UNIVERSITY OF OULU

FACULTY OF TECHNOLOGY

# Possibilities of utilising green hydrogen as fuel in the heavy transport sector in Finland

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Environmental Engineering

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# ABSTRACT


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This bachelor’s thesis presents one possibility of utilising green hydrogen as fuel in the heavy transport sector in Finland. The work is a literature review that includes calculations to estimate the potential hydrogen demand of heavy transportation. The topic is relevant because of the increasing concerns about climate change, and the urgent need to reduce greenhouse gas emissions asks for environment-friendly solutions in all fields including transportation. Green hydrogen has been recognised as a potential zero-emission fuel in future heavy transportation. However, the technologies that are required for this utilisation are still under development and need improvement before the usage could be possible.

The thesis introduces the EU’s and Finland's composed strategies to attain carbon neutrality, the EU in 2050 and Finland in 2035. These strategies spell out targets and guidelines for achieving decarbonisation in various fields, such as heating, electrification, industry, and transport. The strategies also predict the future of the hydrogen economy and provide a picture of the potential scale of hydrogen production and use.

The study examines the current state of the sector, the feasibility of implementing green hydrogen as a fuel, and the potential benefits and challenges of its adaptation into the Finnish fuel chain. The required hydrogen demand and electricity need for this utilisation are calculated by using the exemplary consumption of an ICE hydrogen engine developed by the company Cummins Inc and collected data on Finland´s traffic performances from Statistics Finland. The calculation shows that the required demand per year would be

350 000 tonnes of hydrogen and more than 17.5 TWh of electricity would be needed to satisfy this demand. Theoretically, this electricity demand could be achieved with the current renewable electricity capacity of 36.9 TWh (2021). Although it wouldn´t be possible in practise as the total electricity demand is 69.3 TWh, without renewable hydrogen production. The electrical efficiency of electrolyser technology is, however, expected to improve by about 12.5% in the future. With this improvement, the annual electricity needed for green hydrogen production for heavy transportation would decrease to 15.3 TWh.

*Keywords: green hydrogen fuel, heavy transportation, hydrogen internal combustion engine*

# FOREWORD

This thesis deals with the possibilities of utilising green hydrogen as fuel in the heavy transport sector in Finland and was written from February to May 2023.

I would like to thank for the support and encouragement that I have received from my family throughout the process of completing this thesis. First and foremost, I would like to express my sincere appreciation to my supervisor Julia Kiehle, for her guidance, expertise and patience to this thesis. Without her input and feedback this thesis wouldn´t have come together. I would also like to extend a heartfelt thank you to my aunt, Taru Virtanen, who generously volunteered her time and expertise to help with the grammar of this thesis.

Oulu, 17.5.2023

*Toivo Virtanen*
Toivo Virtanen

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| AWE | Alkaline Water Electrolyser |
| CI | Compression-Ignition |
| $CO_2$ | Carbon Dioxide |
| EU | European Union |
| GW | Gigawatt |
| GWh | Gigawatt hour |
| $H_2$ | Hydrogen |
| ICE | Internal Combustion Engine |
| LHV | Lower Heating Value |
| $m^2$/kWe | Square meter per kilowatt electrical |
| $O_2$ | Oxygen |
| PEM | Proton Exchange Membrane cell |
| SI | Spark-Ignition |
| SOEC | Solid Oxide Electrolysis Cell |
| TJ | Tera Joule |
| TWh | Terawatt hour |

# 1 INTRODUCTION

The increasing concerns about climate change and the urgent need to reduce greenhouse gas emissions have led to a growing interest in renewable energy sources. To tackle this concern, the EU and Finland have composed strategies to attain carbon neutrality, the EU in 2050 and Finland in 2035. These strategies spell out targets and guidelines for achieving decarbonisation in various fields, such as heating, electrification, industry, and transport (European Commission, 2020a).

Aim to achieve these targets can already be seen in our daily life. Fossil fuel-based heating like coal has been replaced with renewable alternatives such as fuel wood. The amount of renewable electricity grows in the energy feed in Finland and seems to cover the whole energy demand in the future (Roques et al., 2021). Industry favours energy efficient ways to produce end products and production emissions are rigorously controlled by different directions and regulations. Transportation is at a turning point and will transform from fossil-based fuels to environmentally friendly options like electricity and hydrogen.

The heavy transport sector is also one of the areas that will need to be decarbonised in the future. Discussion on the possible ways of achieving this, has brought hydrogen, and especially green hydrogen, produced from renewable energy sources to the fore as a potential alternative fuel in heavy transport vehicles. (European Commission, 2020a; Wróbel et al., 2022a). This bachelor’s thesis explores how hydrogen could be used as a fuel in a conventional internal combustion engine to replace diesel fuel in the current transport sector, and what kind of infrastructure it would require.

The thesis aims to demonstrate the possibilities of utilising green hydrogen as a fuel in the heavy transport sector in Finland. The study will examine the current state of the sector, the feasibility of implementing green hydrogen as a fuel, and the potential benefits of and challenges in its adaptation into the Finnish fuel chain. The thesis will also take a look at what would be the required hydrogen demand for this utilisation by using the exemplary consumption of an ICE hydrogen engine from a company called Cummins Inc and collected data on Finland´s traffic performances from Statistics Finland. Overall, the thesis will discuss the preconditions for this utilisation with the following question:

- How much hydrogen would be needed to supply the whole truck fleet in Finland?
- How much electricity generated by renewable energy sources would be needed to satisfy the demand of hydrogen for the heavy transportation sector? And could this be achieved with the current generation capacity?
- Considering the future potential, can the demand be satisfied with the planned capacity?

# 2 UTILISATION OF GREEN HYDROGEN

Hydrogen ($H_2$) is the simplest and lightest element on Earth. It is a highly reactive and versatile energy carrier, and it has been produced since 1761. It can be used for many applications from transport to chemical processes and its production methods are well known. (Dawood et al., 2020) However, there are a few issues concerning the production process and the use of hydrogen as a fuel source. Its production requires a lot of energy making it expensive, it produces greenhouse gas emissions, and it is a difficult gas to store. In 2020, for example, most of the hydrogen (95%) was produced from non-renewable fossil fuels by using steam reforming of natural gas, which emitted 830 million tons of carbon dioxide ($CO_2$) per year. For this reason, production methods have been classified with colour-codes showing the applied technology and the ensuing level of $CO_2$ pollution (see Table 1). (Shiva Kumar & Lim, 2022)

**Table 1. Hydrogen colour shades and their technology, cost and $CO_2$ emissions (Shiva Kumar & Lim, 2022).**

| Hydrogen Colour | Technology | Source | Product | Cost ($/kg $H_2$) | $CO_2$ emissions |
|---|---|---|---|---|---|
| Brown | Gasification | Brown coal | $H_2$+$CO_2$ | 1.2-2.1 | High |
| Black | Gasification | Black coal | $H_2$+$CO_2$ | 1.2-2.1 | High |
| Grey | Reforming | Natural gas | $H_2$+$CO_2$ | 1-2.1 | Medium |
| Blue | Reforming + carbon capture | Natural gas | $H_2$+$CO_2$ (85-95% captured) | 1.5-2.9 | Low |
| Green | Electrolysis | Water | $H_2$+$O_2$ | 3.6-5.8 | Minimal |

The most environmentally friendly of these options is green hydrogen which can be produced with zero greenhouse gas emissions (Shiva Kumar & Lim, 2022).

## 2.1 Green hydrogen

Green hydrogen is a type of hydrogen that is produced by electrolysis, which uses electricity from renewable energy sources like wind, solar or hydro power to split water into hydrogen and oxygen. Green hydrogen is a promising zero-emission energy source that could replace fossil fuels in many applications. (Oliveira et al., 2021)

Versatility is one of the main benefits of green hydrogen. It can be used as a transport fuel and raw material for industrial and chemical processes, it is suitable for the heating and power supply of buildings, and even as a means of storing energy for later use. (Oliveira et al., 2021) In the transport sector, green hydrogen fuel can be used in hydrogen internal combustion engines (ICE) for heavy transport vehicles, such as trucks and public transport, offering a zero-emission alternative to traditional fossil fuel engines (Wróbel et al., 2022a).

## 2.2 Hydrogen strategies in the EU and Finland

In recent years, hydrogen has gained increasing attention as a potential solution to mitigate emissions in various hard-to-decarbonise sectors like heavy transport. The European Union has taken note of the potential of hydrogen and the EU has drafted a comprehensive hydrogen strategy to make Europe a world leader in clean hydrogen technologies. In addition, individual countries –Finland included – have set up their own strategies.

### 2.2.1 EU hydrogen strategy

The European Commission presented a hydrogen strategy for a climate-neutral Europe in July 2020 (COM/2020/301 final). The strategy aims to establish a hydrogen economy in Europe based on the production, distribution and use of renewable green hydrogen. The strategy is part of the EU´s goal to achieve carbon neutrality by 2050 and attain the Paris

Agreement objectives towards zero pollution by reducing greenhouse gas emissions in all fields. (European Commission, 2020b).

To achieve these objectives, the EU has set several European-level targets. The first target is to install at least 6-gigawatts of electrolysers for the production of renewable hydrogen in the EU and to produce 1 million tons of green hydrogen by 2024.The second target is to install at least 40 gigawatts of renewable hydrogen electrolysers between 2025 and 2030 and increase the production to up to 10 million tons of renewable hydrogen by that time. (European Commission, 2020b)

Figure 1 shows the potential of the electolyser capacity in the EU countries in 2030.

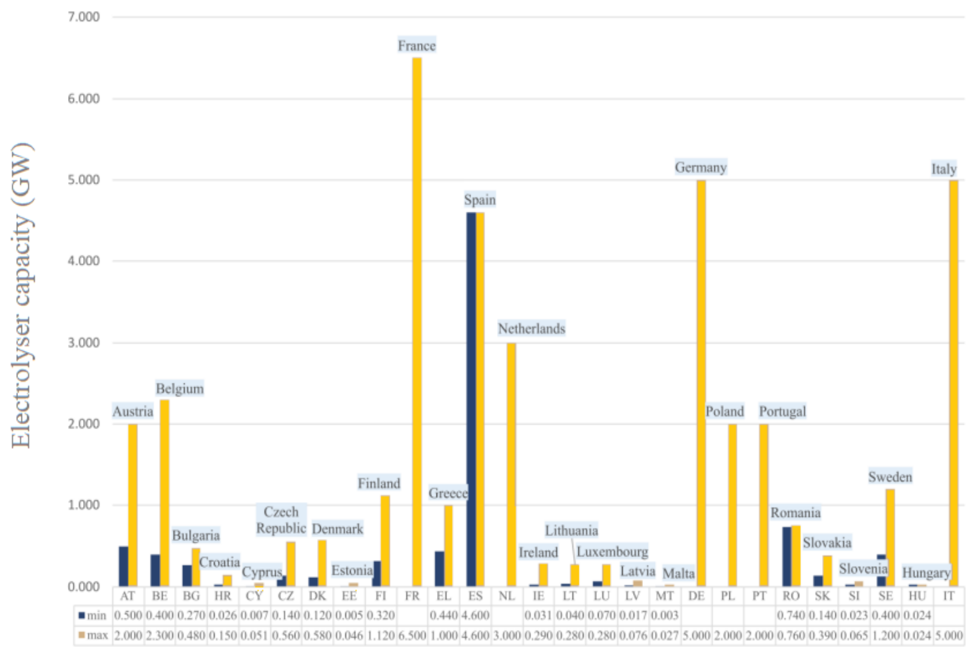


**Figure 1. Potential electrolyser capacity in EU countries in 2030 (in GW) (FCH JU, 2020).**

Furthermore, green hydrogen is also projected to become cost-competitive with fossil fuel-based forms of hydrogen production. Due to the expected increase in the production of renewable energy, and the ensuing decrease in the price of electricity, it can also to be expected that the production and price of hydrogen will follow the same patterns. On the other hand, it is important to develop the EU-wide logistical infrastructure so that hydrogen can be transferred from countries with larger hydrogen production volumes to member states with lesser production volumes. The third and final target between 2030 and 2050, is to develop hydrogen technologies that could be used in all hard-to-decarbonise sectors where other alternatives are not suitable or more expensive. (European Commission, 2020b)

To achieve the set targets, the EU has agreed to provide financial support to the development of hydrogen technologies. By 2030, the EU will invest EUR 24–42 billion in electrolysers and EUR 220–340 billion in solar and wind energy production to achieve the required 80–120 GW capacity to satisfy the demand for renewable electricity for electrolysers. In addition, retrofitting half of the existing hydrogen plants requires around EUR 11 billion, and EUR 65 billion in investments will be directed to hydrogen transport, distribution, and storage technologies. (European Commission, 2020b) Figure 2 shows the scenario of value added to the hydrogen vision development by 2030 in the EU countries.

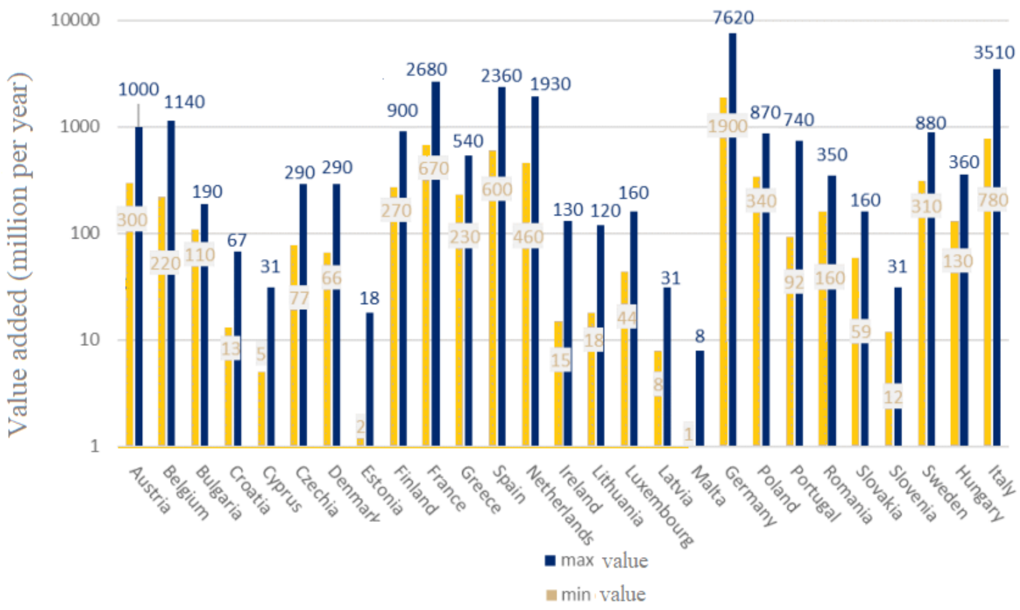


**Figure 2. Value added in the domestic economy (EUR million per year) to hydrogen visions development by 2030 in the EU countries (FCH JU, 2020).**

Overall, the investments into the hydrogen economy would amount to EUR 180–470 billion by the year 2050 (European Commission, 2020b).

To promote these investments and the hydrogen eco-system as a whole, the European Commission has established a European Clean Hydrogen Alliance with the purpose of facilitating and implementing the actions of its hydrogen strategy. The alliance will bring together industry, public authorities, and civil society to identify viable investment projects and coordinate investments and policies along the hydrogen value chain. With the support of this new alliance, the Commission can direct funding to projects in the hydrogen ecosystem in a coordinated manner. (European Commission, 2020b).

### 2.2.2 Finland’s hydrogen strategy

Finland’s hydrogen strategy is largely based on the EU strategy except that Finland aims to reach climate-neutrality already by the year 2035 (Koneczna & Cader, 2021). To support this objective, Finland published in 2022 its national climate and energy strategy – Carbon neutral Finland 2035. The set target for carbon neutrality requires Finland to implement a rigorous and ambitious schedule for the deployment of hydrogen technology. This is also promoted in Business Finland’s Hydrogen Roadmap (Laurikko et al., 2020). The roadmap serves as a knowledge base for the development of the hydrogen economy in Finland. To achieve the established goals, Finland has set up a series of new policy measures:

1. Increasing hydrogen production: On 9 February 2023, the Finnish Government announced the target whereby Finland is to produce at least 10 per cent of the EU’s emission-free hydrogen in 2030 (Ministry of Economic Affairs and Employment, 2023). Considering the EU’s goal in the EU’s hydrogen strategy, this would mean 1 million tons of hydrogen (European Commission, 2020b) .
2. Developing a hydrogen infrastructure: The aim is to develop a wide hydrogen infrastructure, including pipelines for industry and hydrogen refueling stations for vehicles (Laurikko et al., 2020).
3. Supporting research and development: Support to research and development in the hydrogen field, including EUR 150 million in funding for demonstration and innovation projects for the period 2022-2023 (Ministry of Economic Affairs and Employment of Finland, 2022).

4. Encouraging the use of hydrogen in transport: Finland aims to sponsor and favour hydrogen use in the transport sector and marine applications (Laurikko et al., 2020).
5. Promoting the use of hydrogen in the industry: Swedish industrial group SSAB has announced the plan that the blast furnaces in the Raahe steel mill in Finland will be replaced with electric arc furnaces between 2030 and 2040. This means a need for 100,000–120,000 m3/h of hydrogen, which could be covered with 450–500 MWe electrolyser input (Laurikko et al., 2020).

## 2.3 Renewable energy sources for the generation of green hydrogen

The generation of green hydrogen requires renewable energy. This chapter discusses the current capacities of renewable energy sources in Finland. It also examines potential energy production in the future.

### 2.3.1 Current capacities of renewable energy sources

In 2021, Finland had a capacity of 36.9 TWh of renewable electricity. It was more than half (53%) of Finland's electricity production, which was 69.3 TWh in total. (Statistics Finland, 2022b)

The following figure shows the division of Finland's renewable electricity production in 2021:

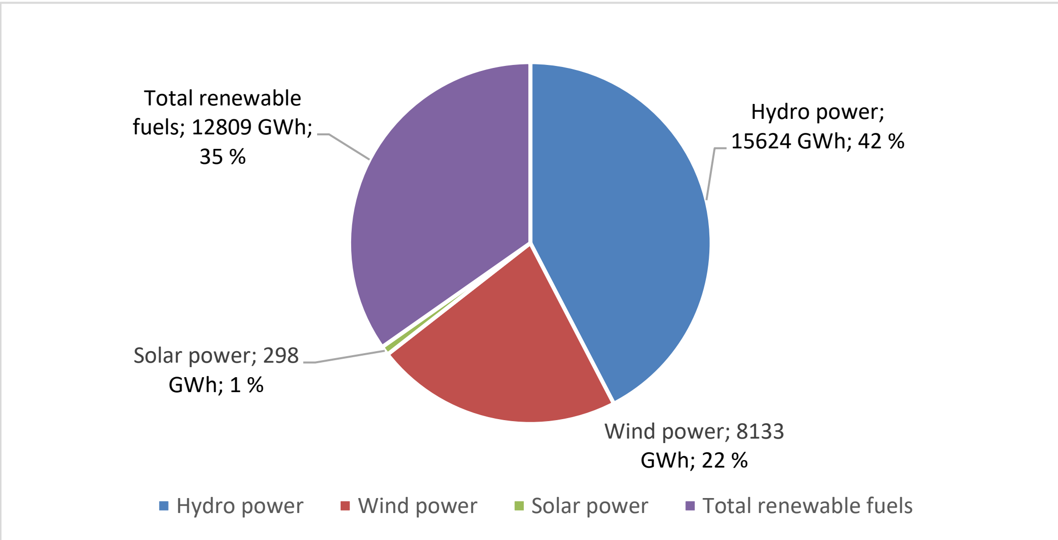


**Figure 3. Electricity by energy source 2021 (GWh) (Statistics Finland, 2022b).**

As can be seen, the capacities of renewable energy sources in 2021 were:

1. Solar power: Although solar energy has rapidly increased its capacity, it is still a relatively small source of renewable energy in Finland. As the figure shows the total installed capacity of solar power in Finland was 298 GWh in 2021. (Statistics Finland, 2022b)
2. Wind power: In 2021, Finland had a total wind power capacity of 8.1 TWh (Statistics Finland, 2022), with 141 wind turbines. A majority of these wind turbines are located in northern Finland. (Finnish Wind Power Association, 2022)
3. Total renewable fuels: In 2021, the second largest share of renewable energy was generated with renewable fuels with a total installed capacity of 12.8 TWh. Renewable fuels include mainly wood-based fuels, the production of which is considerable in Finland. (Statistics Finland, 2022b)
4. Hydropower: The contribution of hydropower varies every year depending on the annual water situation. In 2021, Finland had a total installed hydropower capacity of 15.6 TWh, making it the largest renewable energy source. (Statistics Finland, 2022b)

### 2.3.2 Future potential of renewable energy sources

As mentioned earlier, Finland aims to reach climate neutrality in 2035, and the EU in 2050. This means that the whole energy demand should be covered with environmentally friendly technologies. To achieve the set targets, Finland must make changes in its energy system. This chapter will discuss some of the potential future scenarios. (Roques et al., 2021)

A survey financed by the Finnish Innovation Fund Sitra, *Enabling cost-efficient electrification in Finland*, models the following scenarios for future energy supply in Finland (Roques et al., 2021):

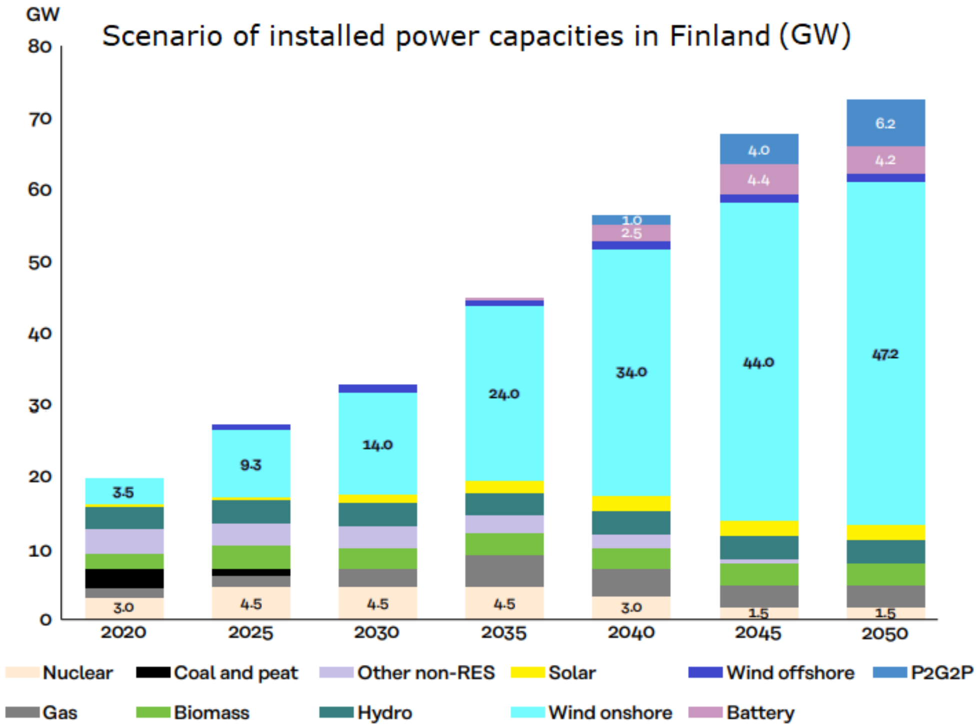


**Figure 4. Installed power capacities in Finland, Direct Electrification Scenario (Roques et al., 2021).**

As the figure shows, Finland's energy demand will grow (more than 20% in 2035, and double in 2050) and at the same time develop towards the carbon neutrality targets. According to the scenario, power generation will mainly be dominated by onshore wind generation support. On the other hand, the rest of the currently available renewable energy sources do not develop much after 2035 and nuclear energy will decrease and eventually lose its importance by 2050 (Roques et al., 2021).

## 2.4 Hydrogen fuel in heavy transport use

Hydrogen is increasingly considered as a potential fuel for heavy transport, such as buses, trucks, and vans. It could be used as a substitute fuel for the currently used fossil-based fuels while using technology that already exists, internal combustion engines (ICE). However, before hydrogen ICE engine-powered heavy transport can be seen on Finnish roads, there are two big issues to tackle: How to manufacture enough green hydrogen for fuel and how to ensure the distribution of hydrogen across the whole country? In short, a proper hydrogen fuel chain is needed to tackle these questions (see Figure 5).

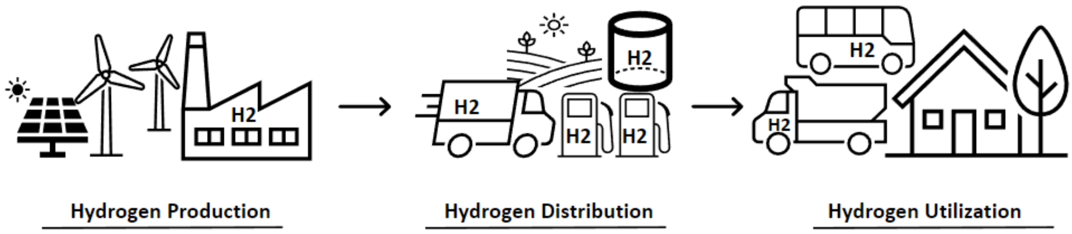


**Figure 5. Simplification of a hydrogen fuel chain.**

### 2.4.1 Heavy transport sector in Finland

As in many European countries, the heavy transport sector in Finland plays an important role in the economy. Because Finland is a country with a significant forest industry, the transport of timber and wood products makes up a major part of this sector. The transport of heavy goods in Finland is primarily carried out by road or rail. For that purpose, Finland has built an extensive road network and at the end of 2019, the total length of highways was 77,925 kilometres. According to the official statistics, the performance of trucks totalled 3,342 million car kilometres in 2019. Another heavy transport sector is bus transport with a performance of 601 million car kilometres in 2019. This makes the traffic performance of all heavy transport in Finland 3, 943 million car kilometres in that year. (Official Statistics of Finland (OSF), 2019)

Transport accounts for 14 per cent of global $CO_2$ emissions and, due to economic growth in developing countries, this share is growing. In 2015, transport accounted for approximately 50 per cent of the total oil end-use. These facts, paralleled with an aspiration for carbon neutrality in Europe, have fuelled conversation on the possibilities to replace fossil-based fuels with renewable alternatives. (Pääkkönen et al., 2019). In the heavy transport sector, this means that the commonly used fuel diesel should be phased out with carbon-neutral options. Hydrogen is considered as one of such options (Wróbel et al., 2022b).

### 2.4.2 Requirements for a hydrogen fuel chain for the transport sector

As pointed out earlier, if the use of hydrogen is to become more common, it requires a proper fuel chain. However, certain preconditions need to be met before the successful introduction of hydrogen:

1. Hydrogen production: The production process should become more efficient, environmentally friendly, and cost-effective in comparison to other energy sources, such as traditional fossil fuels, in order to make its use more common. (Shiva Kumar & Lim, 2022)
2. Storage and transport: Due to hydrogen's light weight and gaseous nature, its storage and transport are one of the main issues to be addressed in the utilisation of hydrogen. The principal storing methods include, for example, compressed hydrogen, liquified hydrogen cryocompressed hydrogen, physically adsorbed hydrogen, metal hydrides, complex hydrides, and liquid organic hydrides. Each of these storing methods has its own implications related to the storing capacity, operating conditions, enthalpy changes, and kinetics of storing and release. Finding the right (safe, reliable, and cost-effective) storage and transport system for each application is challenging and requires further development. (Usman, 2022)
3. Infrastructure: An infrastructure for refuelling stations and a distribution network of hydrogen must be built in order to support the use of hydrogen fuel. This requires investments and effort from policymakers and large companies, demonstrated, for example, in the EU hydrogen strategies. The infrastructure should meet the demand for hydrogen fuel in the future and be accessible to operators. (Kurtz et al., 2019)
4. Safety and regulations: Because hydrogen is a highly reactive gas, safety should be the principal issue in the hydrogen fuel chain. This means that the design of production, transport and distribution systems and the use of hydrogen needs to be safe. (Kurtz et al., 2019) In addition, the users should receive information and training on safe practices. This requires new regulations and standards across

regions and countries to make the global adoption of hydrogen fuel possible. (European Commission, 2020b)

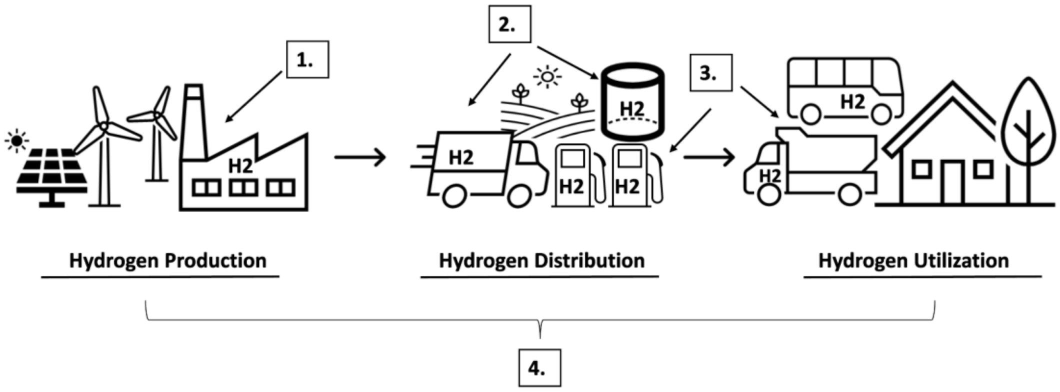


**Figure 6. Visualisation of hydrogen fuel chain requirements.**

Overall, to succeed, the hydrogen fuel chain requires a combination of technological progress, infrastructure investments and regulatory frameworks to ensure the efficient and safe use of hydrogen as a fuel.

### 2.4.3 Production of Green Hydrogen - Electrolyser

The main option for manufacturing green hydrogen is via an electrolyser. The electrolyser is a device that can split water molecules into hydrogen ($H_2$) and oxygen ($O_2$) by using an electric current. This process is called electrolysis and it was discovered in 1800 by Nicholson and Carlisle who first decomposed water with electricity. It is an old innovation that has been in industrial use since 1902. (Zoulias et al., 2004).

An electrolyser consists of an anode and a cathode connected with an external power supply which are inside an electrochemical cell filled with pure water. When the system reaches a certain voltage (critical voltage), the electrodes start forced reduction and oxidation reactions, where the negatively biased electrode or anode starts to produce hydrogen gas and the positively biased electrode or cathode starts to produce oxygen gas. The current passing through this system is directly related to the amount of the produced gases (Zoulias et al., 2004).

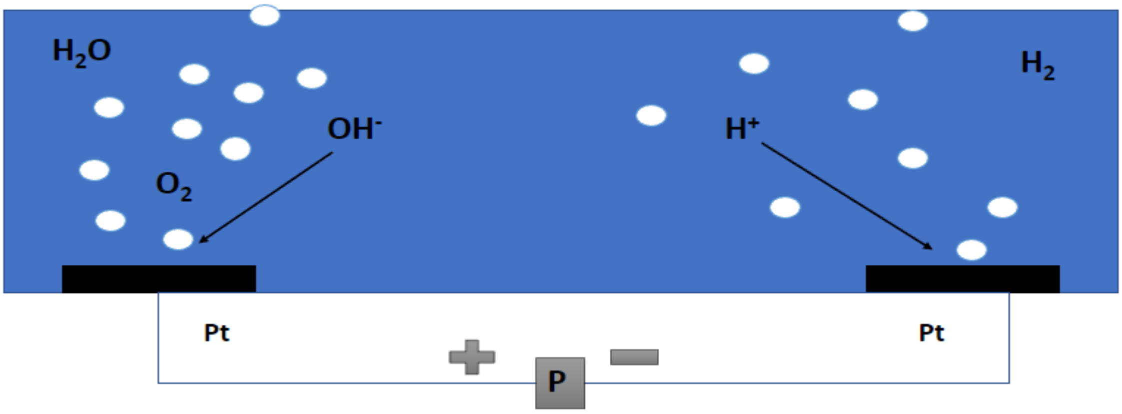


**Figure 7. Sketch of an electrochemical cell (Zoulias et al., 2004).**

Water contains a certain percentage of ionic species $H^+$ and $OH^-$. The quotations of this process can be presented as follows (Zoulias et al., 2004):

$$H_2O\ (l) \leftrightarrow H^+\ (aq) + OH^-\ (aq) \quad (1)$$

Reaction at the anode:

$$4OH- \leftrightarrow 2H_2O + O_2 + 4e^- \quad (2a)$$

Reaction at the cathode:

$$2H+\ (aq) + 2e^- \leftrightarrow H_2\ (g) \quad (2b)$$

The use of electrolysis for hydrogen production has gained increasing attention in recent years because it can be achieved with renewable energy sources. Due to the aspiration to reduce greenhouse gas emissions and promote a more sustainable energy system, green hydrogen will be one of the key factors in the future. Renewable electricity, for example from wind and solar systems, is still expensive, but if the cost continues to decline, it can be expected that the use of electrolysis to produce hydrogen will become more prevalent in the future (Shiva Kumar & Lim, 2022).

### 2.4.4 Electrolyser technologies

Today, there are three major types of water electrolysers: an alkaline water electrolyser (AWE), a proton exchange membrane cell (PEM), and a solid oxide electrolysis cell (SOEC). Here are some basic principles of these techniques (Grigoriev et al., 2020):

The AWE is a well-established and one of the oldest electrolysis technologies. It operates between near ambient temperatures (NAT) and 80°C and the technology involves an alkaline electrolyte solution and potassium hydroxide. As the following table shows, it has high efficiency and durability combined with low cost, which makes it a popular alternative for industrial use. (Zeng & Zhang, 2010).

**Table 2. Techno-economic characteristics of AWE (Grigoiev et al., 2020).**

| | Today | 2030 | Long-term |
|---|---|---|---|
| Electrical efficiency (%, LHV) | 60–70 | 65–71 | 70–80 |
| Operating pressure (bar) | 1–30 | | |
| Operating temperature (°C) | 60–80 | | |
| Stack lifetime (operating hours) | 60,000–90,000 | 90,000–100,000 | 100,000–150,000 |
| Load range (%, relative to nominal load) | 10–110 | | |
| Plant footprint ($m^2/kW_e$) | 0.095 | | |
| CAPEX (USD/$kW_e$) | 500–1,400 | 400–850 | 200–700 |

Notes: LHV = lower heating value; $m^2$/kWe = square meter per kilowatt electrical; CAPEX represents system costs, including power electronics, gas conditioning and balance of plant; CAPEX ranges reflect different system sizes and uncertainties in future estimates.

The PEM also operates between the NAT temperatures and 80°C and it uses an electrolyte membrane based on polyfluorosulfonic acid materials to separate the hydrogen and oxygen gases produced during the electrolysis. The PEM has also a faster response time, which makes it a popular option for hydrogen fuel cell applications (Ayers, 2019). More details are presented in Table 3.

**Table 3. Techno-economic characteristics of PEM (Grigoriev et al., 2020).**

| | Today | 2030 | Long-term |
|---|---|---|---|
| Electrical efficiency (%, LHV) | 56–60 | 63–68 | 67–74 |
| Operating pressure (bar) | 30–80 | | |
| Operating temperature (°C) | 50–80 | | |
| Stack lifetime (operating hours) | 30,000–90,000 | 60,000–90,000 | 100,000–150,000 |
| Load range (%, relative to nominal load) | 0–160 | | |
| Plant footprint ($m^2/kW_e$) | 0.048 | | |
| CAPEX ($USD/kW_e$) | 1,100–1,800 | 650–1,500 | 200–900 |

Notes: LHV = lower heating value; $m^2/kWe$ = square meter per kilowatt electrical; CAPEX represents system costs, including power electronics, gas conditioning and balance of plant; CAPEX ranges reflect different system sizes and uncertainties in future estimates.

The SOEC is a high-temperature electrolysis technology that operates between 650 and 1000°C. It uses solid ceramic oxides such as stabilized zirconia, doped ceria, doped $LaGa_3$, and bismuth oxide as an electrolyte material with, for example, metal, fluorite, and perovskite-related oxides as cathode material to split water molecules. Due to the high temperatures, it is a highly efficient technology, which can produce high-purity hydrogen. However, the technology is still in the development phase, and there are challenges with performance degradation and high costs (Song et al., 2019). See Table 4.

**Table 4. Techno-economic characteristics of SOEC (Grigoriev et al., 2020).**

| | Today | 2030 | Long-term |
|---|---|---|---|
| Electrical efficiency (%, LHV) | 74–60 | 77–84 | 77–90 |
| Operating pressure (bar) | 1 | | |
| Operating temperature (°C) | 650–1,000 | | |
| Stack lifetime (operating hours) | 10,000–30,000 | 40,000–60,000 | 750,000–100,000 |
| Load range (%, relative to nominal load) | 20–100 | | |
| Plant footprint ($m^2/kW_e$) | - | | |
| CAPEX ($USD/kW_e$) | 2,800–5,600 | 800–5,600 | 500–1,000 |

Notes: LHV = lower heating value; $m^2$/kWe = square meter per kilowatt electrical; CAPEX represents system costs, including power electronics, gas conditioning and balance of plant; CAPEX ranges reflect different system sizes and uncertainties in future estimates.

As can be concluded from Tables 2–4, these technologies still face major challenges relating to the cost, management, safety, and electrical efficiency of production. Further development is needed to meet the challenges, but, in the future, these technologies will have a place in a sustainable energy system. (Grigoriev et al., 2020).

### 2.4.5 Hydrogen internal combustion engine vehicle

The internal combustion engine (ICE) is a type of heat engine that converts fuel combustion energy into mechanical work. It is an old engine type widely used in various modes of transport to power vehicles ranging from motorcycles, automobiles, buses and trucks to boats and light aircraft. The basic idea of an ICE engine is to burn an air-fuel mixture inside a combustion chamber creating high pressure and temperature, which pushes a piston, or a series of pistons, converting the pressure into mechanical motion. This linear mechanical motion of pistons is converted into rotary motion by a crankshaft. This rotary motion can then be used to power wheels, propellers, and any other mechanical devices. (Indd, 2018). Figure 8 shows an illustration of a basic ICE engine.

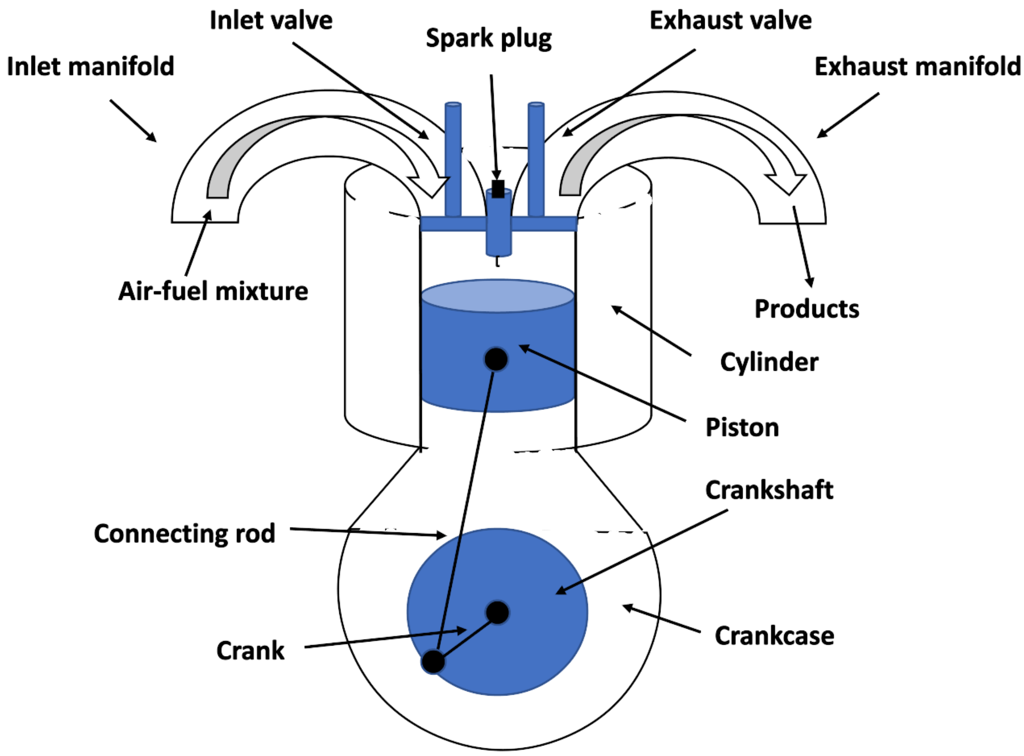


**Figure 8. Picture of basic ICE engine (Indd, 2018).**

There are several types of ICE engines, but the two most common ones are spark-ignition (SI) engines (gasoline engines) and compression-ignition (CI) engines (diesel engines). SI engines use a spark plug to ignite the air-fuel mixture in the combustion chamber while CI engines compress the air-fuel mixture until it reaches a high pressure and temperature, which causes spontaneous ignition. The spontaneous ignition demands high energy density, which, for example, diesel and hydrogen-based fuels have. In the heavy transport field, CI engines are the most used option, due to their suitable features like torque and lower consumption (Indd, 2018).

A hydrogen internal combustion engine is basically a CI engine that uses hydrogen as its fuel source. Over the past few years, a hydrogen ICE engine has gained increased interest in the discussions on ways to reduce greenhouse gas emissions in transport. The heavy transport sector, in particular, considers it as a viable option because it has a good power-weight ratio and a longer range compared to electric or hydrogen fuel cell engines as the two latter mentioned engine types require heavy batteries to function. This reduces the total carrying capacity, which is one of the most important prerequisites in heavy transport. This is a problem not encountered with hydrogen ICE engines (Wróbel et al., 2022b).

# 3 GREEN HYDROGEN AS A FUEL IN THE HEAVY TRANSPORT SECTOR

When the previously mentioned difficulties in the use of hydrogen have been resolved, hydrogen can be considered as a potential fuel for heavy transport. It can be used in familiar engine types in heavy transport ICEs, it provides a longer range for heavy vehicles compared to battery-electric vehicles and, most importantly, it can be implemented with zero emissions. (Boretti, 2020).

This chapter examines the possible benefits of replacing diesel with hydrogen in the heavy transport sector, and the ensuing requirements to achieve this in Finland. To answer these questions, it is first necessary to establish the current energy consumption of the heavy transport sector in Finland. The next step is to calculate the amount of green hydrogen that would need to be produced to cover this demand. This will enable the assessment of the amount of renewable electricity required for hydrogen production and the feasibility of its practical generation.

### 3.1.1 Consumption of a hydrogen-fuelled vehicle compared to a conventional diesel engine

The consumption of any vehicle depends on several factors, namely the vehicle's size, weight and engine efficiency, the driving conditions and carried load. The current thesis will provide a general view of the matter (Boretti, 2020). Table 5 shows the basic parameters of a conventional diesel vehicle, a hydrogen combustion vehicle and a vehicle powered by a fuel cell.

As can be seen, hydrogen internal combustion engine vehicles show both a high efficiency of the propulsion system and low emissions compared to conventional diesel engines.

$$\frac{Ch}{Cd} * 100 = \frac{1{,}4\ kg/100km}{5{,}04\ kg/100km} * 100 = 28\% \qquad (3)$$

where Ch is hydrogen consumption [kg/100km]

Cd is diesel consumption [kg/100km]

**Table 5. Comparison of the basic parameters of conventional diesel engine vehicles, hydrogen ICE vehicles and hydrogen fuel cell vehicles (Albatayneh et al., 2020; Ntziachristos et al., 2014; Wróbel et al., 2022c).**

| | Diesel Vehicle | Hydrogen Combustion Vehicle | Hydrogen Fuel Cell Vehicle |
|---|---|---|---|
| Engine type | internal combustion engine | internal combustion engine | electric motor |
| Efficiency of the propulsion system | ~25–37% | ~40–50% | ~45–55% |
| Fuel consumption * | approx. 6 l or 5.04kg of diesel/100km | approx. 1.4 kg of hydrogen/100km | approx. 1.0 kg of hydrogen/100km |
| Cost of fuel ** | Currently low (~0.1) | Currently high (~0.9) | Currently very high (1.0) |
| Air pollution emissions | high $CO_2$, CO, unburned hydrocarbons, and $NO_x$ emissions | minimal/ very low $CO_2$ emissions, the same or up to 20% higher $NO_x$ emissions compared to gasoline vehicles | minimal / zero $CO_2$ and $NO_x$ emissions |
| State of technology | developed (widely used all over the world) | developed and in diffusion stage (experimental vehicle series) | developed and in diffusion stage (experimental vehicle series) |

*For vehicles with an engine power of 110-150 horsepower

**In parentheses*:* *a*pproximate ratio of fuel prices per unit of mass, data for 2022

In comparison, the consumption of a hydrogen ICE engine is only approximately 28 per cent of the diesel engine's consumption with only minor greenhouse gas emissions as the main product is water. These findings, accompanied by the potential for long distances, make it a competitive option to traditional combustion engines or even for electric-powered vehicles. This is because, in the heavy transport sector, electric-powered vehicles have problems relating to their lower range and poor carrying capacity due to their limited performance and the weight of the batteries. (Boretti, 2020)

## 3.2 Supplying the whole truck fleet with hydrogen in Finland

This chapter will provide an estimate of the required amount of hydrogen to meet the demand of the whole heavy transport sector in Finland. First, it is necessary to establish the amount of hydrogen consumed by one internal combustion engine in heavy transport use. This will be followed by an estimate of the hydrogen demand in the heavy transport sector in Finland as a whole. The calculations are based on the data published by Statistics Finland on vehicle traffic performances and the consumption of a Cummins B6.7H hydrogen ICE engine.

In September 2020, a study published by Cummins Inc. showed that a 6.7-litre hydrogen internal combustion engine could serve as a zero-emission substitute for diesel engines in truck applications across the 10-to-26-ton gross vehicle weight. It performed up to 290hp (216kW) and reached 1200 Nm peak torque. The study promised a potential range of 500 km with a total capacity of approximately 50 kg hydrogen including 10 kg in an auxiliary tank. Based on the study's data, the consumption was approximately 10kg of hydrogen per 100 km (Cummins Inc., 2022):

$$50 \text{ kg}/500 \text{ km} = 10 \text{ kg}/100 \text{ km} \tag{4}$$

The following template (Table 6), published by Statistics Finland, shows traffic performances, in million kilometres (mil. km/a) in 2016–2021:

**Table 6. Template of traffic performances of transport in Finland (Statistics Finland, 2022a).**

| Year | Total mileage | Passenger cars | Vans | Trucks | Buses |
|---|---|---|---|---|---|
| 2017 | 50,225 | 40,614 | 5,611 | 3,370 | 630 |
| 2018 | 50,436 | 40,718 | 5,693 | 3,411 | 614 |
| 2019 | 50,387 | 40,718 | 5,726 | 3,342 | 601 |
| 2020 | 48,543 | 39,092 | 5,667 | 3,261 | 523 |
| 2021 | 48,305 | 38,771 | 5,777 | 3,296 | 461 |
| Average: | 49,579.2 | 39,982.6 | 5,694,8 | 3,336 | 565.8 |

As the above table shows, the average mileage of heavy transport trucks is 3,336 million kilometres per year.

The annual hydrogen need of the heavy transport sector can be calculated from this data as follows:

$$3{,}336 \text{ mil. km/a} * 10 \text{ kg/100 km} = 333{,}600{,}000 \text{ kg/a} = 333{,}600 \text{ t/a} \approx 350{,}000 \text{ t/a} \quad (6)$$

As the calculations show, the annual hydrogen need of the heavy transport sector would be approximately 350,000 t.

## 3.3 Generation of green hydrogen to satisfy the demand for heavy transport

According to a publication by the Ministry of Economic Affairs and Employment, in 2022 hydrogen production in Finland was between 140,000 and 150,000 tons (4.7 and 5.0 TWh). Approximately 99 per cent of the hydrogen was produced with fossil fuels, mainly natural gas. According to the Ministry’s calculations, if this hydrogen had been produced with electrolysis it would have required more than 7 TWh of electricity. This means that, currently, only approximately 40 per cent of the possible hydrogen energy demand (350,000 t) of the heavy transport sector could be covered, mainly with grey or blue hydrogen.

$$\frac{140{,}00\ t}{350{,}000\ t} * 100 = 40\% \qquad (8)$$

This means that, practically, Finland needs to start from zero in the installation of new renewable hydrogen electrolysers to fulfil the estimated demand. (Ministry of Economic Affairs and Employment, 2022)

As previously calculated, the hypothetical demand for hydrogen in the heavy transport sector would be 350,000 tons of hydrogen per year. According to the Ministry of Economic Affairs and Employment, more than 17.5 TWh of electricity would be needed for the production of hydrogen each year to satisfy this demand (Ministry of Economic Affairs and Employment of Finland, 2022):

$$\frac{7\ TWh}{140{,}000\ t/a} * 350{,}000\ t/a = 17{,}5\ \text{TWh} \qquad (9)$$

As mentioned earlier, Finland's renewable electricity capacity was 36.9 TWh in 2021. With this amount of green electricity, it would be theoretically possible to cover the demand for the electricity needed to produce green hydrogen for heavy transport use. However, in practice, this cannot be achieved because Finland's total electricity need, without renewable hydrogen production, totalled 69.3 TWh in 2021 (Statistics Finland, 2022b). And even if this electricity could be used for hydrogen production, heavy transport is not the only sector where hydrogen is needed, so the demand would be much larger. As the goal is to cover this future demand for hydrogen with green hydrogen, Finland needs to scale up its production of both renewable hydrogen and energy. This means investments in new electrolysers and renewable energy plants. To that end, Finland has allocated EUR 156 million to demonstration projects and innovation in the hydrogen field. Currently, some 20 hydrogen projects are in the planning phase. (Ministry of Economic Affairs and Employment, 2022)

## 3.4 Future development

Sitra's survey assessed two different scenarios of hydrogen production. In the first scenario, it was predicted that growth in wind power production of electricity could yield 34 TWh of electricity into electrolysers in 2050. The second scenario, a PtX scenario, was based on the hydrogen economy and predicted that the produced volumes could reach 60 TWh (Roques et al., 2021). In addition, according to the Ministry of Economic Affairs and Employment, green hydrogen production will be promoted in Finland and the target is to raise electrolysis production from 9 MW (2021) at least up to 200 MW in 2025, and at least up to 1000 MW in 2030, while observing the commercialisation and demand of the hydrogen sector. Furthermore, future technological development may enable even greater hydrogen production (Ministry of Economic Affairs and Employment of Finland, 2022).

As mentioned, electrolyser technologies are still under development and will considerably improve in the future. Table 7 shows a comparison of electrolyser technologies electrical efficiency development. With this information, it is possible to calculate the estimated renewable energy need for producing 350 000 t of green hydrogen for heavy transport use in the future.

**Table 7. Comparison of electrical efficiency of different electrolyser technologies (%, LHV) (Grigoriev et al., 2020).**

| Electrolyser technology | Today | 2030 | Long-term |
|---|---|---|---|
| AWE | 60–70 | 65–71 | 70–80 |
| PEM | 56–60 | 63–68 | 67–74 |
| SOEC | 74–60 | 77–84 | 77–90 |
| Average improvement | 0 | 8 | 12,5 |

As can be seen, the average electricity efficiency improvement in electrolyser technologies in the long term would be approximately 12,5%. This means that if now the electricity demand for producing 350 000 t of hydrogen would require 17.5 TWh of renewable electricity, only 15.3 TWh would be needed in the future.

$$\frac{12{,}5\%}{100} * 17{,}5\ TWh = 0{,}125 * 17{,}5\ TWh = 2{,}1875\ TWh \tag{10}$$

$$17{,}5\ \text{TWh} - 2{,}1875\ \text{TWh} = 15{,}3125\ \text{TWh} \approx 15{,}3\ \text{TWh} \tag{11}$$

# 4 SUMMARY AND CONCLUSION

Hydrogen is a highly reactive and versatile energy carrier that can be used in many applications. Green hydrogen, produced by electrolysis using electricity from renewable energy sources, is a promising solution for decarbonising various sectors but its production requires a lot of energy. Green hydrogen fuel can be used as a zero-emission alternative to traditional fossil fuel engines in heavy transport such as trucks and public transport.

The European Union and Finland have published comprehensive hydrogen strategies to establish a hydrogen economy based on the production, distribution, and use of renewable green hydrogen as part of the measures to achieve carbon neutrality, in the EU in 2050 and in Finland in 2035. To achieve this goal, Finland has set up a series of new policies aimed at increasing hydrogen production, developing a hydrogen infrastructure, supporting research and development, and encouraging the use of hydrogen in different fields such as transport.

This thesis aimed to introduce the potential of green hydrogen fuel in the heavy transport sector and demonstrate the possibilities of utilising it for this use. It also discussed the preconditions for this utilisation and answered the following research question: How much hydrogen would be needed to supply the whole truck fleet in Finland? How much electricity generated by renewable energy sources would be needed to satisfy the demand of hydrogen for the heavy transportation sector? And could this be achieved with the current generation capacity? Considering the future potential, can the demand be satisfied with the planned capacity?

To be able to use hydrogen as fuel in the heavy transport sector, it is necessary to establish a proper hydrogen fuel chain that addresses issues relating to the production, storage, and transport of hydrogen as well as issues relating to the necessary infrastructure and the ensuing safety and regulation responsibilities. The efficient and safe use of hydrogen calls for a combination of technological progress, infrastructure investments and regulatory framework. When these requirements have been met, green hydrogen can be considered a potential fuel for the heavy transport sector due to its efficiency, long range and zero emissions.

According to calculated calculations, the amount of hydrogen needed to supply the entire heavy transport sector in Finland would be 350,000 tons annually. To produce this amount of green hydrogen, the need for renewable electricity would be 17.5 TWh per year. Currently, most of the hydrogen produced in Finland is generated from fossil fuels, and if this demand were to be met with electrolysis and green hydrogen, it would require significant investments in renewable energy plants based on, for example, wind power and electrolysis technology. According to the thesis, the electrical efficiency of electrolysers will, however, improve by around 12.5% in the future. This means that the annual electricity needed for green hydrogen production would decrease to 15.3 TWh.

These calculations are however only estimates and give a very ambiguous picture of the possible need for green hydrogen. As said, technologies are still developing, and it is hard to predict what the future potential of these technologies would be and how the energy distribution is allocated to different energy carriers in the future. Only when the technologies become established, it is possible to calculate the accurate assessments of the need for hydrogen fuel and based on that the need for renewable electricity.

After all, the objective of the Finnish Ministry of Economic Affairs and Employment is to raise electrolysis production by at least up to 1000 MW in 2030. This would not be enough to cover the heavy transport sector’s 17.5 TWh electricity need. However, scenarios of the future energy supply in Finland suggest an increase in renewable energy production through onshore wind generation, predicting that the future electricity supply to electrolysers could even be 34 TWh. By the year 2050, the hydrogen production volumes could reach as much as 60 TWh.

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