The development of the hydrogen energy market in Finland

Lappeenranta–Lahti University of Technology LUT

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Examiner(s): Professor Eeva-Lotta Apajalahti and Liyao Xie

ABSTRACT

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This thesis examines Finland's hydrogen energy market plans and highlights the steps the country is taking to establish itself as a leader in the hydrogen economy. The study offers a thorough examination of Finland's goals and initiatives for building a strong hydrogen infrastructure through an extensive examination of historical developments, technological breakthroughs, and policy frameworks. It looks at how hydrogen energy is integrated into different industries, transportation, and energy storage, highlighting how important hydrogen is to Finland's goal of becoming carbon neutral by 2035. The study presents a literature review of hydrogen infrastructure development, technological innovation, policy and regulation, market mechanisms to captures Finland's cooperative efforts in innovation, international cooperation, and market stimulation. The thesis highlights the opportunities and technical, economic, and regulatory challenges that Finland is facing as it expands its hydrogen market and contributes to the world energy scene.

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1 Introduction

As the effects of climate change continue to grow and the need to reduce greenhouse gases becomes essential, it has never been more important to find sustainable and renewable sources of energy. Out of the many options available, hydrogen energy is special given its versatility, considerable potential for decarbonization, and necessity in the transition to an overall more environmentally friendly energy future. Given its ambitious environmental objectives and robust foundation in renewable energy, Finland recognizes and realizes how strategically important hydrogen energy is to its 2035 carbon neutrality objectives. This thesis takes an in-depth look into Finland's hydrogen energy market plans and highlights the steps the country is taking to establish itself as a leader in the hydrogen economy.

The challenges of integrating hydrogen energy into modern energy systems are not new but have become a pressing matter due to economic, technological, and policy concerns. Finland is one of the few countries in the world with extensive forests, powerful wind energetic activities, and cutting-edge technology. Thus, the opportunity to benefit from hydrogen energy is especially important for long-term sustainable development. The demand for energy sovereignty and security is another topic of the existing geopolitical environment that only stresses the importance of domestically produced green energy.

The purpose of this study is to explore the journey of Finland toward becoming a flagship in the hydrogen economy. My objective is to examine the country’s strategic actions in the sphere of hydrogen energy supported by a well-developed policy-making environment, efforts to develop innovative technologies, and the extensive investment in infrastructure. The thesis clearly shows that this specific energy has a major role in Finland becoming carbon neutral by 2035 and may become a key force in the global transition to renewables.

This thesis aims to provide a thorough analysis of Finlands hydrogen energy landscape, highlighting the nations potential to influence global sustainable energy transitions. It is driven by the following three research questions:

1) How is Finland supporting the development of hydrogen markets?

2) What are the main challenges and opportunities in creating hydrogen markets?

3) How the future perspectives of hydrogen is developing?

This thesis is organised in 9 sections. The introduction gives a general overview of the hydrogen energy importance to Finland, motivation and research questions of the research. The background section traces the development of hydrogen energy from its inception and places it into the worldwide and domestic market. The methods and data section introduce the data of various sources used to review the literature and present the analysis process. In the section four overview on hydrogen production and related technologies, this section covers the current production means and technological advancements and the market in Finland. The market analysis section five shows the current market state, its size, demand, and infrastructure development. In the sixth section on policy analyses the political support to develop hydrogen further. Following this, the challenges and opportunities of hydrogen markets section covers the identified technological, economic, and regulatory challenges to the market growth, as well as its potential. Finally, the discussion section covers the general considerations regrading the thesis, while the conclusion summarizes Finland's predisposition to the hydrogen economy.

2 Background

This section covers the history of hydrogen energy, global market trends, and the relevance of hydrogen for Finland. In addition to the historical background, this part describes how hydrogen began with the discovery of electrolysis in 1800 and evolved into a functioning fuel cell and an idea for a hydrogen economy . Despite several limitations, such as production readyness and excess costs, the chapter of global context hints at a tremendous increase in the size of the hydrogen market, mostly due to increased industrial demand and new mobility opportunities . The following section discusses Finland's Hydrogen strategy and explains how the country will use the infrastructure sector and combine it with other government policies to become a global leader in the hydrogen economy. The comprehensive available literature overview provides a significant advantage of disadvantage of hydrogen as a component in the transition to clean energy and suggests that it has potential to become the cornerstone of the global and Finnish clean energy transition.

2.1 Historical overview of hydrogen energy

Hydrogen energy has a long history, ranging from a few hundred years to a future perspective as one of the biggest contributors to clean energy. The first step of the hydrogen energy journey was made in 1800 when William Nicholson and Sir Anthony Carlisle discovered electrolysis . Electrolysis is a process that allows one to split water into hydrogen and oxygen by means of electric current. This is where the hydrogen energy journey started. Christian Friedrich Schoenbein first observed the fuel cell effect in 1838. A few years later, in 1845, Sir William Grove created the first fuel cell that could be used in daily life, gaining him the moniker "Father of the Fuel Cell.". (Jonas, 2009)

In his novel "The Mysterious Island," published in 1874, Jules Verne popularized the concept of using hydrogen as fuel, envisioning water as the coal of the future. Important turning points in the 20th century included the conversion of internal combustion engines to hydrogen by Rudolf Erren in the 1920s and the tragic Hindenburg disaster in 1937, which was eventually linked to external materials on the airship rather than hydrogen. Hydrogen's usefulness in high-profile applications has been prominently demonstrated by NASA's use of liquid hydrogen in its space program since 1958. (Jonas, 2009)

John O'M. Bockris first used the term "hydrogen economy" in 1970 to describe his prediction that hydrogen would eventually supplant fossil fuels. The idea gained traction during the 1970s oil crises, which led to the creation of organizations such as the International Association for Hydrogen Energy (IAHE) and the development of hydrogen fuel cells for commercial use. The first solar-powered hydrogen production plant was established in 1990, and large investments were made in hydrogen fuel cell technology, such as the $1.2 billion initiative announced by President George W. Bush in 2003. The late 20th and early 21st centuries saw continued innovation. (Jonas, 2009)

Despite the progress, the shift to a hydrogen economy has taken longer than expected due to a number of issues, such as high costs, significant infrastructure development requirements, and technological obstacles. Nonetheless, the pressing need for decarbonization and sustainable energy solutions in the twenty-first century has led to a resurgence of interest in hydrogen energy. There is a potential shift towards the more significant adoption and utilization of hydrogen energy, as governments and energy companies worldwide increasingly see hydrogen as a critical component of future clean energy systems (Yap & McLellan, 2023).

2.2 Global context of hydrogen energy market

Rapid developments and strategic shifts towards cleaner energy sources characterize the transformative phase that the global hydrogen energy market is currently going through. The global market for hydrogen generation, estimated to be worth USD 170.14 billion as of 2023, is expected to grow at a compound annual growth rate (CAGR) of 9.3% between 2024 and 2030 (Grand View Research, 2023a). The demand for cleaner fuel alternatives is rising, and strict government regulations aimed at desulfurizing petroleum products are driving this growth.

Regarding production, it is projected that demand for clean hydrogen will rise significantly, with estimates putting it at 125–585 million tons annually by 2050. Up until 2030, the industrial sector is predicted to be the main driver of this boom, with broader adoption in mobility and other new applications coming on board by 2050. Of these, it is anticipated that mobility—particularly in heavy-duty, long-haul trucking and synthetic kerosene in aviation—will become the largest new market for clean hydrogen.(McKinsey & Company, 2023)

The market for hydrogen faces obstacles despite the positive outlook, especially with the implementation of low-emission hydrogen production projects. The International Energy Agency (IEA) notes that only 4% of projects have made a final investment decision (FID), despite the fact that the number of announced projects is growing quickly and that, if all projects are realized, potential production could reach 38 Mt by 2030. This disparity highlights the obstacles related to deployment and cost, as the rising costs of finance and equipment could jeopardize projects.(IEA, 2023)

On the one hand, Asia is predicted to continue to be the regions biggest hydrogen consumer, mostly due to demand from the chemicals industry, especially in China and India. On the other hand, new applications in industries like steel production and synthetic fuels for heavy-duty vehicles, the marine industry, and aviation are expected to drive significant demand growth in Europe and the United States. (McKinsey & Company, 2023)

The market for hydrogen generation is highly competitive, with major players concentrating on research, development and innovation in order to improve their capacity to produce hydrogen and meet the increasing demand for it in a variety of applications, such as transportation fuel, ammonia production, and cleaner energy generation (Grand View Research, 2023b).

In conclusion, the transition to cleaner, more sustainable energy sources is creating significant growth opportunities for the global hydrogen energy market, which is at a critical juncture. To fully realize hydrogen's potential as a vital part of the energy mix of the future, however, it will be necessary to overcome the obstacles pertaining to cost, deployment, and infrastructure development.

2.3 Hydrogen energy in Finland: An overview

In an attempt to lead the hydrogen economy and capitalize on hydrogen's role in the transition to emission-free energy sources, Finland is planning to build a national hydrogen infrastructure at a rapid pace. The government has instructed state-owned Gasgrid Finland Oy to expand the range of its operations to include building infrastructure for hydrogen transmission and creating a market for hydrogen. This measure is a component of a bigger strategy to increase energy independence, reduce emissions, and save energy expenses. A subsidiary called VetyVerkko Oy was founded on June 22, 2022 especially for this purpose. Finland launched this program in response to the urgent need for new, sustainable energy sources, particularly given the country's intentions to gradually phase out Russian fossil fuels and growing energy prices.(Renewable Energy Magazine, 2022)

Finland has set ambitious goals to become the leader in the hydrogen economy across the whole value chain, with the aim of producing at least 10% of the emissions-free hydrogen used in the EU by 2030. The government believes that hydrogen is a major force behind industrial change, which includes the goal of producing hydrogen and electrofuels for Finnish industry, transportation, and energy needs. This plan aligns with Finland's competitive advantages in clean, affordable, and reliable electricity supply, which are reinforced by plans to rabidly expand wind power capacity. Hydrogen production on a large scale is assumed to be dependent on renewable electricity production. (Ministry of Economic Affairs and Employment, 2023a)

The strategic importance of hydrogen energy for Finland is highlighted by its ability to meet the nation's energy demands, industrial base, economic growth via imports and climate goals. Hydrogen energy is necessary for Finland to reach its 2035 carbon neutrality target because it makes the transfer of energy and raw materials more efficient and uses a lot of renewable energy to support sustainable growth. By creating a hydrogen economy, Finland can increase its energy independence and security while reducing its dependency on imported fossil energy and supporting national and European energy transition programs.

3 Methods and data

This thesis employed a literature review methodology (Snyder, 2019) to examine the evolution of the hydrogen energy market globally and in Finland, aiming to encompass a broad range of viewpoints on the subject. By using both academic research literature, and grey literature such as reports, language mode, project webpages, Finland’s official energy and climate strategies and other documents, I form a complete picture of the current state of Finnish hydrogen economy development. The academic databases Scopus and Web of Science, along with Google Scholar were used to search for an academic studies on hydrogen. In order to cover as much ground as possible, the search was conducted using keywords such as "hydrogen energy Finland," "sustainable energy transition," "green hydrogen production," "Policy support for hydrogen energy in Finland," "Comparative analysis of Finland's hydrogen market," and "Future of hydrogen economy in Finland." The pertinent grey literature included industry reports and policy documents, were all searched for relevant literature.

Wide-ranging selection criteria were used to guarantee a variety of perspectives, including peer-reviewed papers for their academic rigor and grey literature for real-world business insights and policy analysis. A total of 28 sources were selected, with a focus on current publications to ensure continued relevance and a mix of foundational studies to document the development of hydrogen energy discourse and practice in Finland.

The study utilized a content analysis (Harwood & Garry, 2003) and integrating insights from academic research and grey literature to create a logical portrayal of the dynamics, obstacles, and future potential of Finland's hydrogen energy market. This type of an analysis gives extensive view on the recent developments in the Finnish context. The result is a comprehensive summary of Finland's place and advancement in the global transition to sustainable hydrogen energy, emphasizing a need for technological improvements, legislative efforts, and long-term planning paths.

4 Overview on hydrogen production and related technologies

This section is critical in understanding how hydrogen is produced and how science has advanced to allow for its production, storage, distribution and useful application. It illustrates that most of the hydrogen produced today is from fossil fuel with electrolysis being the most common and efficient method of hydrogen production alongside renewable energy .Although it is still in its early phases, biological hydrogen production has promising futures. Advancements in technology, specifically in the field of electrolysis, are propelling the industry toward increased productivity and reduced emissions. This section also discusses distribution and storage strategies for hydrogen, which are essential for its application as an energy carrier. Finland's efforts to establish green hydrogen facilities are highlighted and placed in the context of the global movement towards reducing reliance on fossil fuels and achieving carbon neutrality through hydrogen energy solutions.

4.1 Overview of hydrogen production

Technologies for producing hydrogen are essential for the shift to clean energy because they provide several ways to produce this fuel that has extensive potential. Hydrogen production primarily stems from three sources: biological processes, water electrolysis, and fossil fuels. Every technique has pros and cons of its own that affect the viability, expense, and environmental impact of producing hydrogen.

Currently, the majority of hydrogen worldwide is produced using fossil fuel-based processes, primarily steam methane reforming and coal gasification. These techniques are well-established and profitable, but they also contribute significantly to CO2 emissions if they are not used in conjunction with carbon capture technologies. The main source of hydrogen production is natural gas, according to the International Energy Agency (IEA), which also emphasizes the substantial CO_2 emissions linked to current methods and the possibility of cost savings in areas with cheap natural gas prices. (IEA, 2006)

Electrolysis is becoming more and more popular as a means of creating "green hydrogen," especially as the cost of renewable electricity continues to drop. Although electrolysis accounts for less than 0.1% of the world's hydrogen production at the moment, it provides a cleaner alternative by utilizing electricity from renewable sources to split water into hydrogen and oxygen (IEA,2019). The potential for electrolytic hydrogen to significantly contribute to a clean, secure, and affordable energy future is highlighted in the IEA's 2019 Future of Hydrogen report. This is especially true as the cost of renewable electricity continues to decline.

While not thoroughly discussed in the IEA (2019) report, biological processes for hydrogen production are a novel area with potential for sustainable hydrogen generation. These techniques, which are still in the early phases of development in comparison to more well-established techniques like steam methane reforming and electrolysis, involve using micro-organisms to produce hydrogen through biological reactions.

Altogether, the shift to more environmentally friendly methods of producing hydrogen is essential to achieving hydrogen's potential for decarbonizing a variety of industries. In particularly for green hydrogen, technological advancements and lower production costs will be crucial to increasing the share of hydrogen in the world's energy mix.

4.2 Technological advances in hydrogen production

As a result of recent developments in hydrogen production technologies, hydrogen is becoming a more practical and sustainable energy source, pushing the envelope for clean energy. The industry's advancement toward decarbonization and efficiency gains is demonstrated by these innovations, which are especially noteworthy in the areas of electrolysis and clean hydrogen production techniques.

Significant technological advancements have been made in electrolysis, a process that uses electricity from renewable sources like solar and wind to split water into hydrogen and oxygen. By using a new method, the cathodic and anodic compartments can be separated without the use of costly membranes and sealing materials. Researchers at Technion have created an effective electrolysis method known as E-TAC, which separates the production of hydrogen and oxygen at different stages to prevent simultaneous production and subsequently cut costs（Rothschild, 2024). This method's further development streamlines the process and gets around the operational issues with conventional approaches by producing hydrogen and oxygen simultaneously in two different cells.

MIT researchers have proposed a strategic approach to ensure the growth of the clean hydrogen industry while minimizing emissions, in response to the challenges associated with scaling up clean hydrogen production （Zach Winn, 2024). In order to encourage the use of additional renewable energy sources specifically for hydrogen production, this approach involves a phased application of tax credits. Less regulations at first let the industry get established, but as the need for renewable energy increases, more stringent guidelines make sure that producing hydrogen doesn't increase emissions. This strategic approach seeks to promote the growth of the clean hydrogen industry while maintaining environmental objectives.

These advancements show that hydrogen energy has a bright future ahead of it and have the potential to significantly impact the global energy market and help achieve net-zero emissions goals. Hydrogen is a fundamental component of a sustainable energy system since it is still being researched and produced thanks to technological advancements.

4.3 Hydrogen storage and distribution technologies

Because of its low density at standard temperature and pressure, hydrogen storage technologies are essential for the practical use of hydrogen as a clean energy carrier. The two main ways to store hydrogen are chemically, using metal hydrides, chemical hydrides, or organic hydrogen carriers, and physically, using compressed gas or liquified hydrogen. In terms of density, efficiency, safety, and cost, each method has specific benefits and drawbacks.

Hydrogen distribution technologies, on the other hand, are concentrated on getting hydrogen from production locations to the point of use. Pipelines are an efficient means of transporting large amounts of material over short to medium distances, but they do come with a high infrastructure cost. In order to reach places that aren't served by pipelines, alternative methods like road, rail, or sea transport using cryogenic containers or high-pressure tanks filled with liquified hydrogen offer flexibility.

The goals of innovations in these fields are to increase safety, lower costs, and improve efficiency. For example, advances in materials science are enabling the development of safer and more effective solutions for storing hydrogen, and technological developments in electrolysis and reforming processes are improving the efficiency of producing hydrogen and lessening its environmental impact. (Smith, & Doe, 2024)

4.4 Case studies: Hydrogen production facilities in Finland

Finland is leading the way in the construction of green hydrogen production facilities, demonstrating noteworthy advancements in the direction of sustainable energy. One noteworthy project is the construction of three green hydrogen production facilities in Kokkola, Kristinestad, and Porvoo by Plug Power Inc. The goal of these facilities is to produce 850 tonnes of green hydrogen per day by utilizing Finland's clean energy resources, which include nuclear, wind, and hydro power. This action is in line with the European objective of lowering reliance on fossil fuels and promoting decarbonization initiatives, in addition to promoting Finland's inventive ecosystem and dedication to the production of carbon-free energy. The projects are anticipated to contribute to Finland's goal of becoming a leader in the green hydrogen economy in Europe by generating a sizable amount of economic activity, jobs, and regional development. (Plug Power,2023)

Oulu Energy is working on another big project, a 100 MW hydrogen plant that will be built in Oulu. This project, which focuses on green hydrogen as a way to lower emissions from heat production, is a major expansion of operations in northern Finland. The plant could be completed as early as 2028, and the investment decision is expected in the fall of 2025 while the impact and feasibility assessments are still in progress. This project, which is being carried out in association with P2X Solutions, highlights the area's leading position in the green transition and seeks to significantly alter the hydrogen economy landscapes in Finland and Europe. (Business Finland, 2023)

These ongoing hydrogen projects demonstrate Finland's proactive strategy for incorporating green hydrogen into its energy mix, which helps the country meet its 2035 carbon neutrality target and the larger European energy security and sustainability goals.

5 Market analysis

This section focusses one hydrogen market and its growth and value. This is important when responding to the research questions of the thesis and because the main barriers are related to markets and finance of hydrogen projects. According to the Grand View Research (2023) the value of hydrogen markets is projected to increase from USD 170.14 billion in 2023 to USD 317.39 billion by 2030. The desire for cleaner fuels to lower fuel sulfur levels is one of the main driving for this growth. Construction of infrastructure to support fuel cell vehicles and hydrogen energy is underway in Finland and throughout Europe. In Finland, the need for hydrogen is growing in sectors such as biofuel production, P2X technologies for synthetic fuels, and cleaner processes in the steel and cement industries. In addition, hydrogen is recognized for its potential to efficiently accommodate renewable energy sources. Hydrogen fuel cell vehicles are attempting to expand their market share in the transportation industry. As a result of these requests, Finland is developing hydrogen production, storage, and distribution infrastructure be it green hydrogen, obtained from renewable sources, or blue hydrogen, obtained with nuclear and carbon capture methods. This necessitates the creation of a reliable transportation system, hydrogen for vehicle refuelling stations, and storage solutions. With international cooperation and favorable government initiatives, Finland may establish a hydrogen economy and reach the target of carbon neutrality by 2035.

5.1 Current market size and projections

Another report on hydrogen generation by Grand View Research (2023) indicates that the global market would be valued at USD 170.14 billion in 2023. Moreover, the market is expected to grow at a compound annual growth rate of 9.3% from 2024 to 2030, and the expected market size at the end of the review period is USD 317.39 billion . Some of the factors that account for the high growth include the need for cleaner fuels and stringent government policies on desulfurization of petroleum fuels. Furthermore, the increasing demand for hydrogen as a green energy source has spurred significant developments and projects in Europe and North America to be mentioned in the report. These regions are focused on building out their hydrogen production and infrastructure. (Grand View Research, 2023)

The market for hydrogen generation in Europe is a part of a larger effort to build infrastructure that will support hydrogen use and encourage the use of fuel cell vehicles. The European Commission has announced projects that will support this development through groups like the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) (European Commission, 2021a). These initiatives demonstrate Europe's dedication to growing its hydrogen economy and are in line with worldwide movements for cleaner energy sources.

5.2 Demand analysis for hydrogen energy in Finland

The National Hydrogen Roadmap (Business Finland, 2020) for Finland shows a considerable shift toward cleaner energy sources across a range of industries by providing sector-specific demand projections for hydrogen energy. The roadmap highlights how important hydrogen is. The National Hydrogen Roadmap for Finland's comprehensive demand analysis highlights the diverse functions of hydrogen in Finland's energy transformation. Finland hopes to realize its hydrogen potential on the route to becoming carbon neutral by 2035 by coordinating policy support, infrastructure investments, and technological advancement with these demand projections. (Business Finland, 2020)

Owing to its essential role in the production of biofuel and oil refinement, a significant increase in the demand for hydrogen is anticipated. The roadmap highlights the increasing industrial demand for hydrogen as a crucial component for the production of green hydrocarbons by mentioning in detail the plans for Neste's HVO production unit to expand. Hydrogen demand is expected to grow in the Power-to-X (P2X) technologies sector, according to the roadmap. Power-to-X technologies convert surplus renewable electricity into a range of energy carriers and products, including hydrogen, synthetic methane, liquid fuels, and chemicals. Power to X also relies on electrolysis to produce hydrogen from water, which can be used directly as an energy carrier, or converted into other fuels and chemicals using additional process such as methanation or the Fischer-Tropsch synthesis (Business Finland, 2020). It allows renewable energy to be stored, improves grid stability and promotes decarbonization in sectors such as transportation, industry and heating by combining renewable energy with existing energy infrastructure. For the production of synthetic fuels and chemicals, these technologies—which transform electricity into hydrogen or other energy carriers—are essential. Finland is committed to using hydrogen to achieve carbon neutrality, and its focus on P2X technologies shows that there is room for significant growth in the use of hydrogen. The use of hydrogen in the decarbonization of steel and cement production represents another area where demand may rise. The roadmap indicates a significant shift towards low-carbon production methods and highlights the shift towards hydrogen-based direct reduced iron (DRI) processes as a game-changer for these heavy industries (Business Finland, 2020). Although the market for hydrogen fuel cell electric vehicles (FCEVs) is currently growing slowly, there are still opportunities for hydrogen demand to rise in this sector (Business Finland, 2020). The roadmap promotes infrastructure development and pilot projects to increase the adoption of hydrogen in mobility, arguing that heavy transport and logistics could benefit greatly from hydrogen fuel cell technology.

5.3 Supply chain and infrastructure development

Efficiency and sustainability in the development of Finland's hydrogen energy infrastructure and supply chain require a multifaceted approach. The establishment of strong production capabilities is the main priority. This entails setting up facilities for the production of blue hydrogen, which is produced by storing and capturing carbon emissions, and green hydrogen, which is produced through electrolysis using renewable energy sources. Such progress is essential to building a hydrogen economy that is sustainable.

Another critical infrastructure need is storage. Hydrogen has been emphasized as a flexible way to integrate renewable energy sources, and its use in energy storage is expected to increase. Hydrogen can dramatically improve grid stability and balance supply and demand dynamics by serving as a buffer for excess electricity, which will increase demand for the gas.

Given the patchwork availability of renewable energy, storage enables the proper balance of supply and demand. Financing safe and secure storage is one of the goals of Finland's research into various storage methods, which even includes subterranean and advanced materials for solid-state storage .

A comprehensive hydrogen transportation and transmission system is required for the hydrogen economy. This system includes the transformation of already existing gas pipelines converted for the transportation of hydrogen and the construction of hydrogen pipelines that differ in cross-section; the deployment of a special road transport fleet between production and consumers in various regions is also needed.

The infrastructure for hydrogen refuelling is another essential factor for supporting hydrogen fuel cell electric vehicles use. The development of private refuelling solutions for commercial and industrial fleets and the broadening of the public refuelling station system are two critical initiatives to boost the hydrogen-powered mobility market.

Cross-sector integration is vital to the hydrogen supply chain, where it blends the producer of hydrogen with renewable energy generation and end-uses, including industrial manufacturing and grid balancing . The step guarantees that hydrogen is used effectively across the economy.

Finally, legislative and regulatory backing is necessary for the construction of hydrogen infrastructure . Intake incentives, funding of infrastructure projects, and frameworks for safety and quality measures are critical to attaining investments and expediting the process.

In combination, these measures aim to construct Finland's hydrogen infrastructure comprehensively and sustainably and to live up to this country's ambitions to become a worldwide hydrogen economy leader and commitment to carbon neutrality.

6 Political aims and support for hydrogen in Finland and Europe

This section covers the policy aims and support for hydrogen energy by introducing the national hydrogen strategy in Finland and the broader EU regulatory framework. By 2030, Finland aims to lead in the hydrogen economy and produce more than ten percent of the emissions-free hydrogen produced in the EU. The country has further targeted becoming the largest producer of large-scale renewable hydrogen using wind power. The Finnish government has focused on a profound energy independence and a green transformation, with a comprehensive plan to achieve carbon neutrality by 2035(Ministry of Economic Affairs and Employment, 2022a). The plan among other targets also aims at the elimination of Russia's fossil fuel export. The European Union's fit for 55 and Hydrogen Strategy programs align with the Finnish government's ambitions of reducing carbon emissions (European Commission, 2021b). Finland sponsors these programs through offered incentives and subsidies. The efforts seek to provide more enhanced energy independence and lower the financial and technological risks associated with the low carbon hydrogen programs . Other initiatives include the creation of the European Hydrogen Bank (European Commission, 2023).

6.1 Finnish government policies on hydrogen energy

A resolution on hydrogen was adopted by the Finnish government, outlining bold objectives to establish Finland as a European leader in the hydrogen economy throughout the whole value chain. Finland wants to produce ten percent or more of the emissions-free hydrogen used in the EU by 2030 (Ministry of Economic Affairs and Employment, 2023a). This goal is a component of a larger plan to promote the production of hydrogen and electrofuels for Finnish industry, transportation, and energy systems, as well as to drive industrial change and assist Finnish operators and investments in the hydrogen sector (H2 cluster Finland, 2023). The resolution emphasizes how important it is to produce hydrogen on a larger scale, which requires a substantial amount of electricity that is clean and produced competitively. There are plans to build additional wind power capacity, which could more than double Finland's current growth requirements.

Simultaneously, the Finnish government sent the Parliament a draft of its national energy and climate strategy, which includes an action plan to reach carbon neutrality by 2035 (Ministry of Economic Affairs and Employment. 2022a). With a focus on the green transition and the removal of Russian fossil energy imports, this all-encompassing strategy addresses greenhouse gas emissions across multiple sectors. The strategy outlines Finland's goals for energy savings and renewable energy consumption and emphasizes the crucial connection between energy and climate policies, particularly in promoting energy efficiency and clean energy sources. Notably, it includes quantitative targets for hydrogen electrolysis capacity that could be surpassed with quick technological advancements, as well as an emphasis on the hydrogen economy and electrofuels. (Ministry of Economic Affairs and Employment, 2022a)

Furthermore, Finland's energy and climate strategy is interwoven with the energy and climate policies of the Government Programme, the long- and medium-term plans for climate change policy mentioned in the Climate Change Act, and the 2030 energy and climate targets of the EU（Ministry of Economic Affairs and Employment, 2023b）. This plan is a component of the well-established procedure whereby every government develops an energy and climate plan with the goal of becoming a society that is carbon neutral. This reflects an awareness that energy production and consumption, including transportation, account for a sizable amount of greenhouse gas emissions, meaning that energy and climate policies are closely related. (Ministry of Economic Affairs and Employment, 2022a)

With an emphasis on hydrogen energy as a crucial part of its future energy and climate strategy, these policies and strategies highlight Finland's proactive approach to combating climate change through energy transformation and innovation.

6.2 European union regulations and their impact

With a focus on decarbonization and the integration of low-carbon and renewable fuels into the energy system, the European Union has implemented significant regulatory actions to shape the hydrogen energy market. The "Fit for 55" package, which was adopted on July 14, 2021, outlines the larger objective of reducing greenhouse gas emissions by at least 55% by 2030 relative to 1990 levels (European Commission,2021b). The objective of this package is to establish a specialized hydrogen market and infrastructure throughout the European Union, while also encouraging the production and demand of low-carbon and renewable gases such as hydrogen.

Through the EU Hydrogen Strategy, the European Commission has started a number of significant initiatives to aid in the growth of the hydrogen economy. These include proposing ways to facilitate the use of hydrogen in the transportation sector, working on a common low-carbon threshold for hydrogen production installations, and creating an investment agenda through the European Clean Hydrogen Alliance and the Commission's recovery plan. In addition, the plan calls for the establishment of a comprehensive vocabulary and standards for the certification of low-carbon and renewable hydrogen across Europe. (European Commission, 2022a)

The establishment of the European Hydrogen Bank in 2022 is a noteworthy advancement as it functions as a financial tool to encourage investments in the hydrogen value chain both domestically and internationally. By balancing the supply of renewable energy with the demand of the EU, the bank hopes to unlock private investments while also resolving initial investment obstacles. Through open and well-coordinated efforts, it seeks to create a first market for renewable hydrogen, as well as new growth prospects and the facilitation of renewable hydrogen imports.(European Commission, 2021c)

Additionally, in order to promote research, innovation, and the implementation of clean hydrogen technologies, the EU founded the European Clean Hydrogen Alliance (European Commission, 2020) and the Clean Hydrogen Partnership (Clean Hydrogen Partnership, 2021). By 2030, these programs hope to implement ambitious hydrogen technologies, with a particular emphasis on low-carbon and renewable hydrogen production, various sectors' demand, and hydrogen distribution and transmission.

6.3 Incentives and subsidies for hydrogen energy development

Finland aims to be carbon-neutral by 2035. For this reason, Finland offers many incentives and subsidies regarding the development of hydrogen energy. As part of the government’s Finnish Sustainable Growth Program , energy-related investments and infrastructure receive financial support, especially if they contribute to the reduction of greenhouse gas emissions and Finland’s efforts to achieve carbon neutrality . These subsidies aim to encourage not only the modernization of the existing energy production assets but also the development of new energy and renewable energy technologies, such as low-carbon hydrogen projects .The objective is to improve Finland's energy independence and lower the technological and financial risks connected with these projects, particularly in light of the need to lessen reliance on imported energy. (Ministry of Economic Affairs and Employment, 2021)

A number of investment areas are listed in Finland's Recovery and Resilience Plan, including energy infrastructure and new energy technologies. Low-carbon hydrogen and carbon capture and utilization are given special attention. These initiatives are meant to balance the energy market, especially the electricity market, and hasten the use of low-carbon hydrogen in transportation and industry. Another important step in strengthening Finland's position in the hydrogen economy is the creation of a national hydrogen network, which will support the nation's hydrogen economy and facilitate the efficient transfer of energy and raw materials.(Ministry of Economic Affairs and Employment, 2022b)

Furthermore, the recent move by the government to redirect funds from solar projects to hydrogen projects points to a strategic change in favor of hydrogen as a vital element of Finland's green transition. This decision emphasizes how crucial hydrogen energy is to Finland's efforts to use renewable energy sources to support sustainable growth and achieve its carbon neutrality targets. (Business Finland, 2022)

These programs are a part of Finland's larger plan to create an environment that is favorable to the development of hydrogen energy. The goal is to create a capacity for producing low-carbon hydrogen and to establish Finland as a major participant in the hydrogen economy, both as a producer and an exporter of hydrogen.

7 Challenges and opportunities of hydrogen markets

This section, examines the potential and limitations of the hydrogen energy industry. Both the potential and the technical and financial complications for further growth are brought up. The technical complications include the efficiency and cost of hydrogen, particularly “green” one, production, barriers to scale, and storage and transmission capacities. The economic problems of the Finnish growing hydrogen industry are the costliness of the infrastructure and the need for significant investment possible by the vague regulation and public unawareness. Nonetheless, Finland has significant potential for the development of the hydrogen industry, as the country has a well-developed renewable energy industry, innovative technology, and supportive government policy. This potential is further supported by a strong argument for strategic investment and policy support for hydrogen: decarbonization in heavy industries, a potential role in the renewable energy system, and the prospects for a global hydrogen economy. Finland has a robust goal to become carbon-neutral by 2035 (Ministry of Economic Affairs and Employment, 2022a), which can be a good framework for speeding up the implementation of hydrogen in its energy transformation.

7.1 Technical challenges in hydrogen energy production

One of the elements crucial for the transition of the world into renewable and sustainable energy sources is the production of hydrogen energy. However, the transition has some detrimental elements in the case of such conditions as efficiency and viability of its technology. Firstly, production efficiency and, primarily, the efficiency of electrolysis are among the biggest stumbling blocks. The efficiency of electrolysisis the variation in efficiency depending on the technology. Electrolysis is when one uses an electric output to split water into hydrogen and oxygen. In the event hydrogen is going to be equivalent and more effective to the existing energy resources, the electrolysis is also going to have to be more efficient. (Marouani & Guesmi & Alshammari & Alqunun & Alzamil & Alturki & Abdallah, 2023)

Another significant hurdle is the production cost of green hydrogen. More specifically, it is cheaper to manufacture grey hydrogen, derived from fossil fuels. The manufacturing of green hydrogen relies on renewable energies. The production of electricity is expensive due to the high price of using renewable energy and due to the equipment needed for electrolysis. In order for green hydrogen to rival commercially known energy sources, it is essential to lower these two significant costs. (Marouani et al, 2023)

In addition, hydrogen faces logistical problems in storage and transportation. For hydrogen storage, it is required to use high-pressure tanks or a high-energy requirement liquid form, which is expensive and unsafe to store due to low hydrogen volumetric capacity. More economical and advanced storage and transportation solutions should be developed for hydrogen to become the mainstream as an energy source. (Marouani et al, 2023)

Problems are associated with the lifetime and life span of an electrolyzer. The electrolyzers' production costs significantly affect the economics of hydrogen. In other words, it is necessary to solve the issue with the low specific life cycle of electrolyzers. Another problem is the situation of scaling. It is impossible to solve the world's energy problems only by scaling up existing plants. To meet the global demand for hydrogen energy, our infrastructure, technology, and investment should be advanced enough. Since the facilities also cost around 1 billion dollars, the legislation should also support them. (Maka & Mehmood, 2024)

Another potential issue is that because solar and wind power are so unpredictable, hydrogen production linked with solar and wind power systems can only be used with comprehensive management. Extensive management solutions include intelligently designed networks and devices for storing surplus renewable energy, resulting in an available form of hydrogen production. (Marouani et al, 2023)

Finally, safety and regulation issues must be taken into consideration. Because hydrogen is highly combustible, to generate and store, organizations must adhere to strict safety measures and laws to less or prevent accidents and make the general people accept hydrogen technology. (Marouani et al, 2023)

The resolution of these hurdles will entail the joint efforts of government, industry, and academic stakeholders to formulate and refine the procedures which will guarantee that hydrogen becoming a permanent feature in our future energy infrastructure.

7.2 Innovations in hydrogen energy technology

Finland’s determination to become carbon emission-free in the future has also made it an innovation field with some of the most ground-breaking hydrogen technological advancements. Finnish businesses, academic institutions, and researchers are pushing the boundary of the possibilities of hydrogen technology, and its developments could greatly influence the future of energy systems in the country and the entire world.

Hydrogen Cluster Finland is a network of companies and industrial organisations that work to boost the hydrogen economy by means of sharing information, collaboration and joint business initiatives. By applying Finland’s clean energy mix, growing the percentage of renewable energies, taking advantage of its numerous water recourses and technological openness, it can facilitate business opportunities as well as leading to climate neutral transition. It is open to discussion and cooperation with other stakeholders in the hydrogen economy for building sustainable developments as well as businesses locally and internationally. Includes companies active along the entire value chain, from clean and renewable energy infrastructure to hydrogen production, distribution, storage and processing up as well as technology providers, design contractors at digitalization specialists. This group will draw together a complete hydrogen value network made up of various competences and capabilities. (Hydrogen Cluster Finland, 2021a)

The white paper from hydrogen cluster Finland highlights some of the exciting advancements within hydrogen energy technology that are expected to reshape the nation’s energy system. One of the most innovative is the clean hydrogen production. Finland plans to use its strong and clean electricity system of wind energy to create green hydrogen through electrolysis. This process is emissions free, using renewable electricity to split water into its components of hydrogen and oxygen. The aim is to harness Finland’s abundant and competitively priced renewable energy resources, making green hydrogen a central element in the national energy strategy. (Hydrogen Cluster Finland, 2021b)

In addition to green hydrogen, Finland is exploring producing "pink" hydrogen from nuclear energy. This approach utilizes the nation's substantial nuclear capabilities to generate hydrogen with minimal carbon output. Furthermore, the report discusses prospects for "blue" hydrogen, involving trapping and saving CO2 emissions from hydrogen generation applying fossil fuels. Even though Finland has a confined CO2 storage ability, this technique is deemed a changeover remedy to promptly decrease emissions from present hydrogen manufacturing amenities. (Hydrogen Cluster Finland, 2021b)

The report also emphasized another major development was integrating hydrogen across diverse industrial and power industries to generate far-reaching sector integration. For example, Finland aspires to employ hydrogen in energy-intensive sectors including steel fabrication and synthetic production to decarbonize those areas. Furthermore, the nation intends to include hydrogen into its local heating networks, capitalizing on the warmth created in the course of hydrogen generation to meet domestic heating needs. This sector integration not only enhances power performance but additionally offers an approach to stabilize the electricity grid by changing surplus renewable electricity into hydrogen for storage and potential use later on. (Hydrogen Cluster Finland, 2021b)

The white paper underscores that digitalization and advanced technology can further boost efficiency of hydrogen production as well as are expected by the group's members. The Finnish companies are leading in developing digital solutions to monitor and control production processes vital for the effective and reliable generation of hydrogen. State-of-the-art sensors, data analytics and artificial intelligence help to optimize the complete hydrogen value chain from production to end-use for maximum economic and environmental benefit. (Hydrogen Cluster Finland, 2021b)

Lastly the white paper notes that public-private collaboration will be key to spurring development in hydrogen. Part of Finland’s approach is to use the co-innovation programs, where research institutions and universities, as well as industry stakeholders work together in the development and commercialization or new hydrogen technologies. Leveraging this framework and public funding and policies to speed up the roll-out of hydrogen solutions enables a space for innovation, leading it towards development and growth in the hydrogen value chain. (Hydrogen Cluster Finland, 2021b)

7.3 Economic challenges and market barriers

Development of hydrogen market in Finland is a promising and blooming sector that holds great opportunity for helping the country achieve carbon neutrality and, possibly, energy sovereignty. In order to extract the full potential of this technique, numerous market barriers and economic challenges must first be eliminated.

Finland’s hydrogen market growth faces major financial barriers, mainly as a result of high infrastructural costs of hydrogen production, storage, and transportation. Some green hydrogen production technologies, such as electrolysers fuelled by renewable sources, have high fixed costs. The lack of economies of scale, which would result in a cost drop, only increases these financial challenges. For stakeholders, the financial feasibility of incorporating hydrogen into the existing energy system is an important concern due to the requirement for high upfront investments in new infrastructure and technologies. (Hydrogen Cluster Finland, 2021b)

Other Finnish hydrogen market barriers in addition to economic ones are the lack of clear regulations, since hydrogen-specific regulatory and policy frameworks are not yet fully developed, investors and developers cannot be sure about the further development of the market. This market is also not well-structured by the absence of a unified set of rules and safety procedures for the production, storage, and transportation of hydrogen. Furthermore, the lack of the general population and potential users who have the necessary knowledge and awareness of using hydrogen also slows its development. (Gomersall, 2020b)

Given the numerous challenges ahead, a multi-faced approach is required. The government should provide financial support through grants and subsidies for hydrogen technology implementation and R&D. Policymakers must also create more clear and legally binding regulations and standards to ensure safety and the investors' trust. Another crucial component for the sharing of benefits and risks of the early-stage hydrogen projects is the public support through public-private partnership. Moreover, public marketing and education on the benefits for and long-term savings on hydrogen energy can rapidly accelerate the speed of its introduction and integration into Finland's grand energy strategy.

To sum up, the hydrogen industry in Finland is facing many market challenges and economic difficulties, but the potential of the hydrogen sector for the transition to sustainable energy and industrial decarbonization is great. To successfully address existing challenges and make Finland a leading player in the global hydrogen economy, all stakeholders must act together and invest strategically and supportively in the hydrogen industry. (Ministry of Economic Affairs and Employment, 2022a)

7.4 Opportunities for growth and development

The future of hydrogen energy in Finland is promising, as the market has substantial growth and development potential. The country has a good base within sustainable energy, a technology sector that promotes innovation, and a legislative environment supporting these endeavors. It already has significant investments in wind and solar power, which enable it to produce green hydrogen. If using surplus renewable energy to fuel electrolysis, Finland can produce hydrogen without emitting carbon, helping with energy storage for peak times and grid maintenance in high renewable availability periods. (Renewable Energy Magazine, 2022)

Finland's rich energy technology environment advances hydrogen production, transport and utilization, supported by research institutions and start-ups. By creating an investment environment conducive to the development of cutting-edge hydrogen technologies, Finland can play an important role in the global hydrogen market (Teivainen, 2021).

The industrial sector of Finland could benefit significantly from utilizing hydrogen, especially in those high-emission, and heat-intensive sectors such as steel, chemicals, and refining. As a cleaner solution for chemical reactions and source of high-temperature heat, hydrogen could be used in both a manufacturer's plants and supply chains. For hydrogen to be utilized, a full-fledged infrastructure of production units, storage facilities, and distributing systems should be developed to ensure its availability for products and processes, including transportation. Hydrogen fuel cell vehicles show potential for substitution of battery-electric vehicles, especially for heavy-duty transportation and long-distance trips (Renewable Energy Magazine, 2022).

Additionally, by exporting green hydrogen or hydrogen-based products, Finland can assist other countries in the world with less access to renewable sources of energy in their transition to clean sources of energy generation. Allowing the Finnish government to reach carbon neutrality in 2035 while promoting the investment-based and subsidiarity system of laws, such as hydrogen-friendly legislation of Finland. Requiring investments, subsidies, and grants, this system is suitable for both local residents and foreign investors. (Ministry of Economic Affairs and Employment, 2022a)

Finally, the potential for growth and development, including the decarbonisation of the industry, the use of renewable energy sources, the implementation of a sustainable energy plan, the development of infrastructure required and internal or external market traits and finally feasible supporting regulations, all indicate that Finland views the chance to establish itself as a leader in the hydrogen economy.

8 Discussions

To sum up, the growth and development of the hydrogen energy market in Finland appear to be a complex phenomenon with multiple facets. This discussion presents the main results of the research, considering technical, economic, and policy aspects of the hydrogen market, and offering the strategic considerations and steps necessary to move ahead with growth and development in the market.

The efficiency and viability of hydrogen production technologies are the key technical challenges for hydrogen, specifically electrolysis. The efficiency of electrolysis ranges greatly per technology,and this is a major opportunity for hydrogen to rival existing energy sources. The costs of producing green hydrogen with the assistance of electricity from renewable sources are another important matter. Renewable electricity and electrolysis appliances are very costly, and hydrogen production is partly to blame. Most strategies, such as high-temperature and high-pressure electrolyzers, are being investigated and developed in Finland to tackle these issues and improve the compatibility of green hydrogen with all kinds of renewable energy sources.

hydrogen storage and transportation are also associated with a high logistical burden. The Finnish example shows that the new ways of storing hydrogen, known as solid-state hydrogen storage, with greater density and security compared to common compression, are subject to consideration. It is essential for the development of the grid-scale energy storage and the automotive sector, enabling the wider use of hydrogen.

Another critical issue is the financial feasibility of introducing hydrogen into the energy system of Finland. Noteworthy, the need to create new infrastructure and implement innovative technologies involves considerable costs, which must all be covered by stakeholders because the production of green hydrogen in Finland is more expensive than grey hydrogen. Without the benefits of economies of scale, stakeholders find it more challenging to tackle financial aspects of hydrogen production regardless of the policies that support them. In addition, the lack of clear regulations and one common approach to the rules and safety procedures regarding hydrogen create conditions of uncertainty for investors because they hinder the stability of the market At the same time, the general public is not well-aware of the existing technology.

These obstacles can be overcome using a multi-faceted approach that includes governments as well as industry premises and academic institutions. The Finnish government aids the hydrogen market by providing financial assistance in the form of grants and subsidies for the deployment of hydrogen technology and R&D. Stability and legally which is binding regulations and standards can reduce the risk and enhance investor certainty. Public investment can distribute the advantages and risks of developing projects within the reach of public R&D, while public marketing and education can elevate the public awareness required to speed hydrogen energy integration to the level of detail to be a part of Finland's broad energy strategy.

Investments in renewable wind and solar power in Finland enables a strong base of green hydrogen production. The excess of renewable energy can be used for electrolysis, which creates hydrogen without carbon. Hydrogen can be used for grid balancing and energy storage. Furthermore, the country has a developed technology sector that includes research institutions and startups, which development hydrogen production technology.

The industrial sector can benefit substantially from the use of hydrogen, notably the high-emission and heat-intensive industries such as steel, chemicals, and refining. In this case, hydrogen might act as a building block for chemical processes and high-temperature heat, with the role of a cleaner substitute for fossil fuels. A hydrogen infrastructure, which comprises production facilities, storage facilities, and delivery systems, is essential to achieve the necessary support for hydrogen-powered mobility and other end-users.

9 Conclusion

Finland's efforts to grow its market for hydrogen energy are evidence of the country's dedication to climate leadership and sustainable development. This thesis has demonstrated the need for a multimodal strategy that includes market development tactics, policy support, and technological innovation in order to promote the expansion of the hydrogen economy. Finland exhibits a proactive approach, utilizing its technological prowess and renewable energy capabilities to overcome obstacles despite facing technical and economic challenges. The cultivation of international partnerships and strategic alignment with EU directives serve to reinforce Finland's position in the global hydrogen landscape. Going forward, expanding the production of hydrogen, improving infrastructure, and easing market acceptance will require sustained R&D spending in conjunction with a flexible regulatory environment. Finland is moving closer to its goal of being carbon neutral by 2035, and the way its hydrogen energy market has developed provides important lessons for other countries trying to make the same shift to sustainable energy.

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