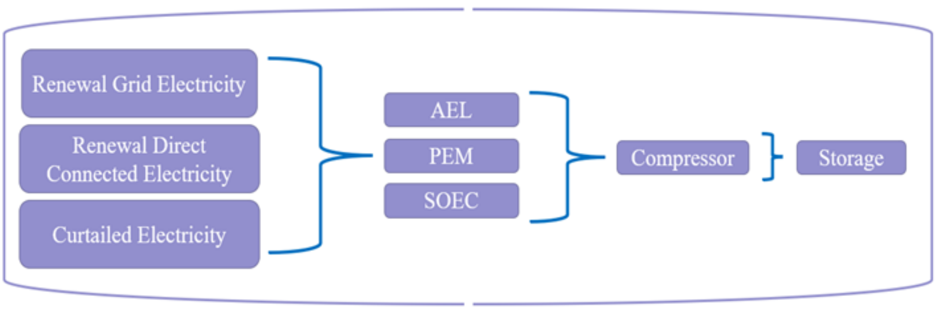


FIGURE 20. System boundary for 1 MW green hydrogen production plant.

As there are many talks on the use of renewables off-peak and curtailed electricity to produce green hydrogen, the following scenario was analyzed:

i. Scenario 1- Renewable grid-connected: This scenario assumes that the electrolyzer is connected to the grid and with the agreement that the grid provides only renewable electricity. In this scenario, hydrogen can in theory be produced with a 100 % capacity factor, where the capacity factor is a ratio of actual electrical energy output over a given period to the maximum possible electrical energy output.

But in real practice it will not be feasible to produce hydrogen with a 100% capacity factor, thus we capacity factor of 90% for this scenario. In this scenario transmission and distribution charges of electricity are included as it is connected to the grid. 50 euro per MWh electricity price was considered for this scenario to calculate LCOH, other costs were according to tables 4,5, and 6.

ii. Scenario 2 - Directly connected: This scenario assumes that electrolyzers are independent of the grid and are connected directly to a renewable electricity generator. In this scenario, the price of electricity is lower than in Scenario 1 because transmission and distribution charges are not considered. However, the intermittency of renewable electricity generation means that the capacity factor of hydrogen production is equal to the renewable energy generator's capacity factor. For simplicity reason capacity factor of 48 % for the wind farm is assumed in this calculation. As the capacity factor is almost 50% it was also assumed that in this scenario lifetime of the plant would be 30 years rather than 20 years. 25 euro per MWh electricity price was considered for this scenario to calculate LCOH, other costs were according to tables 4,5, and 6.

iii. Scenario 3 - Curtailed Electricity: This scenario assumes that the electrolyzer is connected to the grid but serves only as a load balancing/storage entity. It is thought that in times of high renewable generation some energy would need to be curtailed at zero euros per kWh. Yet in Finland, there has not been enough renewable electricity generation that there is a long sustained period of electricity price being zero but for simplicity, we assume that there will be 3 hours per day curtailed electricity available for electrolyzers. As the capacity factor is quite low it was also assumed that in this scenario lifetime of the plant would be 30 years rather than 20 years. 0 euro per MWh electricity price was considered for this scenario to calculate LCOH, other costs were according to tables 4,5, and 6.

Life Cycle Costing (LCC) and Levelized Cost of Hydrogen (LCOH)

LCC is a method to evaluate the total cost of a product or a system over its lifetime. There is no global standard approach that fits all and as literature reveals that LCC discourse has been a long journey. Many different methods in the past have been proposed and they are rather general in approach. Even though the methods are different, many of the main steps are similar to the first methods as the steps in the method by Harvey (1976):

- Define the cost elements
- Define the cost structure
- Establish cost-estimating relationships
- Establish the method of LCC formulation.

Although LCC has been a widely used methodology to evaluate the cost, it is still being criticized. The main drawback of this method comes from the fact that it includes a future estimation and can lead to uncertain results. Despite that, the LCC method still provides a universal method to evaluate and compare different investment opportunities. There has been a pretty clear trend to move with economical calculations from LCC/LCA methods towards Levelized cost of hydrogen (LCOH), which is method widely used to assess the cost of hydrogen. This method is based on the levelized cost of energy (LCOE) method that is used in the renewable energy sector where the LCC of renewables is presented in terms of cost per energy output unit (IRENA, 2012). LCOE has been used before to analyze techno-economic studies for incorporating cost analysis including investment costs, component life, escalation ratios and discount rate. The LCOE is a measure of the average total cost to build and operate a power plant over its lifetime divided by the total energy output over the lifetime of the plant. In other words, LCOE allows one to calculate the minimum price necessary to sell energy to meet a certain hurdle rate – the hurdle rate can be defined as the minimum rate of return on a project or investment. LCOE is a functional approach to measuring hydrogen, as hydrogen output can also be expressed in terms of energy. The Like computation of electricity costs, hydrogen costs can therefore be expressed in terms of cost per unit of energy or mass of hydrogen (Viktorsson et al., 2017). The definition of the LCOE by IRENA can be written as equation (3):

$$LCOE = \frac{\sum_{n=1}^{N}(I_n+M_n+F_n)\cdot(1+i)^{-1}}{\sum_{n=1}^{N}E_n\cdot(1+i)^{-1}} \tag{3}$$

Where I_n is the initial investment cost for year n, M_n is the maintenance cost in year n, F_n is the fuel cost in year n, E_n is the energy generation in the year n, i is the discounted rate and N is the lifetime.

Equation (4) depicts how the investment costs was calculated:

$$C_{inv} = (C_e + C_c + C_s + C_{misc}) \tag{4}$$

Where C_{inv} is the investment costs, C_e is the electrolyzer cost, C_c is the compressor cost, C_s is the storage cost and C_{misc} is miscellaneous costs.

The investment costs were annualized by the capital recovery factor depicted in equation (5).

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{5}$$

Where i is the nominal discount rate and n is the economic lifetime of the plant. The annualized, a, investment costs are therefore as in equation (6).

$$C_{inv,a} = CRF * C_{inv} \tag{6}$$

The operation and maintenance (O&M) costs were divided between fixed and variable expenses. The annual fixed O&M is denoted by equation (7).

$$C_{FixO\&M,a} = C_{mc} + C_{cont} + C_{repm} \tag{7}$$

Where C_{mc} is the maintenance cost for the compressor, C_{cont} is the service contract cost, C_{repm} is the replacement and maintenance cost for elecrolyzer. Replacement and maintenance costs were calculated as 25% of initial electrolyzer cost every 5th year as a single sum.

Similarly, the variable O&M costs are presented by equation (9)

$$C_{VarO\&M,a} = C_e + C_w \tag{9}$$

When subscript is the annual electricity cost and is the annual water costs. The annualized LCC can be therefore expressed by equation (10)

$$C_{LCC,a} = C_{inv,a} + C_{FixO\&M,a} + C_{VarO\&M,a} \tag{10}$$

After the annualized LCC has been calculated the LCOH can be assessed by dividing the annualized LCC noted a subscribe by $C_{LCC,a}$ by the amount of produced hydrogen in kg noted as on an annual basis.

$$\mathrm{LCOH} = \frac{C_{Lcc,a}}{E_{H_2,a}} \tag{11}$$

Green Hydrogen Components Cost Literature Overview

The main costs for green hydrogen come from capital costs, operation and maintenance costs and electricity costs. Figure 21 below shows hydrogen production cost breakdown of an offshore installation to obtain hydrogen from sea, using ocean wave energy, which can be used to generalize all hydrogen production (Blanco-Fernández & Pérez-Arribas, 2017).

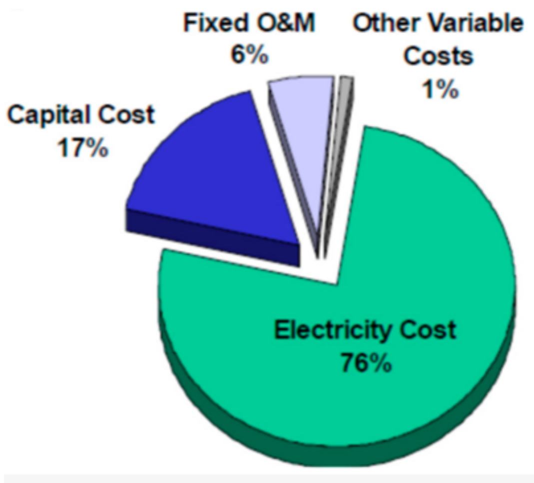


FIGURE 21. Hydrogen production, cost breakdown (Blanco-Fernández & Pérez-Arribas, 2017).

Capital Costs

The second most influential factor for pricing of hydrogen is the capital cost and particularly electrolyzer costs. Water electrolysis investment cost estimations depend on many factors such as plant size and site-specific characteristics. In a 2014 paper Bertuccioli et al. (2014) identified the range for alkaline water electrolysis costs to be in the range of 1000-1200 euros per kW capacity. Based on IRENA 2020 analysis capital costs estimate for large stacks of AEL, PEM and SOEC are 270 USD/kW, 400 USD/kW and over 2000 USD/kW respectively. In a paper published by Oxford Institute for energy studies following costs are estimated for 1 MW electrolyzers in 2019 for AEL 540-900 USD/kW, for PEM 667-1450 USD/kW and for SOEC 2,300-6,667USD/kW.

Compressor cost is another capital cost. A report published by the University of Nebraska at Omaha mentions that typical 350 bars and 700 bars hydrogen compressors cost 50,000 USD – 140,000 USD and consume 2-4 kWh/kg of electricity for compressing 20-350 bar (Richardson et al., 2015). Penev et al. (2019)

have presented data regarding the capital costs, producing capital, and specific energy required to operate such compressors. Penev et al. in their study assume compressors' cost rate to be the rate of 3 USD/kg.

In addition to the compressor, the green hydrogen system will require short-term on-site storage to get it ready to be injected into a pipeline or to be put into tanker trucks and shipped. Data from a hydrogen refueling station in Halle, Belgium in 2017 shows that 50 kg hydrogen storage at 450 bars had an investment cost of 157,500 euros (Viktorsson et al., 2017). A study conducted to assess the potential of green hydrogen fueling for very heavy vehicles in New Zealand in 2021 shows a cost of 0.5 NZD/kg of hydrogen storage (Perez et al., 2021). A case study of a Slovenian hydropower plant shows that a 1 MW nominal power electrolyzer storage system would cost around 200,000 euros (Jovan & Dolanc, 2020). In the journal article "Techno-economic calculations for small-scale hydrogen supply system for zero emission transport in Norway" Ulleberg & Hancke (2020) concluded that hydrogen tanks was costing 6300, 8100, 19800 NOK/kg for tanks rated for 250, 450,700, and 900 bars respectively.

Operation and Maintenance Costs

The annual operation and maintenance costs were divided between fixed and variable costs. The fixed costs were service contract costs, maintenance, and replacement cost for the electrolyzer and compressor.

Stack costs make up to 60% (PEM), 50% (AEL) and 60% (SOC) of plant CAPEX costs and are assumed to need to be replaced every 11 years for PEM, 7 years for SOE and 9 years for AEL over 30 years of technical lifetime. 6 % of compressor investment expenses were used as a compressor maintenance cost (Viktorsson et al., 2017).

The variable expenses included electricity and water costs. Electricity price for households in Finland in 2021 was on average 17.67-euro cents per kWh (Statista, 2022). The current price of water in Vaasa is 1.59 euro/m^3 (Vaasan Vesi, n.d.).

Techno-economic Assumption for LCOH Calculation

For the calculation of LCOH author makes an educated assumption of costs according to the literature reviews and costs mentioned from the literature study in chapter 4.2 of this thesis that would be reasonable for the Vaasa region. Costs were assumed as Low, average, and high scenarios. Table 4, 5 and 6 summarizes the techno-economic assumptions for AEL, PEM, and SOC technology respectively.

TABLE 4. Techno-economic assumptions for AEL.

PARAMETERS	ASSUMPTIONS	LOWEST COST (EUROS)	AVERAGE COST (EUROS)	HIGHEST COST (EUROS)	COMMENT
Electrolyzer cost	1 MW	400,000	600,000	800,000	
Hydrogen Production	300 kg/24 h				Assumed at 100 % capacity factor
Compressor cost		100,000	200,000	300,000	
Storage cost		200,000	300,000	400,000	
Stack replacement cost/maintenance	25 % of the capital cost every 5 years in a lifetime				
Compressor mainte-nance	6 % of compressor cost	6,000	12,000	18,000	
Service contract		100,000	100,000	100,000	Maintaining facilities etc
Electricity price Per MWh	Would be much lower for the industry than for households	25	50	75	0.1767 cents/kWh for average household price in 2021. Would be much lower for the industry than for household
Water costs		1741	1741	1741	1.59 euro/m³ for the average household. Assuming 10 L of water is needed for 1 kg hydrogen production. Would be much lower for the industry than for house-holds in the real world
Miscellaneous costs	1 % of investment cost	7000	11,000	15,000	
Discount rate	7 %				
Lifetime years	20				

TABLE 5. Techno-economic assumptions for PEM.

PARAMETERS	ASSUMPTIONS	LOWEST COST (EUROS)	AVERAGE COST (EUROS)	HIGHEST COST (EUROS)	COMMENT
Electrolyzer cost	1 MW	600,000	800,000	1,000,000	
Hydrogen Production	400 kg/24 h				Assumed at 100 % capacity factor
Compressor cost		100,000	200,000	300,000	
Storage cost		200,000	300,000	400,000	
Stack replacement cost/maintenance	25 % of the capital cost every 5 years in a lifetime				
Compressor maintenance	6 % of compressor cost				
Service contract		100,000	100,000	100,000	Maintaining facilities etc
Electricity price Per MWh		25	50	75	0.1767 cents/kWh for average household price in 2021. Would be much lower for the industry than for household
Water costs		1741	1741	1741	1.59 euro/m³ for the average household. Assuming 10 L of water is needed for 1 kg hydrogen production. Would be much lower for the industry than for households in the real world
Miscellaneous costs	1 % of investment cost	9,000	13,000	17,000	
Discount rate	7 %				
Lifetime years	20				

TABLE 6. Techno-economic assumptions for SOC.

PARAMETERS	ASSUMPTIONS	LOWEST COST (EUROS)	AVERAGE COST (EUROS)	HIGHEST COST (EUROS)	COMMENT
Electrolyzer cost	1 MW	2,000,000	4.000,000	6,000,000	
Hydrogen Production	500 kg/24 h				Assumed at 100 % capacity factor
Compressor cost		100,000	200,000	300,000	
Storage cost		200,000	300,000	400,000	
Stack replacement cost/maintenance	25 % of the capital cost every 5 years in a lifetime				
Compressor mainte-nance	6 % of compressor cost				
Service contract		100,000	100,000	100,000	Maintaining facilities etc
Electricity price Per MWh	Would be much lower for the industry than for household	25	50	75	0.1767 cents/kWh for average household price in 2021. Would be much lower for the industry than for household
Water costs		1741	1741	1741	1.59 euro/m³ for the average household. Assuming 10 L of water is needed for 1 kg hydrogen production. Would be much lower for the industry than for house-holds in the real world
Miscellaneous costs	1 % of investment cost	23,000	45,000	67,000	
Discount rate	7 %				
Lifetime years	20				

Table 7 presents the LCOH for AEL, PEM, and SOC by the techno-economic assumption from Tables 4, 5, and 6 respectively, and table 8 presents LCOH for three scenarios mentioned in chapter 4. The capacity factor for this calculation has been at 100% while in practice this may not be possible, more realistically it would be 90% of the total capacity factor.

TABLE 7. LCOH from different technologies.

TECHNOLOGY	LOWEST COST EURO PER KG	AVERAGE COST EURO PER KG	HIGHEST COST EURO PER KG
AEL	3.69	6.14	8.59
PEM	2.93	4.77	6.6
SOC	3.28	5.95	8.62

Table 8. LCOH from three Scenarios.

SCENARIO	TECHNOLOGY	LOWEST COST EURO PER KG	AVERAGE COST EURO PER KG	HIGHES COST EURO PER KG
1	AEL	6.32	6.82	7.32
	PEM	4.93	5.30	5.68
	SOC	4.98	6.61	8.24
2	AEL	7.56	8.42	9.29
	PEM	6.00	6.65	7.30
	SOC	6.65	9.54	12.43
3	AEL	13.03	16.35	19.66
	PEM	11.04	13.53	16.02
	SOC	15.92	27.03	38.14

Calculated LCOH falls within the range of the literature study. From the result, it can be noticed that the capacity factor in which the electrolyzer is producing hydrogen through its lifetime and the efficiency of the electrolyzer play a significant role just like other costs such as electricity to reduce the end price of hydrogen which is not discussed in literature often. The lowest LCOH for AEL with 25 MWh electricity at 100% capacity factor for 20 of ars production was 3.69 euros per kg whereas for curtailed electricity at 12.5 % capacity factor for 30 years of production was calculated at 13.03 euros per kg

Conclusion

The review of the current situation at the beginning of this report from the Finnish and European perspectives to be carbon neutral by 2050 revealed a real political will toward the hydrogen economy. Targeting to deploy renewable hydrogen on large scale by 2030 is a challenging ambition and many actual projects are needed to achieve it. The literature study highlighted the challenges and opportunities of hydrogen technology and also discussed the different technologies giving a holistic view of hydrogen technology. The review further deepened into three leading electrolysis methods namely AEL, PEM, and SOEC, and assessed their characteristics, advantages, and disadvantages. Different storage technologies were also discussed. Further developments in electrolyzers in term of their lifetime and efficiency is needed to be more competitive and the same for their storage technology. Tax deductions and subsidies will encourage companies to develop this technology further. This work also presented the framework for calculating LCOH and fully transparent calculation, assumption, and results.

There were some limitations in this work. Sources used were only those available freely on the internet, it would have been interesting to read and collect information from some of the articles that were not available freely. As most of the industrial actor wants to maintain some secret some important information on cost calculation had to be assumed. For further studies, it is recommended to collaborate with a company that is establishing a hydrogen production facility and acquire data and compares the costs between literature and actual cost in the Vaasa region.

Hydrogen and its´ current status and future outlook are very much debated at the moment. There are some very skeptical approaches and some players see the current and future situation in a very positive manner. The truth of the hydrogen economy is most likely somewhere between these two views – the future will show us.

References

Agaton, C. B., Batac, K. I. T., & Reyes, E. M. (2022). Prospects and challenges for green hydrogen production and utilization in the Philippines. *International Journal of Hydrogen Energy*, 47(41). https://doi.org/10.1016/j.ijhydene.2022.04.101

Barnard, M. (2021). *Shipping Liquid Hydrogen Would Be At Least 5 Times As Expensive As LNG Per Unit Of Energy*. CleanTechnica. https://cleantechnica-com.cdn.ampproject.org/c/s/cleantechnica.com/2021/12/20/shipping-liquid-hydrogen-would-be-at-least-5-times-as-expensive-as-lng-per-unit-of-energy/amp/

Bertuccioli, L., Chan, A., Hart, D., Lehner F., Madden, B. & Standen, E. (2014). Development of Water Electrolysis in the European Union. *Fuel Cells and Hydrogen Joint Undertaking*, pp. 1-160. [Archived] https://wayback.archive-it.org/12090/20220603132251/https://www.clean-hydrogen.europa.eu/media/publications/development-water-electrolysis-european-union_en

Blanco-Fernández, P. & Pérez-Arribas, F. (2017). Offshore Facilities to Produce Hydrogen. *Energies*, 10(6), p 783. https://doi.org/10.3390/en10060783

Clark II, W., & Rifkin, J. (2006). A green hydrogen economy. *Energy Policy*, 34(17). https://doi.org/10.1016/j.enpol.2005.06.024

Coglianese, C. (1998). Implications of Liberal Neutrality for Environmental Policy. *Environmental Ethics*, 20(1). https://doi.org/10.5840/enviroethics199820144

Coutanceau, C., Baranton, S., & Audichon, T. (2017). *Hydrogen Electrochemical Production*. Elsevier.

Donnelly, G. (2021). A lithium shortage is coming, and automakers might be unprepared. Emerging Tech Brew. https://www.morningbrew.com/emerging-tech/stories/2021/12/13/a-lithium-shortage-is-coming-and-automakers-might-be-unprepared

Dow, J. (2021). *Hyundai pauses Genesis hydrogen fuel cell project just days after ending ICE engines*. Electrek. https://electrek.co/2021/12/29/hyundai-pauses-genesis-hydrogen-fuel-cell-project-just-days-after-ending-ice-engines/

Edwards, P., Kuznetsov, V. L. & David, W. I. F. (2007). Hydrogen energy. *Philosophical transactions of the Royal society A*, 365(1853). https://doi.org/10.1098/rsta.2006.1965

Enapter. (2020a). *Hydrogen: Clearing Up the Colours*. https://www.enapter.com/newsroom/hydrogen-clearing-up-the-colours

Enapter. (2020b). *H2 View Exclusive – Calculating the Cost of Green Hydrogen*. https://www.enapter.com/newsroom/h2-view-exclusive-calculating-the-cost-of-green-hydrogen

European Commission. (2018). *A Clean Planet for all*. EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52018DC0773

European Commission. (2019). *The European Green Deal.* EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN

European Commission. (2020a). *Powering a climate-neutral economy: An EU Strategy for Energy System Integration*. EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:299:FIN

European Commission. (2020b). *A hydrogen strategy for a climate-neutral Europe*. EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301

Fingrid. (n.d.). *Wind power generation*. [Data genarated 30.5.2021]. https://www.fingrid.fi/en/electricity-market-information/wind-power-generation/

Floristean, A. (2019). *EU regulations and directives which impact the deployment of FCH technologies*. HyLAW. https://www.hylaw.eu/sites/default/files/2019-02/D4.4%20-%20EU%20regulations%20and%20directives%20which%20impact%20the%20deployment%20of%20FCH%20technologies_0.pdf

Gasunie. (n.d.). *HyStock hydrogen storage*. https://www.gasunie.nl/en/projects/hystock-hydrogen-storage

Godula-Jopek, A. (2015). *Hydrogen Production: by Electrolysis*. Wiley.

Guo, Y., Li, G., Zhou, J. & Liu, Y. (2019). Comparison between hydrogen production by alkaline water electrolysis and hydrogen production by PEM electrolysis. *IOP Conference Series: Earth and Environmental Science*, 371(4). https://doi.org/10.1088/1755-1315/371/4/042022

Haldane, J. B. S. (1923). *Daedalus; or, Science and the Future. A paper read to the Heretics, Cambridge, on February 4th, 1923*. https://jbshaldane.org/books/1923-Daedalus/haldane-1923-daedalus-ocr.pdf

Harvey, G. (1976). Life cycle costing: a review of the technique. *Management Accounting*, October, pp. 343-347.

Heeger, D., Partridge, M., Trullinger, V., & Wesolowski, D. E. (2017). *Lithium Battery Health and Capacity Estimation Techniques Using Embedded Electronics*. Sandia National Laboratories. https://doi.org/10.2172/1596204

Hydrogen and Fuel Cell Technologies Office. (n.d.-a). *Hydrogen Production: Electrolysis*. https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis

Hydrogen and Fuel Cell Technologies Office. (n.d.-b). *Physical Hydrogen Storage*. https://www.energy.gov/eere/fuelcells/physical-hydrogen-storage

IEA. (2020). *Energy Technology Perspectives 2020*. International Energy Agency. https://www.iea.org/reports/energy-technology-perspectives-2020

IRENA. (2012). *Renewable energy technologies: cost analysis series*. Hydropower. Irena Working Paper, 1(3/5). https://www.irena.org/Publications/2012/Jun/Renewable-Energy-Cost-Analysis---Hydropower

IRENA. (2017). *Electricity Storage and Renewables: Costs and Markets to 2030*. International Renewable Energy Agency. https://www.irena.org/publications/2017/oct/electricity-storage-and-renewables-costs-and-markets

IRENA. (2020). *Green hydrogen: A guide to policy making*. International Renewable Energy Agency. https://www.irena.org/publications/2020/Nov/Green-hydrogen

Jovan, D. J. & Dolanc, G. (2020). Can Green Hydrogen Production Be Economically Viable under Current Market Conditions. *Energies*, 13(24), p. 6599. https://doi.org/10.3390/en13246599

Kakoulaki, G., Kougias, I., Taylor, N., Dolci, F., Moya, J. & Jäger-Waldau, A. (2021). Green hydrogen in Europe – A regional assessment: Substituting existing production with electrolysis powered by renewables. *Energy Conversion and Management*, 228(15). https://doi.org/10.1016/j.enconman.2020.113649

Koivisto, R. (2022). *EKA Composite käynnistää komposiittitehtaan Oravaisissa – "Loistava sijainti Vaasan ja Kokkolan läheisyydessä"*. Vaasa Insider. https://www.vaasainsider.fi/ekonomi-jobb/eka-composite-kaynnistaa-komposiittitehtaan-oravaisissa-loistava-sijainti-vaasan-ja-kokkolan-laheisyydessa/

Koponen, H. (2021). *Enersense sijoittaa 13–18 miljoonaa euroa vedyntuottajayhtiöön*. Kauppalehti. https://www.kauppalehti.fi/uutiset/kl/5531b07a-39c2-4680-8708-9d66efa434ef

Kriittisetmateriaalit.fi. (2021). *Kiinan akkuteollisuuden toimijat investoivat isosti ulkomaille varmistaakseen raaka-aineiden saatavuuden*. https://www.kriittisetmateriaalit.fi/kiinan-akkuteollisuuden-toimijat-investoivat-isosti-ulkomaille/

Lambert, F. (2019). *Caterpillar unveils an all-electric 26-ton excavator with a giant 300 kWh battery pack*. Electrek. https://electrek.co/2019/01/29/caterpillar-electric-excavator-giant-battery-pack/

Lebedev, P., Muller, D., Stewart, C., & Barnshaw, K. (2022). *The Man Who Accidentally Killed The Most People In History*. Veritasium. https://www.veritasium.com/videos/2022/4/22/the-man-who-accidentally-killed-the-most-people-in-history

Lehmann, P., Ammermann, K., Gawel, E., Geiger, C., Hauck, J., Heilmann, J., Meier, J.-N., Ponitka, J., Schicketanz, S., Stemmer, B., Tafarte, P., Thrän, D., & Wolfram, E. (2021). Managing spatial sustainability trade-offs: The case of wind power. *Ecological Economics*, 185. https://doi.org/10.1016/j.ecolecon.2021.107029

Liebreich, M. (2021). *The Clean Hydrogen Ladder*. LinkedIn. https://www.linkedin.com/pulse/clean-hydrogen-ladder-v40-michael-liebreich/

Liu, R., Zhang,Lei, Sun, X., Liu, H., & Zhang, J. (Eds.) (2012). *Electrochemical technologies for energy storage and conversion*. Wiley.

Material Economics. (2020). *Mainstreaming green hydrogen in Europe*. https://materialeconomics.com/material-economics-mainstreaming-green-hydrogen-in-europe-2020.pdf?cms_fileid=1b5777405b1bfbfe098dc5653276bf6f

Material Economics. (2020). Mainstreaming green hydrogen in Europe. https://materialeconomics.com/material-economics-mainstreaming-green-hydrogen-in-europe-2020.pdf?cms_fileid=1b5777405b1bfbfe098dc5653276bf6f

Mercedes-Benz GLC F-CELL. (n.d.). Mercedes-Benz Group. https://www.daimler.com/products/passenger-cars/mercedes-benz/glc-f-cell.html

Morris, J. (2020). *Why Hydrogen Will Never Be The Future Of Electric Cars*. Forbes. https://www.forbes.com/sites/jamesmorris/2020/07/04/why-hydrogen-will-never-be-the-future-of-electric-cars/?sh=7dee35af12fa

Nechache, A. & Hody, S. (2021). Alternative and innovative solid oxide electrolysis cell materials: A short review. *Renewable and Sustainable Energy Reviews*, 149. https://doi.org/10.1016/j.rser.2021.111322

Novia. (n.d.). *Meteoria*. Novia Internet of Things. [Data generated 30.5.2021]. http://iot.novia.fi/data/meteoria_energy.html

OECD. (2015). *The Metropolitan Century: Understanding Urbanisation and its Consequences*. OECD Publishing. https://doi.org/10.1787/9789264228733-en

Penev, M., Zuboy, J. & Hunter, C. (2019). Economic analysis of a high-pressure urban pipeline concept (HyLine) for delivering hydrogen to retail fueling stations. *Transportation Research Part D*, 77, pp. 92-105. https://doi.org/10.1016/j.trd.2019.10.005

Perez, R. J., Brent, A.C., & Hinkley, J. (2021). Assessment of the Potential for Green Hydrogen Fuelling of Very Heavy Vehicles in New Zealand. *Energies*, 14(9), p. 2636. https://doi.org/10.3390/en14092636

Preyser, J. (2021). *Miners experiment with hydrogen to power giant trucks*. BBC. https://www-bbc-co-uk.cdn.ampproject.org/c/s/www.bbc.co.uk/news/business-59576867.amp

Richardson, I. A., Fisher, J. T., Leachman, J. W., Frome, P. E., Smith, B. O., Guo, S, Chanda, S., McFeely & Miller, A. M. (2015). *Low-cost, Transportable Hydrogen Fueling Station for Early FCEV Adoption*. University of Nebraska, Economics Faculty Publications 15. https://digitalcommons.unomaha.edu/econrealestatefacpub/15/

Ritchie, H., Roser, M., & Rosado, P. (2020). *CO_2 and Greenhouse Gas Emissions*. Our World in Data. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

Segura, E. (2021). *The Toyota GR Yaris Hydrogen Concept Is a Race Car Powered By Its Name*. MotorTrend. https://www.motortrend.com/news/toyota-gr-yaris-hydrogen-concept/

Stancell, C., Bonnet-Cantalloube, B., Bortolotti, M., Floristean, A., Mester, F., & Pawelec, G. (2021). *Hydrogen: Enabling A Zero-Emission Society*. Hydrogen Europe; Resolve Media.

Statista. (2022). *Electricity prices for households in Finland from 2010 to 2021, semi-annually*. https://www.statista.com/statistics/418122/electricity-prices-for-households-in-finland/

Storengy. (2021). *"HyPSTER", 1st demonstrator for H2 green storage: First EU-supported large scale Green H2 Underground Storage Demonstrator*. [Press release]. https://www.storengy.com/en/medias/news/hypster-1st-demonstrator-h2-green-storage#:~:text=HyPSTER%20is%20the%20first%20EU,Undertaking%20(FCH%202%20JU)

Syed, M. B. (2021). Technologies for renewable hydrogen production. In A. K. Azad, M. M. Khan (Eds.) *Bioenergy Resources and Technologies* (pp.157-198) Academic Press. https://doi.org/10.1016/B978-0-12-822525-7.00013-5

TEM. (2021). *Yli 64 miljoonaa euroa investointitukea neljälle uuden energiateknologian suurelle demohankkeelle*. Työ- ja elinkeinoministeriö. https://tem.fi/-/yli-64-miljoonaa-euroa-investointitukea-neljalle-uuden-energiateknologian-suurelle-demohankkeelle

Thomas, C. E. (2009). Fuel cell and battery electric vehicles compared. *International Journal of Hydrogen Energy*, 34(15). https://doi.org/10.1016/j.ijhydene.2009.06.003

Toyota Mirai. (n.d.). https://www.toyota.fi/ajankohtaista/uutiset/mirai-2020.json

Tsakiris, A. (2019). Analysis of hydrogen fuel cell and battery efficiency. *World Sustainable Energy Days 2019, Wels/ Austria, 27 February-1 March 2019*. https://c2e2.unepccc.org/wp-content/uploads/sites/3/2019/09/analysis-of-hydrogen-fuel-cell-and-battery.pdf

TÜV SÜD. (n.d.) Hydrogen enables the connection of clean energy and applications. https://www.tuvsud.com/en/themes/hydrogen/explore-the-hydrogen-value-chain/hydrogen-storage-and-distribution

Ulleberg, Ø. & Hancke, R. (2020). Techno-economic calculations of small-scale hydrogen supply systems for zero emission transport in Norway. *International Journal of Hydrogen Energy*, 45(2), pp. 1201-1211. https://doi.org/10.1016/j.ijhydene.2019.05.170

United Nations. (2017). The New Urban Agenda. *United Nations Conference on Housing and Sustainable Urban Development (Habitat III) in Quito, Ecuador, on 20 October 2016*. https://habitat3.org/the-new-urban-agenda/

Vaasan Vesi. (n.d.). *Vaasa Water*. https://www.vaasanvesi.fi/vaasa-water-information-in-english

Vartiainen, E. (2020). *The hydrogen economy is coming – sooner or later*. Fortum, ForTheDoers Blog. https://www.fortum.com/about-us/blog-podcast/forthedoers-blog/hydrogen-economy-coming-sooner-or-later

Vidas, L. & Castro, R. (2021). Recent Developments on Hydrogen Production Technologies: State-of-the-Art Review with a Focus on Green-Electrolysis. *Applied Sciences*, 11(23). https://doi.org/10.3390/app112311363

Vijayenthiran, V. (2021). *BMW iX5 Hydrogen revealed ahead of 2022 start of production*. Motor Authority. https://www.motorauthority.com/news/1133276_bmw-ix5-hydrogen-revealed-ahead-of-2022-start-of-production

Viktorsson, L., Heinonen, J. T., Skulason, J. B. & Unnthorsson, R. (2017). A Step towards the Hydrogen Economy – A Life Cycle Cost Analysis of A Hydrogen Refueling Station. *Energies*, 10(6), p. 763. https://doi.org/10.3390/en10060763

Yue, M. Lambert, H., Pahon, E., Roche, R., Jemei, S., & Hissel, D. (2021). Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renewable and Sustainable Energy Reviews*, 146. https://doi.org/10.1016/j.rser.2021.111180