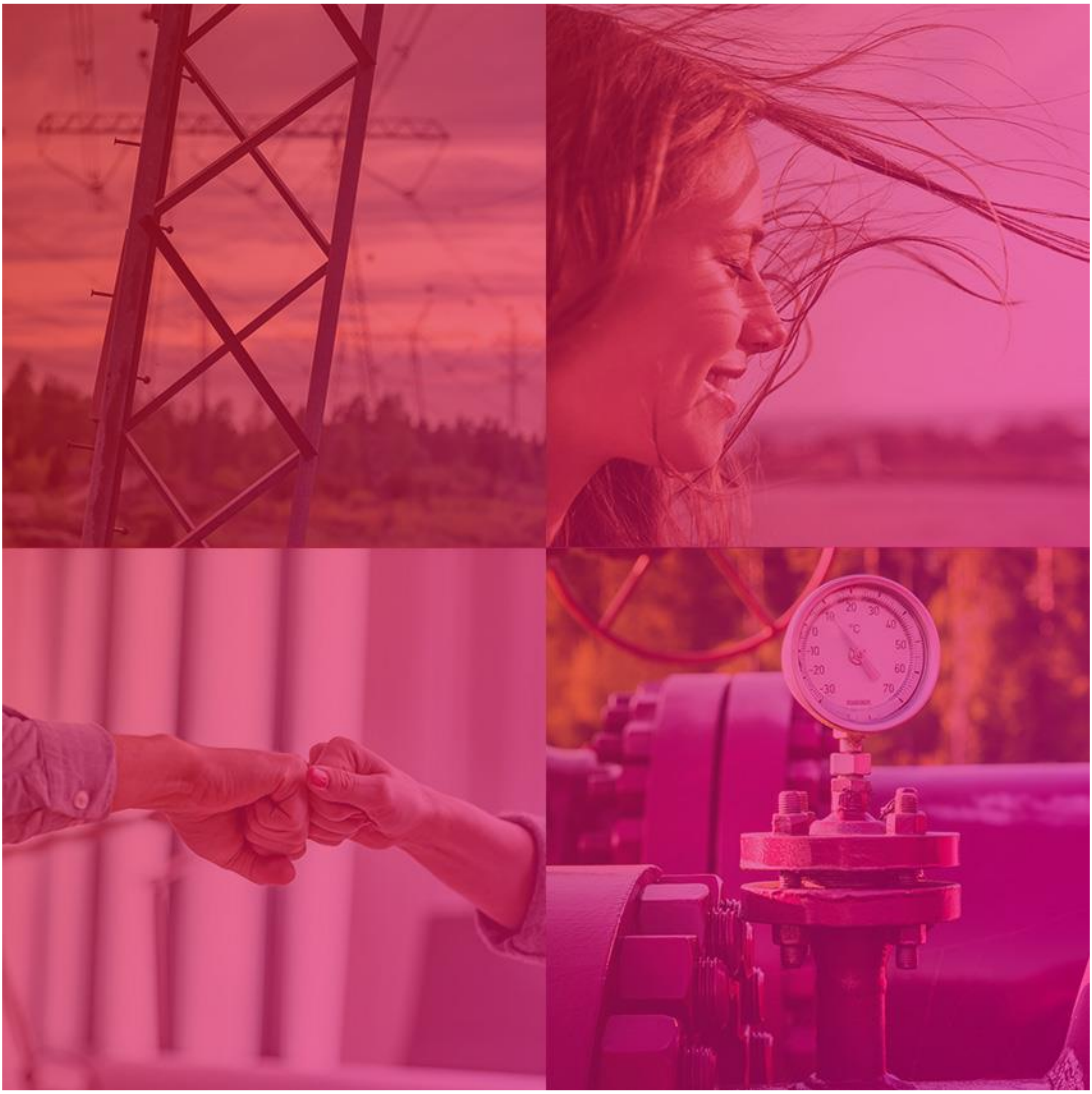

Energy transmission infrastructures as enablers of the hydrogen economy and clean energy system

Final report of the joint project by Fingrid and Gasgrid Finland

FINGRID

GASGRID

Preface

Clean electricity, along with hydrogen and its downstream products produced with clean electricity, are key solutions for reducing emissions across all sectors of society. Finland has an excellent opportunity to be a forerunner in this field and achieve a leading role in the European hydrogen economy.

Finnish electricity production already ranks among the cleanest in the world, and we have every opportunity to at least double our clean electricity production. Finnish onshore wind power is especially cost-competitive. This, combined with a diverse electricity production base, gives our country a competitive advantage in the production of clean electricity and hydrogen.

Our strong energy transmission infrastructure is also becoming an asset in international competition. A reliable electricity transmission main grid that industrial users can easily connect to is an important factor in planning the industrial investments for the green transition. Similarly, a hydrogen transmission infrastructure can attract investments to Finland. A hydrogen transmission infrastructure will also enable the creation of a national and, in time, international hydrogen market, as well as enabling the storage of hydrogen. The transmission of large amounts of energy as hydrogen is cost-effective and it appears clear that, for the higher growth scenarios to be realised, investments in the electricity transmission infrastructure alone will not suffice, but we will also need a strong hydrogen transmission infrastructure. Together, the electricity and hydrogen transmission infrastructures will enable a clean and cost-effective energy system through the integration of these sectors.

Fingrid and Gasgrid Finland have been studying the opportunities offered by an electricity and hydrogen transmission infrastructure since the autumn of 2021. The results of this joint project, titled Energy transmission networks as enablers of the hydrogen economy and a clean energy system, are presented in this final report. The joint project was part of the wider HYGCEL (Hydrogen and Carbon Value Chains in Green Electrification) project funded by Business Finland. In the public part of this project, universities and companies teamed up to study the systemic effects of the energy transformation, energy system and hydrogen economy.

We thank Business Finland for making the project possible and the market operators and stakeholders for their valuable contributions, which provided important feedback for the guidance and development of the study at various points in the project. We would also like to extend our heartfelt thanks to the research and development organisations who participated in the project's implementation and, above all, to the project team. You have all contributed to achieving a significant step in the development of the Finnish energy system!

Even though this marks the conclusion of the joint project for now, cooperation between our companies will continue in the design of electricity and hydrogen infrastructure. It is the companies' joint objective to promote Finland's competitiveness by designing and implementing the most efficient transmission solutions for a developing energy system.

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Contents of the report

List of abbreviations

AFIR	Alternative Fuels Infrastructure regulation
BHC	Baltic Hydrogen Collector
CCfD	Carbon Contracts for Difference
CBAM	Carbon Border Adjustment Mechanism
CO2	Carbon dioxide, a greenhouse gas
DA	Delegated Act
EED	Energy Efficiency Directive
EHB	European Hydrogen Backbone
ENTSO-E	European Network of Transmission System Operators for Electricity / Gas
ENTSOG	European Network of Transmission System Operators for Gas
ETD	Energy Taxation Directive
ETS	Emission Trading System
EU	European Union
FT	Fischer-Tropsch
IEA	International Energy Agency
LRC	Lined Rock Cavern
NHR	Nordic Hydrogen Route
NBHC	Nordic-Baltic Hydrogen Corridor
PEM	Polymer Electrolyte Membrane
PPA	Power Purchase Agreement
RED	Renewable Energy Directive
RFNBO	Renewable Fuels of Non-Biological Origin
rWGS	Reverse water-gas shift reaction
SMR	Steam Methane Reforming
TYNDP	Ten-Year Network Development Plan

Executive summary

Finland has every opportunity to achieve a leading role in the European hydrogen economy. Finland has great potential for renewable electricity production, a strong electricity main grid, an expert workforce and several companies that can operate in the hydrogen value chain. Hydrogen and its downstream products produced with renewable or emission-free energy can replace fossil fuels and develop into a significant export industry for Finland. Dozens of industrial hydrogen projects are underway in Finland, for example in the field of fossil-free steel production and electrofuels refined from hydrogen.

Energy transmission and the location of investments play a key role in ensuring the availability of electricity and hydrogen required for the growth of the hydrogen economy. Energy transmission needs will grow as electricity and hydrogen consumption is distributed more evenly across Finland. The development of electricity and hydrogen transmission infrastructures is key to fulfilling Finland's potential. Major transmission requirements can only be managed through the joint design of electricity and hydrogen infrastructures and the efficient use of both. The location of investments in the hydrogen economy is key to enabling such efficient use. By making use of the hydrogen network, hydrogen production can be located closer to electricity production and energy can be transferred as hydrogen to more distant hydrogen use and refining sites. Based on the study, it is also more cost-effective to transfer large amounts of energy as hydrogen if the energy will ultimately be used as hydrogen. Building international hydrogen transmission connections will also expand the hydrogen market and create new business opportunities at various points in the hydrogen value chain.

A large-scale pipeline transmission infrastructure for hydrogen is feasible. There are no experiences of large-scale transmissions of hydrogen yet in the Nordic countries, but our decades' experience in the use of methane pipelines can be used as a starting point for its design, implementation and use. Furthermore, there is approximately 5,000 km of transmission pipeline designed for hydrogen in use globally. Open questions remain, for example concerning the technical details, technical standards for hydrogen, customers' connection principles and the quality requirements for hydrogen. Enabling the hydrogen infrastructure and market requires further development in these areas in the next few years.

Investments in the hydrogen economy will open a market worth billions. Hydrogen investments may be counted in the dozens of billions in the early 2030s. The hydrogen industry can develop into a new pillar of the Finnish economy as significant investments create jobs, tax income and sustainable growth. The value chains of the hydrogen economy are extensive and multi-layered. In addition to the design, construction and operation of new plants and infrastructure, they create plenty of opportunities for the technology industry and the development of new services. Even though significant investments have been made in the energy infrastructure to enable the development of the hydrogen economy, they remain relatively modest compared to the potential overall investment in the hydrogen value chain. By attracting hydrogen investment to Finland, we can achieve the targets of becoming a leader in the European hydrogen economy and producing over 10% of the hydrogen and its downstream products needed in the EU.

Gasgrid Finland and Fingrid see the joint design of hydrogen and electricity transmission infrastructures as essential for the development of the most cost-effective energy system possible. It is the companies' joint objective to promote Finland's competitiveness by comprehensively developing its energy infrastructure on the basis of future customer needs, as well as by designing and implementing the most efficient transmission solutions for the developing energy system.

1 Project goals and contents of the final report

Fingrid and Gasgrid Finland are Finnish transmission system operators responsible for the development and operation of the country's electricity and gas transmission infrastructures. Gasgrid Finland has also been tasked by the state with promoting the rapid development of the national hydrogen network, national infrastructure cooperation and the Baltic hydrogen market. For this purpose, Gasgrid has established the company Gasgrid Vetyverkot Oy. The companies monitor and actively participate in the development of Finland’s energy systems and markets. As transmission network operators, Gasgrid and Fingrid also seek to develop the markets and systems to better serve Finnish society, industry, businesses and consumers.

In the autumn of 2021, Fingrid and Gasgrid Finland began a joint research project intended to study the roles and opportunities of energy transmission systems in the hydrogen economy and create new competence in this area. The joint project was part of the wider HYGCEL (Hydrogen and Carbon Value Chains in Green Electrification) project funded by Business Finland. In the public part of this project, universities and companies teamed up to study the systemic effects of the energy transformation, energy system and hydrogen economy. Fingrid and Gasgrid implemented their joint research project in parallel with the HYGCEL research project.

The aim of the research project was to create new knowledge and increase competencies in the hydrogen economy, sectoral integration and joint energy system development in companies and across whole ecosystem. **The project’s main goal was to study the role and opportunities of energy transmission systems in supporting the hydrogen economy and enabling exports and to create new competencies in these fields.** The detailed objectives of the project were:

- to create potential scenarios for the hydrogen economy and study their effects on energy systems (electricity, gas/hydrogen);
- to analyse and define the most cost-effective transmission network development paths for Finnish society;
- to define the growth and export potential created for Finland by the hydrogen economy, provided that the transmission networks support this development;
- to study and develop the technical requirements for and costs of building the transmission network;
- to analyse possible operating models for the hydrogen market and the roles of operators in the value chain; and
- to study the development needs of electricity and hydrogen transmission networks based on the needs of customers and the market.

Gasgrid's goal for the project was to build expertise and gain better insight into future business requirements. The key questions regarding the development of competencies and project outputs for gaining insight are listed below:

1. What is the growth and export potential created by the hydrogen economy, provided that the transmission networks support this development? What concrete action will be required to enable the growth and export potential created by the hydrogen economy?
2. How could the gas network support the electricity main grid in meeting increasing electrification and energy transmission requirements? What measures will be required?
3. What are the most economic energy transmission network development paths for society?

4. What do the measures mean for Gasgrid? What is Gasgrid's role in the hydrogen economy and the transmission of Finnish energy and raw materials in the future?

Fingrid's objectives for the project also consisted of building expertise and gaining better insight into the electrified hydrogen economy's impact on electricity transmission needs. Integrating the lessons learned from the project into Fingrid’s ongoing main grid design work was another goal. The key questions regarding the development of competencies and project outputs for gaining insight are listed below:

1. What is the growth and export potential created by the hydrogen economy, provided that the transmission networks support this development? What action will be required to enable the growth and export potential created by the hydrogen economy?
2. How could the gas network support the electricity main grid in meeting increasing electrification and energy transmission requirements? What measures will be required?
3. What are the most economic energy transmission network development paths for society?
4. How does the hydrogen economy impact the electricity consumption and generation structure and, through it, electricity transmission needs and investments into the transmission network?

The joint project sought to generate new knowledge based on comprehensive research and modelling and to answer the questions listed above. At the start of the project, we interviewed several Finnish companies to determine their views of the hydrogen economy. The companies’ answers emphasised the need for the simultaneous development of the electricity and hydrogen infrastructures, considering the whole system needs. Finnish companies saw a number of possible roles for the hydrogen network in Finnish industry. The companies pointed out the importance of cooperation both in infrastructure development and in the formation of industrial value chains.

In the joint project, we studied the role of energy transmission networks as enablers of hydrogen economy growth and a clean energy system, as well as analysed investment requirements and the value of the possible hydrogen market. We outlined different future development scenarios for the hydrogen economy in Finland as well as for the development of the energy infrastructure. In addition, we studied hydrogen economy value chains and investigated technical questions related to hydrogen infrastructure, the construction of hydrogen infrastructure and its costs, as well as the state and development needs of regulation related to the hydrogen economy.

In this report, we first describe the current state of the hydrogen economy (Section 2) and the regulations and legislation affecting the building of the hydrogen economy (Section 3). We then move on to the technical solutions and design principles for the pipe transmission of hydrogen (Section 4). Based on these, we have drawn up three scenarios for the development of the hydrogen economy and transmission infrastructure in Finland (Section 5), for which we also received valuable feedback from stakeholders. Based on the scenarios, we reviewed the development needs of the transmission infrastructure and its role in the Finnish energy system (Section 6) as well as the investments required for the growth of the hydrogen economy (Section 7). Finally, we present the conclusions drawn from the joint project and describe the next steps of our cooperation (Section 8).

2 Description of the operating environment and the hydrogen economy

2.1 The role of hydrogen in a changing energy system

The electrification of society is considered essential for economic growth and the achievement of climate goals. However, certain sectors are challenging to electrify. As potential scalable solutions, hydrogen or its downstream products play an important role in reducing emissions and achieving carbon neutrality targets in these sectors. Hydrogen is also important in enabling the efficient transmission and storage of energy. The growth opportunities of the hydrogen industry are based on the potential of completely replacing fossil raw materials and fuels with hydrogen produced with renewable or emission-free electricity in many sectors of industry and transport. Clean hydrogen plays a major role in achieving the carbon dioxide reduction objectives of Finland and Europe.

The development speed of the hydrogen economy is affected by factors such as regulation at the EU level. As stated in the EU's hydrogen strategy from 2020[1] , hydrogen can be used as a feedstock, fuel, energy carrier and storage. Since the publication of the hydrogen strategy, the European Commission has published a large number of political initiatives related to this theme, especially in the hydrogen and decarbonised gas market package included in the Fit for 55 package. In May 2022, the European Commission published the REPowerEU plan[2], in response to the war started by Russia in Ukraine. The plan aims to decrease imports of fossil-based energy from Russia, significantly increase renewable energy production and expedite the adoption of renewable hydrogen in the EU. According to the target set in the REPowerEU plan, Member States should produce 10 Mt (333 TWh) of clean hydrogen annually and import another 10 Mt of hydrogen from third countries by 2030. In total, this translates to a European hydrogen market of roughly 670 TWh. There are also major binding emission reduction targets for maritime and air transport, along with targets for replacing more than half of fossil-based hydrogen with clean hydrogen by 2035.

2.2 Hydrogen economy value chains

Products can be refined from clean hydrogen produced with renewable energy in various hydrogen value chains, illustrated in Figure 1. Electricity generation and electrolysis are complemented by innumerable applications for hydrogen in industry and transport, multiplying the number of hydrogen value chains. The integration potential between sectors has a significant role in value creation in hydrogen value chains. For example, heat generated as a by-product of hydrogen production can be used in district heating networks, and consumption and production capacity can be operated flexibly by making use of the markets and infrastructure.

Hydrogen economy value chains involve a great deal of opportunity and have various dimensions. Since hydrogen can be used for a variety of purposes and each application has different technological requirements and markets, the continuous development of products, market platforms and technologies play an essential role in the future of hydrogen value chains.

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[1] COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS A hydrogen strategy for a climate-neutral Europe - COM/2020/301 final
[2] REPowerEU (europa.eu)

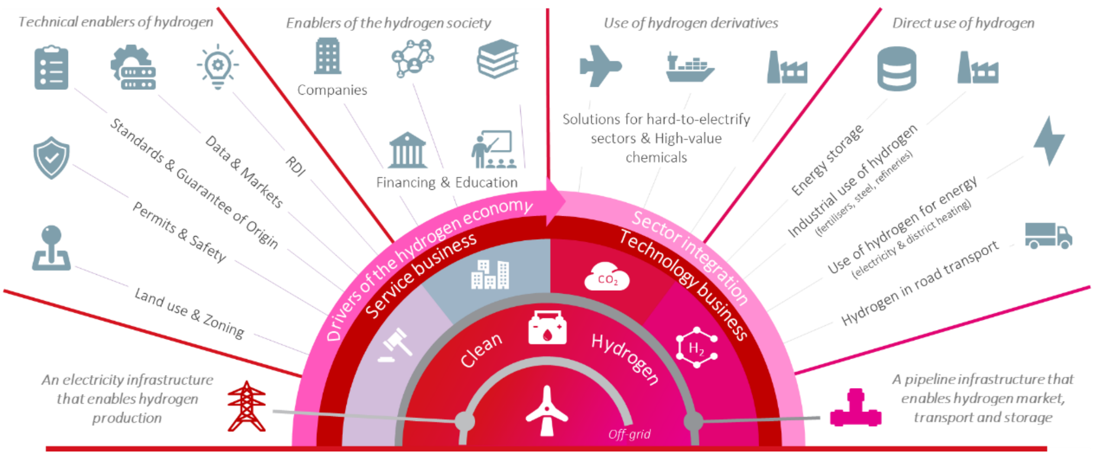

Figure 1. Dimensions of hydrogen value chain development. (Image: Gasgrid Finland)

The hydrogen value chain can be divided into hydrogen enablers, which drive the future of hydrogen use, as well as technical components, in which the utilisation of hydrogen in various sectors is emphasised. In addition to hydrogen production and its downstream products, the service and technology businesses provide important new opportunities for hydrogen value chains and enable rapid project development.

The energy infrastructure and the markets built on it, which face new challenges due to the transition from fossil-based to renewable energy, also have a key role in hydrogen value chains. New solutions and the electrification of society create major requirements for the development of energy transmission systems and deep sectoral integration. This, on the other hand, sets demand on the development of both hydrogen and electricity transmission infrastructures.

2.3 Operational environment is in the middle of a major transition

Approximately 150,000 tonnes (~5 TWh) of hydrogen produced through steam-reforming of fossil-based methane is currently consumed each year in Finland. The transport fuel and petrochemical industries, along with the industrial manufacture of fertiliser, are the major industrial hydrogen users in Finland. In 2021, Finnish electricity consumption amounted to approximately 86 TWh, and Finland's electricity production capacity was approximately 18,000 MW.[3]

However, the energy industry has been going through significant changes for the past two years. In the autumn of 2021, the Finnish government decided that Finland would draw up a hydrogen strategy and make a decision-in-principle to support the hydrogen economy, aiming to produce up to 10% of the clean hydrogen produced in the EU by 2030. Should this goal be achieved, Finland would produce up to a million tonnes of clean hydrogen.

The rate of connection inquiries made to Fingrid has increased considerably during this project. At the outset of the project in 2021, Fingrid had received approximately 100,000 MW worth of connection enquiries[4,5]. When Gasgrid and Fingrid published the project's interim report in March 2022, the volume of connection inquiries had already increased to 150,000 MW. Now, at the conclusion of the

[3] Sähkön toimitusvarmuus vuonna 2022 -report (in Finnish) (Finnish Energy Authority, 2023)
[4] Fingrid's Electricity System Vision 2023 (Fingrid, 2023)
[5] Fingrid Group's Half-Year Report 1.1.-30.6.2021 (Fingrid, 2021)

project, Fingrid has received more than 300,000 MW worth of inquiries for connections to the main grid. Most connection inquiries concern onshore wind power, but the shares of offshore wind power and solar power have grown significantly.

In the project's interim report, we estimated that Finland's clean hydrogen production potential would suffice for both domestic needs and export. At the time, we calculated that should the projects underlying the 150,000 MW worth of connection inquiries be realised, they would generate approximately 500 TWh of electricity per year. Nearly 450 TWh of this could be used for the needs of new industry, corresponding to more than 300 TWh of clean hydrogen production.

Dozens of hydrogen-related projects have also been launched in Finland during the project[6]. The prospects of hydrogen's role in the energy system of the future have increased constantly since the launch of the project, and hydrogen as one solution for enabling carbon neutrality has become a widely accepted axiom in energy industry scenarios.

2.4 Finland has the potential to become a forerunner of the hydrogen economy

The competitiveness of countries is a key factor in deciding where hydrogen production facilities will be established. Competitiveness is significantly influenced by the costs of investing in renewable electricity and hydrogen production, along with the price, availability and emissions of electricity used to produce clean hydrogen. In addition to the above, competitiveness is affected by factors such as the utilisation of by-products and opportunities for downstream operations. The favourability of the investment environment in terms of regulations, permits and social stability is also significant. Connection opportunities to energy transmission networks, the availability of competent labour and companies operating in the hydrogen value chain are also key considerations.

Active identification and elimination of bottlenecks is needed across the value chains to enable the growth of the hydrogen industry. For example, the slowness of obtaining permits is an identified problem that Finland is actively addressing with a programme for centralising permit procedures[7]. The consistency and clarity of regulations concerning renewable energy targets, reasonable reporting obligations, the overall development of the investment environment and increasing Finland’s international visibility are important factors in attracting new investments. The construction of renewable electricity production capacity in Finland and the energy infrastructure's ability to adapt to increased electricity supply and volatility play a key role.

Finland’s key competitive advantage in the production of renewable hydrogen is the competitiveness of Finnish solar and wind power, as demonstrated by Bloomberg's price comparison of long-term power purchase agreements (Figure 2). According to the comparison, Finland's PPA prices rank among the lowest three in the EU. Major changes have occurred in the investment environment of late, such as the increase of interest rates and decline in the profitability of wind power, which have slowed the rate of new wind power investment decisions considerably in Finland in 2023[8]. On the other hand, PPA

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[6] Green investments in Finland – data dashboard by EK (Confederation of Finnish Industries, data fetched on 8.5.2023)
[7] https://ym.fi/-/seurantaryhma-edistamaan-sujuvaa-ymparistollista-luvitusta - in Finnish (Ministry of the Environment, 2.8.2023)
[8] https://yle.fi/a/74-20048410 - in Finnish (YLE, 12.9.2023)

prices have probably risen everywhere since the spring of 2022, and Finland's position in relation to other countries has probably remained similar.

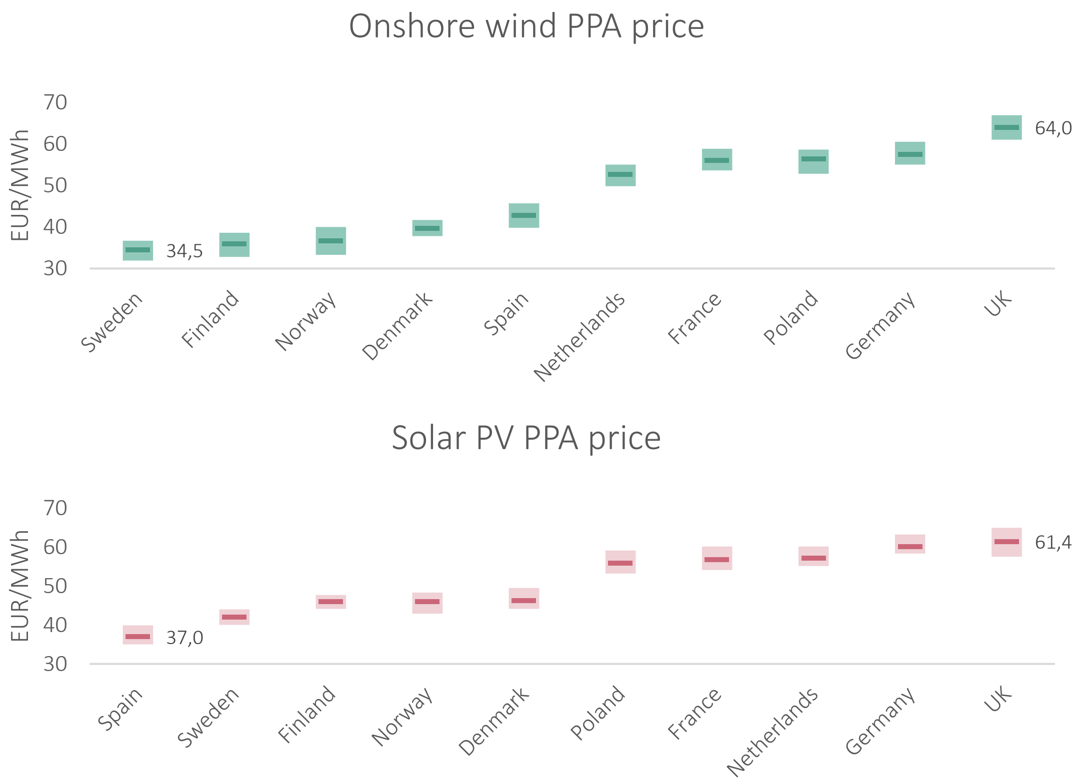

Figure 1. In the first half of 2022, Finnish onshore wind power PPA (power purchase agreement) prices were the second-lowest and solar power PPA prices the third-lowest in Europe[9].

During the project, Gasgrid and Fingrid have actively monitored changes in the environment and analysed potential development paths and opportunities for the hydrogen economy. The increased rate of development and other factors increasing the speed of change in the operating environment may nevertheless cause significant changes in the energy system at fairly short notice, which can be difficult to predict. However, the companies consider that Finland has an excellent opportunity to become a forerunner in the hydrogen economy regardless of any short-term economic fluctuations.

[9] Wind and Solar Corporate PPA prices Rise Up To 16.7% Across Europe (BloombergNEF, 28.4.2022)

2.5 The role of infrastructure in a changing energy system

Thanks to its excellent clean energy resources, strong energy transmission networks, competitive electricity prices and high level of technological expertise, Finland has great potential for leading the development of the hydrogen economy. Leveraging Finland's great renewable energy potential for the hydrogen economy will nevertheless require considerable investments from both electricity and hydrogen producers, other industry actors and transmission and distribution network operators alike.

As the project progressed and the prospects of the hydrogen economy grew, the need arose to also expedite the development of the energy infrastructure to enable the realisation of investments and the creation of various hydrogen economy value chains in Finland.

The prospects of the hydrogen economy make it clear the electricity main grid must be expanded and reinforced to enable the connection of renewable electricity production and the clean hydrogen production using that electricity as well as improve the availability of electricity. If the main grid is not reinforced, it will not be possible to leverage Finland's full hydrogen production potential, since the large-scale production of green hydrogen will be expensive and inefficient if the production of renewable energy and its transmission capacity over the grid are not increased.

The transmission and storage of energy as hydrogen is also an important enabler for achieving Finland's hydrogen economy potential and the development of a cost-effective energy system. The hydrogen network will enable the cost-effective transmission of hydrogen on a large scale between operators, enable the growth of the hydrogen economy and create new business opportunities for operators in the value chain.

The physical connection of hydrogen producers and consumers is important for the availability and competitiveness of hydrogen. Hydrogen infrastructure can connect several producers and consumers, laying the groundwork for wider development of the market. The creation of a large hydrogen market reduces the risks of hydrogen production and consumption. The hydrogen network can also serve as a buffer storage for hydrogen, enable flexible consumption and support the electricity system in the transmission of energy. Furthermore, an international hydrogen network can enable access to more end-user markets as well as geological hydrogen storages outside the borders of Finland.

2.6 Gasgrid's and Fingrid's energy infrastructure development measures

Fingrid has drawn up the Electricity System Vision 2023[10] and updated the Main Grid Development Plan[11], which presents the development needs and planned investments to the main grid for the next ten years. Investments in the main grid will grow to four billion euros from the previous estimate of just over three billion. The goal of the main grid investments is to enable Finland's competitiveness in industrial investments and enable the achievement of carbon neutrality targets by 2035. The development plan is based on network and connection plans drawn up by Fingrid together with its customers, as well as on the needs for reinforcing electricity transmission between the neighbouring countries and regions. The plan is aligned with the European Union's ten-year network development plan (TYNDP).

[10] Fingrid's Electricity System Vision 2023 (Fingrid, 2023)
[11] Main Grid Development Plan 2024–2033 (Fingrid, 2023)

Gasgrid is actively developing its transmission platform and services to correspond to the needs of its customers and the changing energy system. Gasgrid is an active participant in the European Hydrogen Backbone (EHB) group, which is an initiative by 33 European energy infrastructure companies that promotes the vision of a common hydrogen infrastructure and market development in Europe. Gasgrid has participated in drafting the Baltic development vision in the EHB group and launched three concrete major hydrogen infrastructure development projects based on the vision. These projects are:

- Nordic Hydrogen Route – Bothnian Bay, a joint project by Gasgrid Finland and Nordion Energi, which accelerates the birth of the hydrogen economy by developing cross-border hydrogen infrastructure and an open hydrogen market around the Bay of Bothnia. The goals of the project are to promote the achievement of carbon neutrality targets and support regional green industry, economic development and Europe's energy self-sufficiency. The Nordic Hydrogen Route also accelerates the realisation of the hydrogen economy and new investments, which support the European energy transition and improve the availability of competitive domestic green energy.

- The Baltic Sea Hydrogen Collector project explores the possibility of building a large-scale offshore hydrogen pipeline infrastructure connecting Finland, Sweden and Central Europe, which would enable the production of clean and sustainable hydrogen for the needs of Europe. The project partners are Gasgrid Finland, Nordion Energi and the industrial companies OX2 and Copenhagen Infrastucture Partners. Gasgrid's role focuses on enabling the exploitation of wind power in Finland's sea areas and the development of the Baltic market.

- The Nordic-Baltic Hydrogen Corridor project aims at developing hydrogen infrastructure connecting Finland with Germany via Estonia, Latvia, Lithuania and Poland. In the project, Gasgrid focuses on the construction of a hydrogen network covering the whole of southern Finland and the development of the Baltic market. The project seeks to support the diversification of the energy supply and accelerate the adoption of renewable energy. As the hydrogen infrastructure around the Baltic develops, it will also be possible to create a strong hydrogen market that enables the large-scale exploitation of plentiful and competitive renewable energy resources.

All of the hydrogen infrastructure development projects seek to develop the hydrogen infrastructure in Finland and the Baltic region and enable an open hydrogen market by 2030. Figure 3 presents Gasgrid Finland’s large-scale hydrogen transmission infrastructure development projects.

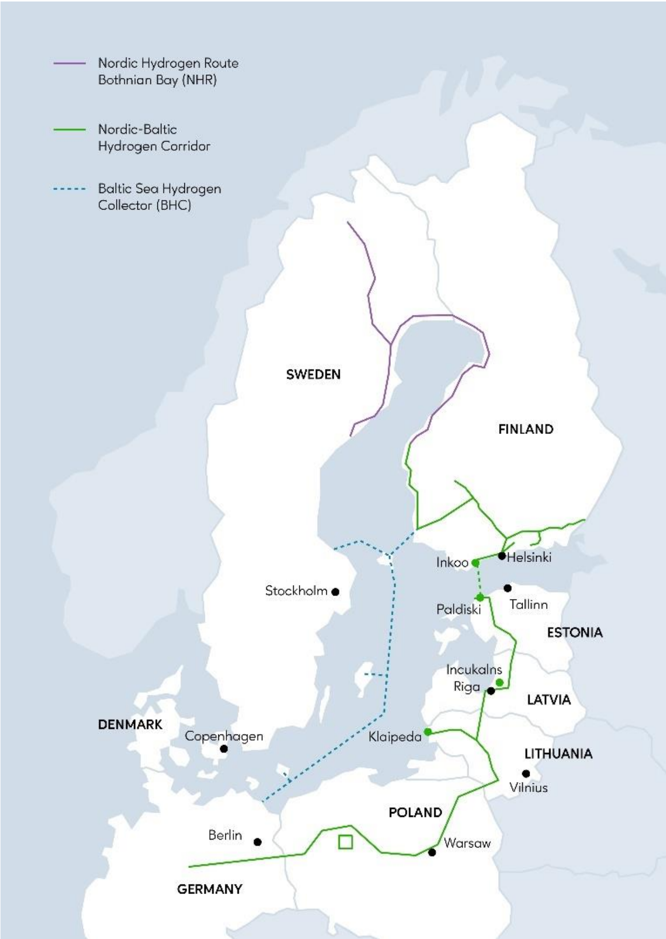

Figure 2. Gasgrid Finland's large-scale hydrogen transmission infrastructure development projects on the map. (Image: Gasgrid Finland)

3 Regulation and legislation

3.1 Regulation and its impact on the development of the hydrogen economy

The development of the hydrogen economy is strongly guided by European energy and climate targets. The European Commission published its Green Deal initiative[12] in December 2019. The initiative sets legislative goals and focuses on climate policy and the circular economy. The Green Deal was followed by the publication of the Fit For 55 package in July 2020. The ambitious emissions reductions required and renewable energy targets set for 2030 in the Renewable Energy Directive cannot be achieved without hydrogen.

The European Commission has also introduced a number of financing mechanisms supporting the hydrogen markets, such as the NextGenerationEU recovery plan adopted during the COVID-19 pandemic, which aims to expedite green investment at the Member State level, as well as the EU Innovation Fund's investment subsidies for greenhouse gas emission reducing technologies. In addition to these, the Commission presented the Hydrogen Bank, which will pilot its first 800-million-euro auction in the final quarter of 2023.

All of these policy initiatives have a direct or indirect impact on the development of the Finnish hydrogen market. The financing mechanisms are open to Finnish companies, offering the possibility of additional funding to complement national systems. Member States have also supplemented the EU legislative framework with their own measures for implementing the hydrogen market.

As hydrogen has a significant role in the achievement of emissions reductions, the European Commission has regulated clean hydrogen comprehensively. The Commission has provided for a definition of renewable hydrogen and rules for its production. It has also established requirements for the use of renewable hydrogen. The most ambitious targets for hydrogen, and especially its derivatives, were set for maritime and air transport, with requirements for fuel consumers and distributors extending all the way to 2050.

Hydrogen and its derivatives will also be added to the distribution obligations of each Member State by 2030, and industries must replace the majority of their fossil-based hydrogen consumption with clean hydrogen by 2035. The downstream and end-use market consumption of clean hydrogen in the industrial and transport fuel sectors is regulated with general requirements on the amount of clean hydrogen to be used in industry, complemented with specific targets, e.g. for aviation fuel produced with clean hydrogen, for transport fuels.

Many packages essentially related to the regulation of hydrogen, such as the Renewable Energy Directive and maritime and air transport regulation package, have been completed this year, thus consolidating the prospects for clean hydrogen demand. The time span of the above-mentioned regulation packages is noteworthy, since the targets set by the Renewable Energy Directive are mostly focused on 2030, while those for maritime and air transport extend all the way to 2050. It is also evident that, for example, the Renewable Energy Directive and production rules for RFNBO hydrogen (delegated acts) will be updated before 2030, which creates some uncertainty regarding hydrogen regulation policy. The hydrogen and low-carbon gas package will probably also be completed in 2023, laying the groundwork for the formation of the hydrogen economy, as well as a package on the use of

[12] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_fi

hydrogen gas in current natural gas networks. Both national and EU subsidies have been planned to support the hydrogen economy. However, there is no certainty about the amounts of these subsidies, or the practices related to them. Figure 4 presents the key regulation packages related to hydrogen.

REGULATED OPERATING ENVIRONMENT OF CLEAN HYDROGEN	INFRASTRUCTURE (Power grids, chargers, pipelines and refueling stations)	CLEAN HYDROGEN AND ITS DERIVATIVES: Production resources (Water, carbon dioxide, electricity)	CLEAN HYDROGEN AND ITS DERIVATIVES: Production process	CONSUMPTION (Industry, transport and households)
Renewable Energy Directive, RED III		☑	☑	☑
RFNBO[1] Delegated Acts	⬚	☑	☑	
REfuelEU Aviation & FuelEU Maritime		⬚	⬚	☑
EU Emissions Trading System, EU ETS		☑	⬚	☑
Energy Efficiency Directive, EED		☑	☑	☑
Carbon Border Adjustment Mechanism, CBAM		☑	☑	☑
Alternative Fuels Infrastructure Regulation, AFIR	☑			
Energy Tax Directive, ETD		☑		
Gas Package[2]	☑	⬚	☑	

(1) RFNBO = Renewable fuels of non-biological origin = EU's definition for renewable hydrogen and hydrogen derivatives; (2) Gas Packages = Directive on internal market rules for renewable and natural gases and hydrogen

Figure 3. Essential clean hydrogen regulation packages, along with their impact on the hydrogen value chain. (Image: Gasgrid Finland)

Annex 3 describes the various regulatory packages affecting the regulated operating environment for clean hydrogen in more detail.

3.2 Legislation related to the safe processing, storage and transmission of hydrogen

Most legislation related to hydrogen is passed at the EU level and implemented into national legislation. The safe processing, storage and transmission of gases is already provided for in national laws and regulations (Table 1), but there are not detailed provisions for the transmission of hydrogen yet. As the first use cases emerge, active dialogue will be conducted with national authorities, such as the Finnish Safety and Chemicals Agency (Tukes), existing regulations will be complied with where applicable, and further studies and planning will be conducted to ensure the safe processing of hydrogen.

It is assumed that transmission legislation will be based on that applying to the transmission of natural gas, as it provides the closest point of reference for established legislation and regulation regarding the transmission of gases. Tukes is preparing the Hydrogen Guidebook, which will also address the transmission of hydrogen outside the plant area.[13] Since the transmission of hydrogen and the related legislation are also being developed outside Finland, it is essential to keep an eye on the international framework. International standards for hydrogen transmission are already in place. In addition to legislation, standards and guidance directly related to the transmission of hydrogen, the legislation and standards related to electrical safety, inspections, maintenance and installation will be taken into account.

[13] The Finnish Safety and Chemicals Agency, Tukes. (27.9.2023). Vedyn turvallinen käsittely ja käyttö. Finnish Gas Association course - Vetytalouden perusteet – vety ja synteettinen metaani – in Finnish

Table 1. Legislation, guidance and international standards related to the safe processing, storage and transmission of gases.

Acts and regulations	Guidance	Standards
Government Decree on the Safe Processing of Natural Gas 551/2009 (”Natural Gas Decree”) Act on the Safe Handling of Dangerous Chemicals and Explosives 390/2005 (”Chemical Safety Act”) Government Decree on the Safety Requirements for the Industrial Processing and Storage of Dangerous Chemicals (856/2012) (”Chemical Safety Decree”) Government Decree on the Monitoring of the Processing and Storage of Dangerous Chemicals (685/2015) Government Decree on Preventing Hazards Caused by Explosive Atmospheres to Employees (576/2003) Pressure Equipment Act 1144/2016 Government Decree on Pressure Equipment 1548/2016	Tukes's guide to the application of the Natural Gas Decree[14] Tukes's recommendations based on the Chemical Safety Act and Decree[15]	ASME B31.12-2019 Hydrogen Piping and Pipelines ASME Code for Pressure Piping, B31 EN 1594 Gas Infrastructure – Pipelines for maximum operating pressure over 16 bar EN ISO 3183 Steel pipe for pipeline transportation systems EIGA/IGC Doc 121/14 Hydrogen Pipeline Systems EIGA/IGC Doc 75/07/E Determination of Safety Distances CGA G-5.5 – 2021 Standards for Hydrogen Vent Systems ISO/TR 15916:2004 Basic considerations for the safety of hydrogen systems NFPA 55 Compressed Gases and Cryogenic Fluids Code NFPA 50A Standard for Gaseous Hydrogen Systems at Consumer Sites API 521 7th Ed. 2020 Pressure-relieving and Depressuring Systems

[14] Tukes (Finnish Safety and Chemicals Agency), 2015. Guidance 7/2015. https://gasgrid.fi/wp-content/uploads/Tukes-ohje-7-2015-Maakaasun-k%C3%A4sittelyn-turvallisuus.pdf – in Finnish
[15] Tukes (Finnish Safety and Chemicals Agency), 2015. Guidance. ISBN 978-952-5649-67-3: https://tukes.fi/documents/5470659/6406815/Productionlaitosten+sijoittaminen/ab664564-66f7-49b7-96bb-316dfefe4517/Productionlaitosten+sijoittaminen.pdf?t=1516707669000 – in Finnish

4 Technical solutions and design principles for the transmission of hydrogen

This Section deals with the properties of hydrogen gas and their impact on the technical solutions for the pipe transmission of hydrogen. The Section also presents the principles for the design and construction of hydrogen transmission pipeline infrastructure.

4.1 Properties of hydrogen

Hydrogen gas (H2) is a colourless, odourless, lighter-than-air, flammable and explosive gas. One of the properties of this gas is that it heats up as pressure decreases. Just 0.02 mJ of energy is enough to ignite a mixture of hydrogen and air (cf. 0.25 mJ for hydrocarbons). Hydrogen ignites at concentrations of 4–75.6%. A leak of pressurised hydrogen can generate so much static charge that the leak appears to ignite spontaneously. Static charge from other sources, sparks, hot surfaces, and flames easily ignite hydrogen. A rusty surface can ignite hydrogen at temperatures considerably lower than the auto-ignition temperature (560 °C).[16]

Due to its small molecule size, hydrogen is one of the most challenging gases in terms of leak management. Pure hydrogen gas is not toxic, but can cause an asphyxiation hazard in large concentrations, as it displaces oxygen. Hydrogen burns with a light blue, nearly invisible flame in air, which makes the flame difficult to detect and thus increases the risk of injury in the event of a fire. In a confined space, a hydrogen leak causes an explosion hazard.

The net calorific value of hydrogen, 120 MJ/kg, is high compared to that of, for example, methane at 50 MJ/kg. However, hydrogen has a relatively low energy density, since the energy density of e.g. liquid hydrogen is 8 MJ/l, while the corresponding value for liquid methane is 22 MJ/l (Figure 5).[17] This low energy density causes differences in the transmission of hydrogen and methane, since the liquation of hydrogen requires extremely low temperatures and its pressurisation consumes more energy than that of methane.

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[16] Työterveyslaitos (Finnish Institute of Occupational Health). (12.7.2022). Vety. https://ova.ttl.fi/Vety - in Finnish
[17] U.S. Department of Energy. (2022). *Hydrogen Storage. Hydrogen and Fuel Cell Technologies Office.* https://www.energy.gov/eere/fuelcells/hydrogen-storage

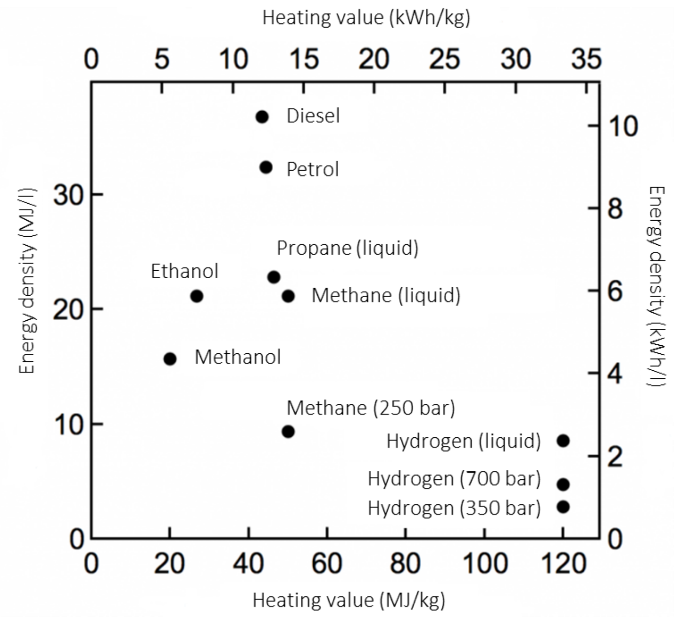


Figure 4. Energy densities and net calorific values of fuels. (Image: U.S. Department of Energy[17])

The exposure of an alloy to hydrogen and the penetration of hydrogen into the material can cause a phenomenon known as hydrogen embrittlement. Welds are particularly susceptible to this phenomenon. This is a corrosion mechanism characteristic to hydrogen. If even minor quantities (ppm) of impurities are mixed into the gas, it can multiply the corrosion problems compared to pure hydrogen. Hydrogen embrittlement is a common term for a number of phenomena connected by hydrogen assisted fatigue crack growth and a reduction of fracture toughness and load.[18] In addition to penetrating pipes during transmission, hydrogen can also enter structures in connection with steel production.

4.2 Alternatives in hydrogen transmission

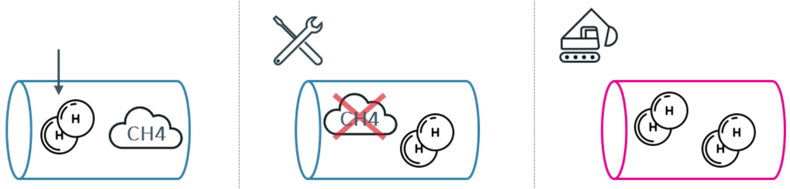
Several projects aiming for the production and use of clean hydrogen have been implemented or are underway globally. Hydrogen can either be used at the place of production or transported to consumption sites, which requires hydrogen transmission solutions. Decentralised hydrogen production and consumption and the construction of large-scale hydrogen storage facilities are expected to increase the need for hydrogen transmission.

Hydrogen can be transported by truck in pressurised (200–700 bar) containers or tanker trailers. It can be transported as either pressurised hydrogen gas or liquefied hydrogen. Trucks can transport a relatively small amount of hydrogen, so road transport is mainly suitable for small amounts of hydrogen (less than 10 tonnes/day) for short distances (under 500 km).

Hydrogen can be transmitted through pipes, either by making use of the existing methane network or constructing a greenfield network specifically designed for hydrogen (Figure 6). Existing methane pipelines can be used either by blending hydrogen with methane or repurposing the pipelines to

[18] Zafra, A., et al. Hydrogen-assisted fatigue crack growth: Pre-charging vs in-situ testing in gaseous environments. Materials Science and Engineering: A 871:144885 (2023).

transfer hydrogen. Both solutions require a case-by-case feasibility study regarding, for example, technical solutions and pipe materials. The different pipeline transmission options differ in terms of the need for changing existing equipment, investment costs and the volume of hydrogen transmitted. In a blending solution, increasing the proportion of hydrogen also increases the need for making changes to equipment, potentially bringing the amount of work close to that required for a greenfield solution.



	Blending	Repurposing	Greenfield
Hydrogen share	Limit defined case by case*	100%	100%
Investment needs	Gas measurement devices, compressor depending on H_2 share, and compressor design, dimensions, and lifetime	Gas measurement devices, compressor, valve actuators, pig traps, venting system, valve applicability must be determined	Complete system
Pipeline routing	Fixed pipeline routing, which is not optimised for hydrogen production and consumption sites	Fixed pipeline routing, which is not optimised for hydrogen production and consumption sites	Designed according to the needs of hydrogen production and consumption sites

*In Finland, the limit for hydrogen share is 1%. Hydrogen blending is applied in several projects in Europe, e.g., with 5% hydrogen share.

Figure 5. Three ways of implementing the pipe transmission of hydrogen. (Image: Gasgrid Finland)

There is approximately 5,000 km of pipeline designed for hydrogen in use around the world, mainly in Europe and the United States (Table 2)[19]. The oldest pipeline still in use dates to the 1930s. These pipelines typically connect current production facilities and industrial consumption sites with onshore pipes with a small diameter (<DN450) and low pressure. The most extensive hydrogen pipeline in Europe is owned by Air Liquide and runs for over 1,000 km at high pressure, but the pipe diameter is small. The new cross-border or even intercontinental hydrogen pipelines being planned are considerably larger in diameter, and the plans include offshore construction.

Table 2. Hydrogen pipelines by owner and location.[19]

Hydrogen pipelines, 2016			
Company	Length	Continent	Length
Air Liquide	1936	USA	2608
Air Products	1140	Europe	1598
Linde	244	Rest of the world	337
Praxair[20]	739	**Total**	**4542**
Others	483		
Total	**4542**		

[19] Hydrogen Tools. (2016). Hydrogen Pipelines. https://h2tools.org/hyarc/hydrogen-data/hydrogen-pipelines
[20] Praxair is nowadays part of Air Products company.

4.3 Developing the hydrogen transmission infrastructure to meet market needs

The design and dimensions of the national hydrogen network involves many open questions since the renewable hydrogen market is still in the early stages of development. The hydrogen infrastructure design process was begun early to enable market actors' own investments in the value chain andthe formation of "hydrogen valleys", thereby supporting the development of the wider market taking shape around hydrogen. The design of the hydrogen network can be viewed as a multi-phase, iterative process (Figure 7), in which the baseline data is constantly being specified as the technological preconditions and factors affecting the operating environment, such as national goals, market actors and value chains, regulation and safety requirements become clearer.

In simplified terms, the formation of the hydrogen architecture can be described as follows:

1. **Scenarios for pipeline routing and connection point volumes and pressures.** These scenarios vary, for example in terms of the locations and growth prospects of renewable energy capacity, the expected production and consumption of hydrogen, the pressure levels needed by customers, the required storage capacity, land use planning and the future development of the network. The current state of electricity production and its development plans will be taken into account in the joint development of the hydrogen and electricity networks. Discussions with stakeholders play a key role in this phase.
2. **Technological possibilities and preconditions for the volumes and pressures according to each scenario.** Due to the different characteristics of hydrogen and methane, not all devices used for methane transmission can be used to transfer hydrogen without modifications. The scale and operation modes of the solutions also affect the suitability of devices. Some of the solutions, such as centrifugal compressors, are still under development. At this stage, discussions with technology suppliers are key to the charting and choice of appropriate and available solutions.
3. **Dimensioning and technology choices for the chosen scenarios.** The hydrogen network and its devices will be dimensioned according to the scenarios and within the existing technical preconditions. This enables the charting and choice of available technologies, devices, and materials. The technical preconditions and possible further information on the needs of the hydrogen market, obtained during the hydrogen network development process, will guide the specification of the pipeline and its routing.

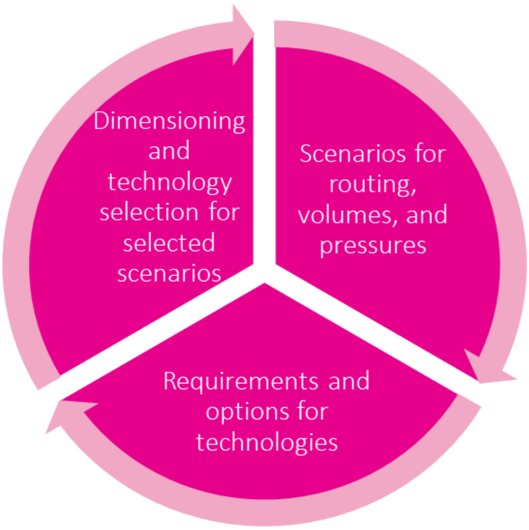


Figure 6. Main stages of the iterative hydrogen network design. (Image: Gasgrid Finland)

The purpose of the part of the hydrogen network being examined and the customer's connection role affect the design process (Figure 7). The purpose of the hydrogen pipeline is to connect hydrogen production and consumption sites spatially and temporally through the transmission and storage of hydrogen. The scope of transmission and storage varies both geographically as well as in terms of volume and the number of parties involved. The sub-sections of the hydrogen network can be divided into the following components according to scope:

- a hydrogen pipe can be a "point-to-point" pipe responding to a specific need by connecting two actors or regions;
- a hydrogen pipeline can form a regional network connecting various actors (a "hydrogen valley");
- a hydrogen pipe can be part of the national hydrogen network; and
- the national hydrogen network can be connected to the hydrogen network around the Baltic Sea.

The possible later connection of sections to each other must be taken into account in the design of the hydrogen network. The simultaneous promotion and development of regional hydrogen valley projects and larger infrastructure projects comprising the main line of the national hydrogen network in a manner meeting the needs of transmission customers is a key consideration in infrastructure design and development. A transmission customer can have the role of hydrogen producer, consumer or storage provider, or a combination of these (Figure 8).

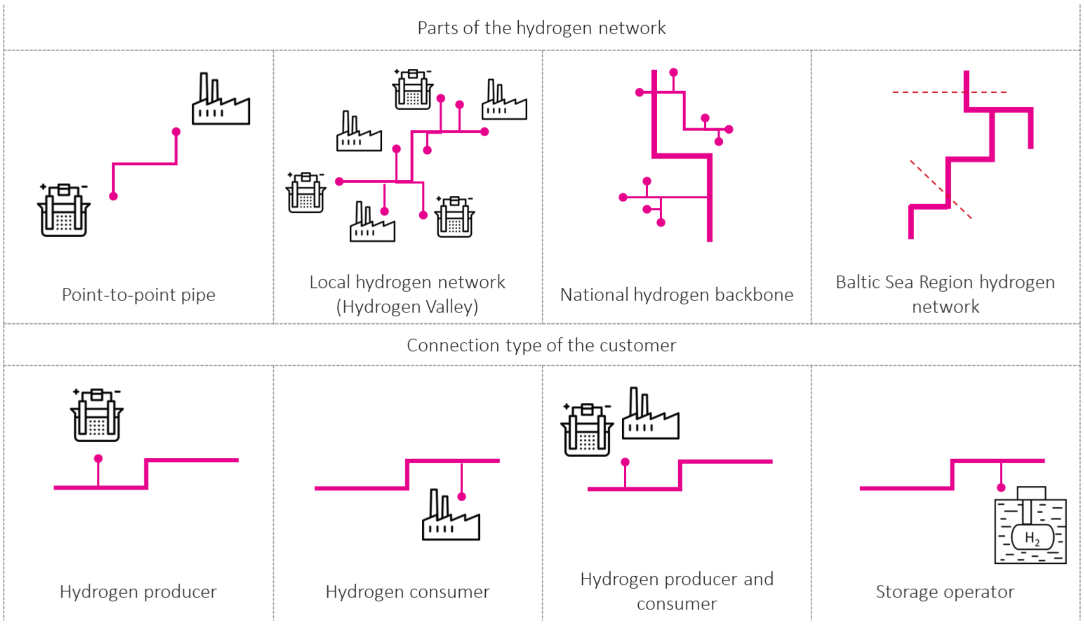


Figure 7. The design of a hydrogen network is influenced e.g., by its purpose and the role of customers in the network. The future needs of the hydrogen network must also be taken into account in the design. (Image: Gasgrid Finland)

4.4 Technical solutions for pipeline transmission infrastructure for hydrogen

The connection principles of the hydrogen transmission infrastructure are still in development. However, certain commonalities with technical solutions employed in the methane system and with biogas feeding principles have been identified during the development process. According to current information (Figure 9), the hydrogen producer increases the hydrogen pressure to the agreed intake pressure required by the compressor in the transmission network. The composition of the hydrogen fed into the transmission network is also analysed and the amount of hydrogen measured. After this, the pressure of the hydrogen is increased to that of the transmission network at the compressor station. The flow of hydrogen in the transmission pipeline is based on pressure differences between different areas of the network. These pressure differences are most often caused by differences between the flow profiles of connection points in the network. Before delivery to the customer, a pressure reduction station in the transmission network reduces the pressure of the hydrogen to that of the distribution network at the consumer's facility. The pressure reduction station also measures the amount of hydrogen. The system is operated and monitored remotely from Gasgrid's control room. Annex 4 describes the various parts of the transmission infrastructure and their operating principles in more detail.

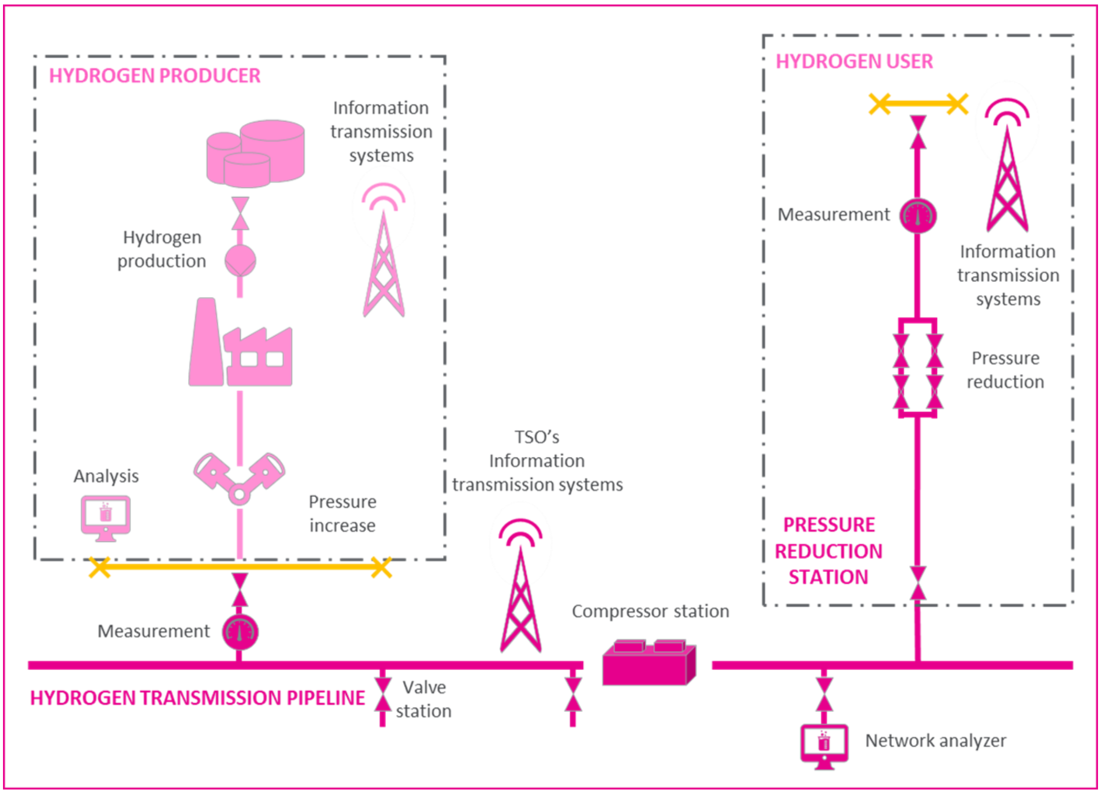


Figure 8. Structure of the pipe transmission infrastructure for hydrogen. Functions under Gasgrid Finland's responsibility in magenta. Processes of the customer connecting to the pipeline in pink. Interfaces between areas of responsibility in yellow. (Image: Gasgrid Finland)

4.5 Factors affecting the costs and design of the hydrogen pipeline

The hydrogen pipeline's design principles are similar to those of the methane pipeline. Decades of experience in safe and reliable design, construction and operation has been accumulated from the methane network, and these experiences will be used in the solutions of the Finnish hydrogen network. Every technical and other limitation along the pipeline's route is taken into consideration in its design, such as suitability for construction, structural integrity, general safety, environmental and socioeconomic impacts, the required permits, maintenance, monitoring of the pipeline's condition, and commissioning requirements. From the perspective of permit processes, hydrogen infrastructure projects can be assumed to be similar to methane and power line infrastructure projects[21].

The factors affecting the costs and design of the pipeline include:

- **Pipeline routing.** Pipelines can be built in fields, forests and underwater. The pipeline route and soil quality affect construction costs. Factors such as population and its density (area category), existing infrastructure (e.g. high voltage power lines, roads, and railways) and nature reserves and groundwater catchment areas. Following the existing methane pipeline could achieve synergies, especially in land use.

[21] For the electricity main grid, a transmission line project duration including all phases is 5–8 years. Detailed description of project stages can be found here: https://www.fingrid.fi/en/grid/construction/project-stages/ (Fingrid, 2023)

- **Land acquisition.** Land acquisition is discussed with landowners. As the competent authority, National Land Survey of Finland (NLS) is responsible for the official processes for changing rights of use and ownership to land. These are multi-stage processes involving several stakeholders. Areas redeemed with rights of use include those required for valve stations, pressure reduction stations, compressor stations, link stations and anode fields. The operator will obtain rights of use to areas through which the pipeline passes.
- **Pipeline.** A hydrogen pipe is thicker than a methane pipe due to hydrogen embrittlement and pressure variation. The diameter of the pipe is determined according to the planned transmission and storage capacity. The mass of the pipe affects material needs, welding needs and installation costs.
- **The compressor station** accounts for a significant percentage of the project’s total costs. The choice of technology and dimensioning are influenced heavily by factors such as flow speed, pressure level and the need for adjustability. It is also noteworthy that, due to the low energy density of hydrogen, the compressor station requires much more space than a methane compressor station.
- **The pressure reduction station and valve stations** affect the total costs of the project. The number of valve stations is determined by the design of the network, which needs to address certain safety aspects.
- **Design pressure and the number of pressure variation cycles.** There is no history data on the effects of the pressure variation range and the number of pressure variation cycles on the durability of pipe materials. A thicker pipe than for methane is required due to hydrogen embrittlement.
- **Design, monitoring, and permit processes** account for a significant portion of a long infrastructure project’s costs.

Ultimately, pipeline design consists of optimising the pipe's route, diameter, pressure level and compressor power in terms of costs and transmission and storage capacity. Aspects influencing the choice of pipe diameter include transmission capacity (MW), storage capacity needs, pressure difference, pipe length, friction coefficient and the greatest permitted flow rate.

Aspects influencing pipe routing include the locations of electricity and hydrogen production plants and those of hydrogen consumption sites. The locations of these, on the other hand, are affected by the locations of plots suitable for production and consumption facilities in relation to the environment, for example in terms of land use planning and other land use, as well as possibilities for utilising side product heat. Furthermore, in the case of the production of downstream hydrogen products, such as synthetic fuels or chemicals, locations are also affected by the availability of carbon dioxide. The locations of production facility investments calculated in the hundreds of millions are affected by the conditions of the overall investment environment, such as the availability of labour, other logistics, public services, and the availability of other commodities. Route planning is facilitated through active dialogue with customers and stakeholders to ensure that the future hydrogen network would serve the needs of actors in the best possible manner.

5 Scenarios driven by a new major export industry

In this Section, the three scenarios drawn up in the joint project to support the development of Finnish energy transmission systems are presented. The scenarios pay particular attention to the possible development paths of the hydrogen economy. The scenarios focus on the alternative development paths of the hydrogen infrastructure, as well as on sectoral integration between the hydrogen, gas and electricity transmission infrastructures. A comprehensive analysis of infrastructure development needs is important to ensure that the future energy system is cost-effective and supports Finland’s competitiveness in the best possible manner.

The joint project's scenarios for the development of Finland’s hydrogen economy are presented in Section 5.1. The premises used for modelling the scenarios are described in Annex 1 followed by a discussion of the key results of the modelling: Section 5.2 examines the production of clean hydrogen in Finland in each scenario, covering domestic demand and export. A summary of electricity production capacity needs is presented in Section 5.3. Finally, Section 5.4 discusses the role of hydrogen storage in balancing the energy system. Detailed modelling results are provided in Annex 2.

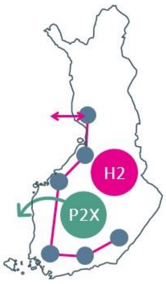
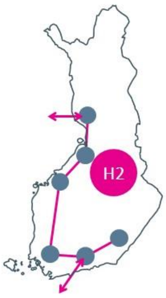
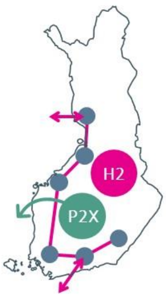
5.1 Development paths for the Finnish hydrogen economy – three scenarios

Ambitious growth assumptions regarding the development of the hydrogen economy were chosen for the scenarios, as these ensure an in-depth exploration of energy system development. Challenging scenarios help ensure that transmission infrastructure development needs are assessed comprehensively and in good time. Actual infrastructure investments will be implemented according to identified needs and through concrete projects. The scenarios also build a picture of Finland's great potential and role in the European hydrogen economy and thus also highlight the hydrogen economy’s wider social impact.

Table 3 presents the guidelines of Gasgrid’s and Fingrid's three scenarios for the development of Finland's hydrogen economy. The scenarios explore different development paths for the energy transmission infrastructure from the perspective of the Finnish energy system. The key variable in these scenarios is Finland’s assumed role in the hydrogen market value chain: Will Finland develop into a major exporter of hydrogen downstream products, hydrogen gas or both for the growing needs of the European market? National hydrogen infrastructures and hydrogen infrastructures oriented towards export and import have been generated for the scenarios based on this variable. The formation of the national and international infrastructures also has extensive effects on the rest of the energy system (see Section 5.4).

The baseline premise for all scenarios is that Finland achieves its carbon neutrality targets and the production of clean hydrogen increases dramatically in Finland. Overall electricity demand is estimated to grow alongside the demand generated by hydrogen production and hydrogen downstream products. Demand will grow in the transport, heating and manufacturing industries as fossil fuels are replaced with electricity. It is also assumed that new electricity-intensive industries, such as battery manufacturing and data centres, will be created in Finland. The electricity consumption of these sectors is assumed to develop similarly in all scenarios.

Table 3. Description of Gasgrid's and Fingrid's hydrogen economy scenarios and illustrative regional hydrogen transmission connections in each scenario.

SCENARIO	DESCRIPTION
Strong Regional Hydrogen Economy  	Electricity production and transmission • A lot of renewable electricity production will be commissioned in Finland, most of which is onshore wind power • The Finnish main grid will be reinforced significantly, and planned cross-border transmission connections to Northern Sweden and Estonia will be commissioned Hydrogen production and consumption • The current Finnish industries that use hydrogen will switch to clean hydrogen • Finland develops into a major exporter of P2X products Hydrogen transmission infrastructure • Domestic hydrogen transmission infrastructure and cross-border infrastructure to Northern Sweden will be commissioned Hydrogen storages • Several hydrogen storage facilities will be commissioned in Finland
European Hydrogen Market  	Electricity production and transmission • A lot of renewable electricity production will be commissioned in Finland, most of which is onshore wind power • The Finnish main grid will be reinforced significantly, and planned cross-border transmission connections to Northern Sweden and Estonia will be commissioned Hydrogen production and consumption • The current Finnish industries that use hydrogen will switch to clean hydrogen • Finland develops into a major exporter of hydrogen gas Hydrogen transmission infrastructure • Domestic hydrogen transmission infrastructure and cross-border infrastructure to Northern Sweden and Central Europe will be commissioned Hydrogen storages • Hydrogen storage facilities will be commissioned in Finland • Finland can make use of the large hydrogen storage facilities in Central Europe
Leading Hydrogen Ecosystem  	Electricity production and transmission • A lot of renewable electricity production will be commissioned in Finland, most of which is onshore wind power • The Finnish main grid will be reinforced significantly, and planned cross-border transmission connections to Northern Sweden and Estonia will be commissioned Hydrogen production and consumption • The current Finnish industries that use hydrogen will switch to clean hydrogen • Finland develops into a major exporter of P2X products and hydrogen gas Hydrogen transmission infrastructure • Domestic hydrogen transmission infrastructure and cross-border infrastructure to Northern Sweden and Central Europe will be commissioned Hydrogen storages • Several hydrogen storage facilities will be commissioned in Finland • Finland can make use of the large hydrogen storage facilities in Central Europe

In all the scenarios, clean hydrogen will replace the grey hydrogen currently used by Finnish industries, and clean hydrogen will also be used in the manufacturing of products such as fossil-free steel and electrofuels. In addition to the growth of domestic demand, Finland will grow into a major player in the European hydrogen market and most of the demand will ultimately be created by export, either as downstream products and/or as hydrogen gas for the needs of the European market.

The electrification of society will require extensive reinforcement of both national and cross-border electricity transmission connections. The Finnish electricity main grid will be reinforced significantly to connect producers and consumers and increase transmission capacity. The north-south capacity (across the cross-section of Central Finland, see Figure 15) is assumed to increase to 13 gigawatts by 2040. In addition, the Aurora Line cross-border electricity transmission connection between Northern Sweden and Finland will be in use in all scenarios, and the Aurora Line 2 and Estlink 3 cross-border connections will be built in the 2030s.

All scenarios assume that hydrogen pipe connections are available in Finland and between Finland and Sweden from 2030 onwards. The transmission capacity of the hydrogen pipe is assumed at 13 GW of hydrogen, corresponding to a pipe with a diameter of 1.2 metres. In the draft scenarios, the pipe capacity was 7.2 GW based on the pipe dimensions used in the Bothnian Bay Hydrogen Valley study[22] but increased hydrogen demand will require larger pipes, especially in 2040. Furthermore, in the *European Hydrogen Market* and *Leading Hydrogen Ecosystem* scenarios, a pipe connection from Finland to Central Europe will be built by 2030. The transmission capacity of this connection was set at 13 GW of hydrogen based on the European Hydrogen Backbone study[23].

5.1.1 The scenarios and their underlying premises are described in more detail in the following Sections.The ’Strong Regional Hydrogen Economy’ scenario

In the *Strong Regional Hydrogen Economy* scenario, hydrogen demand is driven particularly by Finland’s growth into a major exporter of hydrogen downstream products, such as electrofuels. Plenty of new industries are created in Finland in local hydrogen clusters formed around hydrogen production and refining. Clean hydrogen is produced for domestic needs, particularly by exploiting Finnish onshore wind power, which also reduces the emissions of Finland’s existing industry.

In this scenario, Finland’s internal energy transmission infrastructure is developed and a hydrogen pipeline transmission connection to northern Finland is built in the Bay of Bothnia region, but this is not complemented with hydrogen pipe transmission connections to Central Europe. Hydrogen demand will also grow significantly in Northern Sweden, where hydrogen is used for applications such as the direct reduction of iron for the steel industry. The need for a transmission connection has been charted in, for example, a study by the Lappeenranta University of Technology (LUT), in which the transmission capacity of the cross-border pipe was envisioned at 7.2 GW of hydrogen[19]. Gasgrid is currently working on the Nordic Hydrogen Route project together with Nordion Energi. The project is charting the possibilities for cross-border hydrogen infrastructure and transmission capacity needs in the Bay of Bothnia region[24].

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[22] Bothnian Bay Hydrogen Valley – Research report. LUT Scientific and Expertise Publications 134. (Karjunen, et al., 2021)
[23] Extending the European Hydrogen Backbone (EHB, 2021)
[24] https://nordichydrogenroute.com/project/

The need for Nordic hydrogen storage is greatest in the *Strong Regional Hydrogen Economy* scenario, since the Finnish hydrogen system is not connected to salt caverns in Central Europe, which enable seasonal storage. Hydrogen needs to be stored so that hydrogen production with an electrolyser can be managed flexible according to energy prices while retaining a stable hydrogen supply all year round. In this scenario, many domestic hydrogen storage facilities will be built to enable this.

5.1.2 The 'European Hydrogen Market' scenario

In the *European Hydrogen Market* scenario, grey hydrogen will be replaced, and the needs of the Finnish steel industry will be met, but the hydrogen downstream industry will not grow in line with hydrogen production. Instead, the growth of hydrogen production will primarily be driven by export opportunities for hydrogen gas through pipe connections to Europe, particularly by 2040.

A corresponding hydrogen pipe connection will be built from Finland to Northern Sweden as in the *Strong Regional Hydrogen Economy* scenario. Demand for hydrogen will grow more quickly in Sweden than in Finland, and export to Sweden via the northern cross-border connection will accelerate the growth of the Finnish hydrogen economy. A large pipe connection to Central Europe will also be built through the Baltic region by 2030. The connection will increase export volumes considerably, especially in the long term. Finland's hydrogen economy is thus driven by the great demand for clean hydrogen in the Baltic region and Central Europe. Finland's affordable onshore wind power is able to meet this demand more cost-effectively than Central Europe's own renewable energy resources.

A hydrogen transmission infrastructure to Central Europe via the Baltic region gives access to Central European gas storage facilities. Large gas storage facilities, for example in salt caverns, are already in use elsewhere in Europe. It is assumed that large salt caverns can be used to store hydrogen at very low costs, and the Baltic pipe connection gives Finland access to the flexibility they afford. This decreases the need for and viability of domestic hydrogen storage.

5.1.3 The 'Leading Hydrogen Ecosystem' scenario

The drivers of demand in the other scenarios combine in the *Leading Hydrogen Ecosystem* scenario. Strong domestic demand is created in Finland like in the *Strong Regional Hydrogen Economy* scenario, and Finland will also meet Central European demand for clean hydrogen as in the *European Hydrogen Market* scenario. In this scenario, pipe connections for export will be built to Northern Sweden and Central Europe, contributing to the flexibility of the energy system and decreasing the need for domestic storage capacity.

In the scenario, Finland produces extremely large quantities of clean hydrogen, which demands a corresponding volume of clean electricity production. Roughly 4 GW of onshore wind power alone will be built in Finland each year, which is roughly double the rate of construction in 2022. This could increase Finnish onshore wind power capacity to approximately 60 gigawatts by 2040. This scenario makes use of all onshore wind power production that can be built within the limitations set for the scenario, and offshore wind power and solar power plants will be built as well.

5.2 Finland to produce clean hydrogen for domestic use and export

In all scenarios, hydrogen production capacity will increase significantly to enable the export of hydrogen and its downstream products from Finland. Figure 10 presents summaries of Finland's current grey hydrogen consumption, the domestic consumption and export of clean hydrogen, as well as the electrolyser capacity required for the production of this hydrogen in each scenario.

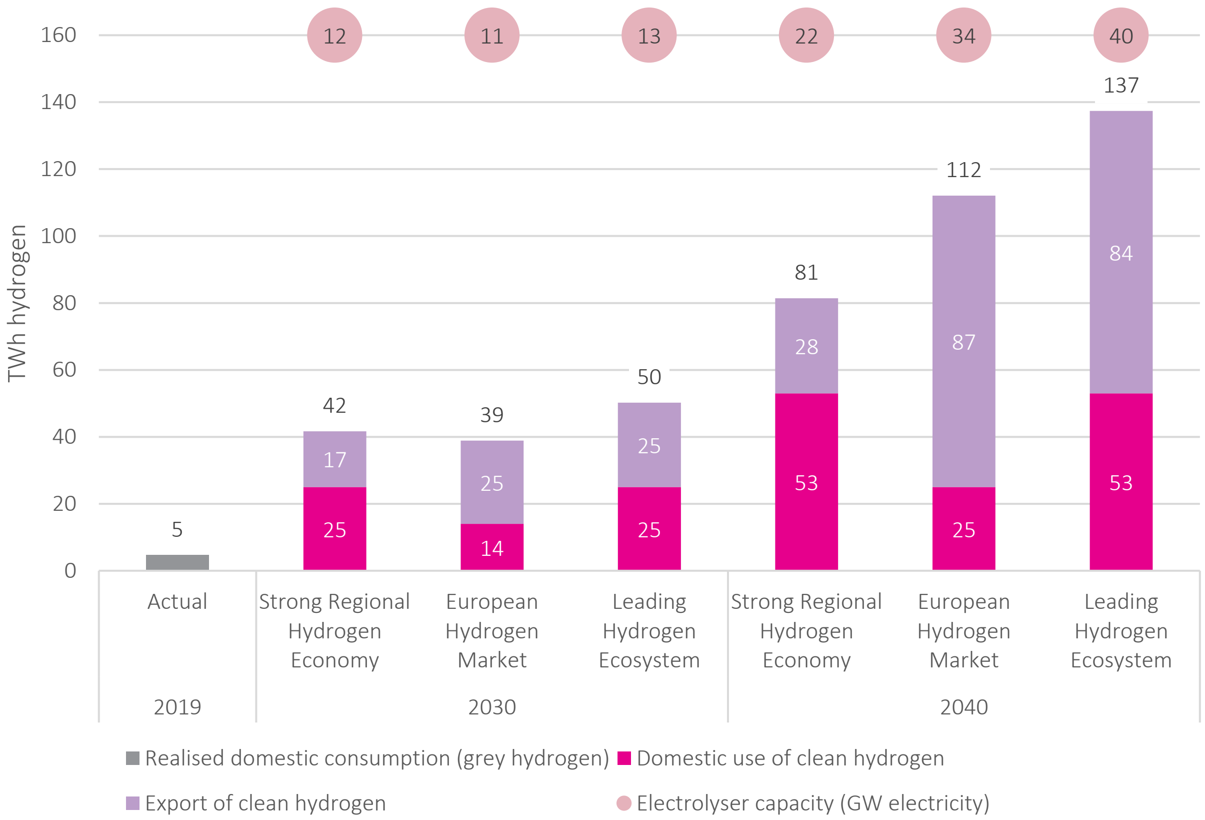

Figure 9. Finland's actual grey hydrogen consumption and scenarios for the domestic consumption and export of clean hydrogen and the electrolyser capacity required for its production.

In these scenarios, Finland will produce around 35–50 TWh of clean hydrogen in 2030 and 80–135 TWh in 2040. To produce such amounts, Finland has 10–15 GW of installed electrolyser capacity by 2030, and this capacity will multiply to the level of 25–40 GW by 2040.

5.3 Growth of electricity production in each scenario – Cost-competitive Finnish wind power as a driver

In all scenarios, Finnish electricity consumption will nearly double by 2030 and triple or quadruple by 2040, mainly driven by the electricity needs of hydrogen production (Figure 11). In each scenario, hydrogen production will be the largest application for electricity in Finland. Depending on the scenario, hydrogen production will consume 50–70 TWh of electricity in 2030 and 110–190 TWh in 2040. In 2040, more electricity will be used for hydrogen production than for all other applications combined, despite projected growth in the consumption of electricity due to the electrification of industry, transport and heating, as well as the creation of new industries and data centres.

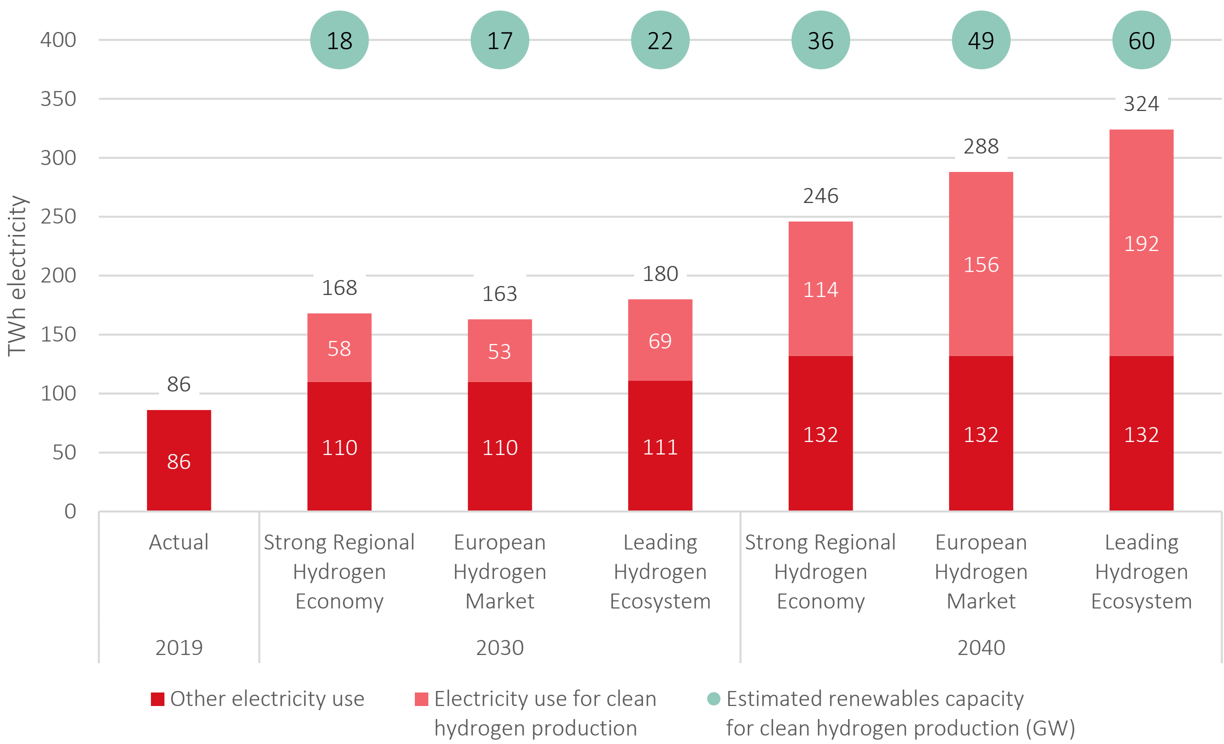

Figure 10. Finnish electricity consumption divided between clean hydrogen production and other applications, along with the estimated renewable capacity required for clean hydrogen production.[25,26]

Significant investments in renewable energy production are required to satisfy the growth of electricity consumption with clean electricity. Onshore and offshore wind power and solar power production will increase significantly to satisfy this demand. Figure 11 presents an estimate of the renewable electricity production capacity required for clean hydrogen production. Renewable sources will also satisfy other growth in demand. Most of these sources consist of onshore wind power, which is the most competitive form of new electricity production in Finland, with many production projects currently under development.

In all scenarios, onshore wind power capacity will increase to 20 gigawatts by 2030 and to 50–60 gigawatts by 2040. This requires an annual increase of 3–4 GW in onshore wind power capacity in the

[25] Source for Finnish electricity consumption in 2019:Statistics Finland (SVT, 2019): Statistics Finland - Energy supply and consumption
[26] In this context, renewable electricity production capacity refers to onshore and offshore wind power and solar power. Capacity estimated at an average of 3,200 full load hours.

2030s, while the maximum growth rate for the next few years has been anticipated at 2 GW per year. The construction rate of renewable forms of energy production, especially onshore wind power, is thus a key uncertainty in these scenarios.

If additional onshore wind power capacity would be built more quickly, Finland's clean hydrogen production volumes could even exceed those presented in the scenarios. On the other hand, slower construction of additional onshore wind power capacity would also limit the production of clean hydrogen. A fast permit procedure for wind power and the required energy transmission infrastructure, along with tapping eastern Finland's wind power potential, would thus create better conditions for the realisation of hydrogen investments. In addition to onshore wind power, 4–9 GW of offshore wind power and 7–15 GW of solar power production would be built in Finland by 2040 in all scenarios.

The total onshore and offshore wind power and solar power production will reach 100–115 TWh by 2030 and grow further to 215–290 TWh by 2040 in each scenario. This means that most of the Finnish electricity production would vary according to the weather. That creates an enormous need for flexibility in consumption to keep the electricity system in balance.

5.4 The role of hydrogen storage facilities in each scenario – Storing hydrogen enables flexibility in the energy system

Hydrogen storage facilities can make the energy system more flexible and cost-effective. The sectoral integration of the electricity and hydrogen systems enables the production of huge amounts of renewable electricity with onshore and offshore wind power and solar power, regardless of weather variations. For example, an extensive hydrogen network can serve as an energy buffer.

The strong growth of hydrogen production and consumption outlined in the scenarios will require the storage of significant quantities of hydrogen to balance weather-dependent wind power and industrial hydrogen consumption, which is assumed to be fairly stable. That is why the role of hydrogen storage facilities has been modelled as one factor in balancing the energy system and differences between production and consumption in the scenarios. Figure 12 presents the capacities of these hydrogen storage facilities in energy amounts and filling capacity.

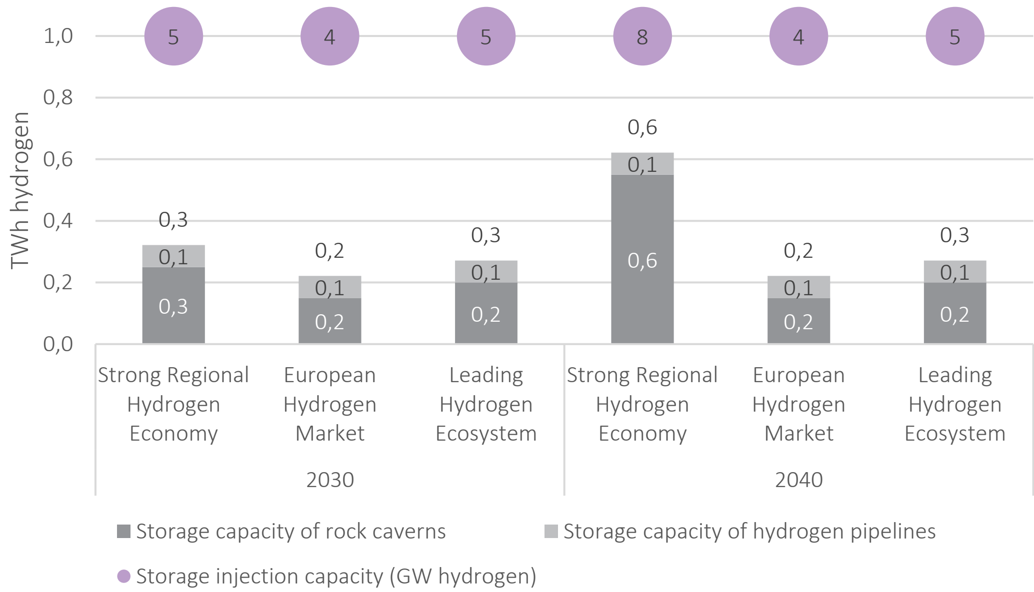

Figure 11. The capacities and filling capacities of hydrogen storage facilities in each scenario.

Both storage facilities in excavated rock caverns and the hydrogen transmission infrastructure's storage capacity, or buffer capacity, have been taken into account in the storage amounts. In all scenarios, the need for system flexibility and thereby hydrogen storage will increase significantly by 2040, but there are some differences in the scenarios. Storage in Finnish rock caverns plays a significant role in the *Strong Regional Hydrogen Economy* scenario, whereas in the other scenarios, domestic storage capacity is mainly based on that of the pipe network. The need for domestic storage capacity is smaller in these scenarios, since they assume access to the capacity of Central Europe's salt caverns through a hydrogen pipe connection.

In the *Strong Regional Hydrogen Economy* scenario, the total storage capacity of domestic hydrogen storage facilities corresponds to roughly 4–5 days' domestic hydrogen consumption. In this scenario, the storage facilities' filling capacity corresponds to approximately half of the electrolysers' hydrogen production capacity. The capacity of domestic storage facilities is smaller in the other scenarios, because flexibility is achieved through hydrogen export and import making use of the large and more cost-effective salt cavern storage facilities in Central Europe.

The hydrogen transmission infrastructure will enable the creation of a larger hydrogen market if international connections are built. It will improve the security of the hydrogen supply, as more operators (production, consumption and storage) will be involved in balancing consumption and production, and the hydrogen flow direction can be determined according to the market balance. From the perspective of security of supply, domestic hydrogen storage facilities are needed to complement the salt cavern facilities abroad in balancing variations in production. A part of domestic storage needs will be fulfilled by the hydrogen pipeline's storage capacity, but additional rock cavern storage facilities are considered necessary in all scenarios.

6 Transmission infrastructure enables investments in Finland

In this Section, the development needs for Finland's transmission infrastructure in each scenario is discussed. The geographic factors affecting energy transmission needs in each scenario are described in Section 6.1, followed by a description of the development of transmission in Section 6.2. The transmission amounts in electricity and hydrogen are then outlined in Section 6.3, assuming that the limitations of the electricity and hydrogen networks are taken into consideration and the networks are used cost-effectively. Finally, Section 6.4 justifies the need for location-based incentives by presenting a scenario in which the costs and use of the transmission infrastructures are not optimised.

6.1 Factors affecting transmission needs

The production of clean hydrogen with an electrolyser requires a lot of electricity. Electricity is also needed for the industrial production of downstream hydrogen products. Even though the locations of production and consumption facilities are influenced by a variety of factors, such as opportunities for making use of waste heat, the availability of carbon dioxide in the production of synthetic fuels from hydrogen, end-product logistics and land use, the availability of electricity is essential. Therefore, the location of hydrogen production facilities and consumption sites in relation to electricity production is a highly significant factor in the siting of facilities and has a decisive effect on Finland's internal energy transmission needs. Figure 13 illustrates the factors affecting transmission needs through four examples.

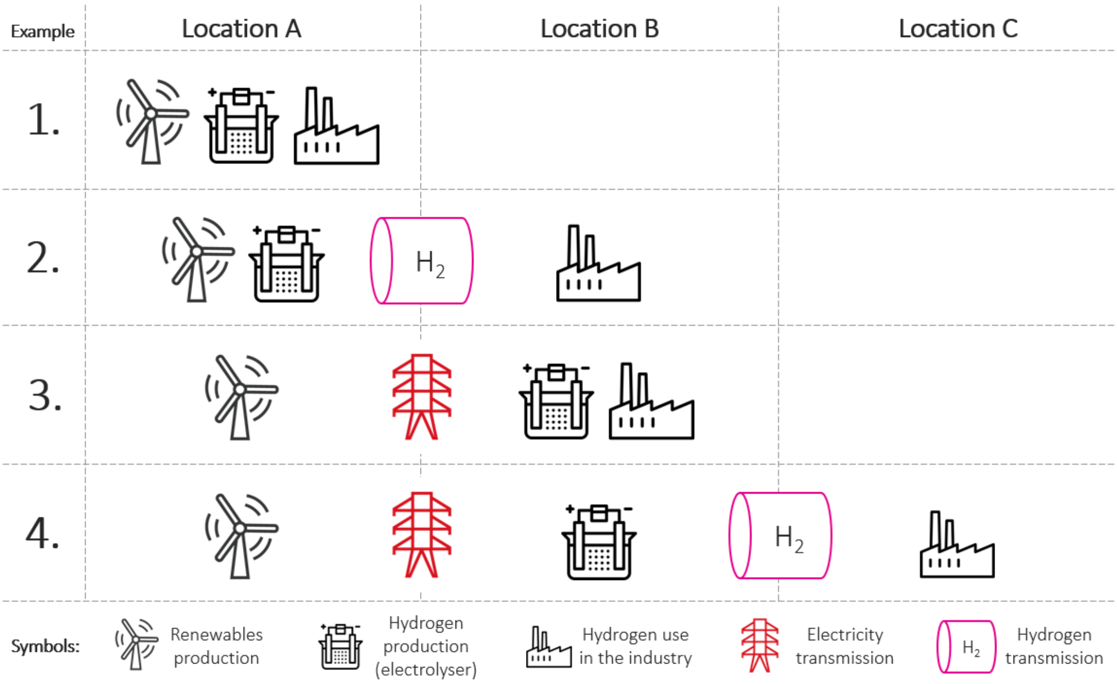

Figure 12. Energy transmission needs will be determined by the locations of renewable electricity production, hydrogen production and hydrogen consumption facilities relative to each other.

1. Renewable electricity production, hydrogen production and hydrogen consumption facilities all situated in location A: **no major national energy transmission needs (transmission as downstream products**
2. Renewable electricity production and hydrogen production situated in location A, consumption site situated in location B: **energy is transferred to the consumption site as hydrogen**

3. Renewable electricity production situated in location A, hydrogen production and hydrogen consumption facilities in location B: **energy is transferred to the consumption site as electricity**
4. Renewable electricity production situated in location A, hydrogen production in location B and hydrogen consumption facilities in location C: **energy is transferred both as electricity for hydrogen production and as hydrogen to the consumption site**

In simple terms, transmission needs as both electricity and hydrogen are the lowest if both renewable electricity production and hydrogen production and consumption facilities are located as close to each other as possible (example 1). The need for hydrogen transmission is pronounced if hydrogen production facilities are located close to renewable electricity production but far from hydrogen consumption sites (example 2). On the other hand, electricity transmission will be the decisive factor if hydrogen production and consumption facilities are located far from renewable electricity production (example 3). Energy will need to be transferred as both electricity and hydrogen if all components of the system are located in different places (example 4). The energy contained in electricity and hydrogen used in hydrogen refining will ultimately be bound in the downstream products, such as chemicals and fuels, which can be transported by ship.

The location hydrogen production facilities will determine whether energy is transferred as electricity or hydrogen. For example, an electrolyser connected to a northern wind farm could produce clean hydrogen, which could then be transferred to a consumption site in the south. Correspondingly, the electrolyser could be located close to the consumption site and far from electricity production facilities, in which case the energy would be transferred as electricity. If the energy is transferred as electricity, more energy will have to be transferred to produce the same quantity of hydrogen, since the energy loss in electrolysis is approximately 30% (Figure 14). On the other hand, most of the loss can be recovered as waste heat, which could support the placement of hydrogen production facilities close to large cities and their district heating networks.

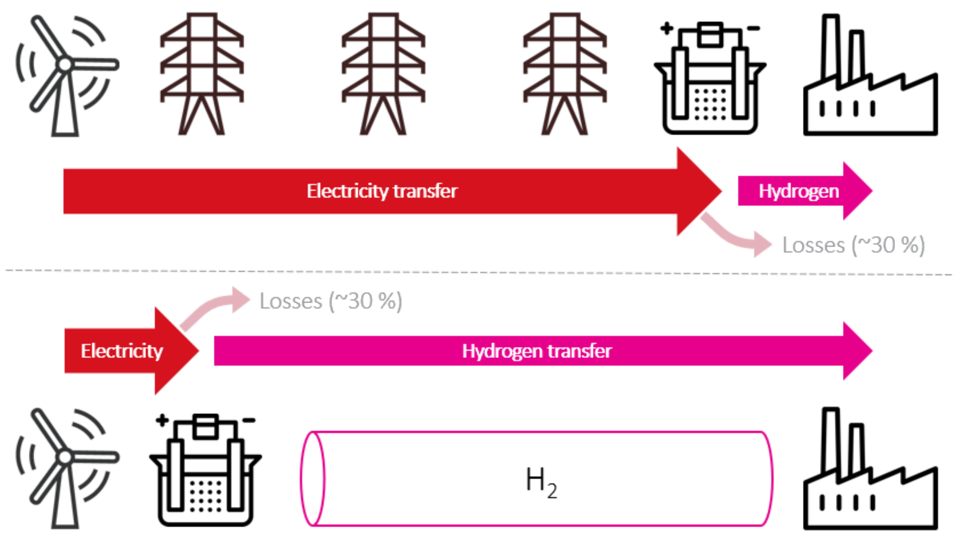

Figure 13. Energy used as hydrogen is more efficiently transferred as hydrogen.

Energy infrastructure requirements are also affected by energy storage needs, which the hydrogen infrastructure can meet with its buffer storage capacity and by enabling access to geological storage facilities abroad.

6.2 Finland's internal energy transfer needs will be multiplied

To achieve the potential demonstrated by the scenarios, Fingrid and Gasgrid must recognise their customers' potential in time and upgrade the energy transmission networks in advance to enable the development of the energy system. To enable the high-growth scenarios, it is essential for both renewable electricity production and hydrogen production and consumption facilities to be located sensibly in view of the overall system and to be flexible when required. The market should guide the transfer of electricity and hydrogen in the optimal manner for society. The electricity and hydrogen systems can work well together and support each other, which would enable the growth projected in the scenarios in the most cost-effective manner.

In Finland, electricity consumption is largest in the south, while a significant part of the growth potential in renewable electricity production is in the north. The locations of renewable electricity production and the clean hydrogen production which relies heavily on it have a great impact on transmission needs. Within Finland, the north-south transmission need has been identified as particularly important and a potential impediment to the development of the system.

In modelling the scenarios, Finland has been divided into northern and southern regions by a line running across Central Finland (Figure 15). This "Cross-section of Central Finland" is used to illustrate energy transmission needs inside Finland. It is important to anticipate transmission needs across this cross-section, as it has been defined as a factor restricting north-south transmission capacity in the current electricity system. The scenarios in Fingrid's Electricity System Vision[27] already foresaw the need to gradually multiply north-south electricity transmission capacity in the long term.

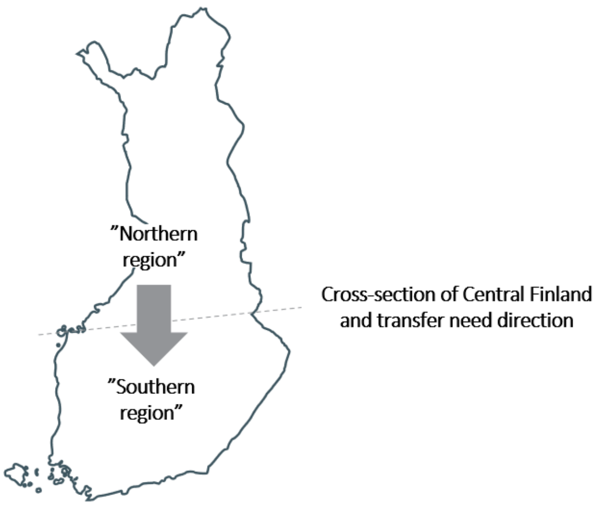

Figure 14. Cross-section of Central Finland; the arrow shows the typical direction of transmission needs.

Most current Finnish wind power plants are located in Ostrobothnia, while there are hardly any wind power plants in the south and east of Finland. In southern Finland, the potential of wind power is limited by the higher population density. In eastern Finland, radar surveillance requirements limit the areas available for wind power construction and the scale of projects, which makes it less attractive for developers. Due to these limitations, most new wind power projects are located in western and

[27] Fingrid's Electricity System Vision 2023 (Fingrid, 2023)

northern Finland. The scenarios nevertheless assume that the limitations caused by radar surveillance in eastern Finland will be resolved[28] and onshore wind power plants will also be built in the east. However, most of the growth in renewable electricity production is located north of the Central Finland cross-section in all scenarios.

Hydrogen is currently used by the Finnish chemical industry, especially in southern Finland[29], and hydrogen production is largely concentrated in the same industrial areas housing the hydrogen-consuming facilities. In the scenarios, the existing industrial plants replace grey hydrogen with clean hydrogen, and the creation of new industries is also an important driver of clean hydrogen use. Most of the Finnish hydrogen projects announced to date are in the south [30], for example in Vantaa, Porvoo and Inkoo[31]. In addition to these, several projects are planned on the coast of Ostrobothnia[32] and there are also some growth prospects in eastern Finland[33]. However, the domestic demand for hydrogen is concentrated in the south in all scenarios.

Hydrogen is currently mainly produced close to the consumption sites but, in the energy system of the future, hydrogen production and consumption can be located in different areas if the hydrogen infrastructure develops sufficiently to enable transmission between them. The geography of hydrogen production is thus one of the most significant questions in the scenarios and has a major impact on energy transmission infrastructure requirements.

In all scenarios, the growth of renewable electricity production is concentrated in the north and the demand for hydrogen in the south of Finland. The location of hydrogen production facilities, or electrolysers, remains the decisive factor for Finland's internal energy transfer needs between the northern and southern regions.

6.3 Joint development of electricity and hydrogen infrastructures enables the energy transfer

The transfer needs described in the scenarios can be satisfied cost-effectively by utilising the transmission capacity of both electricity and hydrogen infrastructures and taking the importance of location into account, especially in the siting of hydrogen production. The siting of hydrogen production in Finland is managed within the given transmission capacities in all scenarios, taking the limitations and costs of energy transmission into account.

This Section presents Finland's annual electricity and hydrogen production amounts, along with the consumption and storage of hydrogen in the northern and southern regions in each scenario. Deducting consumption from production gives the annual balance that determines the energy transmission requirement between regions. There are also transmission needs inside regions if

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[28] Potential solutions have been presented on a recent study: Itäisen Suomen tuulivoimarakentamisen tehostaminen (Räty, 2023) – in Finnish
[29] Business Finland, National Hydrogen Roadmap for Finland (Laurikko, et al., 2020)
[30] Valtioneuvoston kanslia, Vetytalous – mahdollisuudet ja rajoitteet – report of Prime Minister's Office (Sivill, et al., 2022) – in Finnish
[31] Neljän miljardin euron investointi suunnitteilla Inkooseen – announcement, in Finnish (Business Finland, 3.1.2023)
[32] BotH$_2$nia network (for more information: https://www.both2nia.com/en/network)
[33] Suomen Vetylaakso ry perustettu edistämään itäisen Suomen elinvoimaa ja teollisia investointeja (Lappeenranta.fi, 2.2.2023) – in Finnish

production and consumption sites are not located in the same spot. Net electricity and hydrogen exports or imports, which also affect domestic transmission needs, are presented.

6.3.1 The ’Strong Regional Hydrogen Economy’ energy transfers

Figure 16 and Table 4 show Finland’s annual electricity and hydrogen production and consumption and hydrogen storage in the *Strong Regional Hydrogen Economy* scenario. Renewable electricity production will increase, especially in the north, while most of the consumption will take place in the south. To make use of this electricity, hydrogen production will be concentrated in the north, reducing the north-south electricity transmission need. There is also significant hydrogen production in the south, where the production and consumption of hydrogen are almost balanced.

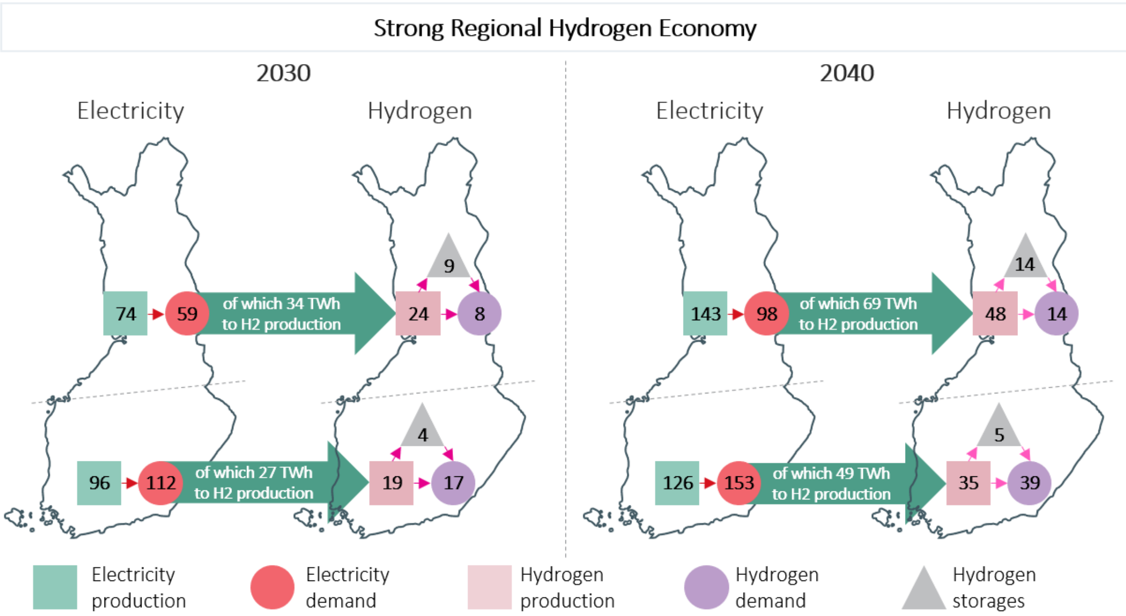

Figure 15. Finland’s annual electricity and hydrogen production and consumption and hydrogen storage in the Strong Regional Hydrogen Economy scenario. Figures in TWh electricity/hydrogen.

*Table 4. Finland’s electricity and hydrogen production and consumption by region in the Strong Regional Hydrogen Economy scenario. *electricity for hydrogen production, **the balance is affected by rounding. Figures in TWh electricity/hydrogen.*

STRONG REGIONAL HYDROGEN ECONOMY		2030 ELECTRICITY	HYDROGEN	2040 ELECTRICITY	HYDROGEN
NORTHERN REGION	Production	74	24	143	48
	Consumption (of which H2*)	59 (34*)	8	98 (69*)	14
	Balance	**+15**	**+15****	**+45**	**+34**
SOUTHERN REGION	Production	96	19	126	35
	Consumption (of which H2*)	112 (27*)	17	153 (49*)	39
	Balance	**-16**	**+2**	**-27**	**-5****

Figure 17 presents the electricity and hydrogen balances (production - consumption) in Finland's northern and southern regions and the transmission need between them in the *Strong Regional Hydrogen Economy* scenario. This balance will decrease the need for transmission between the regions, but transmission from production to consumption facilities is needed within the region if these are not located in the same spot. In addition, the hydrogen transmission infrastructure enables storage for all operators in the region, both in the pipe's buffer capacity and in large rock caverns. There is a significant amount of hydrogen storage capacity, especially in the northern part of Finland. The surplus of electricity in the north will grow with the increase in renewable electricity production, whereas the deficit in the southern region will grow with increased consumption. This will increase the need for north-south electricity transmission.

Hydrogen production and consumption are nearly balanced in the southern region, whereas there is a surplus in the north. In this scenario, large quantities of hydrogen are exported to Northern Sweden each year, which would require a hydrogen pipe running from the Swedish border all the way to Ostrobothnia in order to exploit the hydrogen production in that region. However, north-south transmission need between regions will remain lower than in the other scenarios, since hydrogen production is mainly located in the northern region.

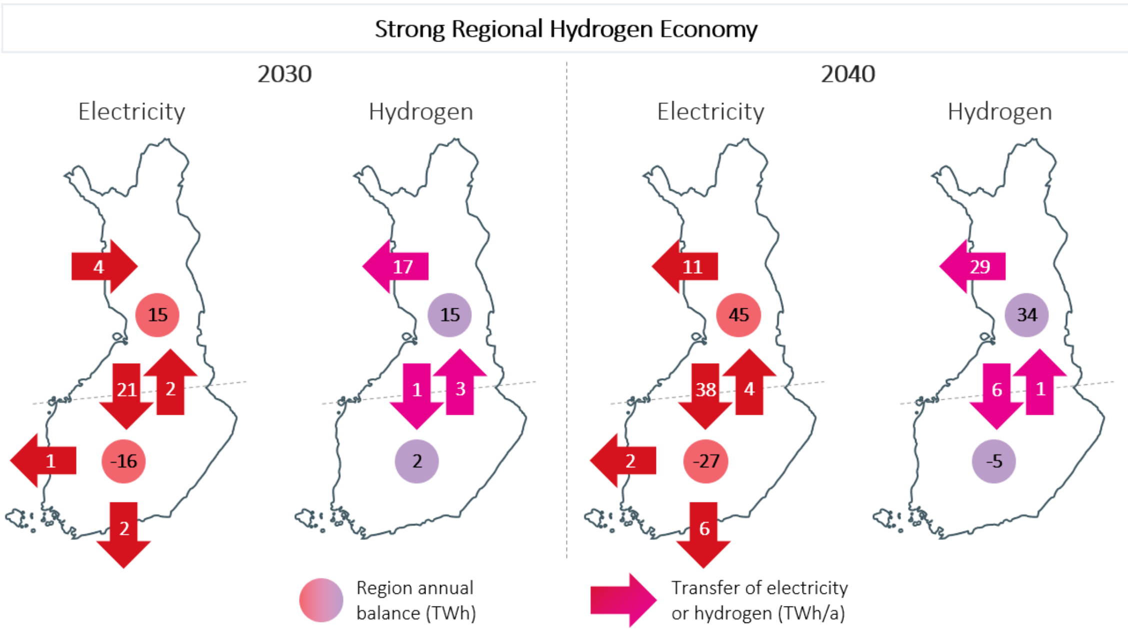

Figure 16. Finland's annual electricity and hydrogen balances (production minus consumption by region) and transmissions in the "Strong Regional Hydrogen Economy" scenario. Figures in TWh electricity/hydrogen.

6.3.2 The 'European Hydrogen Market' scenario energy transfers

Figure 18 illustrates regional production and consumption in the electricity and hydrogen system in the *European Hydrogen Market* scenario, and Table 5 presents the regional balances in electricity and hydrogen. The development of the production and total consumption of electricity is largely similar to that in the *Strong Regional Hydrogen Economy* scenario: the majority of production is located in the north and the majority of consumption in the south. However, Finnish hydrogen consumption is much smaller in this scenario but still concentrated in the southern region.

A large percentage of the electricity produced is used for hydrogen production, which is divided evenly between the regions, especially in 2030. The establishment of hydrogen production in the south is driven by the benefits of using the waste heat generated by electrolysis, shorter transmission routes to consumption sites in the south, and transmission between Finland and Central Europe. On the other hand, there are drivers for the establishment of hydrogen production in the north, especially the good availability of electricity production in the region.

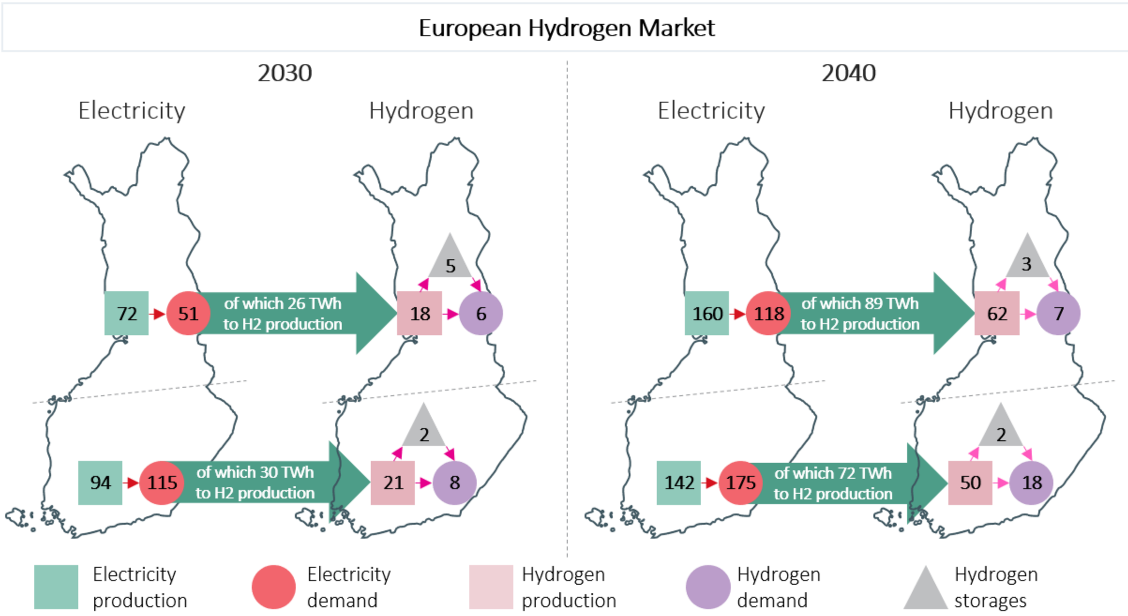

Figure 17. Finland’s annual electricity and hydrogen production and consumption and hydrogen storage in the European Hydrogen Market scenario. Figures in TWh electricity/hydrogen.

*Table 5. Finland’s electricity and hydrogen production and consumption by region in the European Hydrogen Market scenario. *electricity for hydrogen production. Figures in TWh electricity/hydrogen*

EUROPEAN HYDROGEN MARKET		2030		2040	
		ELECTRICITY	HYDROGEN	ELECTRICITY	HYDROGEN
NORTHERN REGION	Production	72	18	160	62
	Consumption (of which H2*)	51 (26*)	6	118 (89*)	7
	Balance	**+21**	**+12**	**+42**	**+55**
SOUTHERN REGION	Production	94	21	142	50
	Consumption (of which H2*)	115 (30*)	8	175 (72*)	18
	Balance	**-21**	**+13**	**-33**	**+32**

Figure 19 shows Finland's electricity and hydrogen balances and transmissions in the scenario. In the electricity balance, surplus will increase in the north and deficit in the south, leading to a significant increase in north-south transmission needs. The hydrogen balance is strongly positive and the hydrogen transmission infrastructure enables competitive net export of hydrogen at the annual level. The hydrogen transmission infrastructure is capable of balancing momentary regional surpluses and deficits.

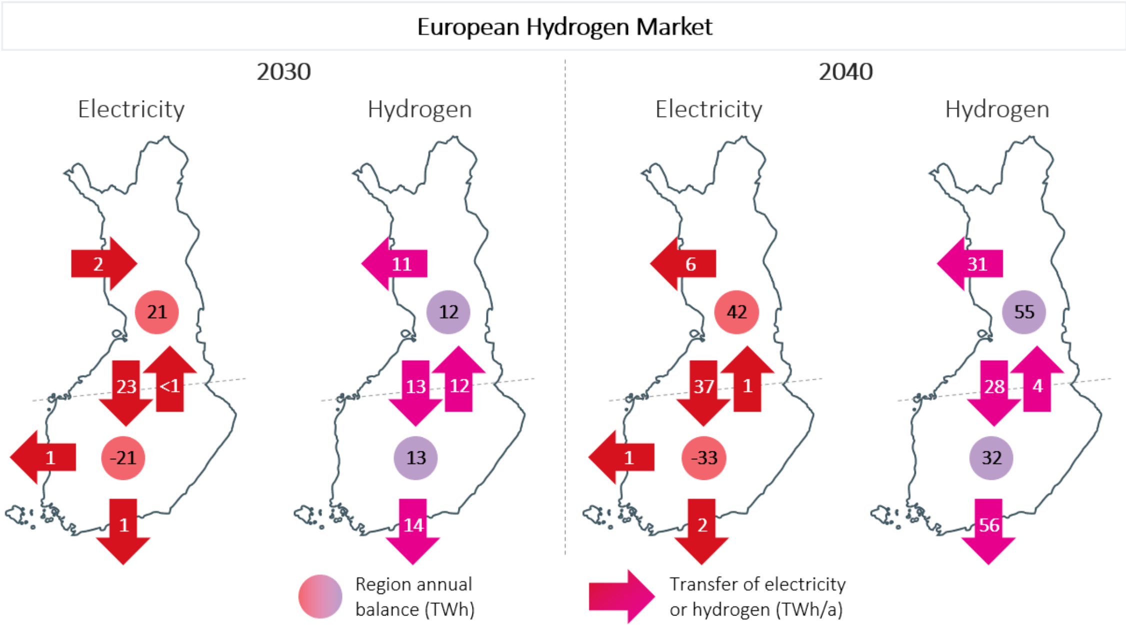

Figure 18. Finland's annual electricity and hydrogen balances (production minus consumption by region) and transmissions in the European Hydrogen Market scenario. Figures in TWh electricity/hydrogen.

In 2030, north-south hydrogen transmissions are nearly balanced in Finland. Hydrogen is transferred in both directions, depending on the current regional balances of production, storage and consumption. Two-way hydrogen transmission also takes place through the cross-border transmission infrastructure, especially the Central European pipe connection, which gives access to the flexibility offered by the large salt cavern storage facilities for hydrogen in Europe. Hydrogen is imported, for example during periods of low electricity production in Finland, when producing hydrogen with domestic electricity would be more expensive than importing it.

Both electricity and hydrogen transfer needs from north to south will increase considerably by 2040. The electricity transmission need alone will almost quadruple from today with the growing deficit in the southern region. If more hydrogen production would be established in the south, it would mean an even greater transmission need for electricity. Hydrogen exports will increase significantly by 2040 thanks to the competitiveness of Finnish hydrogen production.

Transferring the corresponding amount of energy to Europe as electricity (56 TWh of hydrogen corresponds to approximately 80 TWh of electricity) at the same full load hours would require almost 19 GW of electricity transmission capacity, or 19 cross-border connection of the current type, which would not be efficient for the electricity system. A hydrogen network enables extremely high volumes of energy transmission and thus a more balanced spread of hydrogen production inside Finland, access to Central European storage facilities and the export and import of hydrogen according to the market situation.

6.3.3 The 'Leading Hydrogen Ecosystem' scenario energy transfers

Figure 20 and Table 6 present electricity and hydrogen production, storage and consumption by region in the *Leading Hydrogen Ecosystem* scenario. The production of both electricity and hydrogen is much higher in this scenario than in the others. Like in the other scenarios, the growth of electricity production is focused on the north and the growth of hydrogen consumption on the south. Hydrogen production amounts are reasonably balanced in 2030 but by 2040, most of the hydrogen would be produced in the north close to the electricity production. Therefore, a part of the energy used as hydrogen could more efficiently be transferred from north to south as hydrogen.

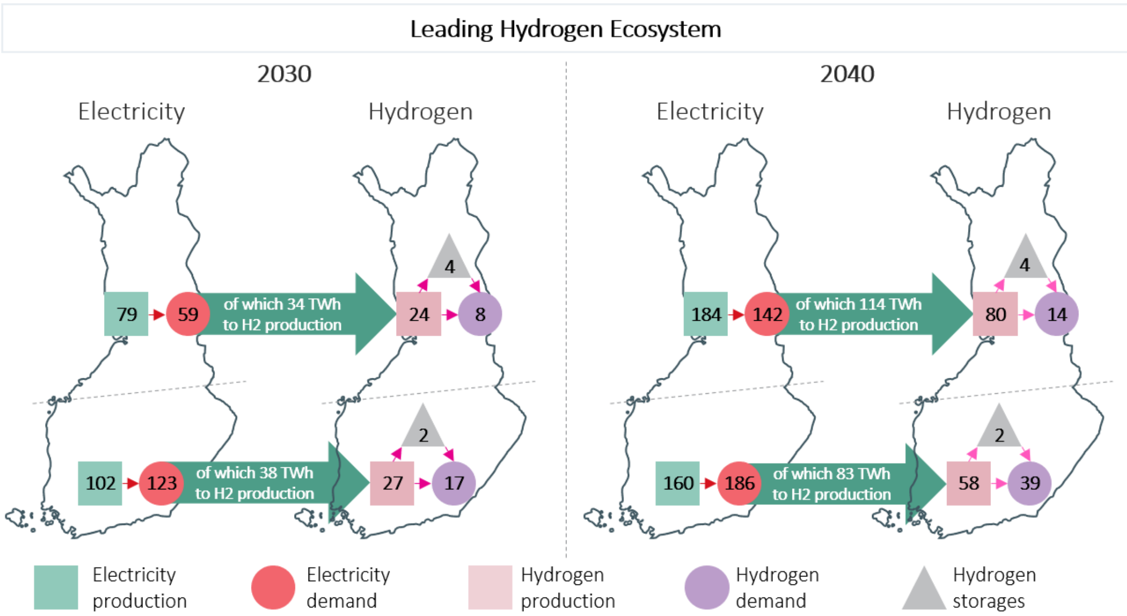

Figure 19. Finland's annual electricity and hydrogen production and consumption and hydrogen storage in the Leading Hydrogen Ecosystem scenario. Figures in TWh electricity/hydrogen.

*Table 6. Finland's electricity and hydrogen production and consumption by region in the Leading Hydrogen Ecosystem scenario. *electricity for hydrogen production, **the balance is affected by rounding. Figures in TWh electricity/hydrogen.*

LEADING HYDROGEN ECOSYSTEM		2030		2040	
		ELECTRICITY	HYDROGEN	ELECTRICITY	HYDROGEN
NORTHERN REGION	Production	79	24	184	80
	Consumption (of which H2*)	59 (34*)	8	42 (114*)	14
	Balance	**+20**	**+16**	**+41****	**66**
SOUTHERN REGION	Production	102	27	160	58
	Consumption (of which H2*)	123 (38*)	17	186 (83*)	39
	Balance	**-21**	**+10**	**-26**	**+19**

Figure 21 presents gross north-south transmissions consisting of the regional electricity and hydrogen balances in Finland and net export or import amounts. This scenario involves the efficient utilisation of

Finland's internal electricity and hydrogen transmission infrastructures: transmissions as electricity and hydrogen are in the same order of magnitude in both years under examination.

As electricity, energy is mainly transferred from the surplus in the north to the deficit in the south. Both regions have surpluses of hydrogen in 2030, and transmissions are more balanced in both directions as well as over cross-border connections. Internal north-south transmissions of both electricity and hydrogen will increase significantly by 2040. Hydrogen transmission needs are focused on the north-to-south direction, as well as on increasing exports to Northern Sweden and Central Europe.

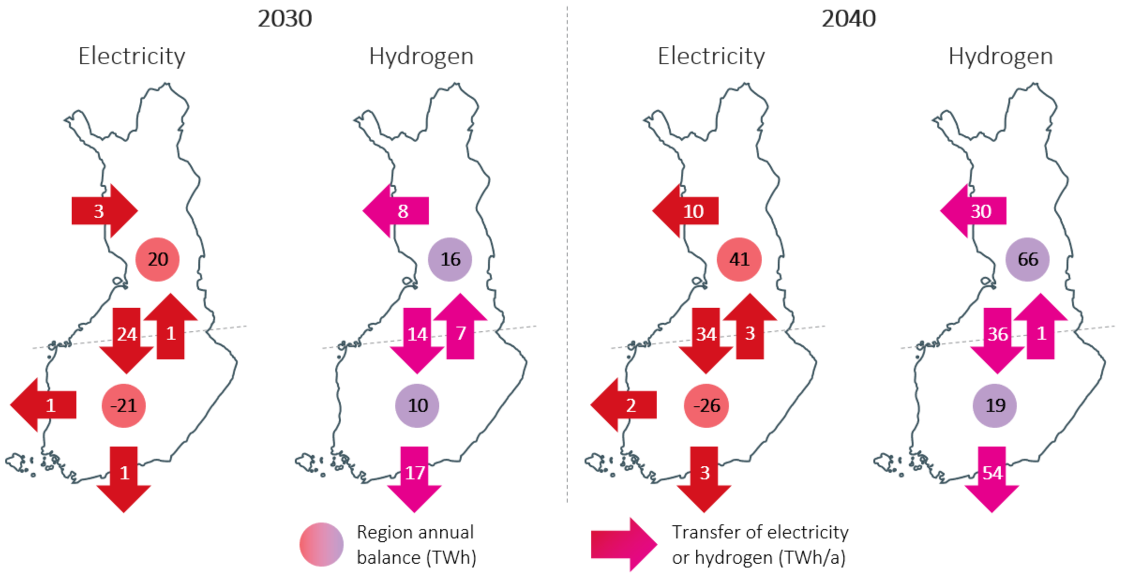

Figure 20. Finland's annual electricity and hydrogen balances (production minus consumption by region) and transmissions in the Leading Hydrogen Ecosystem scenario. Figures in TWh electricity/hydrogen.

6.4 Location-based incentives are needed to make use of Finland's potential

According to Fingrid and Gasgrid Finland, achieving major growth requires the ability to anticipate growing transmission needs to focus investments accordingly. To ensure the sufficient transmission capacity, it is important to obtain an overall picture of investments in electricity and hydrogen production and consumption so that the locations and scope of transmission infrastructure investments can be optimised. Transfer needs for both electricity and hydrogen will increase significantly in all scenarios even though transmission capacity and efficiency have been taken into account as factors guiding the location of investments. Without such factors, there is the risk of transfer needs exceeding capacity, preventing cost-effective transmission.

The current net transmission of electricity over the cross-section dividing Finland into northern and southern regions is currently approximately 10 TWh per year. This means that electricity transmission from north to south exceed those from south to north by 10 TWh, even though transmissions occur in both directions according to the consumption situation. According to the previous figure, the energy transfer need across the cross-section will at least double by 2030 and multiply from that by 2040 in all scenarios.

The north-south energy transfers needed in the scenarios will not be possible over the electricity network alone. In the scenarios, the efficient use of both electricity and hydrogen infrastructures will enable Finland to increase its production of clean hydrogen and its downstream products. However, the efficient use of the transmission infrastructures on the scale described in the scenarios requires the siting of production and consumption sites to be managed according to energy transfer needs.

The siting of hydrogen production facilities is managed within the given transmission capacities in all scenarios, taking the limitations and costs of energy transmission into account. These incentivise the establishment of electrolysers in a manner that prevents energy transmission bottlenecks from forming in north-south transmission inside Finland. In practice, this would mean the more efficient use of the electricity and hydrogen transmission infrastructures built in the scenario. For example, hydrogen could be produced close to electricity production in the northern region and transferred to consumption sites in the south (as in Figure 13 in example 2).

Finland's internal energy transfer needs across the cross-section are also examined in an alternative case in which hydrogen production would be located in the same region as hydrogen consumption ("Hydrogen production location not managed"). In this alternative case, a larger part of hydrogen production would be in the south of Finland. Figure 22 illustrates this difference in hydrogen production in the *Leading Hydrogen Ecosystem* scenario in 2040.

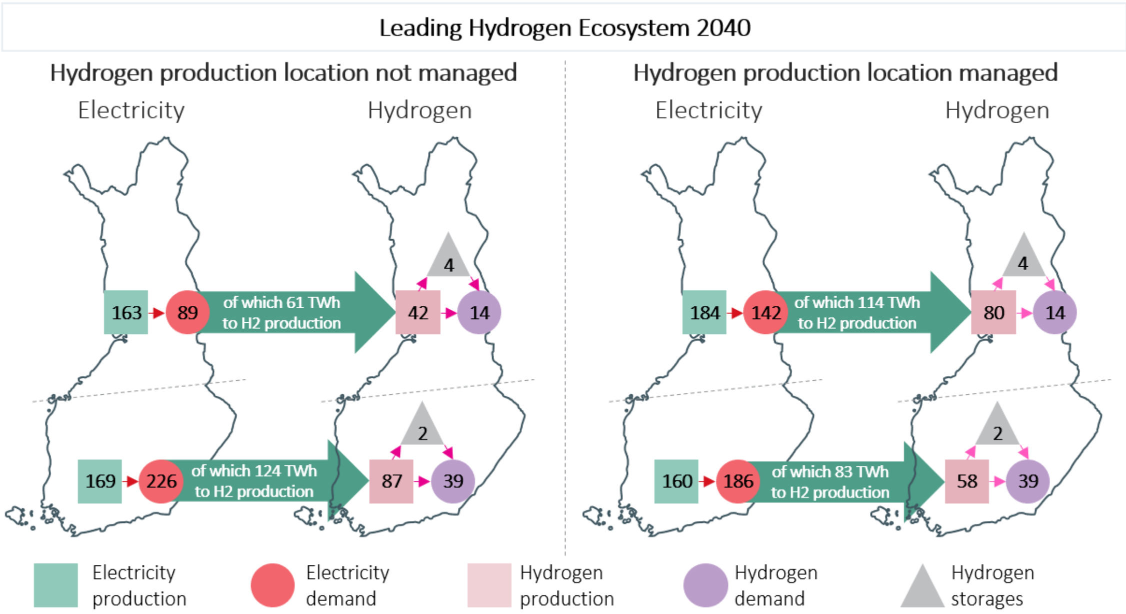

Figure 21. Comparison of Finland's annual electricity and hydrogen production and consumption and hydrogen storage in the Leading Hydrogen Ecosystem scenario in 2040. Figures in TWh electricity/hydrogen.

This would increase the surplus in the northern electricity balance and the deficit in the southern one (Table 7). As a result, most energy transfers would be made as electricity (as in Figure 13 in example 3), posing a challenge to the electricity main grid's transmission capacity, especially in the north-south direction. Figure 23 presents the annual electricity and hydrogen transmission amounts in these two alternatives in the Leading Hydrogen Ecosystem scenario in 2040.

*Table 7. Finland's electricity and hydrogen production and consumption by region in the Leading Hydrogen Ecosystem scenario in 2040. *electricity used for hydrogen production in the region **NB. rounding affects the balance "Not managed": Hydrogen production focuses on the south.*

LEADING HYDROGEN ECOSYSTEM 2040		NOT MANAGED ELECTRICITY	NOT MANAGED HYDROGEN	MANAGED ELECTRICITY	MANAGED HYDROGEN
NORTHERN REGION	Production	163	42	184	80
	Consumption (of which H2*)	89 (61*)	14	142 (114*)	14
	Balance	**+74**	**+28**	**+41****	**66**
SOUTHERN REGION	Production	169	87	160	58
	Consumption (of which H2*)	226 (124*)	39	186 (83*)	39
	Balance	**-57****	**+48****	**-26**	**+19**

In practice, the "not managed" alternative will mean that not all of the north's renewable electricity production can be used for the production of clean hydrogen as electrolysers are mostly located in the south. For this reason, the production amounts of electricity and hydrogen are higher and hydrogen exports greater in the managed alternative (Figure 23).

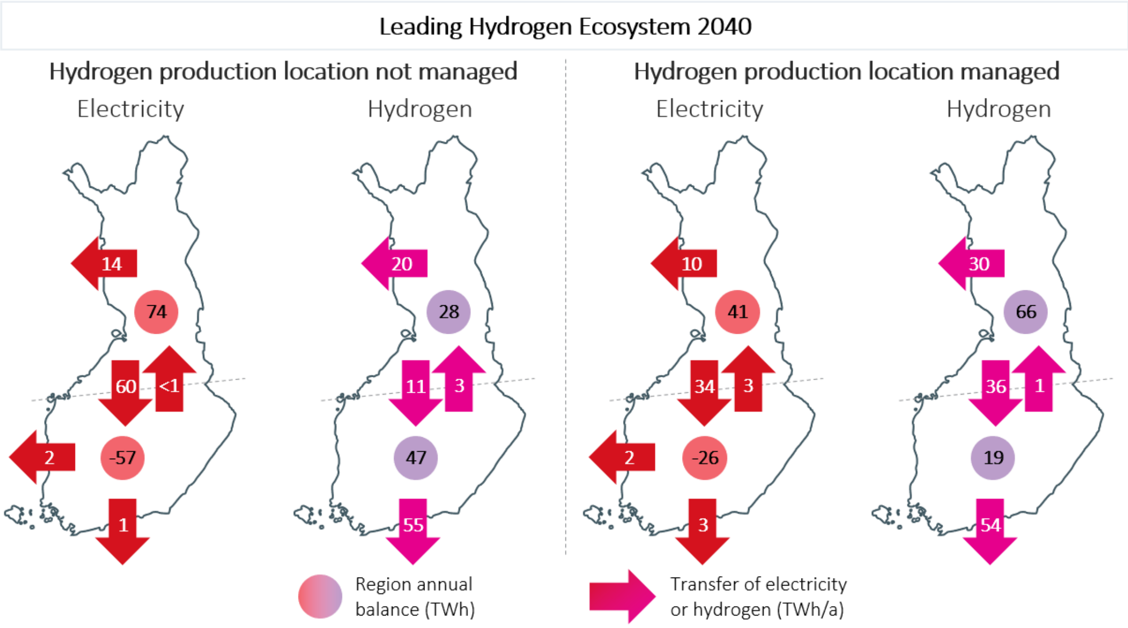

Figure 22. Comparison of Finland's annual electricity and hydrogen balances and transmissions in the Leading Hydrogen Ecosystem scenario in 2040.

If the locations of hydrogen production facilities are managed, energy transfer from north to south will be a more balanced mix of electricity and hydrogen. In this scenario, a larger part of hydrogen would be produced in the north close to renewable electricity production and the surplus hydrogen can be transferred to consumption sites in the south through a large hydrogen pipe. The total amount of energy transferred would thus also be lower since more electricity would have to be transferred to account for the losses in hydrogen production stemming from electrolyser efficiency of 70 %.

If more hydrogen production would be located in the south in the scenarios, it would mean an even greater need for the north-south transmission of electricity for hydrogen production. It could lead to a situation in which electricity would first be transferred from north to south, followed by the transfer of hydrogen to northern consumption sites and export from the south. This would result in the transfer of large amounts of energy in opposite directions as electricity and hydrogen, which is not efficient from the perspective of the transmission infrastructure.

Figure 24 further illustrates the transmission capacity required across Finland's cross-section with a duration curve. The duration curve shows the energy transfer need as a percentage of hours in the year, from the largest north-to-south (+) to the largest south-to-north (-) transmission.

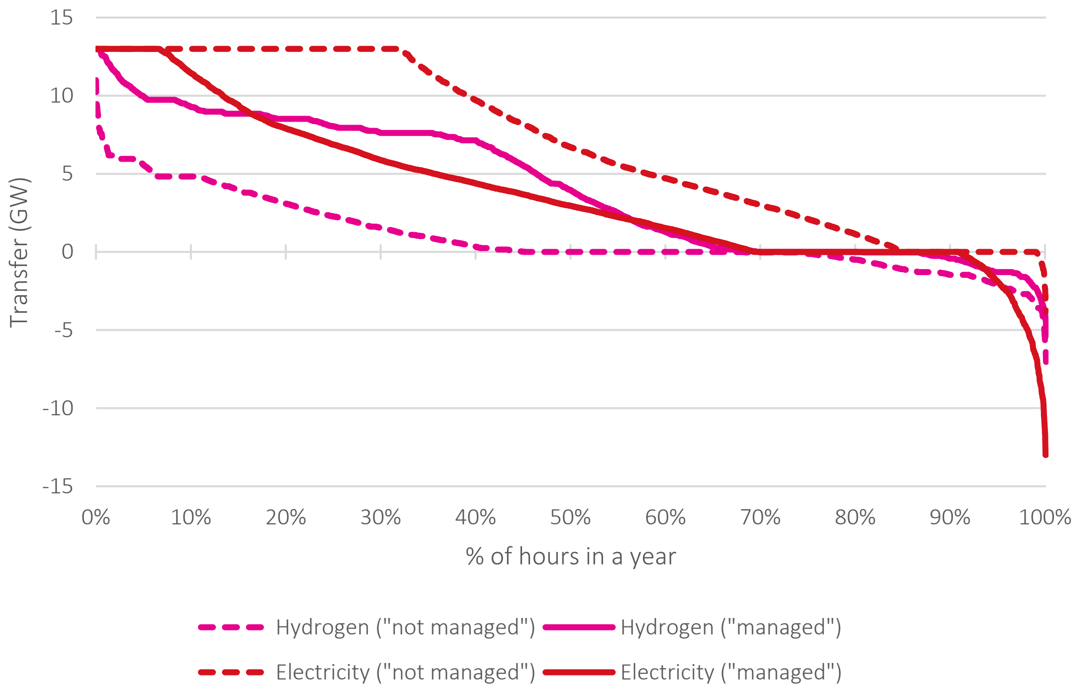

Figure 23. Duration curve of energy transmissions as hydrogen and electricity across Finland's cross-section in the Leading Hydrogen Ecosystem scenario in 2040.[34]

If hydrogen production focuses on the south (”not managed”), north-to-south transmissions of electricity will account for more than 80% of the hours in the year and electricity transmission will be at full capacity for a third of the year's hours. This would mean more electricity transmission needs, but with the limitations of the network creating a bottleneck for the transmission amount. At the same time, use of the hydrogen transmission infrastructure would be low, with north-to-south transmission only occurring for about 40% of the hours in the year, and the transmission infrastructures would thus not be used efficiently.

In the “managed” alternative, the transmission need is still prevalently from north to south, but the hydrogen transmission infrastructure is also used efficiently to meet this demand. In this case, transfer of both hydrogen and electricity from north to south account for roughly 70% of the hours in the year and no bottleneck is created in the electricity network. The establishment of hydrogen production, that

[34] Examples for hourly transfer needs are from one weather year with average weather conditions

is, electrolysers, in a manner taking the needs of energy transmission infrastructure into consideration would significantly decrease the electricity transfer need and thus the risk of potential bottlenecks.

From the land use perspective alone, it is more sensible to build a single large hydrogen pipe than several electricity transmission lines. This is the case already in 2030 and in the other scenarios, even though the greatest transmission need over Finland's cross-section will increase considerably by 2040 and be especially pronounced in the *European Hydrogen Market* and *Leading Hydrogen Ecosystem* scenarios.

From the perspective of developing the system, it is vital for Fingrid and Gasgrid to identify their customers' energy transfer needs in time and respond to them by designing and building the required transmission infrastructure. As the sectoral integration of the electricity and hydrogen infrastructures progresses, the companies also need to take each other's transmission infrastructure development into account and seek to create the most cost-effective energy system possible for Finland through joint design.

6.5 Increasing energy system flexibility with storages

Electrolysers can be operated according to renewable electricity production and the price of electricity. However, hydrogen consumption will probably not follow the variable production profile but be more stable, especially in industrial applications. It is thus important to decouple the use of electricity for electrolysis and the end-use of hydrogen with large-scale hydrogen storage. Large-scale energy storage facilities will be increasingly necessary for the energy system at large, if only to offset seasonal variation, as the amount of variable renewable energy production increases rapidly and energy self-sufficiency and security become more and more important. Storing energy in gaseous form offers storage facilities in the TWh scale (Figure 25).

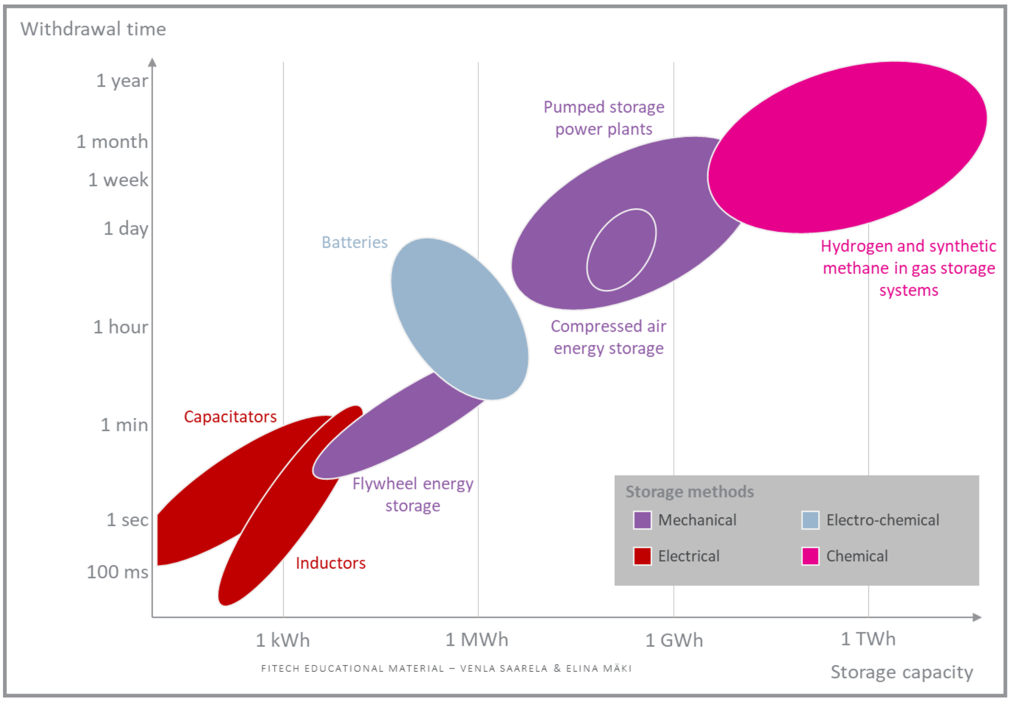

Figure 24. Capacities and discharge times of energy storage technologies. (Edited from: ETIP SNET [35])

Hydrogen can be stored as a gas under high pressure, as a liquid, in cryo-compressed form or bound to another substance. Gaseous hydrogen can be stored in, for example, salt caverns, lined rock caverns, steel tanks and hydrogen pipes. Hydrogen is pressurised for storage due to its low energy density. The increased storage density also increases energy consumption and the technical requirements for storage. There are no geologically suitable formations for the salt cavern storage of hydrogen in Finland, unlike elsewhere in Europe.[36] Lined rock caverns are seen as a potential large-scale storage solution in Finland. The HYBRIT project in Sweden successfully piloted a 100 m^3 rock cavern storage facility based on Lined Rock Cavern (LRC) technology, storing hydrogen at a maximum pressure of 250 bar.[37,38] At a later stage, the HYBRIT project will consider the construction of a full-scale lined rock cavern storage facility in the 100,000–120,000 m^3 size.[39]

A hydrogen pipe provides some storage capacity (*linepack*[40]). The pipe diameter and pressure difference determine the storage capacity. Cavern storage facilities are not always located optimally regarding hydrogen production and consumption, or cannot be excavated in such locations, but this challenge can be overcome with the pipeline transmission of hydrogen.

Since hydrogen solutions couple different sectors, they can offer system services that benefit the entire system, especially in the form of increased flexibility. Such flexibility can be roughly divided into solutions for two time scales[41]:

1) **Short-term flexibility**: Electrolysers can be operated as a function of electricity price, directing electricity consumption to times when the electricity supply is high and the price low. Such flexibility is possible if hydrogen consumption can follow the production profile or a hydrogen storage facility is available. Hydrogen storage is possible in the hydrogen transmission pipeline infrastructure, for example, which offers transmission and storage possibilities to hydrogen producers. The producer's own storage tanks or similar solutions could be an alternative. Electrolysers can offer flexibility services to the electricity network by participating in the reserve market.

2) **Medium- and long-term flexibility**: Hydrogen can serve as a chemical storage medium for electricity at the weekly or monthly level, or even as a seasonal storage solution, serving different sectors during peak demand or when there is not enough electricity available. In addition to electrolysers, this would require investments into hydrogen transmission and storage infrastructure.

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[35] ETIP SNET. (2023). Hydrogen's impact on grids – Impact of hydrogen integration on power grids and energy systems. https://op.europa.eu/en/publication-detail/-/publication/34a5ce58-42fb-11ee-a8b8-01aa75ed71a1
[36] Business Finland. (2020). National Hydrogen Roadmap for Finland. https://www.businessfinland.fi/4abb35/globalassets/finnish-customers/02-build-your-network/bioeconomy--cleantech/alykas-energia/bf_national_hydrogen_roadmap_2020.pdf
[37] HYBRIT. (23.9.2022). HYBRIT: Milestone reached – pilot facility for hydrogen storage up and running. https://www.hybritdevelopment.se/en/hybrit-milestone-reached-pilot-facility-for-hydrogen-storage-up-and-running/
[38] Vattenfall. (16.10.2023). HYBRIT: Hydrogen storage reduces costs by up to 40 per cent. https://group.vattenfall.com/press-and-media/pressreleases/2023/hybrit-hydrogen-storage-reduces-costs-by-up-to-40-per-cent
[39] HYBRIT: A unique, underground, fossil-free hydrogen gas storage facility is being inaugurated in Luleå - SSAB (3.11.2023)
[40] Linepack means the volume of gas stored in the pipeline.
[41] ETIP SNET. (2023). Hydrogen's impact on grids – Impact of hydrogen integration on power grids and energy systems. https://op.europa.eu/en/publication-detail/-/publication/34a5ce58-42fb-11ee-a8b8-01aa75ed71a1

7 Hydrogen economy investments and markets

The production of clean hydrogen at the scale discussed in this report will require huge investments in renewable electricity production, electricity and hydrogen transmission infrastructure, electrolysers and energy storage. Investments are also needed for the refining of clean hydrogen into downstream products. Section 7.1 presents the investments required to produce clean hydrogen in Finland in each scenario, while Section 7.2 discusses the role enabled for Finland by these investments in the EU hydrogen market worth billions of euros. More information on industrial value chains and alternative downstream processes for hydrogen is provided in Annex 5.

7.1 A clean energy system requires huge investments

Figure 26 illustrates the scale of the investments required by the production, transmission and storage of clean hydrogen by 2030 and 2040. The total investments amount to 30–40 billion by 2030, increasing to 60–90 billion by 2040.

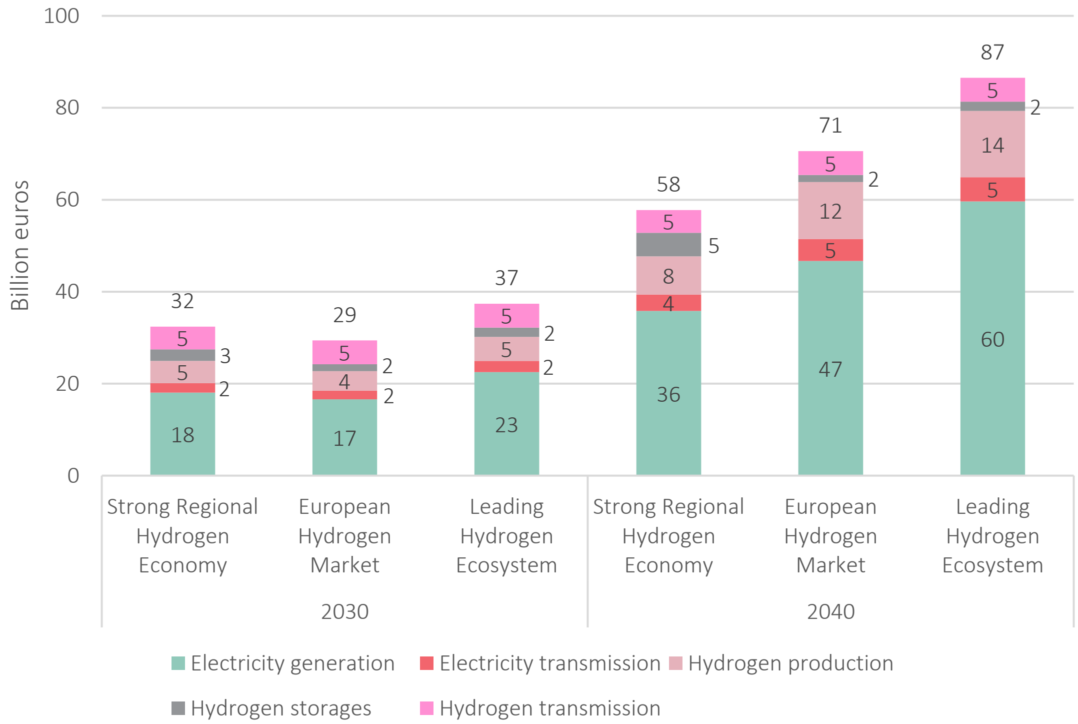

Figure 25. An estimate of the investments required for the production of clean hydrogen in Finland by 2030 and 2040, cumulative – investments in hydrogen use or downstream operations not taken into consideration.

In addition to the above-mentioned investments, considerable investments will be required in hydrogen-using industries and refining hydrogen into downstream products. According to a study by VTT[42] and the Confederation of Finnish Industries' Green Investment Data Dashboard[43] , the value of current hydrogen economy projects is around 10–20 billion euros, with investments in hydrogen

[42] Pre-study on transition to hydrogen economy, specifically in Northern Ostrobothnia (Kiviranta et al., 2023)
[43] https://ek.fi/en/green-investments-in-finland/ (Confederation of Finnish Industries, data fetched on 30.10.2023)

reduction to produce fossil-free steel and in methanation and ammonia plants for the production of electrofuels standing out.

Electricity production will require the lion's share of the investments, and investments in it will grow to approximately 15–25 billion euros by 2030 and 35–60 billion euros by 2040. These investments correspond to the renewable electricity production capacity required for the electricity consumed in the production of clean hydrogen (see capacities, Figure 11). The estimate is based on the development and investment costs of onshore and offshore wind power and solar power in the scenarios. Most investments will be made in onshore wind power, but offshore wind power will gain a foothold in the 2030s. In practice, these investments would mean the construction of around 100–200 onshore wind farms, 2–6 offshore wind farms and dozens of large-scale solar power plants by 2040[44].

The investments in hydrogen production will be in the magnitude of 5 billion euros by 2030, increasing to a total of 8–14 billion by 2040. The estimate is based on the electrolyser capacity built and investment costs used in the scenario. The electrolyser capacity of currently known projects varies from a few to several hundred megawatts, and project sizes exhibit a growing trend. In any case, the investments would be distributed over dozens if not hundreds of hydrogen consumption facilities.

The magnitude of investments required for the storage of hydrogen in rock caverns (see capacities, Figure 12) has been estimated at 2–3 billion euros by 2030, which would correspond to several large rock caverns. In addition to these, the buffer capacity provided by the pipe offers valuable added flexibility for the system, and this investment is included in the investments in hydrogen transmission infrastructure. The need for domestic hydrogen storage will only grow up to 2040 in the *Strong Regional Hydrogen Economy* scenario, in which the total storage investments will reach 5 billion euros. Storage investments are thus considerable compared to, for example, investments in electrolysers, but they provide benefits in the form of lower hydrogen production costs and improved reliability of supply in the scenarios. However, the development of hydrogen storage involves considerable uncertainties[45].

Regarding electricity transmission, the assessment is based on Fingrid's main grid development plan[46], with the development of the hydrogen economy according to the scenarios estimated to require about half of the 4 billion total investment in the main grid by 2030. In addition, development in the 2030s is estimated to require investments corresponding to the current development plan over a 10 year period, of which the growth of the hydrogen economy will require a considerable share. The total main grid investments required for the hydrogen economy are estimated at 4–5 billion euros by 2040, and the increase in other electricity production and consumption will also increase investment needs. The scale of these investments will be thousands of kilometres of new 400 kV power lines and hundreds of substation projects by 2040.

Both the main pipeline of the hydrogen transmission infrastructure to be built in Finland and half of the offshore pipeline to be built between Finland and Estonia have been taken into account in the hydrogen transmission investments. The investments are based on preliminary estimates of those parts

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[44] Based on the estimated average power plant size: 200 MW for onshore wind farms, 1,000 MW for offshore wind farms and 100 MW for solar power
[45] It must be noted that the hydrogen storage investments involve significant uncertainties, e.g. related to the construction costs and technical solutions of hydrogen storage facilities. Various storage solutions have been built for natural gas, but large-scale storage facilities for hydrogen are still in the pilot stage. In Sweden, for example, a rock cavern is being piloted for hydrogen storage as part of the HYBRIT project
[46] Main grid development plan (Fingrid, 2023).

of Gasgrid's Nordic Hydrogen Route and Nordic-Baltic Hydrogen Corridor projects[47] that involve Finland. The total investment in the hydrogen infrastructure is estimated at roughly 6 billion euros, including compressors, and would be implemented by 2030 in all scenarios. The premise for the scenarios is a 13 GW hydrogen pipeline with a cost estimate based on the EHB's study[48]. In practice, this would mean one steel pipe with a diameter of 1.2 metres and a total length in the region of 1,500 kilometres in Finland. Enabling the transmission and storage of hydrogen would also require smaller pipeline branches or other cross-border connections, but these have not been considered in the scenarios' investment estimates.

The required energy transmission investments are significant, but relatively moderate compared to the overall upstream investments in the hydrogen value chain described in the scenario. Additional investments in hydrogen economy value chains (for example hydrogen refining) have not been taken into account in the magnitude of the proposed investments, which further emphasises the cascade effects of infrastructure investments on the creation of new industries.

7.2 Investments will open a hydrogen market worth billions

It is essential to take the EU targets for a clean hydrogen market into consideration when assessing Finland's role as a producer of hydrogen and its downstream products. The volume of the EU hydrogen market has been estimated at approximately 670 TWh in 2030[49] and roughly 1,300 TWh in 2040[50]. The REPowerEU sets a target of covering half of the EU's hydrogen demand with hydrogen produced in the EU by 2030, with the other half being imported from other regions.

Considering these targets and the Finnish production of clean hydrogen in the scenarios, Finland's share of hydrogen produced in the EU would be 11–14% in 2030 and 12–21% in 2040 (Figure 27). The scenarios show that Finland has the opportunity to become larger than its size, assume a leading role in the European hydrogen economy and produce over 10% of the EU's clean hydrogen according to the Government's decision-in-principle.

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[47] Nordic Hydrogen Route ja Nordic-Baltic Hydrogen Corridor hankkeet (Gasgrid Finland, 2023).
[48] Extending the European Hydrogen Backbone (EHB, 2021)
[49] Based on the EU's REPowerEU plan, taking into account both the EU's 10 Mt production target and 10 Mt import target by 2030 (European Commission, 2022)
[50] Based on the scenarios in the ENTSO-E and ENTSOG development plan NB. The impact of the REPowerEU plan has not been taken into account in the scenarios, and the estimated hydrogen demand thus appears low. (ENTSO-E, ENTSOG, Ten Year Network Development Plan 2022)

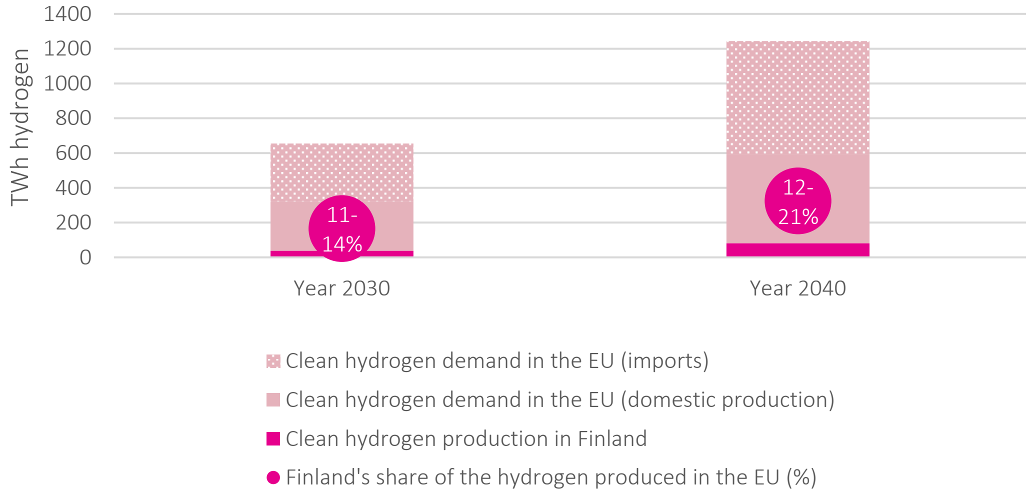

Figure 26. Estimate of Finland's share of the EU's clean hydrogen production.[51]

Major investments in clean hydrogen production give access to the EU clean hydrogen market valued in the billions of euros (Figure 28). The competitive price for clean hydrogen is estimated at EUR 2.5/kg in 2030, falling to about EUR 2/kg by 2040[52]. Calculated at these prices, Finland's annual clean hydrogen production would be worth 3–4 billion euros in 2030, increasing to 5–8 billion euros by 2040. In addition, Finland will generate added value by refining hydrogen into downstream products, such as electrofuels, and this industry is much more valuable than simple hydrogen production. This added value has not been taken into consideration in this report, because it was not possible to examine the end-product markets and the refining processes required by them in sufficient depth within the scope of this project. However, Guidehouse[53] has estimated that the development of the hydrogen economy could bring 16–34 billion euros in 2035 and 41–69 billion euros in 2045 into the Finnish economy.

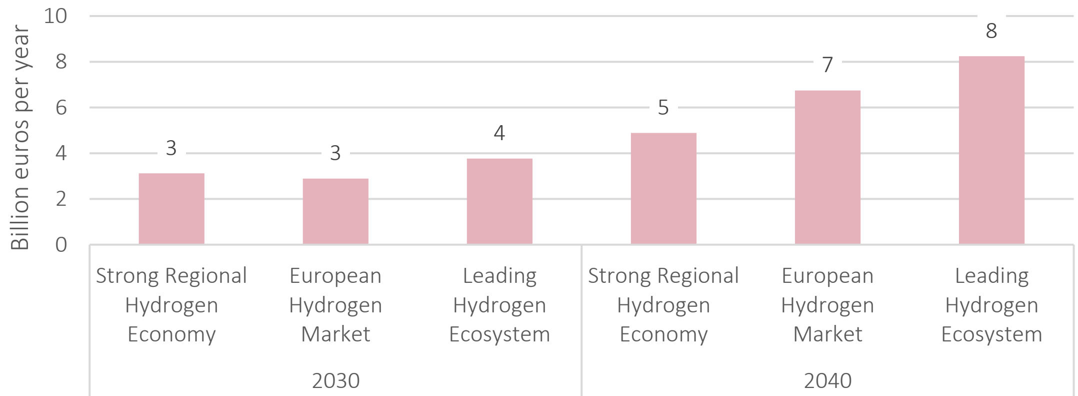

Figure 27. Estimated annual value of Finland's clean hydrogen production – only includes the estimated value of hydrogen gas, not that of downstream products.

[51] The estimate takes into account the above sources as the EU's hydrogen demand, and that half of the demand would be covered by imports from regions outside the EU based on the goals of the REPowerEU plan for 2030, which means that half of the demand would be covered by hydrogen production in the EU. The figure shows the range of scenarios of this report in Finland's clean hydrogen production.
[52] Five Hydrogen supply corridors for Europe in 2030, s. 115 (EHB, 2022)
[53] Clean hydrogen economy strategy for Finland supporting analysis report. Unpublished. (Guidehouse, 2023)

8 Conclusions

Finland has excellent potential to become a forerunner of the hydrogen economy. Hydrogen produced from clean electricity and its downstream products can grow into a major export industry for Finland. Finland has significant renewable electricity production potential, which can be used for the electrification of society and harnessed for new, electricity-intensive industries. In addition to renewable electricity production resources, Finland has a strong national grid, an expert workforce and several companies that can operate in the hydrogen value chain. Finland has a strong ambition to promote the hydrogen economy and seeks a leading role in all parts of the European hydrogen economy’s value chain, as set out in the Government's decision-in-principle.

Active development work is still needed to complement Finland’s identified strengths. The favourability of Finland's investment environment in terms of regulations, permits and social stability is significant. Consistent and clear regulation is essential for the development of the hydrogen economy. The future hydrogen economy largely relies on well planned, supported and implemented regulation, both in the EU and globally. If successful, regulation can create strong demand for hydrogen and its derivatives and give companies the confidence to invest in the future. The definitions, standards and market regulations for clean hydrogen, referring to a great deal of EU regulation applying to, for example biofuels and natural gas, play an integral role in this. Connection opportunities to energy transmission networks, the availability of competent labour and companies operating in the hydrogen value chain are also key considerations.

The scenarios examined in the project present three development paths for Finland’s role in the European hydrogen market’s value chain. In the scenarios, Finland grows into a major producer of either hydrogen downstream products, hydrogen gas or both for the growing needs of the European market. In line with the goal set in the Government’s decision-in-principle, Finland achieves a leading role in the European hydrogen economy and increases its market share to more than 10 per cent of the clean hydrogen produced in the EU by 2030 in all scenarios. The growth assumptions described in the scenarios raise tough questions regarding the development of the energy system and thus help ensure that the development needs of both electricity and hydrogen transmission infrastructures are assessed comprehensively and in time.

To achieve the potential demonstrated by the scenarios, Fingrid and Gasgrid must recognise their customers’ potential in time and develop the energy transmission infrastructure in advance to enable the growth of the energy system. Energy transfer needs increase dramatically in all scenarios, as the production and consumption of both electricity and hydrogen are distributed across Finland. The energy required by the hydrogen industry can be transferred either as electricity, as is the case today, or in future also as hydrogen as outlined in the scenarios. Both domestic and cross-border electricity and hydrogen transmission infrastructures are developed in the scenarios. The creation of a hydrogen transmission infrastructure also enables the import and export of clean hydrogen gas, which is an essential component of the scenarios and has a far-reaching impact on the energy system.

Hydrogen can be transferred through existing methane pipes by blending it with methane, by converting existing methane transmission pipes for hydrogen transmission, or by building new hydrogen transmission pipes. The first two options are being implemented in several projects in Central Europe, but the development of new hydrogen transmission infrastructure is seen as the most viable alternative for Finland, because Finland lacks an extensive natural gas network with little-used parallel pipes. In addition, the current gas network is limited to southern Finland and is not located close to the potential hydrogen production sites. A large-scale hydrogen pipeline is technically feasible, even though there are no experiences of its use in the Nordic environment yet. The decades-long experience of Finland's methane infrastructure and its operation can be used as a starting point for design, implementation and use. However, there are some differences in the technical implementations of the pipelines, which need to be taken into account in planning.

The energy transfer needs described in the scenarios can be satisfied cost-effectively through the joint design of the electricity and hydrogen infrastructures, utilising the transmission capacity of both electricity and hydrogen infrastructures and taking the importance of location into account, especially in the siting of hydrogen production. The energy transfer needs in the scenarios would not be manageable or even possible with the electricity transmission network alone. That is why the hydrogen network plays a key role in tapping Finland's full potential. By using the hydrogen transmission infrastructure, hydrogen producers can establish themselves closer to electricity production regardless of the location of hydrogen consumption and refining sites, which will reduce the need to transfer energy as electricity. In addition, a hydrogen transmission infrastructure enables the large-scale storage of hydrogen, which also helps with balancing the electricity system. Developing international hydrogen transmission connections will expand the hydrogen market and create new business opportunities at various points in the hydrogen value chain.

Gasgrid Finland and Fingrid see the joint design of hydrogen and electricity transmission infrastructures as essential for the development of the most cost-effective energy system possible and realisation of the Finnish hydrogen economy's maximum potential. There are still many open questions and much to study concerning the development of the hydrogen economy, for example regarding the market's operating models, regulation, sectoral integration, plant concepts and operating models, the realisation rate and locations of investments, technical standards, customer connection principles, quality requirements for hydrogen, and so on. The companies will thus continue working together to resolve these questions and develop the energy system even after the conclusion of the project, promoting the holistic design of the energy system as proactively and openly as possible.

Annex 1: Scenario modelling and underlying premises

The objective of modelling the scenarios is to anticipate the market-based investments in electricity and hydrogen production that would be made if the business environment were to develop as described in the scenario. Fingrid did the modelling for the scenarios with AFRY's BID3 electricity market model[54], which is used by Fingrid more widely as well. The model is used to analyse the functioning of the market both at the hourly level and at that of various investment horizons for production and consumption plants. The Baltic region and most of Western and Central Europe are taken into account in the modelling. For example, the export of hydrogen from Finland thus requires hydrogen produced in Finland to be cheaper than that produced in the importing country at the time of export.

The driving factor behind the scenarios is a growing demand for hydrogen. Domestic hydrogen demand will grow according to the development paths presented in Section 5.1. Swedish hydrogen demand has been estimated based on, the Energiforsk[55] and Fossilfritt Sverige[56] reports, modified to use similar demand drivers for the export of hydrogen and its downstream products in Finland and Sweden. Hydrogen demand in other European countries has been determined based on ENTSO-E's scenario[57]. The scenario does not include recent changes in the operating environment, so the scenarios have been updated with the impact of the RePowerEU programme on the amounts of clean hydrogen and renewable energy sources.

The scenarios use the national minimum targets set for renewable electricity production in various European countries as starting points for the development of electricity production capacity. It was assumed that investments required for the achievement of national targets would be subsidised if they do not seem viable on market-based terms. On the other hand, the scenarios also specify maximum amounts for renewable electricity production capacity and a maximum annual construction rate that the countries are assumed to be capable of. These maximums will be reached with market-based investments, especially in Central Europe, which reflects the insufficiency of renewable electricity production resources in relation to the high demand in the region.

In Finland, the growth of production is limited by the assumption that at most 4 GW of onshore wind power can be built in a year. However, it was assumed that the limitations caused by radar surveillance in eastern Finland will be resolved and onshore wind power can be built more freely in the east as well. This will enable the maximum utilisation of Finland’s onshore wind power potential. The geographical dispersion of wind power also improves its profitability, since local variation in winds improves the profitability of wind power investments. At the same time, the total wind power production will be more stable as production can be distributed over regions with different wind conditions.

Market-based investments in wind and solar power, electrolysers and hydrogen storage facilities have been determined so that operating margin obtained by the investment on the wholesale market will cover the balanced investment costs and provide the required return on capital[58]. Electricity and hydrogen production, consumption and storage are optimised in the calculation model with a regional

[54] https://afry.com/en/service/bid3-power-market-modelling
[55] The role of gas and gas infrastructure in Swedish decarbonisation pathways 2020-2045. (Energiforsk, 2021)
[56] Strategy for fossil free competitiveness – Hydrogen. (Fossil Free Sweden, 2021)
[57] Ten Year Network Development Plan 2022 – Scenario report (ENTSO-E, 2022)
[58] A real 5% return on capital was assumed

common market, which has been simulated with the assumptions of full competition and complete information with a 10-day time horizon.

Investment costs

The assumed investment, operating and maintenance costs of electricity production are mainly based on the above-mentioned ENTSO-E scenario. The investment costs of renewable onshore and offshore wind power and solar power will all decrease, but onshore wind power will remain the most competitive option. Connection costs have been taken into account in the investment costs. For example, the length of the connection cable required for offshore wind power causes variation in the costs. Table 8 presents a summary of how the cost of investing in renewable wind and solar power will develop. The fixed operating costs have been estimated at 1–2% of the investment cost. The assumed service life was 30 years for wind power and 40 years for solar power.

Table 8. The development of investment costs in renewable electricity production capacity (capex, EUR 2021/kW).

Technology	2030	2040
Onshore wind power	960	880
Offshore wind power	1710–1920	1560–1750
Solar power	380	330

An electrolyser efficiency of 70% and a cost development based on an alkaline electrolyser were used for electrolysis in the modelling. Other electrolyser technologies include polymer membrane and solid oxide cell electrolysers, but the costs of these are estimated to be higher than those of an alkaline electrolyser. The estimate on cost development was compiled from the IEA study[59] used for Finland's hydrogen roadmap and from other sources[60,61]. Table 9 presents the assumptions used for the development of electrolyser investment costs in the scenarios. The fixed annual operating costs of an electrolyser were assumed to be 4% of investment costs, including "stack replacement" costs. It was assumed that technological advances will increase service life from 26 to 32 years.

Table 9. The development of investment costs in hydrogen production capacity (capex, EUR 2021/kWe)

Technology	2030	2040
Alkaline electrolyser	400	300

Hydrogen can be stored insalt caverns, rock caverns, steel tanks and hydrogen pipes. Of these, large-scale cavern solutions can be a particularly cost-effective solution suitable for long-term energy storage

[59] Business Finland, National Hydrogen Roadmap for Finland: (Laurikko, et al., 2020)
[60] https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf
[61] https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf

compared to, for example, electricity storage facilities, which usually have a limited capacity to meet long-term flexibility requirements for cost reason[62]. Rock caverns were assumed to be the most cost-effective form of large-scale hydrogen storage in Finland.

The cost estimates for hydrogen storage are based on several sources, such as a study by the Danish energy authority [63], a report ordered from the Lappeenranta University of Technology[64] and studies conducted in the HYBRIT project[65], but they still contain major uncertainties due to the novelty of the storage technologies. Table 10 presents the assumptions used in the scenarios for the development of hydrogen storage investment costs with the solutions relevant to Finland, that is, rock caverns and steel tanks. The fixed annual operating costs of storage have been estimated at 2% of the investment cost. The storage capacity of rock caverns was assumed to be 168 hours and that of steel tanks 12 hours, and the service lives of both at 30 years. In addition to the above-mentioned solutions, hydrogen can be stored cost-effectively in the transmission pipeline.

Table 10. The development of investment costs in hydrogen storage capacity (capex, EUR 2021/kWe).

Technology	2030	2040
Rock cavern storage (168 h)	500	380
Steel tank storage (12 h)	540	320

The hydrogen network's investment costs and technical specifications are based on the EHB study[66] and the largest pipe size discussed in it, with a diameter of 1.2 metres and capacity of 13 GW. The investments costs of a large hydrogen pipe are approximately EUR 0.26/kW/km. The buffer capacity available for the storage of hydrogen was estimated at 50 GWh/1,000 km. The costs for the electricity network are based on Fingrid's realised investments in the 400 kV AC overhead line network. According to a rough estimate, the investments costs would be approximately EUR 0.3/kW/km.

[62] https://gasgrid.fi/wp-content/uploads/Gasgrid_Study-on-the-Potential-of-Hydrogen-Economy-in-Finland_ENG-FINAL.pdf
[63] https://ens.dk/sites/ens.dk/files/Analyser/technology_data_catalogue_for_energy_storage.pdf
[64] Electrolysis Technologies (Liikanen & Moilanen, 2022) – literature study, unpublished
[65] https://www.hybritdevelopment.se/en/research-project-1/researchlibrary/
[66] Extending the European Hydrogen Backbone (EHB, 2021)

Annex 2: Detailed results of scenario modelling

Clean hydrogen for domestic industry and export products

In all scenarios, domestic hydrogen demand is based on current industries switching to clean hydrogen and demand for clean hydrogen in the new hydrogen industry, but the amounts differ depending on the scenario (Figure 29). In all scenarios, the level of domestic demand in 2030 is assumed to be based on the replacement of grey hydrogen with clean hydrogen and the public objectives[67,68,69], for using clean hydrogen in new applications, such as in the steel industry and fuel refining. Most of the consumption would come from the new hydrogen industry, and hydrogen would be produced for the production of electrofuels in particular.

In the *Strong Regional Hydrogen Economy* and *Leading Hydrogen Ecosystem* scenarios, 19 TWh of hydrogen would be used to produce electrofuels in 2030 and 43 TWh in 2040. In the *European Hydrogen Market* scenario, domestic electrofuel production is small-scale, requiring 8 TWh of hydrogen in 2030 and 15 TWh in 2040. In all scenarios, demand for hydrogen used for other purposes than electrofuel production would be at the same annual level of 6 TWh in 2030, growing moderately to 10 TWh by 2040.

Based on the scenarios, the total demand for hydrogen would at least triple and perhaps even quadruple from today's level by 2030. This would mean an annual growth of 3–5 TWh in the demand for clean hydrogen, if the growth would mainly occur in 2025–2030.

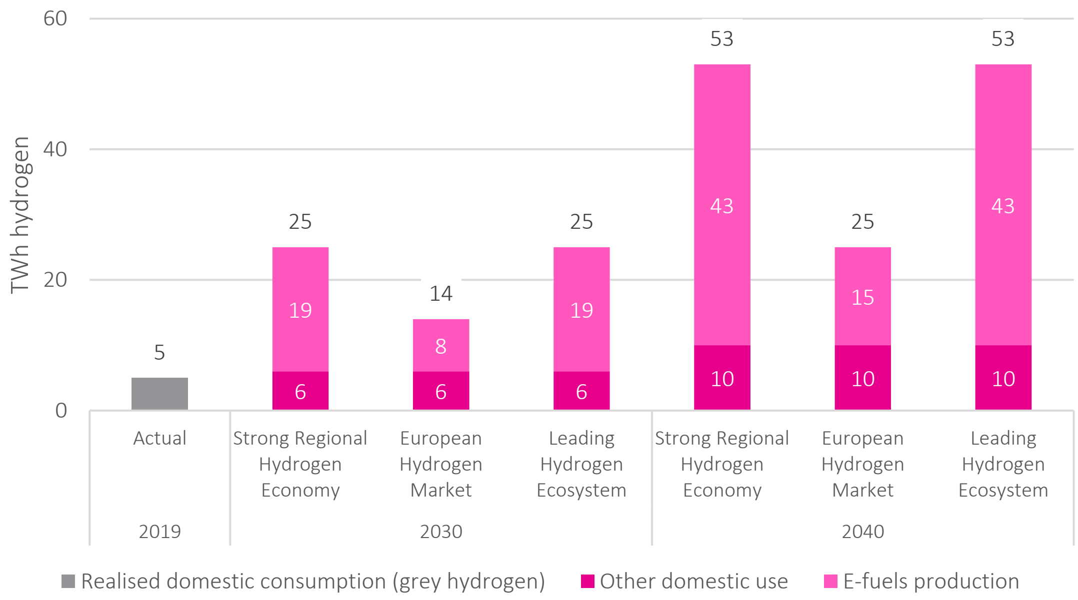

Figure 28. Actual hydrogen demand in Finland in 2019 and clean hydrogen demand in the scenarios.

The 2040 estimate for the domestic consumption of hydrogen is over 50 TWh in the *Strong Regional Hydrogen Economy* and *Leading Hydrogen Ecosystem* scenarios. This estimate is based on the highest

[67] Ren-Gas: 2,5 TWh of renewable gas fuel for heavy transport. (Company website, accessed on 27 May 2022)
[68] P2X Solutions: 1,000 MW of electrolysis power over the next ten years (P2X Solutions, 2022)
[69] Business Finland, National Hydrogen Roadmap for Finland: approximately 170 kt/a (~6 TWh) growth in hydrogen consumption, especially in the oil refining and steel industries (Laurikko, et al., 2020)

demand scenario in the hydrogen economy report commissioned by the Prime Minister's Office[70], which has been used in the modelling of the above-mentioned scenarios. This would mean an annual growth rate of around 3 TWh in demand during the 2030s. Domestic demand in the *European Hydrogen Market* scenario remains at 25 TWh, since in that scenario, the growth of the Finnish hydrogen economy is mostly based on the export of hydrogen gas.

Hydrogen export volumes as hydrogen gas in the scenarios

In the scenarios, hydrogen transmission was modelled based on assumed pipe connections as well as a balance of hydrogen demand and supply in Finland and the other states around the Baltic. A pipe connection to Northern Sweden is built in all scenarios, complemented by a pipe connection to Central Europe in the *European Hydrogen Market* and *Leading Hydrogen Ecosystem* scenarios. Figure 30 presents the export amounts of clean hydrogen gas to countries in the Baltic region. Finland becomes a competitive hydrogen producer in all scenarios and exports hydrogen to both Northern Sweden and Central Europe in addition to satisfying domestic demand.

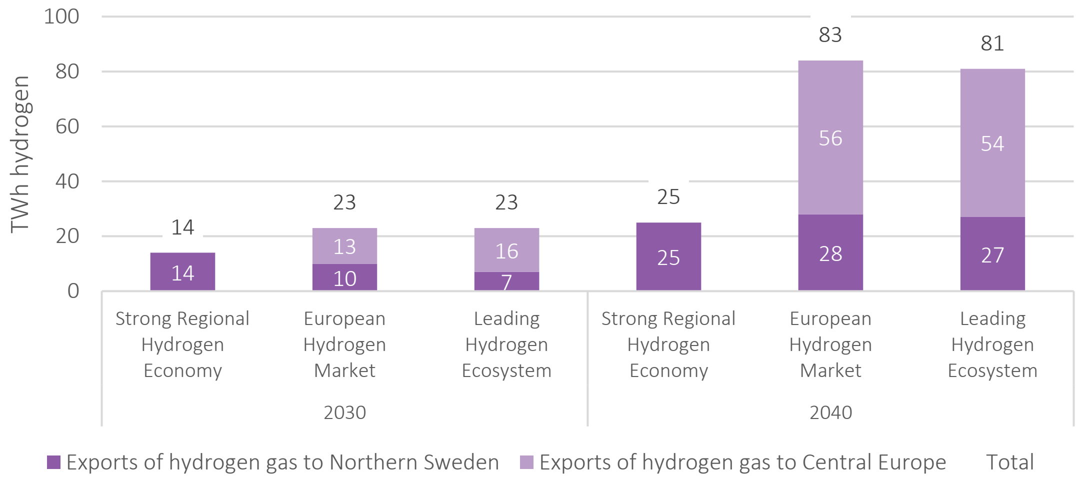

Figure 29. Net Finnish hydrogen gas exports through the pipe connections to Northern Sweden and Central Europe.

In 2030, net exports of hydrogen through the pipe connection for the needs of Northern Swedish industries will be approximately 7–14 TWh, complemented by a net export of 13–16 TWh to other European countries through a pipe connection in two of the scenarios. The export volume to Northern Sweden will grow to around 25–27 terawatt hours by 2040. The most significant growth will be seen in hydrogen exports to Central Europe, especially in the *European Hydrogen Market* scenario, in which exports will reach up to 80 TWh. In the *Leading Hydrogen Ecosystem* scenario, the export of hydrogen gas will remain slightly lower, since extremely high domestic demand will take up most of the available resources, renewable electricity in particular.

[70] Valtioneuvoston kanslia, Vetytalous – mahdollisuudet ja rajoitteet – report of Prime Minister's Office in Finnish, s. 162 (Sivill, et al., 2022)

Annex 3: Regulation and strategies influencing the development of the hydrogen economy

This Annex summarises the EU legislation concerning the hydrogen market and the funding mechanisms with a direct or indirect impact on the formation of the hydrogen economy. The Annex looks at the national initiatives of Finland and its neighbours Sweden, Denmark, Estonia and Germany with a direct impact on the Finnish hydrogen economy. This summary was compiled by KREAB Oy.

EU-level regulation related to the hydrogen economy

EU Emissions Trading System (EU ETS)

The most significant legislative proposal in the Fit for 55 package is an update of the EU Emissions Trading System, EU ETS[71]. The update removes free emission rights from the market, which will probably increase the price of emission rights. Increasing costs will incentivise industries to invest in clean and emission-free technology. Emissions trading fees will be allocated to different funding mechanisms, the Social Climate Fund, the Modernisation Fund and the EU Innovation Fund. With these funds, the EU seeks to support regional development and the development of a clean energy market. The new EU ETS II, adding new sectors such as maritime transport, road transport and buildings, into the scope of the Emissions Trading System, was introduced to the Emissions Trading System as a new component. The new system will be in use from 2025 and guides sectors towards the adoption of clean technologies, such as synthetic fuels, green steel and green concrete.

The update of the proposal has been completed and has entered into force. EU ETS II limits the costs of emission rights to 45 euros/CO2t until 2027. Member States have the option not to implement ETS II if they tax carbon dioxide emissions more heavily than the ETS II cost level. This is the case in Finland, so the impact of ETS II will remain minor here.

The Renewable Energy Directive update (RED III)

The direct impact of ETS I & II on the building of the Finnish hydrogen ecosystem will be marginal, but the impact of the Renewable Energy Directive, or RED, update will be crucial for the future of hydrogen. The preliminary agreement between EU institutions was adopted in March 2023, and national transposition is meant to be complete by 2025. The revised Directive sets minimum quotas for renewable energy by 2030 and minimum quotas for RFNBO (renewable liquid and gaseous fuels of non-biological origin, including hydrogen produced with renewable energy) for industry and road transport. The RED also authorises the European Commission to issue delegated acts (DA). According to the Directive, industries must increase the use of renewable energy by 1.6 per cent annually. The Member States have agreed that 42% of the hydrogen used by industry must come from renewable liquid and gaseous fuels of non-biological origin (RFNBOs) by 2030, increasing to 60% by 2035. For road transport, RED III sets the binding target of reducing greenhouse gas emissions by 14.5% or increasing the share of renewable energy sources to at least 29% by 2030. It also sets a combined 5.5% sub-target for advanced biofuels and RFNBOs, of which at least 1% must be achieved with RFNBOs.

For hydrogen, the European Commission has already passed delegated acts on production rules for RFNBO hydrogen according to the additionality principle. The DA issued under Article 27, paragraph 3 states that, by 2030, the renewable electricity used to produce clean hydrogen must be produced

[71] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32003L0087

within the same calendar hour. Another DA under Article 28, paragraph 5 specifies the calculation method for greenhouse gas reductions so that hydrogen can be counted as renewable by achieving CO2 reductions of 70%[72]. The delegated acts will be revised in 2028–2029.

Finland will update its distribution obligation legislation for road transport in the autumn of 2023 and lower the minimum quota for advanced biofuels (including RFNBO). The legislation was amended in 2022 and will be revised again in 2024 to align it with RED III. Regulatory uncertainty can hinder investment in the sector. Uncertainty on the supply and demand side and in feedstock availability creates a chicken-and-egg scenario, in which initial investments must be made at greater risk than normal for capital investment. Regulatory certainty is key to reducing the investment risk.

The Energy Efficiency Directive (EED)

The Energy Efficiency Directive seeks to reduce the end use of energy in the EU by setting targets for reducing the end use of energy both at the EU level and for individual Member States. The EU institutions approved the revision of the Directive in the summer of 2023, and the Directive will now proceed to national transposition[73].

The revised EED sets that the final energy consumption in Member States must be 11,7% lower by 2030 than estimated in 2020. In the case of Finland this would mean that final energy consumption should be lowered by nearly 50 TWh from the current 290 TWh.[74]

The production of clean hydrogen requires emission-free electricity. If Finland seeks to become an exporter of hydrogen technology, expertise and production as well as hydrogen and its derivatives, transposition of the EED is of vital importance. The Directive gives very little room for manoeuvre in applying for national derogations for the energy consumption resulting from hydrogen production, but Finland could apply for a derogation pursuant to the general additionality principle, according to which renewable energy production built and used solely for hydrogen production could be excluded from the final energy consumption value. This would also help the EU achieve the main goal of the EED reform, which is finding real energy savings.

The Carbon Border Adjustment Mechanism (CBAM)

The CBAM aims to reduce carbon leaks, that is, prevent companies from transferring emission-intensive production out of the EU/EEA. In practice, the currently valid EU emissions rights would have to be bought for materials covered by the CBAM at the EU border. The CBAM entered into force on 1 October 2023 and covers the following product categories: iron and steel, aluminium, electricity, certain fertilisers, cement and hydrogen, as well as certain cathode-active materials and a limited number of downstream products, such as screws and bolts. The construction of green steel, cement and fertiliser capacity in Europe will increase the demand for clean hydrogen in the EU[75]. This will drive investment in the EU.

For Finland, this opens a great opportunity to achieve a leading position in EU's internal hydrogen market. The largest consumer of clean hydrogen will probably be Germany. The decisive factor here is

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[72] https://ec.europa.eu/commission/presscorner/detail/en/qanda_23_595
[73] https://www.consilium.europa.eu/en/press/press-releases/2023/07/25/council-adopts-energy-efficiency-directive/
[74] https://tem.fi/-/tyoryhma-valmistelemaan-energiatehokkuusdirektiivin-toimeenpanoa - In Finnish
[75] https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021PC0564&from=DE

the way in which Finland can enter the German market, for example by exporting hydrogen through possible transmission pipes, hydrogen derivatives, clean electricity through PPAs, technology, etc. This means that Finland should focus on strategically important hydrogen markets.

The Energy Tax Directive (ETD)

The Energy Tax Directive (ETD) sets minimum tax rates for all feedstocks and forms of energy at the EU level. The revision of the ETD differs from the other regulation packages in the Fit For 55 package by not being discussed in the European Parliament at all. The European Council will decide on the proposed Directive.

Since the European market has a strongly divided energy consumption base, finding a consensus will not be easy. The Nordic countries are very dependent on renewable energy sources, whereas the eastern parts of the Union rely on natural gas, coal and oil. There are also great differences in the role of nuclear energy between Member States.

The ETD has become stuck in the Council due to these differences. It may be difficult to bring the matter to a close before the end of Spain's Presidency at the end of 2023. Belgium chairs the Council until the end of the current term and will probably try to find a consensus in the matter. For Finland, the taxation act only sets a minimum level of taxation. The ETD has no impact on building the Finnish hydrogen economy. The only negative effects could come from heavier taxation of bio-based feedstock or unfavourable treatment of biogenic carbon dioxide.

The Alternative Fuels Infrastructure Regulation (AFIR) and CO2 standards

The AFIR sets EU-level requirements for building a hydrogen distribution network and an electric car charging infrastructure[76]. The other part of the equation comes from the recently adopted CO2 standards for road vehicles[77]. Both instruments seek to reduce emissions from road traffic. Essentially, the new Regulation on CO2 standards would make the sale of internal-combustion engines using fossil fuels nearly impossible after 2035. This de facto ban may yet be changed, however. The CO2 Standards Regulation obliges the next European Commission to pass a regulation on RFNBOs, which would prohibit the sale of internal-combustion engines not using RFNBOs after 2035. This will open a market for RFNBOs produced in Finland. The AFIR obliges Finland to also build production capacity for other alternative fuels.

Member States have some options as to how to implement the Regulation and which parties to authorise or incentivise to build the charging and refuelling networks. One solution would be that the companies now obliged to deliver renewable biofuels to the road transport network would also build these alternative fuel networks. A second implementation alternative would be to set up an auction-based model for companies competing for building rights and incentivising them to apply for funding or guarantees from the state as part of the auction. The current problem for the building of alternative fuel infrastructures is the lack of demand. Why buy a car that you cannot charge or refuel anywhere, and why build infrastructure if no-one will buy the car? That is why government intervention is needed.

[76] https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A52021PC0559
[77] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0556

REFuelEU Aviation & FuelEU Maritime

As part of Fit For 55, the European Commission has also proposed tighter emissions reduction targets for air and maritime transport. REFuel Aviation sets minimum levels for renewable fuels and RFNBOs until 2050. FuelEU Maritime sets emissions reduction targets for vessels and stipulates how vessels and ports must arrange their charging and fuel bunkering capabilities going forward.[78]

Both political initiatives guide navigation and air transport towards renewable sources of energy and increase the demand for hydrogen. REfuelEU Aviation sets a binding 70% target for the use of sustainable aviation fuels (SAF), of which at least 32% must consist of synthetic aviation fuels, by 2050. FuelEU Maritime sets a binding target for reducing CO2 emissions by 80% by 2050. At the moment, hydrogen and its derivatives, such as RFNBOs, are more expensive than fossil fuels. Finland must find solutions for mitigating the negative effects during the transition period and production ramp-up.

Hydrogen and Decarbonised Gas Package

The reform of the Gas Directive (2009/73/EC) and Gas Regulation (EC) No 715/2009 is commonly called the Gas Package. It seeks to facilitate the building of hydrogen transmission systems, support the growth of hydrogen production and enable hydrogen transmission through existing gas transmission networks. The package is in the trilogue stage and is estimated to be completed by the end of 2023. The package will bring clarity to the gas and hydrogen market management model and the use of the existing network for hydrogen transmission by blending hydrogen with natural gas. The package also stipulates how cross-border tariffs are to be applied to hydrogen transport according to its definition.[79]

The final Gas Package will have a direct impact on Finland's industry and hydrogen economy. The industry must be able to use the blending ratio of hydrogen in natural gas transmission pipes. High hydrogen blending ratios in the EU would also extend the use of natural gas pipes and slow the building of new hydrogen pipes. The role and blending ratio of biomethane are also important to Finland.

The hydrogen strategies of key Member States

Finland

Finland delivered the draft update of its national energy and climate plan (NECP[80]) to the Commission in June 2023. The current Government has set ambitious targets for hydrogen in its Government Programme. Even though there are no specific production targets, there is a non-binding target for achieving an electrolysis capacity of 200 MW by 2025. Carbon capture and storage or utilisation (CCS/CCU) solutions could also give Finland a competitive advantage in the hydrogen derivatives economy. Finland also generates plentiful biogenic CO2, which could be used to produce synthetic fuels by combining CO2 with clean hydrogen. The wider goal is to lift Finland to the top of the European hydrogen value chain in the medium to long term by leveraging Finland's plentiful and clean electricity supply.

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[78] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0561 & https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0562
[79] https://energy.ec.europa.eu/topics/markets-and-consumers/market-legislation/hydrogen-and-decarbonised-gas-market-package_en
[80] https://valtioneuvosto.fi/en/-//1410877/finland-submits-its-draft-update-of-the-national-energy-and-climate-plan-to-the-commission

The NECP also underlines the critical role of the renewable energy and hydrogen working group (NAFH) composed of Nordic authorities and energy experts. The group is committed to formulating renewable energy policy in the Nordic countries. It seeks to increase the use of renewable energy and green hydrogen, focusing on their smooth integration into existing systems and technological innovations.

H2 Cluster Finland published its Clean Hydrogen Economy Strategy[81] on 27 June 2023. According to the strategy, Finland aims to be the leading hydrogen producer in the EU by 2035 by way of derogation from the Government's NECP draft, which sets the target at 2030. Instead of setting concrete production targets, Finland aims to act quickly and effectively to leverage its strengths and grasp opportunities throughout the value chain. The hydrogen strategy outlines four key measures. Firstly, a favourable market must be created to accelerate the development of the hydrogen economy.

Secondly, the formation of hydrogen valleys and international cooperation must be promoted. Thirdly, decision-making must be expedited and harmonised. Fourthly, Finland must gain a reputation as a hydrogen economy leader by attracting investors and influencing the development of the hydrogen economy at the EU level.

The Clean Hydrogen Economy Strategy recognises that, even though Finland has a well-developed and robust electricity network, the rapid large-scale introduction of clean energy and hydrogen production requires decisive action. The joint study by Gasgrid Finland and Fingrid shows that hydrogen pipes and storage facilities can accelerate the adoption of renewable electricity by resolving bottlenecks in energy transmission. Cooperation with other countries around the Baltic Sea in the construction of hydrogen pipes is thus essential for Finland. Such projects will ensure access to open, reliable and secure hydrogen markets.

Germany

On 26 July 2023, the Federal Cabinet updated its national hydrogen strategy[82], which had originally been adopted in June 2020. The updated version increases Germany's hydrogen targets. Germany aims to accelerate the ramp-up of the market to be the leading supplier of hydrogen technology by 2030. seeks to double its domestic green hydrogen production capacity from 5 GW to 10 GW. By 2027/2028, Germany intends to establish an 1,800 km "hydrogen start-up network" with IPCEI[83] support and connect it to the European Hydrogen Backbone[84]. The applications of hydrogen include industry, transport, electricity and heating. Germany is committed to promoting its strategy through efficient planning, standardised processes and certifications at the national and EU levels.

The Federal Cabinet has outlined measures for the short, medium and long terms (up to 2030), with the focus on securing the supply of hydrogen. The strategy anticipates a strong growth in demand for green hydrogen energy from 55 TWh to 95–130 TWh by 2030. This requires 50–70 per cent of this hydrogen to be imported by 2030, mainly by sea and, after 2030, through pipelines. The long-term

[81] https://h2cluster.fi/wp-content/uploads/2023/06/H2C-H2-Strategy-for-Finland.pdf

[82] https://www.bmwk.de/Redaktion/DE/Publikationen/Energie/fortschreibung-nationale-wasserstoffstrategie.pdf?__blob=publicationFile&v=3
[83] https://competition-policy.ec.europa.eu/state-aid/legislation/modernisation/ipcei_en
[84] https://ehb.eu/

scenarios predict an increase in industrial hydrogen demand to 290–440 TWh by 2045. The diversification of import sources is a key goal for Germany. However, it remains to be seen on which energy exporters Germany will rely. Germany has not made it clear whether it will continue diversification by keeping energy suppliers from outside Europe, such as Saudi-Arabia and the Arab Emirates, on the table, or whether it will primarily look at the EU/EEA. A separate hydrogen import strategy will be published later this year.

The State aid planned by Germany increase the attractiveness of investing in the German market. Germany seeks to even out the differences in the cost of green and decarbonised hydrogen in the short and medium terms. It has also introduced climate protection agreements[85], a demand-side funding mechanism tied to the EU's carbon dioxide pricing system (CCfD[86]). There is also the H2Global programme[87], an international green hydrogen purchasing system.

However, a study by PwC[88] raises concerns about the transmission of hydrogen in southern Germany, such as the Freiburg–Munich axis, which could result in an insufficient hydrogen supply. It is interesting that high hydrogen demand is expected precisely in this region. Germany's strategy is undeniably ambitious, but its ability to achieve its goals remains to be seen.

Germany is likely to become the biggest consumer of hydrogen in Europe. Its heavy industry needs huge amounts of hydrogen, which its domestic production cannot supply. Germany's import and export strategy for hydrogen and energy is crucial for Finland and its hydrogen ecosystem. Germany has already signed memorandums of understanding with Saudi-Arabia[89] and Algeria[90] as well as announced close cooperation with Norway and other states. Finland should follow these countries in actively seeking a role of this kind.

Denmark

Denmark seeks to increase the production of green hydrogen and its use in navigation, air transport and heavy transport. The government also wants to promote the export of green hydrogen and assume a leading position in the advancement of electrolysis technology. These objectives are presented in the government's Power-To-X (P2X) strategy[91] published in 2021. Denmark is planning on building 4–6 GW of electrolysis capacity by 2030. As the contracting authority, the Danish Energy Agency[92] organised a DKK 1.25 billion call for tenders[93] to produce green hydrogen in Denmark as part of the P2X State aid programme. The call for tenders concluded on 1 September 2023.

Regardless of Denmark's objectives[94], experts have concerns about the P2X technology. Industry experts are afraid that it may not be cost-effective, especially considering the uncertainty of the fuel market and State aid. On the other hand, university researchers have paid more attention to the limited production capacity and current level of technological development. According to them, one positive

[85] https://www.bmwk.de/Redaktion/EN/Pressemitteilungen/2023/06/20230605-start-of-the-carbon-contracts-for-difference-funding-programme.html
[86] https://www.bmwk.de/Redaktion/DE/Wasserstoff/Foerderung-National/018-pilotprogramm.html
[87] https://www.h2-global.de/project/h2g-mechanism
[88] https://www.strategyand.pwc.com/de/en/hydrogen-economy.html
[89] https://saudiarabien.ahk.de/en/themes/hydrogen
[90] https://www.arabnews.com/node/2219361/business-economy
[91] https://ens.dk/sites/ens.dk/files/ptx/strategy_ptx.pdf
[92] https://ens.dk/en
[93] https://ens.dk/en/press/power-x-tender-now-open
[94] https://www.mdpi.com/1996-1073/14/4/913

aspect of P2X is that it can decrease the need for biomass in fuel production, but the users of the technology do not view this as a significant benefit. Both scientists and users agree that P2X regulation must be improved to make use easier.

Finland competes with Denmark over energy exports to energy-intensive regions. Denmark works in close cooperation with Germany in the field of green hydrogen. Creating a green hydrogen transport route from Jutland to Northern Germany is a major focus of this cooperation. This will be achieved by building a hydrogen pipe connecting the two countries, and the pipeline should be in use by 2028. The earlier completion of the pipeline and geographical proximity to Germany are advantages Denmark enjoys over Finland.

Sweden

In November 2021, the Swedish energy agency[95] proposed a national decarbonised hydrogen strategy[96], which sets targets for 2030 and 2045 and promotes the development of the hydrogen economy. The proposal set green hydrogen production targets at 22–42 TWh by 2030 and 44–84 TWh by 2045. The same strategy seeks to achieve an overall electrolysis capacity of 5 GW by 2030 and 15 GW by 2045. The strategy would increase electricity demand by approximately 60–126 TWh/a.

The use of electrolysis equipment is becoming increasingly important for industries such as the iron, steel, chemical and refining industries. However, the availability of electricity can become a limiting factor in Sweden, especially for industries located in areas in which the capacity of the electricity network is weak. As a result, these industries must investigate alternatives for ensuring the availability of energy to enable production.

Connecting larger Swedish industries to the electricity network will require a controlled adjustment of electricity production and investments in electrolysis equipment and hydrogen storage to avoid overcapacity investments to balance the energy system with hydrogen solutions, for example. Since the profitability of clean hydrogen production is bound tightly to the price of electricity, companies are being urged to adapt their production schedules to make use of low electricity prices.

One significant project is BotH2nia, a joint project by Finnish and Swedish companies, municipalities and other hydrogen actors to create *Strong Regional Hydrogen Economy*. At the same time, the Nordic Hydrogen Route (NHR) cooperation between the Finnish and Swedish gas grid operators would support development in the region. The NHR hydrogen network would satisfy the region's 65 TWh hydrogen demand by 2050.[97]

Estonia

On 8 March 2023, Estonia published the Estonian Hydrogen Roadmap 2023[98], which outlines a two-phase strategy. In 2021–2030, the country will focus on pilot projects for building green hydrogen infrastructure and technology with the aim of creating a long-term market. In 2036–2050, it intends to expand the industry beyond domestic consumption by leveraging affordable renewable energy and

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[95] https://www.energimyndigheten.se/en/
[96] https://www.energimyndigheten.se/nyhetsarkiv/2021/forslag-till-nationell-strategi-for-fossilfri-vatgas/
[97] https://nordichydrogenroute.com/fi/
[98] https://www.mdpi.com/1996-1073/14/4/913

technologies. The timeliness of the roadmap's objectives and actions is evaluated at least every three years.

These pilot projects provide a major investment opportunity in green hydrogen. The cross-border BalticSeaH2 project coordinated by Gasgrid Finland is complemented by the Estonian Hydrogen Valley project coordinated by the Estonian Hydrogen Association[99]. The goal of the hydrogen valley project is to create favourable conditions for the adoption of green hydrogen technology. The first production units, distribution solutions and applications are meant to be created during the next six years. The initiative enjoys broad-based support from over 30 local and international institutions.

Estonia is currently an energy importer. The increase in the costs of the EU Emissions Trading System have made Estonia switch from an exporter to an importer of energy. This is largely because Estonia is closely dependent on carbon-intensive oil shale for its energy production. This has weakened its position relative to cleaner producers, with the result that the country imported approximately 42% of its electricity in 2020 and 30% in 2021. Estonia is seeking to increase its renewable energy capacity to change this situation.

Estonia and the other Baltic states have a clear interest in close cooperation with Finland in the building of the hydrogen network. Stable hydrogen prices can be achieved through cooperation, which also reduces the need for expensive hydrogen storage facilities. When the hydrogen network has been completed around the Baltic, Finland will gain access to cost-effective salt caverns suitable for the storage of hydrogen. The countries thus benefit from each other's efforts.

[99] https://h2est.ee/en/

Annex 4: Description of the hydrogen transmission infrastructure

Transmission pipeline

The plan is to transfer hydrogen over long distances in a high-pressure underground pipeline (Figure 31). This can be complemented by the construction of hydrogen distribution networks with lower pressure, for example in the vicinity of industrial plants or "hydrogen valleys". Hydrogen gas is mainly transferred from the production plant to consumption sites through steel pipes coated on the outside with, for example, polyethylene (2–3 mm) to prevent corrosion. Pipeline corrosion is also prevented electrochemically with a cathodic protection system. The inside of the pipe can also be coated with epoxy (80 µm) to decrease friction loss if necessary. The transmission pipe extends to the vicinity of the customers' processes at both ends, and customers are responsible for connecting their processes to the pipe. The pipeline will be installed at a depth of 1–2 metres. The locations of methane pipes are indicated with yellow marker poles. Similar markings specific to hydrogen will be introduced for the hydrogen transmission pipe. Above-ground sections of the pipeline must additionally be painted with the sign colour.

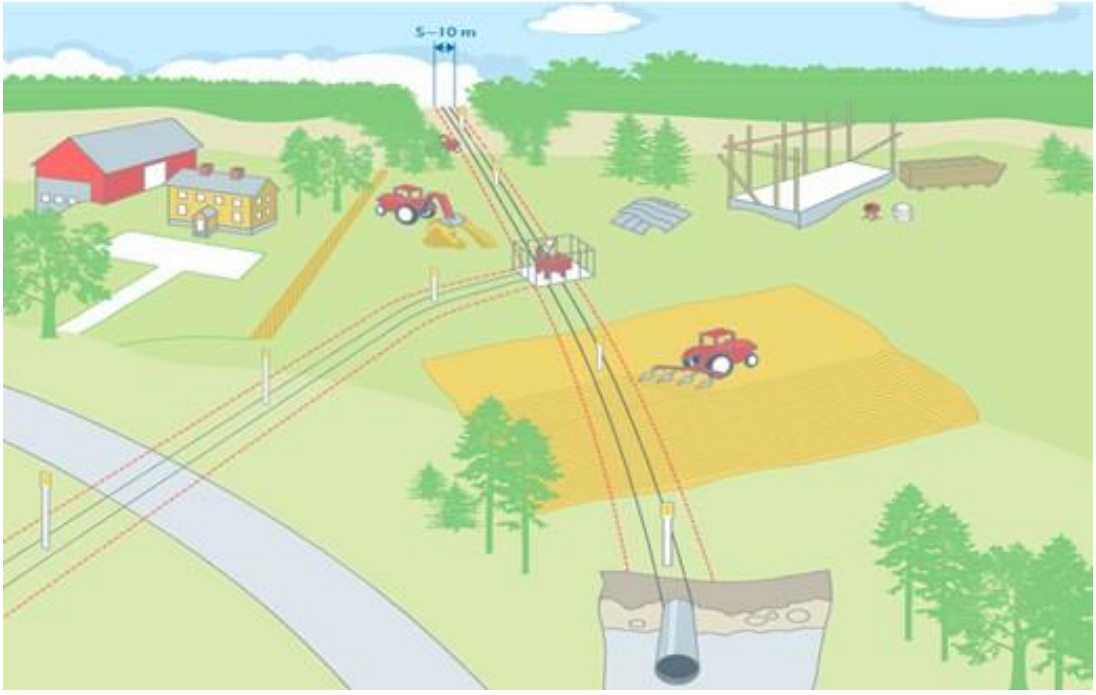

Figure 30. A treeless zone 5–10 metres wide can be seen in forests and built-up areas, with the underground hydrogen pipeline running in the middle of it. (Image: Gasum [100], edited)

The normal gas pressure in the existing methane transmission pipeline is 30–54 bar and pipe diameter varies between DN100 and DN1000. The pressure and diameter of the hydrogen pipeline will be specified at a later stage of design. In preliminary studies, the design pressure of the hydrogen pipeline has been 80 bar as in methane pipes. The pipe size and pressure together determine the network's capacity for energy storage and transmission. According to preliminary plans, the transmission pipe would be dimensioned to enable short-term storage capacity (linepack) for the first customers. All

[100] Gasum. Construction of natural gas pipelines. Brochure 2003.

sections of the pipeline also have significant additional transmission capacity for potential new transmission customers. The transmission and storage capacities will be confirmed when more details are available about the production and consumption profiles of the customers connecting to the transmission network and the pressure in the pipeline. Pipeline design is optimisation between the pipe diameter, pressure, and compressor power.

The large diameter and high pressure of a hydrogen pipe subject it to loads and set new types of requirements for pipe thickness and material strength compared to methane pipes. These can set limits on the pipeline's gas storage potential. In addition, the pipeline is subjected to repeated pressure variations if it is used for hydrogen storage to balance variable renewable electricity production and fluctuations in demand. Pressure variations are more significant for a hydrogen pipe than for a methane pipe since fatigue cracks can grow at up to ten times faster in a hydrogen pipe.[101]

It is commonly held that the risk of hydrogen embrittlement increases with the strength of the steel. High-strength steels as well as titanium and aluminium alloys are particularly susceptible to hydrogen embrittlement. In Finland, methane pipes are typically made of materials X42, X52, X60 and X70. Similar materials will be used for hydrogen pipes, but possibly at lower strengths to minimise the risk of hydrogen embrittlement. Lower strength together with higher pressure and pressure variations will probably require hydrogen pipes to be thicker than methane pipes. However, there are no long-term experiences or data available on large-scale hydrogen systems and high pressures as of yet. The first systems will thus be built with higher safety factors than pipelines potentially built later.

Based on preliminary analyses and discussions with the authorities, the technical specifications of methane pipes are a good starting point for estimating safety distances (Figure 32). These include the Act on the Safe Handling of Hazardous Chemicals and Explosives (390/2005, main legislation with regard to technical operation and safety) and the Government Decree on the Safe Handling of Natural Gas (551/2009, "Natural Gas Decree"), for which Tukes has issued application guidelines. As the hydrogen legislation is still under development, the safety distances for hydrogen will be assessed separately.

[101] Wesselink, O., Krom, A., van Agteren, M. (2022). Balancing Hydrogen Networks Safely: A Method for Calculating Linepack Potential Without Causing Integrity Risk Due to Hydrogen-Enhanced Fatigue. Proceedings of International Pipeline Conference, 26-30 September 2022, Calgary, Canada. https://doi.org/10.1115/IPC2022-86674

Building safety distances to underground natural gas transmission pipeline

Nominal pipe diameter mm	Group A distance	Group B distance
DN ≤ 200	10 m	5 m
200 < DN ≤ 500	16 m	8 m
DN > 500	20 m	10 m

Safety distances to above-ground parts of the natural gas transmission pipeline

Transmission pipeline device	Group A distance	Group B distance	Highway, main road railway; distance
Pressure reduction-, block valve- and scarper stations	50 m	25 m	25 m
Pressure reduction station	100 m	50 m	50 m

Figure 31. The Natural Gas Decree determines the safety distances from methane transmission pipes and above-ground sections of the transmission pipeline. Group A: Public buildings intended for multiple users, such as premises intended for sleeping accommodations or gatherings and residential buildings, as well as installations manufacturing, storing, or using explosives and installations handling hazardous chemicals industrially. Group B: Residential buildings, office buildings, non-residential buildings regularly occupied by people and separate fenced-off areas. (Image: Gasgrid Finland[102])

Compressor stations

Compressor stations are used to maintain and raise gas pressure in the transmission pipeline and thus increase the transmission and storage capacity of the hydrogen gas network. The need for compressor operation depends on the pressure in the transmission pipeline, which is affected by the current transmission and storage needs and the customers' entry and exit pressure at the connection points. Production is expected to be more uneven than in the methane pipeline, since it is largely based on variable renewable energy production. The choice of compressor is affected by factors such as the hydrogen volume flow, pressure ratio, gas properties and operating method (need for flexibility). The hydrogen can be compressed with either reciprocating or centrifugal compressors at the compressor stations.[103,104] The greatest difference between compressing hydrogen and methane arises from hydrogen's much lower energy density. For this reason, hydrogen requires much more energy to compress than methane and the compressor and compressor facility need considerably more space.

A centrifugal/turbo compressor is the recommended option for greater flow rates. This type is also used to increase the pressure of methane. However, centrifugal compressors suitable for compressing methane are not directly suitable for use with hydrogen since the rotation speed must be at least three

[102] Gasgrid Finland. (2023). How to identify a gas pipeline. https://gasgrid.fi/en/gas-network/identification-and-activities/

[103] Witkowski, A., Rusin, A., Majkut, M., Stolecka, K. Comprehensive analysis of hydrogen compression and pipeline transportation from thermodynamics and safety aspects. Energy, 141 (2017), pp. 2508-2518.

[104] Gaseous Hydrogen Compression. U.S. Department of Energy. (2022).

times as fast. What is known as the choke and surge phenomenon also creates limitations for centrifugal compressors. Hydrogen losses also pose a challenge when using a centrifugal compressor. On the other hand, the benefits of centrifugal compressors include the possibility for a large volume flow, which is required for hydrogen due to its low density.

A reciprocating compressor is best suited to low flow rates (≤ 1,700 m/h) and it achieves a high pressure ratio.[104] A reciprocating compressor offers better adjustability of the volume flow compared to a centrifugal compressor. Reciprocating compressors suitable for the compression of methane are also suitable for hydrogen with minor adjustments. Hydrogen’s large volume flows create challenges to the use of reciprocating compressors. The minimum and maximum flows are restricted by the size of the piston and speed of the cylinder. A reciprocating compressor requires clean and dry hydrogen.

According to the preliminary plans, hydrogen pressure will be raised with reciprocating compressors powered by electricity. The high pressure ratio requires several compressor stages. If a large operating range in terms of volume flow is needed, it is possible to connect several reciprocating compressors in parallel. This is also important for redundancy.

Valve stations

Like in methane transmission pipelines, hydrogen transmission pipelines are fitted with valve stations and scraper stations. Their safety cut-off devices can be used to direct the flow of gas and, if necessary, cut off gas transmission and distribution and empty transmission pipeline sections of gas. Probes can be introduced into the pipeline at valve stations to monitor the condition of the pipe, collect data and clean and inspect the pipe. There are valve stations every 8–32 km in the methane pipeline. Remote-controlled valve stations increase the safety of the transmission network and their safety cut-off devices can be operated from the TSO's, i.e. Gasgrid's control room. There are yet no national laws or standards for dividing a hydrogen pipeline into sections and thus specifying the maximum distances between valve stations. ASME B31.12 specifies the maximum distances between valve stations according to their location category (32, 24, 16 and 8 km) as the Natural Gas Decree does for valve stations on a methane pipeline.

A methane pipe can be emptied directly into the atmosphere with a blowdown, whereas a hydrogen blowdown can ignite and solutions suitable for hydrogen must be defined. As a section of pipe will have to be emptied in a reasonable time, the valve stations may be located at closer intervals than on the methane pipeline. The valve stations will be equipped with continuous hydrogen leak detectors and flame sensors. Link stations of the pipe network's own data transmission system, which are used to transfer monitoring and alert data to the central control room, are usually also placed close to the valve stations.

Pressure reduction stations

A pressure reduction station is constructed at the interface between the transmission pipeline and distribution pipeline or consumption point to regulate gas pressure to a level suitable for the customer. The impact of future maintenance or possible device malfunctions on gas transmission is taken into account in the design of pressure reduction stations to prepare for these eventualities. In a methane pressure reduction station, the gas is filtered and heated, and its pressure is regulated and volume measured. Gas volume meters determine the volume of gas delivered for invoicing purposes. Methane is odourised at the pressure reduction station before delivery to the customer. In special cases, the gas can be delivered unodourised, but this requires permission from the authorities. In hydrogen pipelines, the pressure regulation of the gas and the measurement of its volume take place in the pressure reduction station. The odourisation of hydrogen is challenging and requires further study.

Control room functions

The plan is to operate the future hydrogen network from Gasgrid Finland's central control room, from which the current methane transmission network is operated. The control room is in operation round the clock and its personnel are prepared for all gas transmission emergencies. In normal circumstances, the control room operates the transmission network to keep sufficient pressure in the network for gas deliveries. The control room monitors and operates the transmission network remotely with the meters and control devices on the equipment and through automation. If necessary, the control room operator will dispatch a technician to perform repairs or maintenance. In the event of an emergency, the control room operator initiates the required corrective measures.

Annex 5: Hydrogen downstream value chains

Figure 33 illustrates alternative direct applications and downstream processing value chain for clean hydrogen and the technology options for them in various sectors using the end products.

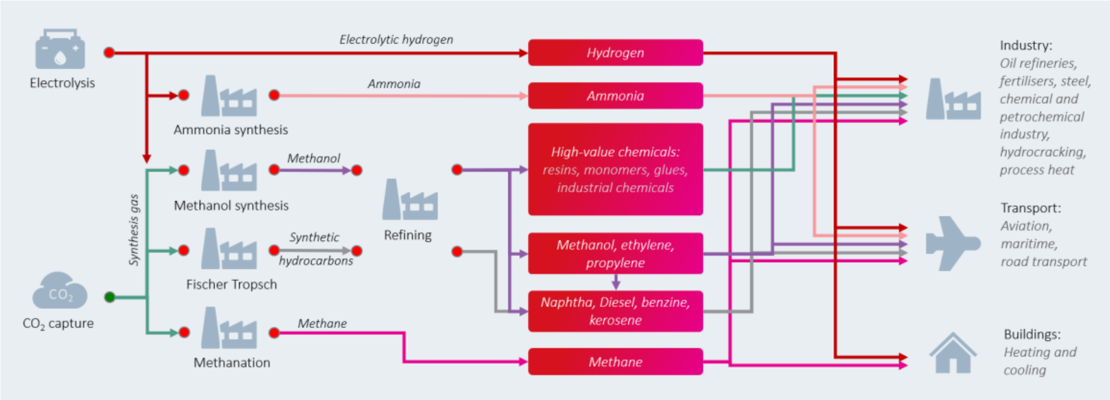

Figure 32. Alternative technology value chains and end uses of hydrogen produced with electrolysis. (Image: Gasgrid Finland)

Clean hydrogen as an enabler of electrofuel production

Fischer Tropsch synthesis technology (FT) enables the production of synthetic fuels from various feedstocks containing carbon and hydrogen. The captured carbon dioxide (from a biogenic process) depicted in Figure 33 can be replaced with a solid carbon source (various waste and side streams) converted into gaseous form ("synthesis gas", CO and hydrogen) to be usable in the FT reaction. In the clean hydrogen value chain, hydrogen is produced with electrolysis and the carbon is already in gaseous form. These gaseous components are processed into a synthesis gas, which is then converted into a synthetic hydrocarbon compound (synthetic crude) by the catalytic FT reaction. The refining process reduces oxygenated hydrocarbon components by hydrogenation and splits long hydrocarbon chains into the desired distribution by cracking with a suitable catalyst. The required fuel components (diesel, benzine, kerosene) or, for example, diesel oil used as a feedstock in the petrochemical industry are separated from the refined hydrocarbon compound.

Similar fuel components can be manufactured via the "methanol value chain", starting with hydrogen produced with electrolysis and captured carbon dioxide. In this value chain, the first phase produces methanol (e-methanol), which is catalytically converted into ethylene and/or propylene in the refining process. Depending on the target hydrocarbon distribution profile in the end product, the ethylene and/or propylene is processed into longer fuel components in the "oligomerisation" stage. Methanol can be refined into various feedstocks for the chemical and petrochemical industries, as well as into downstream products like glues, resins, fuel additives and acids.

The synthetic hydrocarbon compound's two-phase state is a special feature of the FT process. The product splits into liquid and solid (wax) fractions in room temperature. This characteristic favours a centralised production model for the FT process, with both the FT process and downstream operations being performed at the same site to avoid transporting the solid wax fraction.

The production model in the methanol value chain could be implemented with a decentralised model in which the production of e-methanol and the unit operations related to its refining can be carried out at different sites. This would naturally reduce the local need for energy and feedstock and thus the pressure for joint procurement, unlike in the FT route. This marks a significant difference in the scalability of the two technologies.

The methanol and FT value chain also share similarities. Using these processes for the production of synthetic fuels will require significant modifications to existing production processes and major new investments throughout the value chain. The stability and predictability of the availability and prices of clean energy (electricity/hydrogen) will play a major role in determining the profitability of production. That is why the development of electrolysis technology (its efficiency) will play a key role in the energy system at large and in the usability of (energy) side streams, both within manufacturing processes and through sector integration. It should be remembered that chemical industry processes are much less flexible in terms of operation than electricity production.

Utilisation of clean hydrogen in the chemical and steel industries

The direct replacement of current steam methane reforming -based (SMR) or "grey" hydrogen with clean hydrogen in refineries and as a "drop-in" chemical in the fertiliser industry (e.g., in ammonia production) will enable considerable carbon dioxide emission reductions in these industries. The amount of hydrogen used in refineries will be heavily influenced by regulations on RFNBO hydrogen, which is still open to interpretation due to the ambiguity of current regulation.

The end use of ammonia, including for reducing carbon dioxide emissions from shipping in the future, has been identified as an alternative for other fossil maritime fuels. The regulation of maritime transport is based on the reduction of total emissions (in contrast to aviation), which leaves the operator free to choose the method for reducing the emissions and does not set distribution obligations for specific fuels.

Decarbonised hydrogen reduction technologies for the metal industry and hydrogen-based steel production have been developed in close cooperation with the industries in both Finland and Sweden. Fossil-free steel production aims to replace the traditional coke with hydrogen in the reduction of iron. The traditional reduction method using fossil-based carbon generates significant amounts of carbon dioxide as a by-product of the process. The new production technology will lower the carbon dioxide emissions of steel production close to zero. This can help with achieving the sustainability targets for heavy transport through the automotive industry's material choices and increase the energy-efficiency of truck and bus manufacturing.

Polymerisation reactions and various chemical reaction plants are among the most energy-intensive processes in the chemical industry (excluding fuel production). Many high-value chemicals can be produced via the methanol value chain, and the products can be used directly (resins, glues, polymers, fuel components and additives) or as feedstock for downstream operations (esters, acids).

Industrial basic chemical production, e.g., the hydrogen peroxide process, currently uses fossil-based hydrogen as a feedstock. Hydrogen peroxide is widely used as a feedstock for downstream products in the chemical industry, for example in the production of preacetic acid and as a bleaching chemical in the pulp industry. Ammonia is currently produced solely from fossil-based hydrogen and is very energy-intensive overall.

In spring 2021, Gasgrid Finland, the Finnish gas transmission system operator, and Fingrid, the Finnish electricity transmission system operator, started a cooperation aimed at exploring the potential of the hydrogen economy in Finland, as well as the role of energy infrastructure in enabling the hydrogen economy. The cooperation continues concretely in Gasgrid and Fingrid's joint research and development project, which is implemented as part of the broader HYGCEL research project consortium consisting of several Finnish companies and research institutes. On 28 October 2021, Business Finland granted support for both the Fingrid-Gasgrid joint project and the broader entity.

Gasgrid Finland Oy is a Finnish state-owned company and transmission system operator with system responsibility. We offer our customers safe, reliable and cost-efficient transmission of gases. We actively develop our transmission platform, services and the gas market in a customer-oriented manner to promote the carbon-neutral energy and raw material system of the future. Find out more: www.gasgrid.fi/en

Fingrid is Finland's transmission system operator. We secure reliable electricity for our customers and society, and we shape the clean and market-oriented electricity system of the future. Fingrid delivers. Responsibly. www.fingrid.fi/en/