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Green Hydrogen for Carbon Neutral Society: Opportunity, Challenges and Levelized Cost of Production

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Master's of Engineering

Degree Programme in Industrial Management and Engineering

Vaasa **2022**

MASTER'S THESIS

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Degree Programme: Master of Engineering, Industrial Management and Engineering

Specialization: Leadership and Management

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Title: Green Hydrogen for Carbon Neutral Society: Opportunity, Challenges and Levelized Cost of Production

Date June 3, 2022 Number of pages 42 Appendices

Abstract

Energy systems in the world are transitioning towards a carbon neutral society. Especially in EU and in Finland one can already notice a big change in policies and mind shift of the public. Hydrogen and specifically green hydrogen have a potential to accelerate the process of transitioning by allowing its usages in different scenarios such as fuel for electric vehicles and energy storage.

This thesis investigates the current status of hydrogen production and storage technology through a literature review. It also identifies and highlight the opportunities and challenges for green hydrogen technologies. Furthermore, this study aims to define a methodology based on existing literature and evaluated levelized costs of hydrogen (LCOH). This work examines the LCOH in different realistic scenarios from a regional perspective of the Vaasa region. This work has been done under project "H2 Ecosystem Roadmap". This project has been funded by the Regional Council of Ostrobothnia through European Regional Development Fund and Vaasa city.

LCOH at 100% capacity factor for AEL were 3.69, 6.14 and 8.59 euro/kg for low, average, and high cases respectively. LCOH for PEM were 2.93, 4.77 and 6,61 euro/kg for low, average, and high cases respectively. LCOH for SOC were 3.28, 5.95 and 8.62 euro/kg for low, average, and high cases respectively.

Finally, conclusion shows that continuous efforts on performance improvements, technical prospects and political support are required to enable a cost-competitive green hydrogen economy.

Language: English Key words: green hydrogen, Levelized cost of hydrogen

Table of contents

1 Introduction

Energy systems globally are experiencing a change of scenery. Increasing interest in sustainable development, environmental concerns and energy security is forcing business and society to look for new solutions to ensure economic growth and fight climate change. In 2019, the European Commission presented Green Deal [1], outlining the new growth strategy which aims to transform the European Union (EU) in to 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 pay significant role in reducing GHG and help reach no net emission of GHG by 2050. Green hydrogen is produced when electricity from renewal resources is used to split water into hydrogen and oxygen gas through process called electrolysis [2]. 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 [3]. Unlike batteries and thermal storage, hydrogen can be stored for long period of time 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 the increasing interest in green hydrogen production. Hence, it requires more focus and research to be widely used. Moreover, price of hydrogen production is interesting topic for all actors who are involved in energy market. There are many other reports on topic of cost calculation but with varying degree of transparency to cost assumptions. Thus, the focus of this thesis 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 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.

This work has been carried out for project "H2 Ecosystem Roadmap (for Ostrobothnia)" in the department of research and development at Novia University of Applied Sciences. Project H2 ecosystem roadmap aims to build the 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. It is a collaboration project between three Universities in Vaasa namely Novia University of Applied Sciences, Vaasa University of Applied Sciences (VAMK) and Hanken School of Economics. Project is funded by the European Regional Development Fund through the Regional Council of Ostrobothnia and Vaasa city through university consortium.

1.1 Background and Objectives

Zero net emission of GHG by 2050 is an ambitious target. To succeed this, different technologies will play 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 not sun shining all the time and wind does not blow according to our demand. This means that some period we will have energy surplus and other time we have deficit if we are 100% renewable. This is challenging because there is not yet an appropriate solution to store large quantity of energy in our surplus period and use them when we are in deficit. Figure 1 and 2 shows the fluctuation of wind and solar energy production. Figure 1 shows the wind power generated in MWh/h during period of 17.52021-23.5.2021 by Fingrid. Figure 2 shows the production fluctuation of solar energy during period 17.05.2021-23.05.2021 at 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 [4]. Green hydrogen could be part of the solution in this situation, and it need more research in its overall perspective. Also cost of production of green hydrogen is important aspect to parties that are interested in hydrogen technology and specially in green hydrogen. There are many reports on LCOH with varying degree of transparency to cost assumption and method used. Thus, there is need for transparent work on how LCOH is calculated, and all the assumption made during the calculation. This report hopes to fulfill this need.

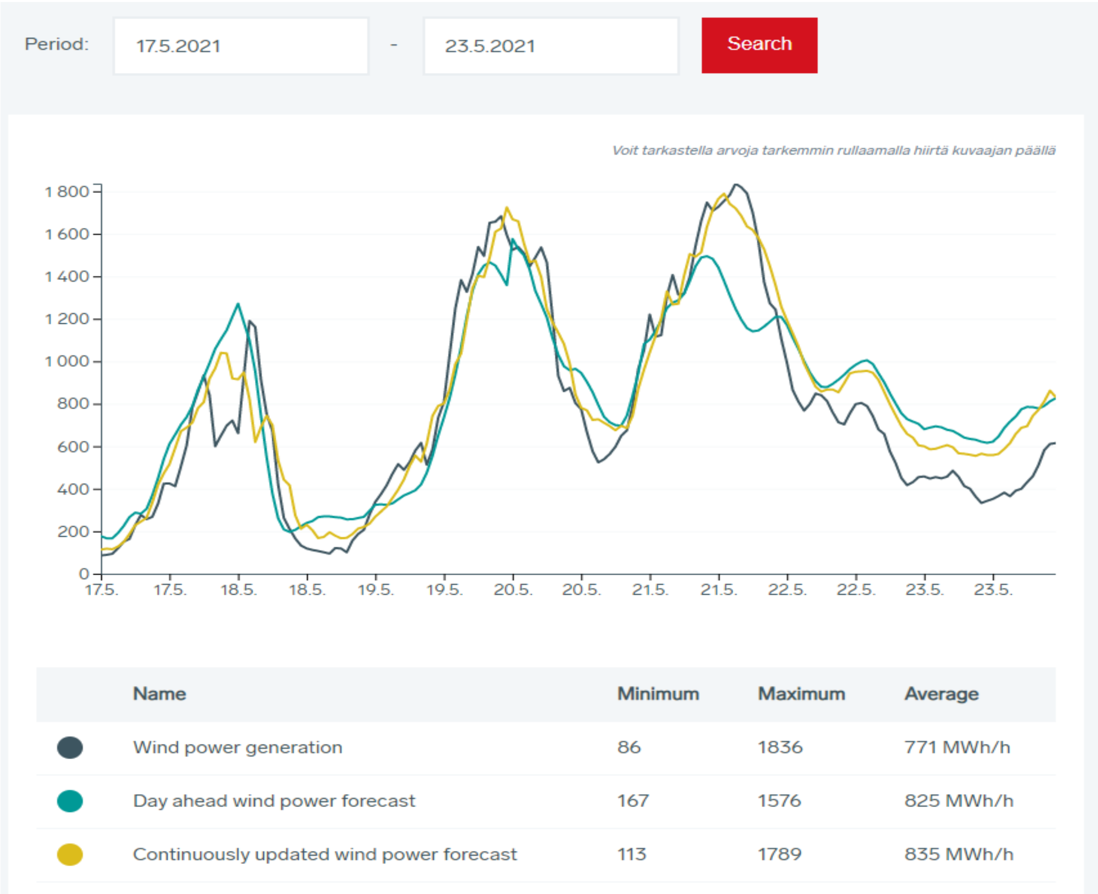

Figure 1: Wind Energy production fluctuation during the period 17.05.2021 and 23.05.2021 [5].

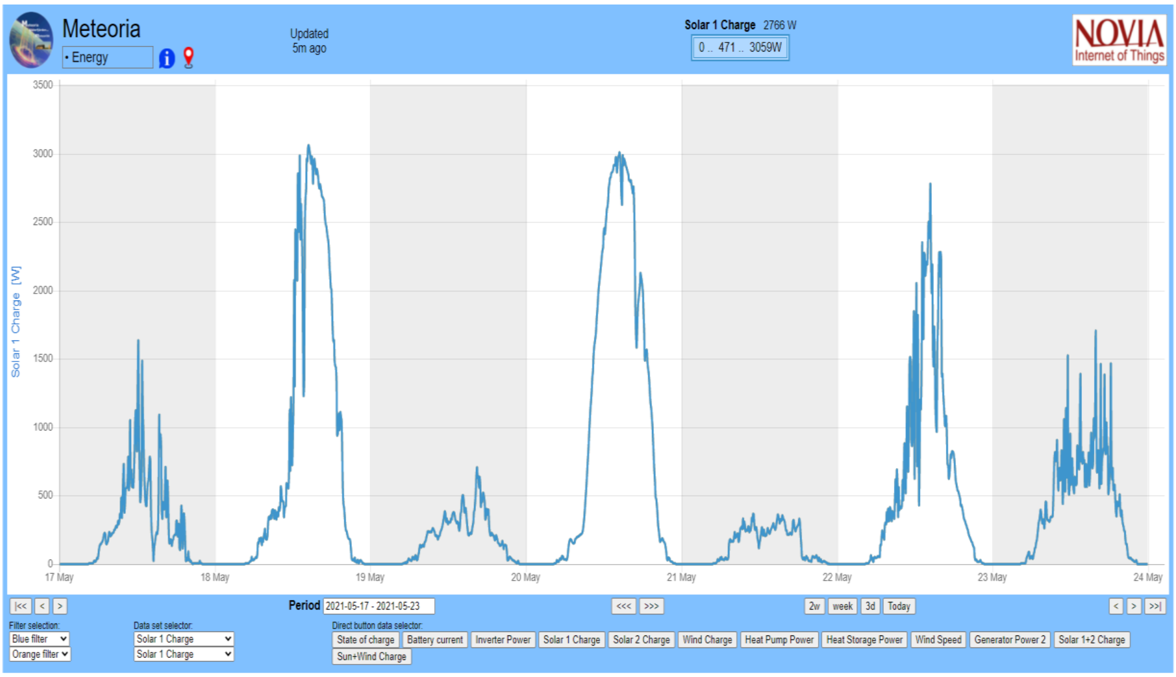

Figure 2: Solar Energy production fluctuation during the period 17.05.2021 and 23.05.2021 [6].

1.2 Research Methodology

The research method that will be used for this thesis is review of literature and reports from institutions applying, hydrogen technology and policy makers 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 scientific and industrial world in recent time and there is a need for review of this knowledge in one condensed form where reader gets the resent holistic view of the technology and its background.

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, method and assumptions for calculation were presented in fully transparent way. Furthermore, 3 different scenarios (see chapter 4 for different scenarios and calculation method) for green hydrogen production were created and LCOH were calculated for these scenarios to get more insights in costs of hydrogen in euro per kg. Parameters and assumptions were taken with wide and recent literature study that would fit real case scenarios to get realistic cost of green hydrogen production.

1.3 Research Questions

As mentioned above to reach 2050 target set by Green Deal and to achieve sustainable development, individuals, companies, and countries are pursuing new solutions for energy system [1]. Future of energy and energy storage system will be diverse. Production and usage of green hydrogen solves number of challenges faced currently. Nevertheless, this technology itself has pros and cons which need to be researched and this knowledge should be spread widely.

The main question for this research is how the green hydrogen option looks from current technical and economical perspective. Moreover, how much will the green hydrogen costs? From this initial question, the following study questions can be concluded:

- How hydrogen can be produced and what is current status of hydrogen technology?
- What is European Union (EU) strategy on hydrogen and energy system integration?
- What are the key issues regarding the choices between different technologies?

- What is Levelized cost of energy (LCOE) and LCOH and how it is calculated?

- How does the LCOH looks in different scenarios?

2 EU Strategy on Energy System Integration and Hydrogen

Energy system integration 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 with the objective of delivering low-carbon, reliable and resource-efficient energy services with minimum cost for society. It encompasses three complementary and reinforcing concepts. [7].

- 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.

Highly integrated system 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 EU level to slowly gradually a new integrated energy system meanwhile respecting the different starting points of different member states [7]. 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 [7].

Hydrogen is enjoying rapid growing attention in 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 great share of the EU energy consumption in 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 transport fuel, ensuring back up for seasonal variations [8]. Europe is highly competitive in green hydrogen technologies manufacturing and has positioned itself to benefit from global development of green hydrogen. Cumulative investment in green hydrogen in EU could be up to 180-470 billion euros by 2050 [8]. However, green hydrogen and low-carbon hydrogen are not yet 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 below figure 4 one can see the concept path towards a European hydrogen eco-system step by step developed by EU.

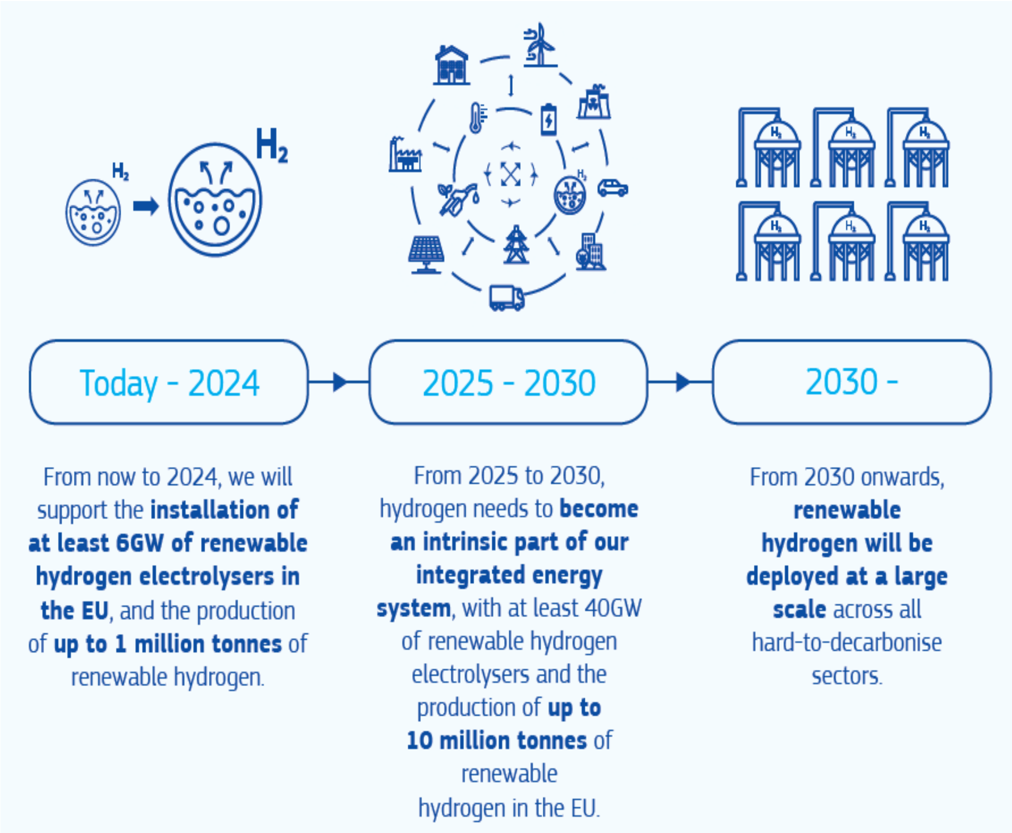

Figure 3: Step by step path towards a European hydrogen eco-system [8].

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" and 14 states have put hydrogen in the context of their alternative fuels infrastructure national policy framework. Furthermore, EU has put action plans to achieve advancements in hydrogen technologies and harness all possible benefits form it, these actions are follows:

1. **An investment agenda for the EU:** To support investments and emergence of a hydrogen eco-system, 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. [8].

2. **Boosting demand for and scaling up production:** To help boost demand and scaling 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 in other related policy initiatives. Furthermore, additional support measures, including demand-side policies in end-use sector, for green hydrogen building on the existing provisions of Renewable Energy Directive. It has also work to introduce a 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 program particular to support the production of low carbon and circular steel, and chemicals. [8].

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 considering the planning of a network of fueling stations. It has design enabling market rules to deployment of hydrogen, including removing barriers for efficient hydrogen infrastructure development and ensure 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 a100Mw 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. [8].

4. **The international dimension:** Eu has strengthened its leadership in international for a for technical standards, regulations, and definitions on hydrogen. It has developed 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. [8].

3 Hydrogen in Energy Context

Hydrogen gas is colorless, odorless, tasteless, and non-toxic. It is also noncorrosive, but it can embrittle some metals. Hydrogen is the lightest and smallest element represented by the symbol H but mostly expressed as H2 or H_2. It is in gaseous form under standard temperature and pressure (0^oC and 1014 hPa) [9]. Some of the physical properties of hydrogen are presented in Table 1.

Table 1: Physical properties of Hydrogen [9].

Parameter	**Value**	**Unit**
Molecular weight	2.016	mol
Melting point	13.96	K
Boiling point	14.0	K
Density solid at 4.2K	0.089	g/cm^3
Density liquid at 20.4K	0.071	g/cm^3
Gas density (0^oC, 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 air	0.017	mJ
Ignition energy in oxygen	0.0012	mJ

Hydrogen as a fuel is expected to play 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.

$$2\,H_2 + O_2 \rightarrow 2\,H_2O + 572\text{ kJ} \qquad (1)$$

Hydrogen is one of the simplest and abundant elements found on earth. 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 good energy density by weight, but poor energy density by volume compared to hydrocarbons. Table 2 shows different fuels and their specific energy and energy density.

Table 2: Specific energy and energy density of different fuels [10] [11] [12].

FUEL	SPECIFIC ENERGY (kWh/kg)	ENERGY DENSITY (kWh/dm^3)
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
Anhydrous Ammonia	5.8	4.33
Methanol	5.5	4.4
Wood	4.2	3.0

3.1 Hydrogen and its Different Shades

Hydrogen can be produced from 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, and Turquoise etc., depending on GHG emissions released into atmosphere during its production process [13]. These color code naming is not universal and may differ in different countries.

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 [14].

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 are released in the atmosphere, which makes these technologies not suitable for net-zero emissions [14].

Blue hydrogen is produced from fossil fuels in similar way like grey hydrogen, but the carbon produced in the process is captured and stored or utilized in industrial uses. Almost three-quarters of hydrogen currently produced comes from natural gas, thus carbon capture and storage (CCS) would allow continuous flow of hydrogen with low GHG emissions while green hydrogen ramps up production and storage capacity [14].

Turquoise hydrogen is produced as 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 high energy demanding thermal process being powered with renewable energy and the carbon being permanently stored. [14].

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 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 [13]. In below picture one can see the different shades of hydrogen.

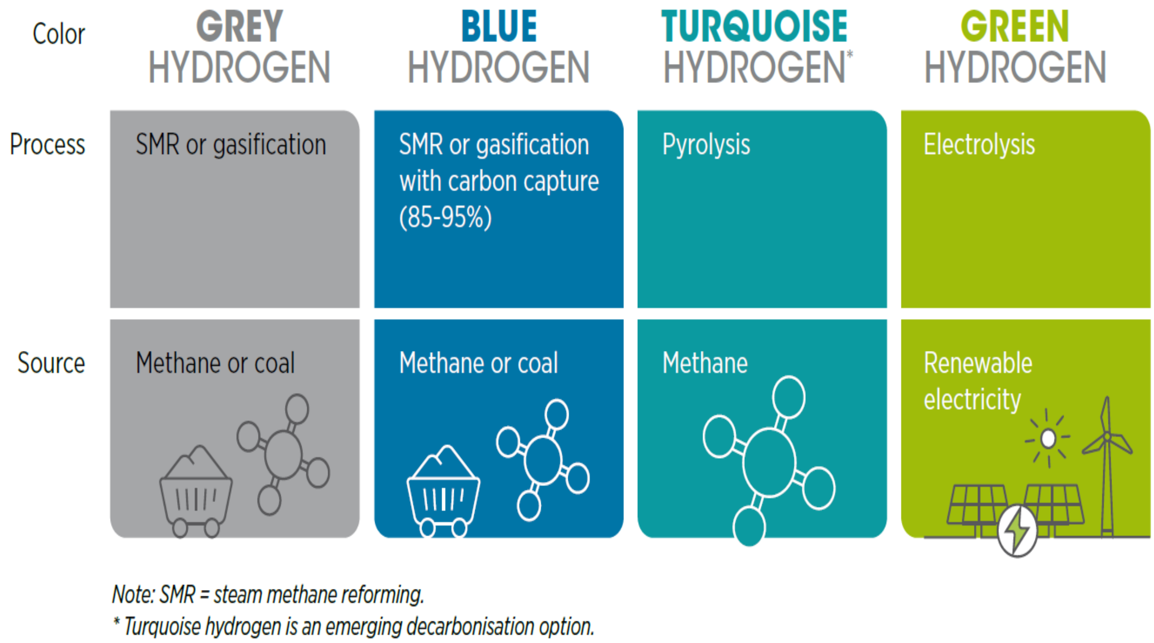

Figure 3: Different shades of hydrogen [14].

3.2 Green Hydrogen: Drivers and Barriers

As mentioned in above chapters green hydrogen is an energy carrier that can be used in many ways. Figure 4 shows 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 are 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 [14]. Approximately 70-100 million tonnes of CO_2 annually are released in the EU to produce hydrogen from fossil fuels [8]. Hydrogen accounts for less than 2% of EU's current energy consumption and is mostly used to produce chemical products, such as plastics and fertilizers. 96 % of this hydrogen are 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 weight of fuel matters.

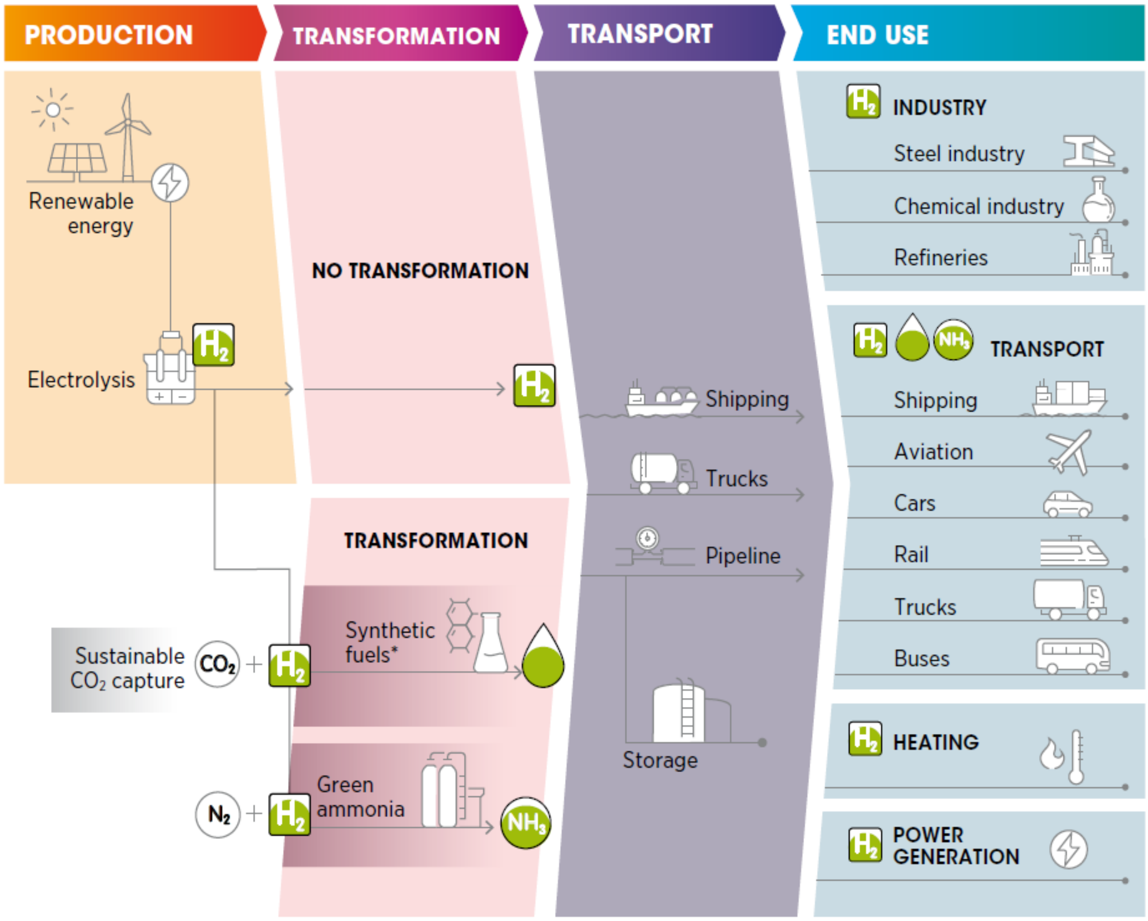

Figure 4: Production, transformation, transport, and end use of green hydrogen [14].

This is not the first time when 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 [14]. Recently there has been few mega trends that sparked the interest in green hydrogen again. First of all, electrification of city life. According to United Nations report by 2050, the worlds urban population is expected to nearly double [15]. 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 [16]. This will put a huge pressure on the infrastructure in those cities. Feeding population, electrification of mobility and trend of digitalization are some other mega trends that will require large increasement 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 by 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 few important barriers faced by green hydrogen are mentioned.

1. **High production cost:** Today green hydrogen is not cost-competitive against fossil-based hydrogen. Cost of fossil-based hydrogen is highly dependent on natural gas prices, and it is around 1.5 euro per kilogram (€/kg) whereas, cost of green hydrogen is about 2.5-5.5 €/kg for EU [8]. On top of this adopting green hydrogen technologies can be expensive for end users. Vehicles with fuel cells and hydrogen tank are almost two times the price of fossil fuel counterparts [14].

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 [17], 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 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. [18].

   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 percentage [18]. In below figure one can see the amount of hydrogen that can be produced by 55-kilowatt hour (kWh) of electricity and how much electricity and heat energy can be recovered.

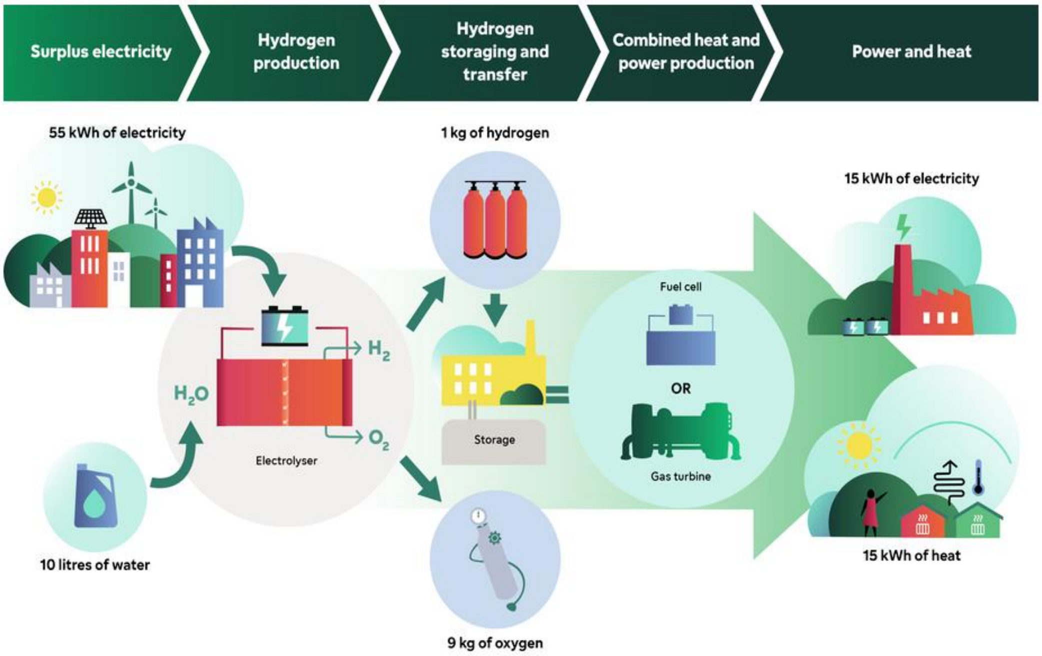

Figure 5: Production of green hydrogen from 55 kWh renewable energy. [18]

4. **Lack of value recognition:** Currently there is no market for green hydrogen, no green steel, no green shipping fuel and basically there is no valuation for the lower GHG emissions that green hydrogen brings. There is also no internationally recognized way to differentiating green from grey hydrogen which limits the demand for green hydrogen. [14].

3.3 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 consist of an anode, a cathode separated with 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) [19]. 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 [19].

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

In standard conditions of temperature (T = 298 K) and pressure (P = 1 bar) water is liquid and hydrogen and oxygen are gaseous [19]. Enthalpy, entropy, and Gibbs free energy standard changes for reaction in equation 2 are, respectively:

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

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

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

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 reaction non-spontaneous [19]. Water vapor can also be dissociated into gaseous hydrogen and oxygen according to:

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

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

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

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

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

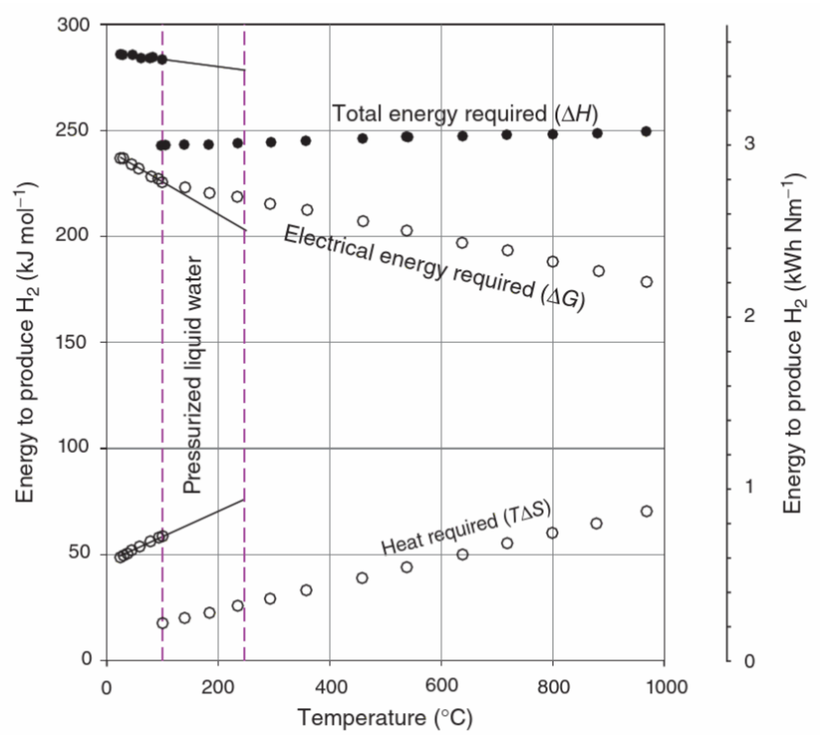

Figure 6: $\Delta G, \Delta H$ and $T\Delta S$ of the water splitting reaction at 1 bar. Data for pressurized liquid water up to 250°C [9].

From the figure 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 ℃, 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 case expensive then heat. According to figure 6, water electrolysis can be performed at different temperatures. At any operating temperature T, $\Delta H(T)$ is the total amount of energy that is required to split 1 mole of water, $\Delta G_d(T)$ is the amount of electrical work needed and $T.\Delta S\ (T)$ is the heat demand. This is given by following equation 2.2

$$\Delta H(T,1) = \Delta G_d(T,1) + T.\Delta S\ (T,1) \qquad (2.2)$$

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

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

Thermoneutral voltage (V) in volt is defined as

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

Under standard temperature and pressure

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

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

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

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

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. [20]

3.3.1 Alkaline Electrolysis

Alkaline water electrolysis has a lengthy history in chemical industry [21]. Alkaline water electrolysis is a mature technology. The principle of alkaline water electrolysis is simple. Oxygen and hydrogen are separated from the water when the direct current is applied to the water. Hydrogen arises at cathode and at the anode, oxygen arises. Alkaline electrolyzers contains caustic water solution and 25% to 30% of potassium hydroxide (KOH). Sodium hydroxide (NaOH) and sodium chloride (NaCl) are used as catalyst [21]. Liquid electrolyte allows ions to be transported between the electrodes and is not consumed in the chemical reaction but is gradually replenished depending on the loses in the system. The direct current density used in alkaline electrolyzer is around 2000 A/m^2 - 4000 A/m^2, the working temperature is generally maintained at 80℃-90℃ and working pressure is maintained within 3.2 MPa [22]. Alkaline electrolyzers are most used hydrogen generators in the industry. 99% pure hydrogen is produced through this process, after certain purification processes higher purity can be reached that is required for hydrogen fuel cells. The operating principle of an alkaline electrolysis is described in Figure 7.

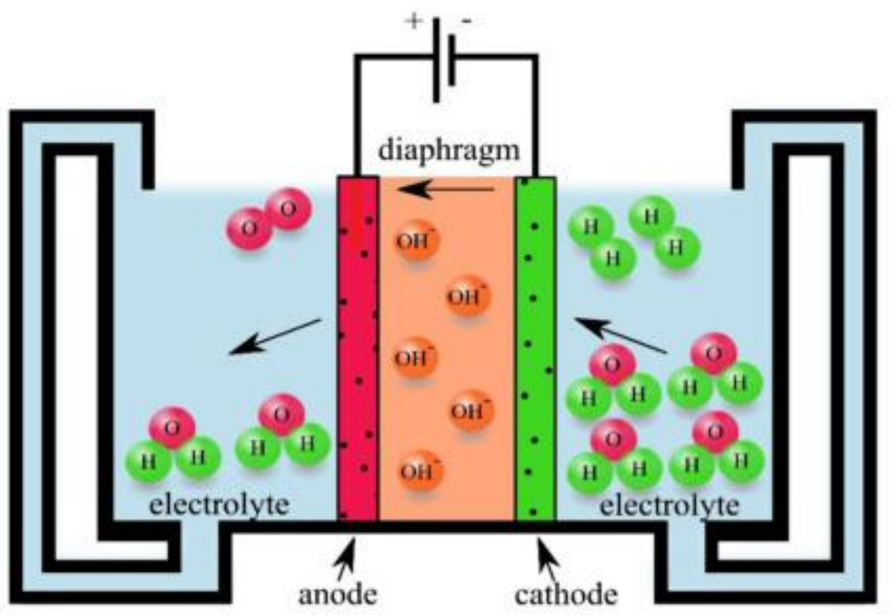

Figure 7: Operating principle of an alkaline electrolysis cell [23]

3.3.2 Polymer Electrolyte Membrane (PEM) Water Electrolysis

In modern electrochemical literature, solid polymer electrolyte (SEP) is referred to as proton exchange membrane or PEM cells [9]. In PEM cells, a thin proton-conducting membrane is used as 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 lab [9]. 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 8 describes the operating principle of PEM cells.

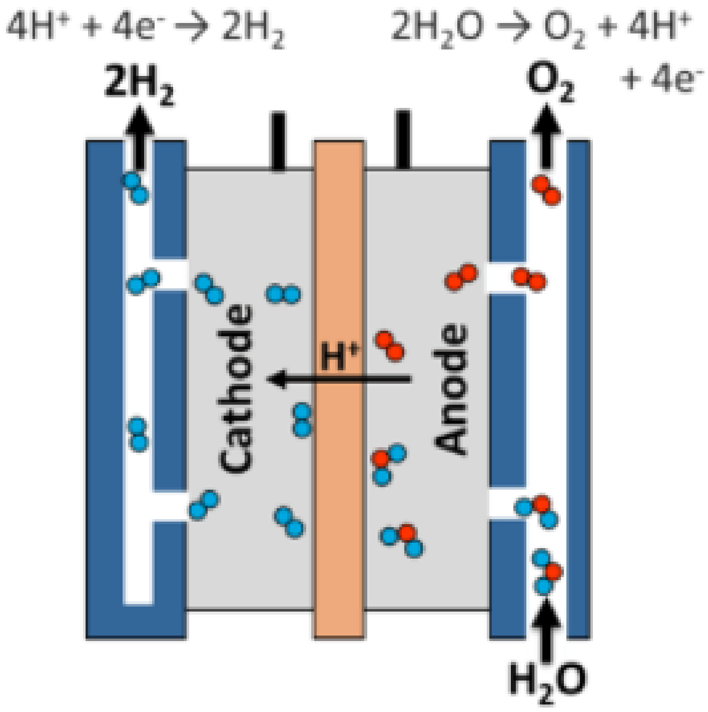

Figure 8: Operating principle of PEM electrolysis cell [24].

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 due to the fact that because the electrolyte is confined in the polymeric membrane, tolerance of cell component dimensions is more demanding and requires sophisticated mechanical tools [9].

3.3.3 High Temperature Electrolysis

A typical technology for high temperature electrolysis is the solid oxide electrolysis cells (SOEC). A SOEC is basically 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 is typically 700-1000℃. 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 constitute of an oxygen electrode (anode) and a hydrogen electrode (cathode) separated by a dense ionic conducting electrolyte [25] . 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 cross the electrolyte to eventually form oxygen by oxidation at the anode side [25].

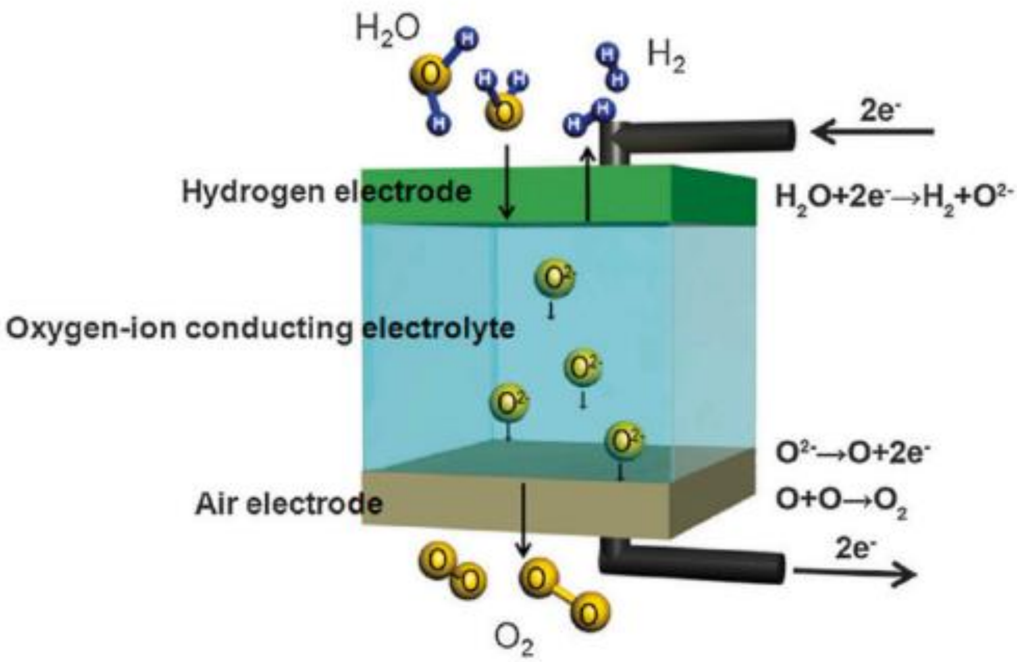

Figure 9: Solid oxide electrolysis cell principle for hydrogen production from water [25].

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 H2O + CO2 co-electrolysis, CO by CO2 electrolysis, etc. …). [25].

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 [25]. In table 3 one can find the characteristics of different water electrolysis technologies.

Table 3: Characteristics of different water electrolysis technologies [26].

Characteristics	**AEL**	**PEM**	**SOEC**
Operation parameters			
Temperature (°C)	40-90	20-100	650-1000
Pressure (bar)	< 30	<200	<20
Current density (A/cm^2)	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 (m^2)	<4	<0.13	<0.06
Production rate (m^3/h)	<1400	<400	<10
Gas purity (%)	>99.50	>99.99	>99.90
System Details			
Energy consumption (kWh/m3)	~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 Parameter Capital costs (EUR/kWh) Maintenance cost (% of investment/year)	740-1390 2-3	1300-2140 3-5	>2000 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 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

3.4 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 for its widespread application as an effective energy carrier and feedstock [9]. 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 oxidation of reactive metals such as lithium, sodium, magnesium, with water.

Nowadays the most proven, tested and commercially available hydrogen storage is in compressed gaseous form or in liquid form. To achieve a satisfying energy density with compressed gas storage system, the operating pressure has been raised up 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 [9].

The storage of hydrogen in metal hydrides is another technology that has several advantages with respect to 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 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 size and weight of tank are a significant concern. Physical storage is the most mature hydrogen 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 [27]. Figure 9 describes the components of a pressurized hydrogen storage tank.

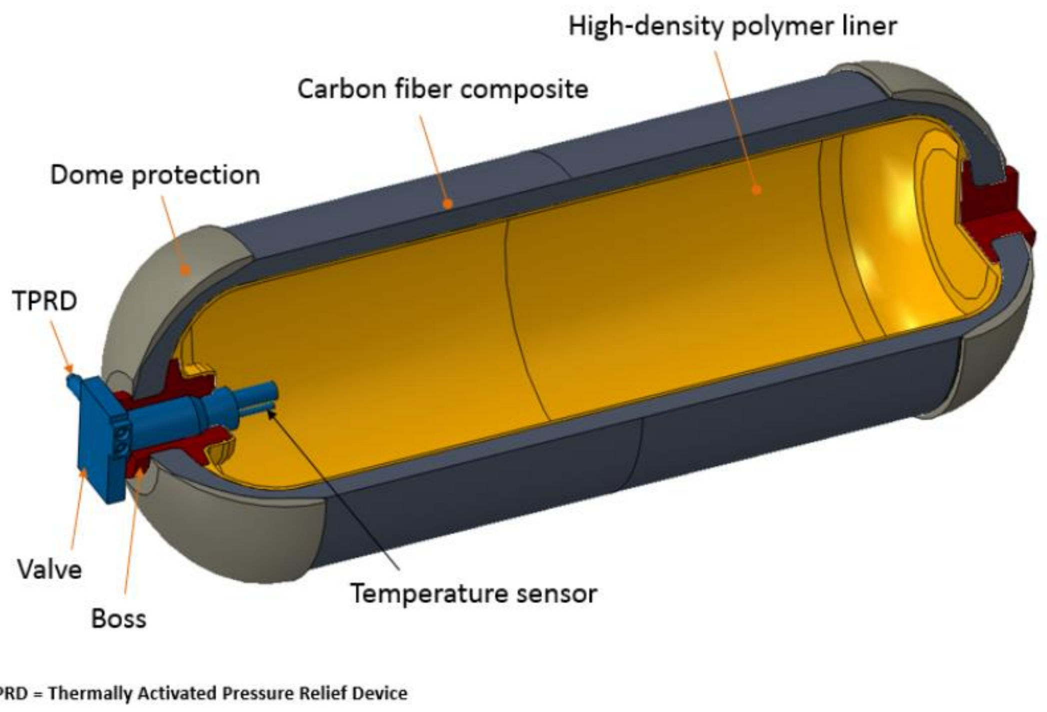

Figure 10: Components of a pressurized hydrogen storage tank [27].

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 good solution if large amount of hydrogen needs to be distributed. Gas pipelines usually can transport 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, methane pipeline could transport 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 shorter lifespan of pipelines. Factors such as dynamic stress and existing fractures need to be consider as well if one plans to transport hydrogen through existing methane pipeline. It is also possible to mix natural gas with hydrogen to mitigate these risks and decrease the requirements for adaptations to the existing pipelines. However, if in the share mixture percentage of hydrogen exceeds by 40 %, parts like compressors and turbines likely need to be exchanged to cope with high volume flow of hydrogen. [28].

Storage and distribution of hydrogen onsite are also feasible, but it requires a safety concept and testing before commissioning. 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 [28]. 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.

3.5 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 writing this thesis. The more one digs in the more it comes to conclusion that it is not apple to apple comparison. They have similar purpose but are two different technologies with their own 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 are type of lithium-ion batteries commonly used in electric vehicles whereas LFP are types of lithium-ion batteries used primarily for energy storage. When we talk about energy storage system few main scenarios come in one’s mind. Number one being able to store large amount of renewable energy for deficit period, second, being able to be used in different transport vehicles and thirdly being able to use in small scale either in off grid scenarios or on grid connections. Also, economy and scalability play a significant role for technology to be 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 comparison of 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 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 two technology is that 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.

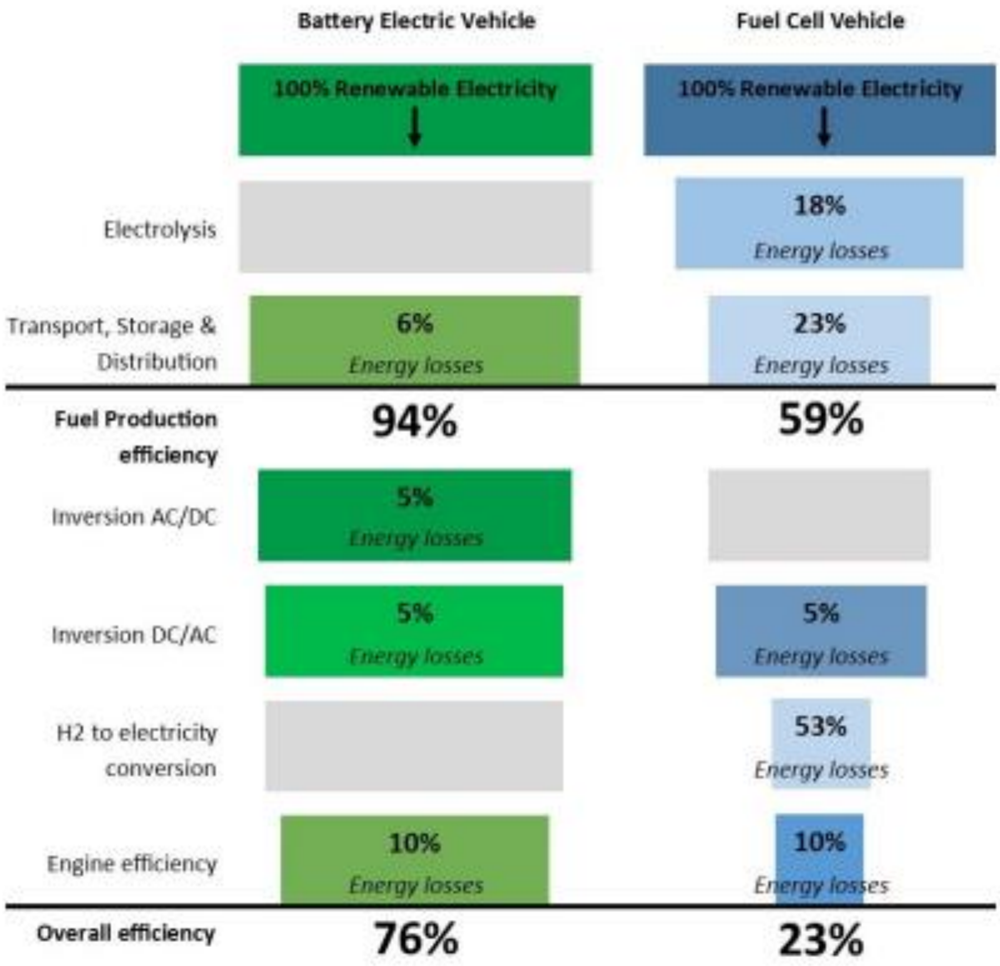

Figure 11: Comparison of the efficiency of battery electric vehicle and fuel cell vehicle [29].

On the other hand, hydrogen seems to have a major advantage to batteries when it comes to energy storage for a long period of time and has potential to store a large amount of energy in an already existing cavern. Salt caverns, exhausted oil and gas fields can all provide underground hydrogen storage on an industrial scale. Storing hydrogen in 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 Hystock hydrogen storage in Netherlands by Gasunie and HyPSTER in France are some projects to demonstrate the ability of hydrogen storage in industrial scale [30], [31].

Compressed hydrogen and fuel cells can provide electricity to a vehicle traction motor with weights that are much less than batteries [32]. 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 extra mass. This is one drawback for battery power electric vehicle. Hydrogen offers a promising solution to this problem and could be best suited for heavy-duty transport, aviation, and shipping.

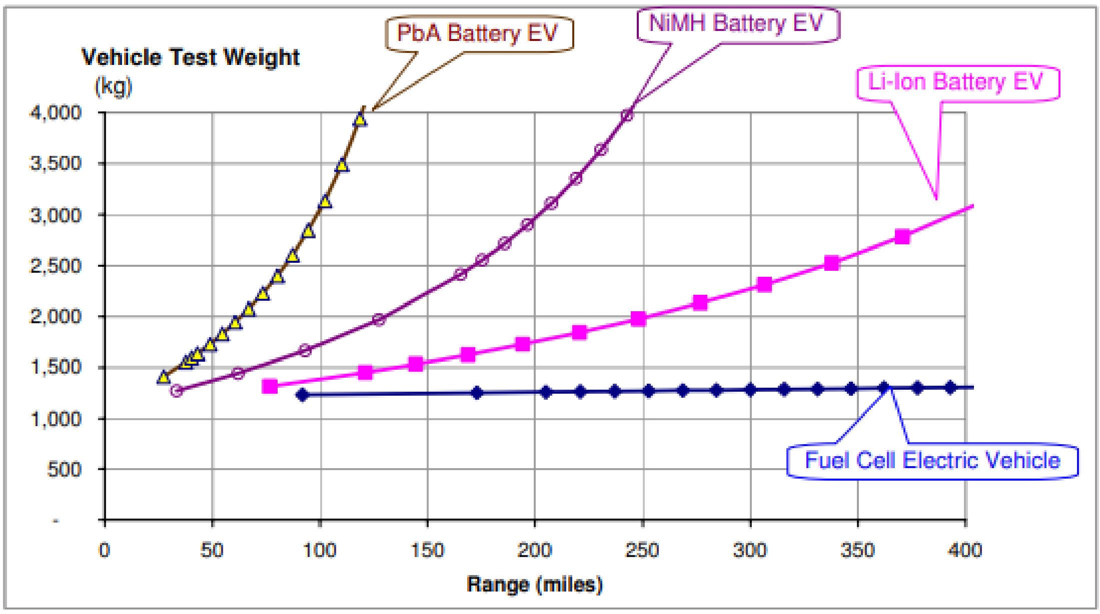

Figure 12: Calculated weight of fuel cell electric vehicles and battery electric vehicles [32].

It should also be noted that after 80% of depth of discharge the voltage drops sharply for LFP as shown in figure 12. This implies 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.

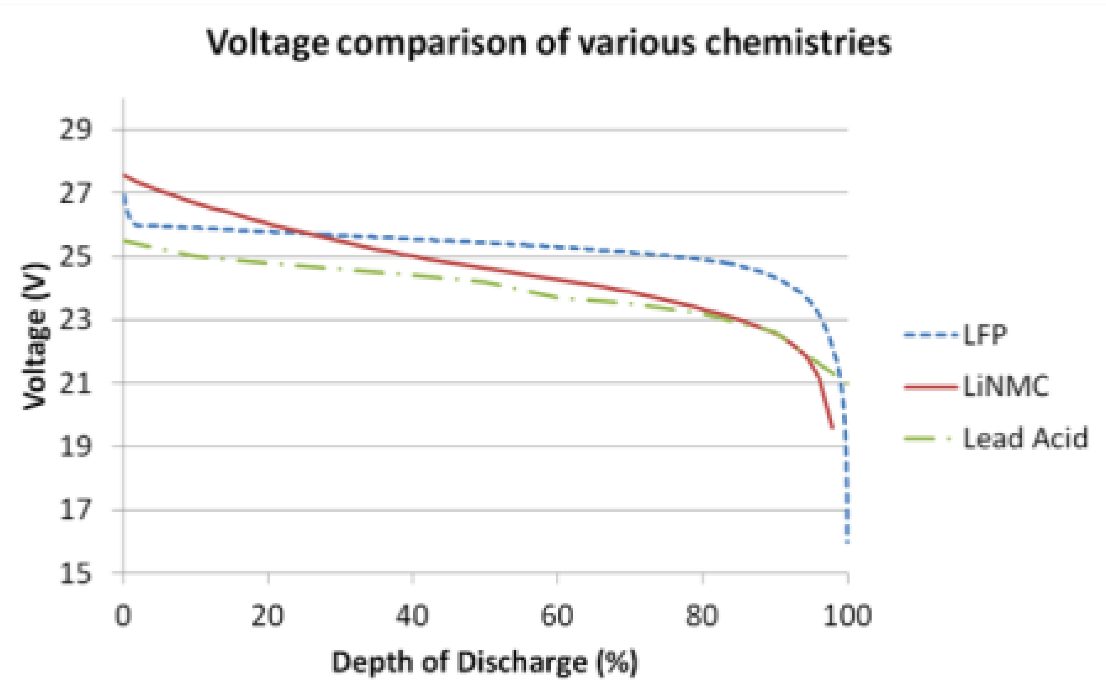

Figure 13: The voltage of each chemistry relative to its capacity for various 24 V packs [33].

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

4 Green Hydrogen Cost

In the EU, the green hydrogen is currently expensive than the conventional fossil fuel. 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, that 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 are produced on-site by steam methane reforming method.

When talking about costs of green hydrogen, its production cost is mainly influenced by the capital expenditure (CAPEX), the operating expenses (OPEX), Lifetime and efficiency [34]. This chapter tries to estimate the levelized cost of hydrogen per kilogram (kg) in different scenarios. This will help reader get some insights of green hydrogen costs and how levelized cost of hydrogen production is calculated. Author creates three different cases for costs calculation lowest costs case, average costs case and high-cost case. Low costs case assumes lowest investment and operating costs and similarly average and highest cost case assumes average and highest investment and operating cost respectively. Furthermore, author creates 3 different scenarios for use of renewable electricity on how green hydrogen is produced. To make it as close to real life scenario authors goes through wide range of resources and makes assumptions that would be very reasonably appliable here in Vaasa region. The focus of this study was set to understand the green hydrogen production cost; thus, scope was limited to production and short-term storage only. To make it simple the size 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 13.

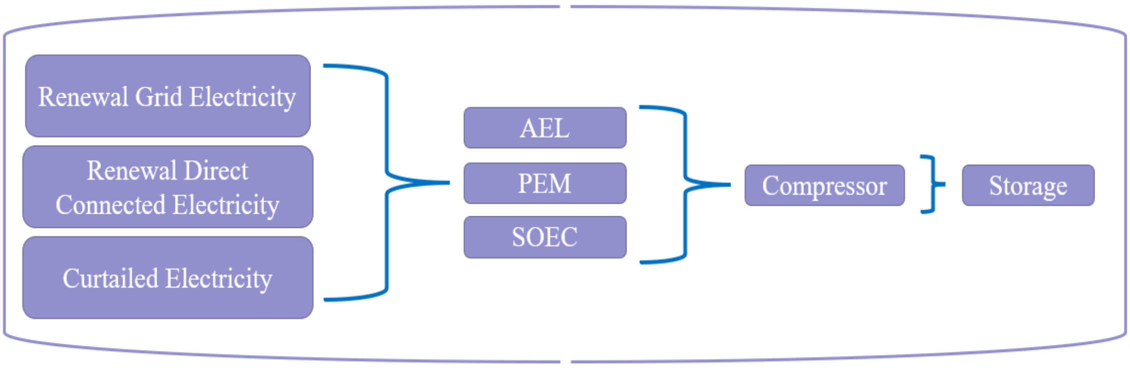

Figure 14: System boundary for 1 MW green hydrogen production plant.

As there are many talks on use of renewable, off peak, and curtailed electricity to produce green hydrogen, following scenario were analyzed:

i. Scenario 1- Renewable grid connected: This scenario assumes that the electrolyzer is connected to grid and with the agreement that grid provides only renewable electricity. In this scenario hydrogen can in theory be produced with 100 % capacity factor, where capacity factor is ratio of an actual electrical energy output over a given period to the maximum possible electricity energy output. But in real practice it will not be feasible to produce hydrogen with 100% capacity factor, thus we capacity factor of 90% for this scenario. In this scenario transmission and distribution charges of electricity are includes as it is connected to grid. 50 euro per MWh electricity price was considered for this scenario to calculate LCOH, other costs were according to table 4,5 and 6.

ii. Scenario 2 - Direct 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 the renewable electricity generation means that capacity factor of hydrogen production is equal to the renewable energy generator's capacity factor. For simplicity reason capacity factor of 48 % for wind farm is assumed in this calculation. As capacity factor is almost 50% it was also assumed that in this scenario lifetime of 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 table 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 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 capacity factor is quite low it was also assumed that in this scenario lifetime of 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 table 4,5 and 6.

4.1 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 a 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 [35]:

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

Although LCC has been 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 this the LCC method still provides universal method to evaluate and compare different investment opportunities.

Levelized cost of hydrogen (LCOH) method is 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 LCC of renewables is presented in terms of cost per energy output unit [36]. LCOE has been used before to analyze techno-economic studies for incorporating cost analysis including investment costs, component life, escalation ratio 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 in order 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 in measuring hydrogen, as hydrogen output can also be expressed in terms of energy. Like computation of electricity costs, hydrogen costs can therefore be expressed in terms of cost per unit of energy or mass of hydrogen [37]. The definition of the LCOE by IRENA can be written as equation (3):

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

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:

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

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).

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

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).

$$C_{inv,a} = CRF * C_{inv} \qquad (6)$$

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

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

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)

$$C_{VarO\&M,a} = C_e + C_w \quad (9)$$

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

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

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

$$\text{LCOH} = \frac{C_{Lcc,a}}{E_{H_2,a}} \quad (11)$$

4.2 Green Hydrogen Components Cost Literature Overview

Main costs for green hydrogen come from capital costs, operation and maintenance costs and electricity costs. Figure 13 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 in all hydrogen production [38].

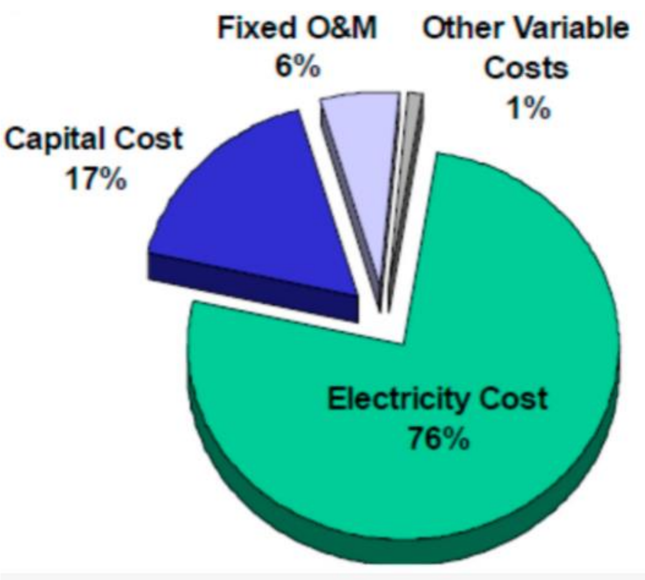

Figure 15: Hydrogen production, cost breakdown [38].

4.2.1 Capital Costs

The second most influential factor for pricing of hydrogen is the capital cost and particularly electrolyzer costs. Water electrolysis investment cost estimations depends on many factors such as plant size and site- specific characteristics. In a 2014 paper Bertuccioli et al. identified the range for alkaline water electrolysis costs to be in range of 1000-1200 euros per kW capacity [39]. 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 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. In report published by University of Nebraska at Omaha mentions that typical 350 bars and 700 bars hydrogen compressors costs 50,000 USD – 140,000 USD and consumes 2-4 kWh/kg of electricity for compressing 20-350 bar [40]. Penev et al. have presented data regarding the capital costs, producing capital and specific energy required to operate such compressor [41]. Penev et al. in their study assume compressors cost rate to be rate of 3 USD/kg.

In addition to compressor green hydrogen system will require short-term on-site storage in order to get it ready to be injected into a pipeline or to be put into tanker trucks and shipped. Data from hydrogen refueling station in Halle, Belgium in 2017 shows that 50 kg hydrogen storage at 450 bars had investment cost of 157,500 euros [37]. Study conducted to assess the potential of green hydrogen fueling of very heavy vehicles in New Zealand in 2021 shows cost of 0.5 NZD/kg of hydrogen storage [42]. A case study of Slovenian hydro power plant shows that 1 MW nominal power electrolyzer storage system would cost around 200,000 euros [43]. In journal article “Techno-economic calculations for small-scale hydrogen supply system for zero emission transport in Norway” Ulleberg and et al. has concluded that hydrogen tank was costing 6300, 8100, 19800 NOK/kg for tank rated for 250, 450 and 900 bars respectively [44].

4.2.2 Operation and Maintenance Costs

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

Stack costs makes up to 60% (PEM), 50% (AEL) and 60% (SOC) of plant CAPEX costs and are assumed to need to be replaces 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 [37].

The variable expenses included electricity and water costs. Electricity price for households in Finland 2021 was on average 17.67-euro cents per kwh [45] . The current price of water in Vaasa is 1.59 euro/m^3 [46].

4.3 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 literature study in chapter 4.2 of this thesis that would be reasonable for Vaasa region. Costs were assumed as Low, average, and high scenario. 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 capital cost every 5 years in lifetime				
Compressor maintenance	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 industry then for households	25	50	75	0,1767 cents/kwh for average household price in 2021. Would be much lower for industry than for household
Water costs		1741	1741	1741	1.59 euro/m^3 for average household. Assuming 10 L of water is needed for 1kg hydrogen production Would be much lower for industry than for household in real world
Miscellaneous costs	1% of investment cost	7000	11,000	15000	
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 capital cost every 5 years in 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 industry than for household
Water costs		1741	1741	1741	1.59 euro/m^3 for average household. Assuming 10 L of water is needed for 1kg hydrogen production Would be much lower for industry than for household in real world
Miscellaneous costs	1% of investment cost	9,000	13,000	17,000	Maintaining facilities etc
Discount rate (euros)	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 capital cost every 5 years in lifetime				
Compressor maintenance	6 % of compressor cost				
Service contract		100,000	100,000	100,000	Maintaining facilities etc
Electricity price Per MWh	Would be much lower for industry then for household	25	50	75	0,1767 cents/kwh for average household price in 2021. Would be much lower for industry than for household
Water costs		1741	1741	1741	1.59 euro/m^3 for average household. Assuming 10 L of water is needed for 1kg hydrogen production

					Would be much lower for industry than for household in real world
Miscellaneous costs	1% of investment cost	23,000	45,000	67,000	Maintaining facilities etc
Discount rate	7%				
Lifetime	20 years				

5 Result and Discussion

Table 7 presents the LCOH for AEL, PEM and SOC in accordance with the techno-economic assumption from table 4, 5 and 6 respectively and table 8 presents LCOH for three scenarios mentioned in chapter 4. Capacity factor for this calculation has been at 100% while in practice this may not be possible, more realistically it would be 90% of 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	6.61
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	Highest 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 literature study. From the result it can be noticed that capacity factor in which electrolyzer is producing hydrogen through its lifetime and efficiency of electrolyzer plays significant role just like other costs such as electricity to reduce the end price of hydrogen which is not discussed in literature often. Lowest LCOH for AEL with 25 MWh electricity at 100% capacity factor for 20 years production was 3.69 euros per kg whereas for curtailed electricity at 12.5 % capacity factor for 30 years production was calculated at 13.03 euro per kg.

6 Conclusion

The review of current situation in the beginning of this thesis from Finnish and European perspective to be carbon neutral by 2050 revealed a real political will towards the hydrogen economy. Target to deploy renewable hydrogen in large scale by 2030 is a challenging ambition and many actual projects are needed to achieve it. Literature study highlighted the challenges and opportunities of hydrogen technology and also discussed the different technologies giving the holistic view of hydrogen technology. The review further deepened into three leading electrolysis methods namely AEL, PEM and SOE and assessed their characteristics, advantages, and disadvantages. Different storage technologies were also discussed. Further developments in electolyzers in term of its lifetime and efficiency is needed to be more competitive and same for its storage technology. Tax deduction 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 in internet, it would have been interesting to read and collect information’s 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 costs calculation had to be assumed. For further studies it is recommended to collaborate with a company that is establishing hydrogen production facility and acquire data and compare the costs between literature and actual cost in Vaasa region.

7 References

[1] "Communication from the commission to the European Parliament, the European council, the concil, the European economic and social committee and the committee of the regions : The European Green Deal," European Commission , Brussels, 2019.

[2] G. Kakoulaki, Kougias, N. Taylor, F. Dolci, J. Moya and A. Jäger-Waldau, "Green Hydrogen in Europe-regional assessment: Substituting existing production with electrolysis powered by renewables," *Energy Conversion and Management* , 2021.

[3] "A European strategic long-term vision for a prosperous, modern, competitive and climate netural economy," European Commission, Brussels, 2018.

[4] "Electricity Storage and Renewables: Costs and Markets to 2030," International Renewable Energy Agency , 2017.

[5] "https://www.fingrid.fi," Fingrid, 30 05 2021. [Online]. Available: https://www.fingrid.fi/en/electricity-market/electricity-market-information/wind-power-generation/.

[6] Novia University of applied sciences , 30 05 2021. [Online]. Available: http://iot.novia.fi/data/meteoria_energy.html.

[7] "Powering a climate-neutral economy: An EU Strategy for Energy System Integration," European Commission, Brussels, 2020.

[8] "A hydrogen strategy for a climate-netural Europe," European Commission, Brussels, 2020.

[9] G. J. Agata, Hydrogen Production by Electrolysis, WILEY-VCH Verlag Gmbh Co. KGaA.

[10] P. Edwards, Kuznetsov, V. David and N. Brandon, "Hydrogen and fuel cells: Philosophical Transactions of the Royal society," *Energy Policy,* vol. 36, no. 5, pp. 1043-1056, 2007.

[11] T. Brown, "Ammonia for Power: a literature review," Ammonia Energy Association, 2018.

[12] G. Thomas and G. Parks, "Potential Roles of Ammonia in a Hydrogen Economy," U.S. Department of Energy , 2006.

[13] "https://www.enapter.com/," 9 September 2020. [Online]. Available: https://www.enapter.com/hydrogen-clearing-up-the-colours. [Accessed 22 September 2021].

[14] "Green Hydrogen: A guide to Policy Making," The International Renewable Energy Agency (IRENA), Abu Dhabi, 2020.

[15] "New Urban Agenda," United Nations, 2017.

[16] "The Metropolitan Century: Undertanding urbanisation and its Consequences," OECD, Paris, 2015.

[17] "Energy Technology Perspectives 2020," International Energy Agency, 2020.

[18] E. Vartiainen, Fortum, 30 April 2020. [Online]. Available: https://www.fortum.com/about-us/blog-podcast/forthedoers-blog/hydrogen-economy-coming-sooner-or-later. [Accessed 22 October 2021].

[19] A. Godual-Jopek and D. Stolten, Hydrogen Production: By Electrolysis, John Wiley & Sons, Incorporated, 2015.

[20] R.-S. Liu, L. S. X. Zhang and H. Z. J. Liu, Electrochemical Technologies for Energy Storage and

Conversion, 2012, John Wiley & Sons, Incorporated.

[21] C. Christophe, B. Stève and A. Thomas, "Hydrogen Production From Water Electrolysis," *Hydrogen Energy and Fuel Cells Primers,* 2018.

[22] G. Yujing, "Comparison between hydrogen production by," 2019.

[23] B. M. Syed, "Technologies for renewable hydrogen production," *Bioenergy Resources and Technologies,* pp. 157-198, 2021.

[24] "ENERGY.GOV," [Online]. Available: https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis. [Accessed 25 January 2022].

[25] A. Nechache and S. Hody, "Alternative and innovative solid oxide electrolysis cell materials: A," *Renewable and Sustainable Energy Reviews,* no. Elsevier Ltd, 2021.

[26] L. Vidas and R. Castro, "Recent Developments on Hydrogen Production Technologies: State-of-the-Art Review with a Focus on Green-Electrolysis," MDPI, 2021.

[27] "energy.gov," [Online]. Available: https://www.energy.gov/eere/fuelcells/physical-hydrogen-storage. [Accessed 28 Janaurary 2022].

[28] "tuvsud.com," [Online]. Available: https://www.tuvsud.com/en/themes/hydrogen/explore-the-hydrogen-value-chain/hydrogen-storage-and-distribution. [Accessed 28 January 2022].

[29] A. Tsakiris, "Analysis of hydrogen fuel cell and battery efficiency," Copenhagen Centre on Energy Efficiency, Copenhagen, 2019.

[30] "storengy.com," [Online]. Available: https://www.storengy.com/en/medias/news/hypster-1st-demonstrator-h2-green-storage#:~:text=HyPSTER%20is%20the%20first%20EU,Undertaking%20(FCH%202%20JU).. [Accessed 4 Feb 2022].

[31] "gasuie.nl," [Online]. Available: https://www.gasunie.nl/en/projects/hystock-hydrogen-storage. [Accessed 4 Feb 2022].

[32] C. E. Thomas, "Fuel Cell and Battery Electric Vehicles Compared," Virginia.

[33] D. Heeger, M. Partridge and V. Trullinger, "Lithium Battery Health and Capacity Estimation Techniques Using Embedded Electronics," 2017.

[34] "Enapter.com," [Online]. Available: https://www.enapter.com/newsroom/h2-view-exclusive-calculating-the-cost-of-green-hydrogen. [Accessed 28 Febrary 2022].

[35] G. Harvey, "Life cycle costing: A review of the techniqur," 1976.

[36] "RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES," International Renewable Energy Agency, 2012.

[37] V. Ludvik, T. J. Heinonen, B. S. Jon and R. Unnthorsson, "A Step towards the Hydrogen Economy—A Life Cycle Cost Analysis of A Hydrogen Refueling Station," University of Iceland, Reykjavik, 2017.

[38] B.-F. Pilar and P.-A. Francisco, "Offshore Facilities to Produce Hydrogen," *Energies,* vol. 10(6), p. 783, 2017.

[39] L. Bertuccioli, A. Chan and D. Hart, "Study on development of water electrolysis in the EU," 2014.

[40] T. Jacob and E. Patrick, "Low-cost, Transportable Hydrogen Fueling Station for Early FCEV Adoption," 2015.

[41] M. Penev, J. Zuboy and H. Chad, "Economic analysis of a high-pressure urban pipeline concept (HyLine) for delivering hydrogen to retail fueling stations," *Transportation Research Part D,* vol. 77, no. ELSEVIER, pp. 92-105, 2019.

[42] R. Perez, A. Brent and J. Hinkley, "Assessment of the Potential for Green Hydrogen Fuelling of very heavy vehicles in New Zealand," energies, 2021.

[43] D. Jovan and G. Dolance, "Can Green Hydrogen Production Be Economically Viable under Current Market Conditions," energies, 2020.

[44] O. Ulleberg and R. Hancke, "Techno-economic calculations of small-scale hydrogen supply systems for zero emission transport in Norway," *i n t e r n a t i o n a l journal o f hydrogen energy,* vol. 45, no. ELSEVIER, pp. 1201-1211, 2020.

[45] "Statista .com," Statista , 29 March 2022. [Online]. Available: https://www.statista.com/statistics/418122/electricity-prices-for-households-in-finland/. [Accessed 19 April 2022].

[46] "Vaasanvesi.fi," [Online]. Available: https://www.vaasanvesi.fi/vaasa-water-information-in-english. [Accessed 19 April 2022].

[47] "Vedantu.com," Vedantu, [Online]. Available: https://www.vedantu.com/chemistry/faradays-laws-of-electrolysis. [Accessed 10 November 2021].