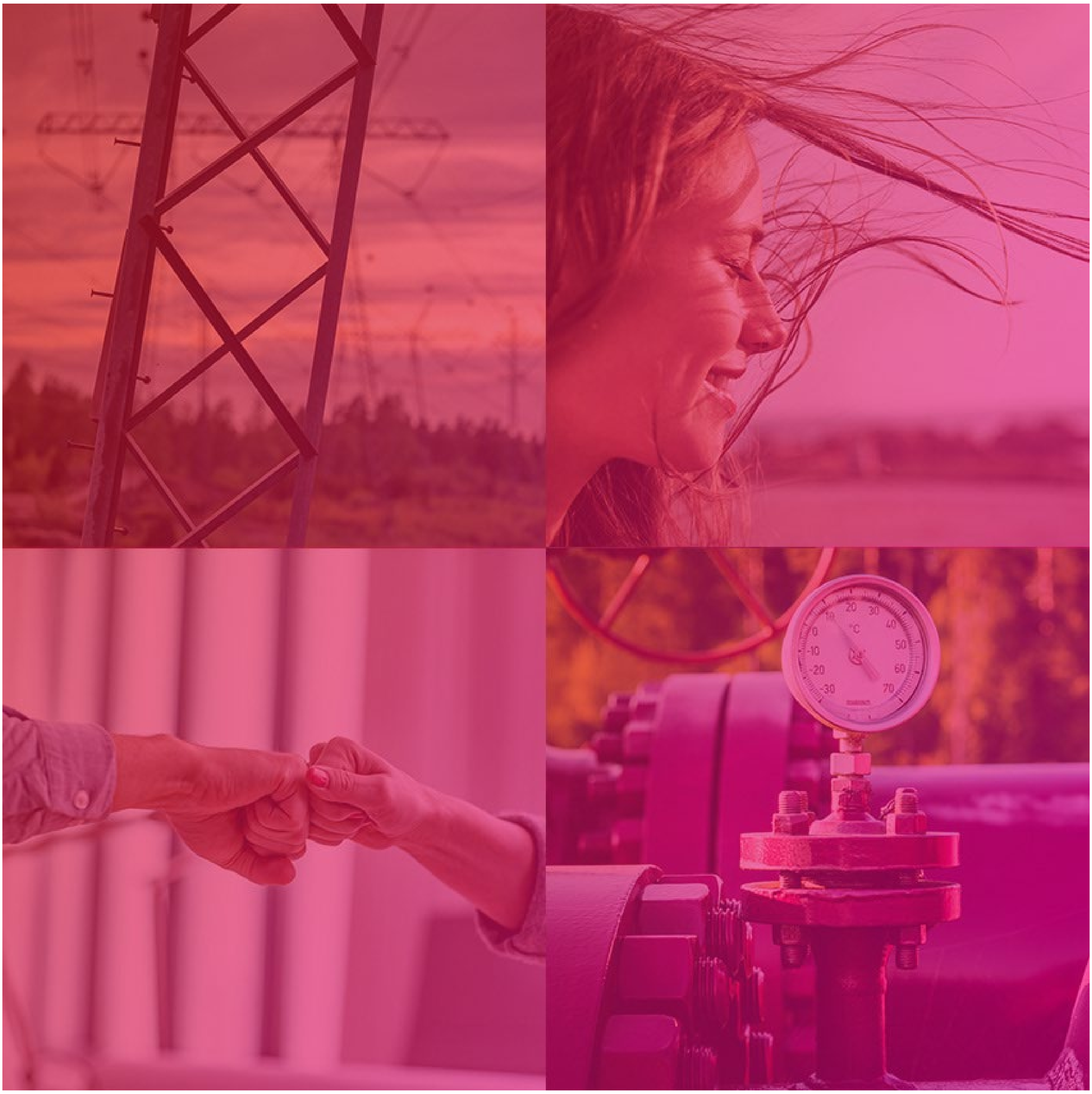

Scenarios: Energy transmission infrastructures as enablers of hydrogen economy and clean energy system

Stakeholder consultation on the draft scenarios of the joint project between Fingrid and Gasgrid Finland

FINGRID

GASGRID

Foreword

Fingrid and Gasgrid Finland are running a joint project that examines the potential trends in the hydrogen economy and their impact on the energy system. The joint project is part of a project portfolio titled HYCGEL (Hydrogen and Carbon Value Chains in Green Electrification) funded by Business Finland. The public part of HYCGEL brings together universities and companies in order to jointly study the systemic impacts of the energy revolution, the energy system and the hydrogen economy.

This consultation report is a continuation from our previous stakeholder interviews and the intermediate report we published in March. We have outlined a range of scenarios that describe at a general level how the hydrogen economy could become a reality in the energy system. Based on these draft scenarios, we have created some preliminary energy system models in order to assess the significance of different infrastructure solutions in different situations.

We ask stakeholders to share their views and expectations regarding the scenarios outlined in this consultation report so that we can take the comments into account in the final scenarios and models. Please send your feedback by 19 August 2022. For more detailed instructions on how to provide feedback, see Chapter 6 at the end of the report.

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1 Introduction

In autumn 2021 and spring 2022, Gasgrid and Fingrid outlined scenarios for the development of the hydrogen economy. We interviewed several Finnish companies in autumn 2021 to find out their views on the hydrogen economy. The companies' views highlighted the need to develop the electricity and hydrogen infrastructure in parallel as a whole. Finnish companies saw several possible roles that the hydrogen network could play in Finnish industry. The companies highlighted the importance of broad cooperation both in the development of the infrastructure and in the creation of industrial value chains. The views expressed in the interviews served as input for the draft scenarios.

Finland is well placed to be a forerunner in the hydrogen economy, since our energy infrastructure is robust and we have cost-effective renewable energy resources for the competitive production of clean hydrogen. The purpose of the scenarios is to find the most cost-effective infrastructure development paths for the Finnish energy system in a range of future scenarios. The core of the scenarios consists of the different development paths for hydrogen infrastructure and the sectoral integration between the hydrogen, gas and electricity transmission infrastructures. It is essential to carry out a comprehensive analysis of infrastructure development needs in order create a cost-effective energy system that supports Finland’s competitiveness in the best possible way.

The operating environment is undergoing a significant change

Since the start of the project, hydrogen's role in the energy system of the future has become increasingly strong, and hydrogen has become a widely accepted basic assumption in energy sector scenarios. The growth potential of the hydrogen industry is based on the fact that hydrogen, produced using renewable electricity, can replace fossil raw materials and fuels in many industries and transport sectors. This is also the basis of the European Commission’s REPowerEU plan, published in May 2022, which aims to reduce the imports of Russian fossil-based energy and significantly increase the production of renewable energy and accelerate the adoption of renewable hydrogen in the EU.

The plan is to have the EU produce 10 Mt (333 TWh) of clean hydrogen and also import 10 Mt of hydrogen from outside the Union already by 2030. In total, this would create a European hydrogen market of approximately 670 TWh.[1] This change is about improving energy self-sufficiency, changes in trade flows, and Europe’s response to the war started by Russia against Ukraine. The change requires in-depth sector integration, which sets requirements on the development of both the hydrogen and electricity transmission infrastructure.

Gasgrid has participated actively in the initiative of the European Hydrogen Backbone (EHB), a group of 31 European energy infrastructure companies. The EHB Group promotes the vision of an integrated hydrogen transmission infrastructure and market development. Analyses by EHB have discovered that the Nordic and Baltic countries not only have excellent conditions for the creation of a hydrogen-powered industry, but also significant potential for constructing additional wind power. In the future, the region could produce a significant amount of hydrogen for the domestic industry while also exporting significant quantities of hydrogen, e-fuels and other downstream hydrogen products to European and world markets.

[1] REPowerEU (europa.eu)

The latest publication of the EHB group is a vision of five major hydrogen supply corridors that meet the objectives of the RePowerEU plan. The analysis states that the hydrogen production potential in the Nordic and Baltic countries will be up to 127 TWh per year already in 2030. This represents approximately 20% of the total target of REPowerEU for 2030 and approximately 38% of the target for hydrogen produced in the EU.[2] On the other hand, Finland's renewable energy resources and the ongoing renewable energy projects could produce more than 300 TWh[3] of pure hydrogen in Finland, which corresponds to approximately 45% of the estimated European market in 2030.

Finland's advantage in the production of renewable hydrogen is the competitiveness of solar and wind power, as shown by the graphs below (Bloomberg's price comparison of long-term power purchase agreements (PPAs)). The comparison indicates that Finnish prices are among the three most affordable in Europe (Figure 1).

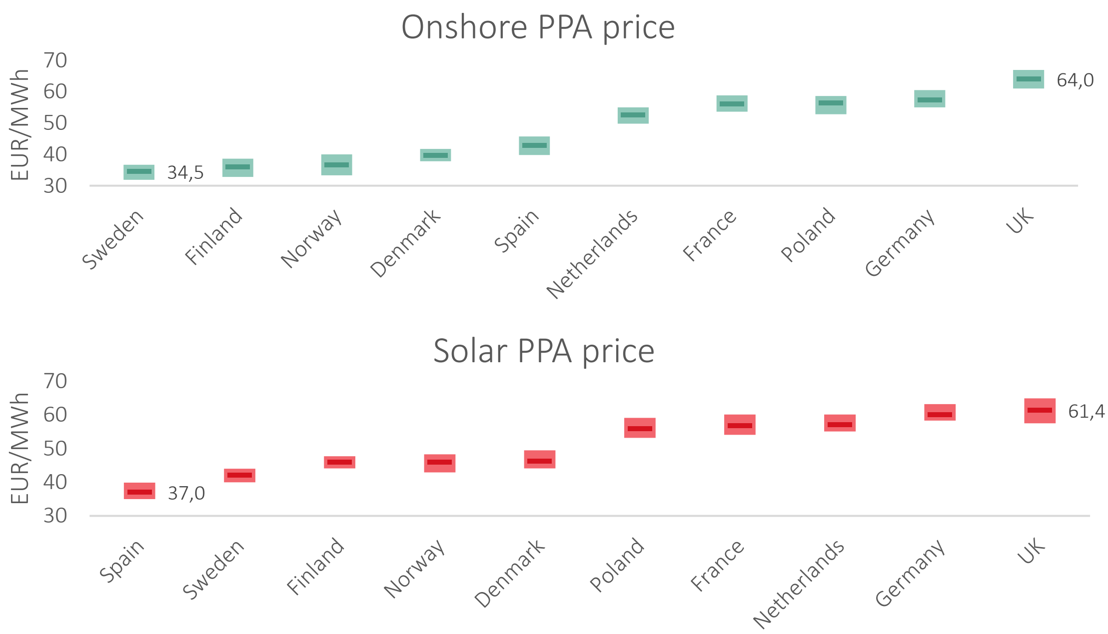

Figure 1 In the first half of 2022, the PPA price of Finnish onshore wind power was the second lowest in Europe; for solar photovoltaic power, the third lowest [4]

Affordable clean hydrogen and its downstream products could become a significant export industry in Finland. Finland has plenty of resources for the production of renewable electricity, a robust main grid, a skilled labour force and several companies that can operate in the hydrogen economy value chain. As a result, Finland can punch above its weight in the hydrogen economy. However, in order to maintain Finland's competitiveness, it is important that the energy infrastructure is developed comprehensively, taking into account future energy transmission needs. By ensuring competitiveness and attracting

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[2] Five hydrogen supply corridors for Europe in 2030. (EHB, 2022).
[3] Intermediate report: Energy transmission infrastructure as an enabler of the hydrogen economy and clean energy system. (Fingrid, Gasgrid, 2022)
[4] https://about.bnef.com/blog/wind-and-solar-corporate-ppa-prices-rise-up-to-16-7-across-europe/

hydrogen economy investments, Finland can gain a significant market share in the European hydrogen industry, for example in the production of e-fuels.

2 Scenario descriptions – The scenarios are based on the emergence of a significant new export industry

This chapter describes the draft scenarios created by Fingrid and Gasgrid. The drafting of scenarios purposefully made ambitious assumptions about the development of the hydrogen economy, since the scenarios pose a strong challenge to the development of the energy system. Scenarios like these also highlight the wider social impacts of the hydrogen economy better than more cautious scenarios.

2.1 Development trends in Finland's hydrogen economy – three scenarios

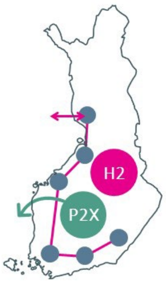
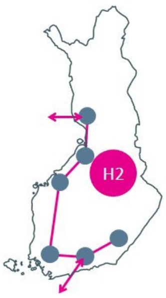
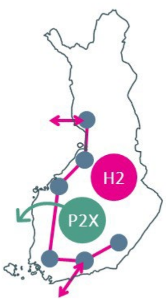
Table 1 describes the development trends in Finland's hydrogen economy outlined by the three draft scenarios. The scenarios explore a range of development trends in the energy transmission infrastructure from the perspective of the Finnish energy system.

The basic assumption in all scenarios is that Finland will achieve its carbon neutrality targets and the production of clean hydrogen in Finland will grow strongly. In addition to the increase in demand for electricity used for hydrogen production and P2X products, demand for electricity for other purposes is also expected to increase. The demand will increase in transport, heating and the existing industry as fossil fuels are replaced by clean electricity. In addition, Finland is expected to become home to new electricity-intensive industries, such as battery manufacturing and data centres. These sectors are expected to develop in the same way in all scenarios. Electricity consumption (excluding electricity used for hydrogen production) will increase by approximately 30% by 2030 and by approximately 50% by 2040.

The scenarios assume that clean hydrogen will replace the grey hydrogen currently used by the domestic industry and that clean hydrogen will also be used in the manufacture of fossil-free steel and electric fuels, among other things. In addition to meeting domestic demand, Finland will develop into a significant player in the European hydrogen market, and most of the demand will eventually be driven by exports, either as downstream products and/or as hydrogen gas for the needs of the European market.

A key variable in the scenarios is Finland's role in the hydrogen market value chain: Will Finland develop into a significant exporter of P2X products, hydrogen gas or both to meet the increasing demand in the European market? Based on this variable, the scenarios contain a hydrogen infrastructure intended for exports and imports. The formation of the hydrogen infrastructure also has a wide impact on the rest of the energy system (see, for example, Chapter 3.3).

Table 1. Description of the draft hydrogen economy scenarios of Gasgrid and Fingrid and illustrative regional hydrogen transmission connections in the scenarios

SCENARIO	DESCRIPTION
Strong Regional Hydrogen Economy  	Generation and transmission of electricity • A lot of new renewable electricity production will be built in Finland, focusing on onshore wind power • The planned cross-border connections will be built to Northern Sweden and Estonia Production and use of hydrogen • Finland's current hydrogen-using industry switches to clean hydrogen • Finland becomes a major exporter of P2X products Hydrogen transmission infrastructure • Cross-border hydrogen transmission connections will be built in Northern Sweden Storage of hydrogen • Several hydrogen storage facilities will be built in Finland • Finland cannot take advantage of the large amount of hydrogen storage in Central Europe due to the lack of the necessary hydrogen transmission infrastructure, which increases the profitability of domestic hydrogen storage
European Hydrogen Market  	Generation and transmission of electricity • A lot of new renewable electricity production will be built in Finland, focusing on onshore wind power • The planned cross-border connections will be built to Northern Sweden and Estonia Production and use of hydrogen • Finland's current hydrogen-using industry switches to clean hydrogen • Finland becomes a major exporter hydrogen Hydrogen transmission infrastructure • Hydrogen transmission pipelines will be built in both Northern Sweden and Central Europe for large-scale exports of hydrogen. Storage of hydrogen • Hydrogen storage facilities will be built in Finland • The hydrogen transmission infrastructure enables Finland to utilise the large hydrogen storage facilities in Central Europe, which reduces the profitability of domestic hydrogen storage
Leading Hydrogen Ecosystem  	Generation and transmission of electricity • A very large amount of new renewable electricity production will be built in Finland, focusing on onshore wind power • The planned cross-border connections will be built to Northern Sweden and Estonia Production and use of hydrogen • Finland's current hydrogen-using industry switches to clean hydrogen • Finland becomes a very significant exporter of hydrogen **and** P2X products Hydrogen transmission infrastructure • Hydrogen transmission pipelines will be built in both Northern Sweden and Central Europe for large-scale exports of hydrogen Storage of hydrogen • Hydrogen storage facilities will be built in Finland • The hydrogen transmission infrastructure enables Finland to utilise the large hydrogen storage facilities in Central Europe, which reduces the profitability of domestic hydrogen storage

The following chapters describe each scenario and their underlying assumptions in more detail.

2.1.1 The 'Strong Regional Hydrogen Economy' scenario

In the *Strong Regional Hydrogen Economy* scenario, the demand for hydrogen is driven in particular by Finland's development into a major exporter of P2X products, such as e-fuels. A lot of new industry will emerge in Finland, in local hydrogen clusters centred around the production and further processing of hydrogen. Clean hydrogen is produced for the needs of domestic industry, especially by utilising Finnish onshore wind power, which also reduces emissions from Finland's existing industry.

In this scenario, Finland has an internal energy transmission infrastructure and a hydrogen transmission pipeline to Northern Sweden in the Bothnian Bay, but not to Central Europe. In Northern Sweden, the demand for hydrogen will also grow significantly, since hydrogen is used for direct reduction of iron ore for the steel industry, among other things. The need for a transmission connection has been examined in a study by LUT, envisioning a cross-border pipeline with a capacity of 7.2 GW (of hydrogen)[5]. Gasgrid Finland and Nordion Energi have launched a joint project called the Nordic Hydrogen Route. At present, the project is investigating the need for cross-border hydrogen infrastructure[6] and transmission capacity in the Bothnian Bay region.

Since, in this scenario, Finland's hydrogen system is only connected to Northern Sweden via a pipeline, the need for domestic hydrogen storage is high in order to control the production of hydrogen flexibly during the variations in the production of renewable energy. On the other hand, the lack of competition with the storage in other hydrogen systems increases the profitability of domestic hydrogen storage. Therefore, a large amount of hydrogen storage will be built in Finland.

2.1.2 The 'European Hydrogen Market' scenario

In the *European Hydrogen Market* scenario, clean hydrogen replaces grey hydrogen and meets the needs of the domestic steel industry, but the P2X industry does not develop in line with the growth of hydrogen production. Instead, the growth of hydrogen production is driven by the potential of exporting hydrogen gas along a pipeline to the rest of Europe, especially by 2040.

Finland builds a hydrogen pipeline to Northern Sweden similar to that in the *Strong Regional Hydrogen Economy* scenario. In Sweden, the demand for hydrogen will grow faster than in Finland, so in 2030, exports to Sweden via the northern cross-border connection speed up the growth of Finland's hydrogen economy. Exports to Sweden speed up the growth of renewable electricity generation and hydrogen production capacity at the time that hydrogen transmission links in the Baltic Sea region are still under construction.

A large pipeline connection to Central Europe will be built through the Baltic Sea region in the 2030s, with a capacity of approximately 13 GW. As a result, export volumes will increase considerably. In the long term, therefore, Finland's hydrogen economy will be driven by the high demand for clean hydrogen in the Baltic Sea region and Central Europe. Finland's cheap onshore wind power can meet this demand more cost-effectively than Central Europe's renewable energy resources.

The hydrogen transmission infrastructure through the Baltic Sea region to Central Europe enables the utilisation of the gas storage facilities in the region. Some regions of Europe already have large natural

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[5] Bothnian Bay Hydrogen Valley – Research report. LUT Scientific and Expertise Publications 134. (Karjunen, et al., 2021)
[6] https://nordichydrogenroute.com/fi/hanke/

gas storage facilities, such as salt caverns. Large salt caverns are also expected to be able to store hydrogen at a very low cost, and the Baltic Sea pipeline connection will also enable their flexibility to be leveraged in Finland. This reduces the need and profitability of domestic storage, and thus the amount of domestic storage capacity specified in the *Strong Regional Hydrogen Economy* will not be built.

2.1.3 The 'Leading Hydrogen Ecosystem' scenario

This scenario is a combination of the demand drivers of the other scenarios. Finland is home to strong domestic demand, as in the *Strong Regional Hydrogen Economy* scenario, and Finland also exports clean hydrogen in response to the Central European demand, as in the *European Hydrogen Market* scenario.

In this scenario, pipeline connections are built to Northern Sweden and Central Europe, which also contributes to the flexibility of the energy system. The need for domestic storage capacity is at the same level as in the *European Hydrogen Market* scenario, despite higher hydrogen production.

In this scenario, Finland produces a very large amount of clean hydrogen, which requires a lot of clean electricity generation. The increase in production is limited by the assumption that no more than 4 GB of wind power can be built in Finland per year, which is approximately twice the expected rate of construction in the next few years. This would mean that Finland's wind power capacity could increase to approximately 60 gigawatts by 2040. This scenario utilises all onshore wind capacity that can be built within the limits, as well as some offshore wind and solar power. If the construction rate of onshore wind power were increased to more than 4 GW per year and there were some unused potential remaining, Finland could meet an even higher share of Europe's hydrogen demand (see Chapter 3.2).

2.2 Scenario modelling and background assumptions

The purpose of the modelling of the scenarios is to forecast market-driven investments in electricity generation and hydrogen production if the operating environment were to develop as described in that particular scenario. The modelling of the scenarios was carried out by applying an electricity market model to analyse the functioning of the market both at an hourly level and at the level of the investment horizons of various production and consumption facilities. The electricity market model used Afry's BID3 [7], which is also used for other purposes at Fingrid. The modelling covers the Baltic Sea region and the majority of Central and Western Europe. For example, in order to export hydrogen from Finland, hydrogen produced in Finland must be cheaper at the time of export than hydrogen produced in the destination country.

Domestic demand for hydrogen was determined separately for each scenario according to the development paths described in Chapter 2.1 above. Sweden's demand for hydrogen was assessed on the basis of reports by Energiforsk[8] and Fossilfritt Sverige[9] among others, but these were modified to make the demand drivers of hydrogen exports and downstream hydrogen products similar in Finland and Sweden. The demand for hydrogen in other European countries was determined on the basis of a scenario by ENTSO-E[10]. The scenario by ENTSO-E does not take into account the recent changes in the

[7] https://afry.com/en/service/bid3-power-market-modelling
[8] The role of gas and gas infrastructure in Swedish decarbonisation pathways 2020-2045. (Energiforsk, 2021)
[9] Strategy for fossil free competitiveness – Hydrogen. (Fossil Free Sweden, 2021)
[10] Ten Year Network Development Plan 2022 – Scenario report (ENTSO-E, 2022)

operating environment, which is why efforts were made to update the final scenarios. An example of such updates is the impact of the RePowerEU plan on the volumes of clean hydrogen and renewable sources of energy.

The electricity generation capacity trends in the scenarios take into account the national minimum requirements for the production of renewable energy in the different European countries. The scenarios assume that if the investments needed to achieve the national targets do not appear to be profitable on market terms, they will be granted support as necessary. On the other hand, the scenarios also set maximum levels for the capacity of renewable electricity generation by country. These maximum levels will be reached by market-driven investments, particularly in Central Europe, reflecting the challenges of constructing enough renewable electricity generation to meet to the high demand in the region.

Market-term investments in wind and solar power, electrolysis and hydrogen storage were determined by applying a method in which the operating margin obtained by the investments on the wholesale market covers the levelised investment costs and the required return on capital investments[11]. The calculation model optimises the production, consumption and storage of electricity and hydrogen on a region-wide common market, the simulations of which assume perfect competition and complete information over a 10-day time horizon.

The assumptions about the investment costs, operation costs and maintenance costs of electricity generation are primarily based on the ENTSO-E scenario mentioned above. The investment costs of renewable onshore and offshore wind and solar power will decrease, but onshore wind will remain the most competitive one. The investments take into account the connection costs, which are higher in offshore wind power than onshore wind power, for example.

The main categories of electrolysis technologies are alkaline (ALK), polymer membrane (PEM) and solid oxide electrolyser cell (SOEC). The model assumes a 70% efficiency and cost trend for electrolysis, which is in line with alkaline electrolysis. Sources for the estimate of cost trends are the IEA study[12], which was also used for Finland's Hydrogen Roadmap, and other sources[13][14].

Hydrogen can be stored, for example, in salt caverns, rock caverns and steel tanks that resemble a hydrogen pipeline. Of these, the larger caverns, in particular, might be a cost-effective and suitable solution for long-term energy storage compared to grid energy storage, whose capacity to provide flexibility over a longer term is usually limited due to cost reasons[15]. Rock caverns were assumed to be the most cost-effective form of hydrogen storage in Finland.

Fingrid and Gasgrid seek to refine the cost estimates in the final scenarios.

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[11] The default required return on capital investments is 5% in real terms
[12] Business Finland, National Hydrogen Roadmap for Finland: (Laurikko, et al., 2020)
[13] https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf
[14] https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf
[15] https://gasgrid.fi/wp-content/uploads/Gasgrid_Study-on-the-Potential-of-Hydrogen-Economy-in-Finland_ENG-FINAL.pdf

3 Key results of the modelling in the draft scenarios

This chapter presents the key results of the modelling in the draft scenarios. Chapter 3.1 discusses the production of clean hydrogen in Finland for each scenario, including domestic demand and exports. A summary of the need for electricity and production capacity is given in Chapter 3.2. Chapter 3.3 then discusses the role of hydrogen storage in balancing the energy system.

3.1 Hydrogen production volumes, electrolyser capacities and their use in different scenarios – Clean hydrogen for consumption use and export

In the scenarios, the hydrogen production capacity increases significantly to enable the export of P2X products and hydrogen from Finland. Figure 2 summarises Finland's current consumption of grey hydrogen and the production of clean hydrogen in each scenario, and the electrolysis capacity used to produce hydrogen in the scenarios.

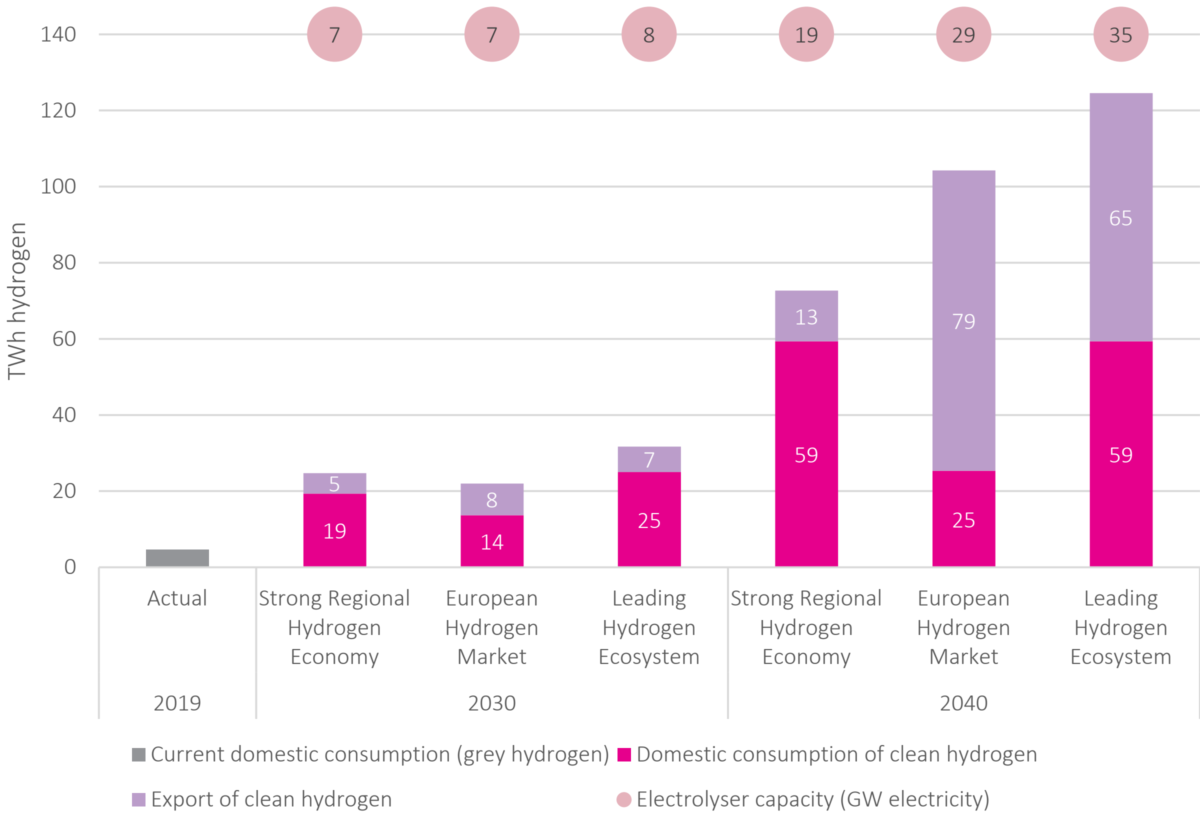

Figure 2 Finland's consumption of grey hydrogen and the production volumes of clean hydrogen and electrolyser capacity in the scenarios

In the scenarios, approximately 20–35 TWh of clean hydrogen will be produced in Finland in 2030 and 70–125 TWh in 2040. To produce these volumes, Finland will be home to 7–8 GW of electrolyser capacity already by 2030, and the capacity will increase to approximately 20–35 GW by 2040.

3.1.1 Clean hydrogen for the domestic industry and P2X exports

The domestic demand for hydrogen in the scenarios is based on the existing industry's shift to clean hydrogen and the emerging P2X industry's demand for clean hydrogen, but the volumes vary depending on the scenario (Figure 3). In all scenarios, the level of domestic demand in 2030 is based on the replacement of grey hydrogen with clean hydrogen and on public targets[16,17,18] in which clean hydrogen is used in new applications such as the steel industry and fuel refining. Most of the consumption would take place in new P2X industry, and hydrogen would be produced especially for the production of e-fuels.

Under the Strong Regional Hydrogen Economy scenario, 13 TWh of hydrogen would be used for producing e-fuels in 2030, increasing to 19 TWh in 2040. In the *European Hydrogen Market* scenario, the corresponding demand is 8 TWh in 2030 and 15 TWh in 2040; in the *Leading Hydrogen Ecosystem* scenario, the demand for hydrogen for the production of domestic e-fuels is 19 TWh in 2030 and 49 TWh in 2040. In all scenarios, the annual demand for hydrogen used in the production of non-e fuels remains the same at 6 TWh in 2030 and increases moderately to 10 TWh by 2040.

Based on the scenarios, the total demand for hydrogen will increase at least threefold and even fourfold from the current level by 2030. This means an annual increase of approximately 3–5 TWh in hydrogen demand if most of the increase takes place between 2025 and 2030.

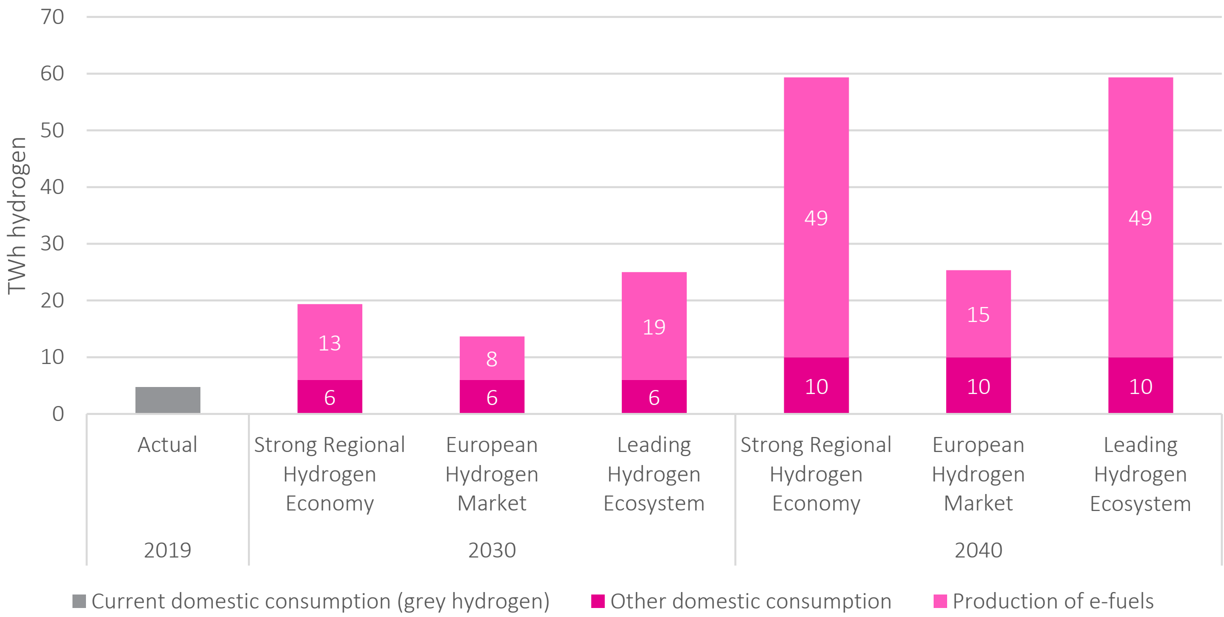

Figure 3 Actual Finnish demand for hydrogen in 2019 and the domestic demand for clean hydrogen in the scenarios

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[16] Ren-Gas: 2.5 TWh of renewable gas fuels for heavy transport. (Company website, accessed on 27 May 2022)
[17] P2X Solutions: 1,000 MW of electrolysis power over the next 10 years. (P2X Solutions, 2022)
[18] Business Finland, National Hydrogen Roadmap for Finland: the consumption of hydrogen will grow by 170 kt (~6 TWh) per year, especially in the oil refining and steel industry (Laurikko, et al., 2020)

The 2040 estimate for domestic consumption of clean hydrogen in the *Strong Regional Hydrogen Economy* and *Leading Hydrogen Ecosystem* scenarios is close to 60 TWh. This estimate is based on the highest demand level in the scenarios outlined in the study of the hydrogen economy commissioned by the government[19], which was utilised in the modelling of the scenarios above. This level of demand could be achieved if the growth of the annual demand for clean hydrogen in the late 2020s continues at the same level throughout the 2030s. In the *European Hydrogen Market* scenario, the domestic demand remains at 25 TWh, since in this scenario, the growth of the Finnish hydrogen economy is based on exports of hydrogen gas.

3.1.2 Hydrogen export volumes as hydrogen gas in different scenarios

Hydrogen transmission in the scenarios has been modelled on the basis of assumed pipeline connections and the balance between the demand and supply of hydrogen in Finland and other Baltic Sea countries. The graph below shows the quantities of clean hydrogen exported as gas to countries in the Baltic Sea region. The calculations indicate that Finland will first become a hydrogen exporter to Northern Sweden in the 2030s, which is made possible by the Nordic Hydrogen Route. The exports will then expand to Central Europe, provided that the necessary pipeline connections are constructed.

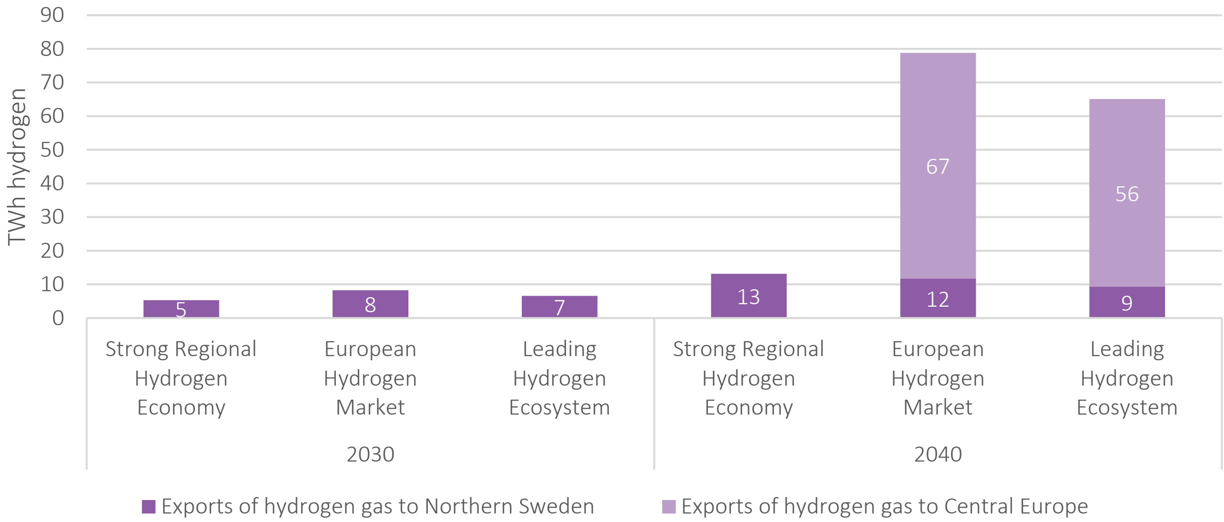

Figure 4 Finland's net exports of hydrogen gas via pipeline connections to Northern Sweden and Central Europe

In 2030, Finland's net exports of hydrogen amount to 5–8 TWh, delivered via a pipeline to meet the demands of industry in Northern Sweden. By 2040, the volume of exports to Northern Sweden will increase to approximately 9–13 TWh. In the other scenarios, the volume of hydrogen exports will increase thanks to the pipeline connection to Central Europe. This is particularly evident in the *European Hydrogen Market* scenario, in which exports will reach up to approximately 70 TWh. In the *Leading Hydrogen Ecosystem* scenario, exports of hydrogen as hydrogen gas are slightly lower due to the restrictions imposed on the construction of onshore wind power (see Chapter 3.2), since a large proportion of the available resources are tied to meeting the domestic demand, which is already very high.

[19] Prime Minister's Office, Hydrogen economy – Opportunities and limitations, p. 162 (Sivill, et al., 2022)

3.2 Growth in electricity generation in the scenarios – Finland's affordable wind power as a driver of competitiveness

In the scenarios, Finland's electricity consumption will almost double from the current level by 2030 and triple by 2040. This trend is mainly driven by electricity needed for hydrogen production (Figure 5). Hydrogen production will become Finland's largest consumer of electricity in the scenarios. In 2030, 30–45 TWh of electricity will be used for hydrogen production, and by 2040, the figure will be 100–180 TWh, depending on the scenario. In 2040, hydrogen production uses more electricity than all other demand facilities combined, despite the fact that the consumption of electricity will also increase in other sectors due to the electrification of industry, transport and heating, as well as the emergence of new industry and data centres.

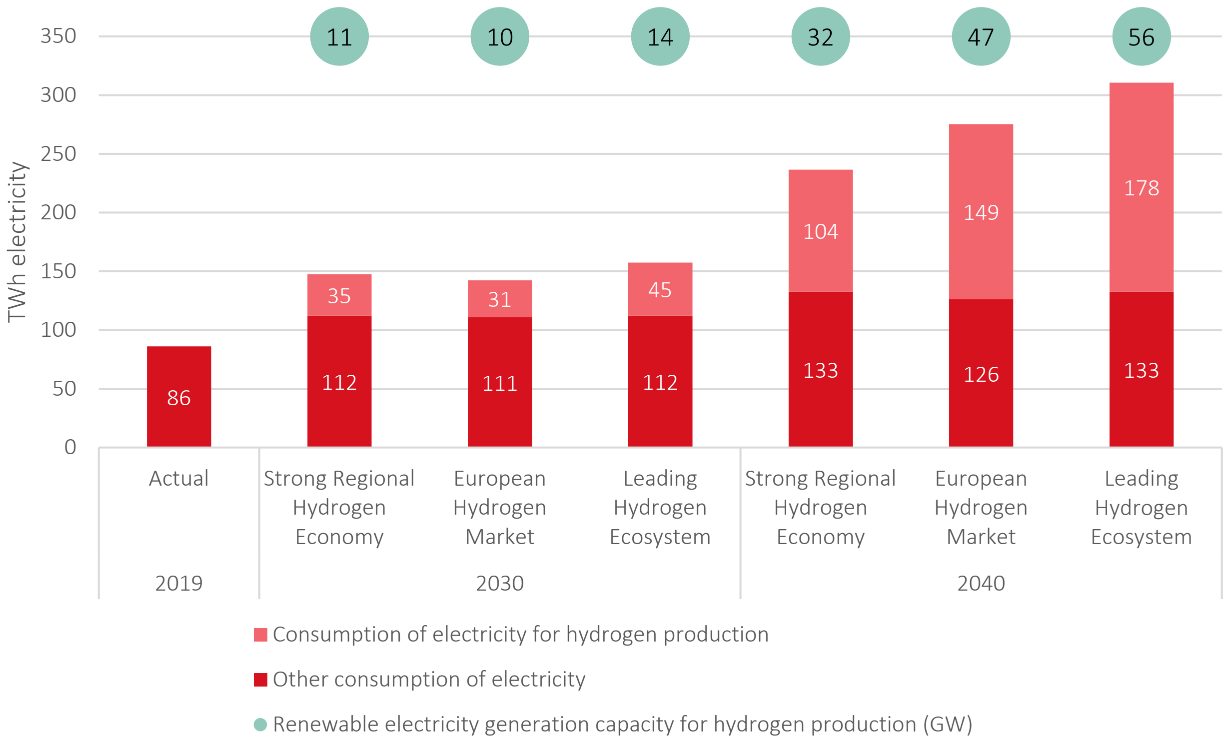

Figure 5 Consumption of electricity in Finland and the renewable capacity required for producing hydrogen[20,21]

The generation of clean electricity requires very significant investments in clean renewable electricity generation. The volume of onshore and offshore wind and solar power will increase considerably in order to meet the demand. The figure shows an estimate of the renewable electricity generation capacity needed for hydrogen production. In addition, renewable sources of energy also meet other increased demand. Most of this is onshore wind power, which is the most competitive new electricity generation in Finland and is the basis for a very large number of electricity generation projects under development.

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[20] Source for electricity consumption in Finland in 2019: Official Statistics of Finland (OSF, 2019): Energy supply and consumption

[21] In this context, 'renewable electricity generation capacity' refers to onshore and offshore wind power and solar power. The capacity is estimated at an average utilisation period of maximum load of 3200 hours.

In the scenarios, onshore wind capacity will increase to more than 20 gigawatts by 2030 and to 50–60 gigawatts by 2040. This requires the capacity of onshore wind power to increase by approximately 3–4 GW per year in the 2030s, while the annual growth rate in the next few years is projected to be around 2 GW at most. As a result, the growth rate of onshore wind power is one of the key uncertainties in the scenarios.

If the additional construction of onshore wind power progressed faster, the production volumes of clean hydrogen in Finland could be even higher than those presented here. For example, if the additional construction of wind power were increased to 6 GW per year, the wind power capacity in 2040 would be 80 GW, which would correspond to an annual electricity generation of 280 TWh/a and thus a higher hydrogen production potential. On the other hand, if additional onshore wind power were constructed at a slower rate, this would also limit the production of clean hydrogen. Therefore, rapid licensing of wind power and the energy transmission infrastructure it requires, as well as the utilisation of the wind power potential of Eastern Finland, would contribute to the actualisation of investments in hydrogen. In addition to onshore wind power, 4–9 GW of offshore wind power and 7–15 GW of solar power will be built in Finland by 2040 in all scenarios.

In the scenarios, the generation of onshore and offshore wind and solar power will reach 85–95 TWh by 2030 and will increase further to 195–255 TWh by 2040. This means that most of Finland's power generation would vary by the weather conditions. This requires an enormous need for demand flexibility in order to keep the electricity system in balance.

3.3 The role of hydrogen storage in different scenarios – Hydrogen storage brings flexibility to the energy system

Hydrogen storage can bring flexibility and cost-effectiveness to the energy system. By integrating the electricity and hydrogen system, enormous amounts of renewable electricity can be generated for hydrogen production with onshore and offshore wind power and solar power, although their output varies depending on weather conditions. For example, an extensive hydrogen network can itself act as an energy buffer in the energy system.

The strong increase in hydrogen production and consumption outlined in the scenarios also requires significant hydrogen storage capacity in order to balance wind power, which varies according to the weather, with the steady consumption of hydrogen in the industry. Therefore, the scenarios model the role of hydrogen storage in the balancing of the energy system and smoothing out the differences between production and consumption. Figure 6 presents the capacities of these hydrogen storage facilities as energy quantity and as back filling capacity of the storage facility.

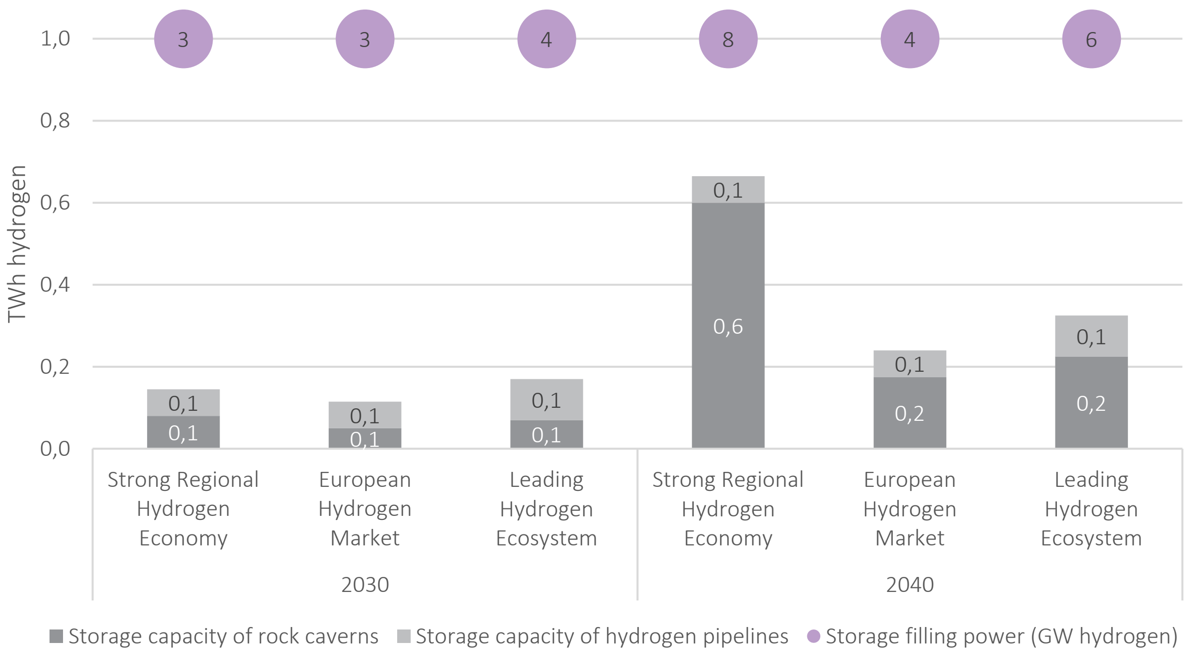

Figure 6 Capacity and back filling power of hydrogen storage in the scenarios

The storage volumes take into account both storage in rock caverns and the storage capacity of the hydrogen transmission infrastructure, meaning the so-called buffer capacity. In all scenarios, the need for flexibility in the system and consequently for hydrogen storage will increase significantly by 2040, but the scenarios diverge in this respect. Domestic rock cavern storage plays an important role in the *Strong Regional Hydrogen Economy* scenario, whereas in the other scenarios, the domestic storage capacity is primarily based on the storage capacity of the pipeline network. In these scenarios, the need for domestic storage capacity is lower, since the huge salt cavern storage facilities in Central Europe can be used, thanks to the hydrogen pipeline connecting to the region.

In the Strong Regional Hydrogen Economy scenario, the combined storage capacity of domestic hydrogen storage facilities corresponds to approximately 1.5 days of domestic hydrogen consumption in 2030 and the consumption of approximately 3 days in 2040. The back filling capacity of the storage facilities in the scenario corresponds to approximately one third of the hydrogen production capacity of the electrolysers. In the other scenarios, the capacity for domestic hydrogen storage is lower, since flexibility in the hydrogen system is obtained through hydrogen exports and imports.

4 Investments and markets in the hydrogen economy

4.1 Massive investments pave the way to a clean energy system

Producing clean hydrogen on the scale presented herein requires massive investments in the production of clean hydrogen and electricity. Investments are also needed in hydrogen storage and energy transmission. Large-scale investments are expected to be carried out on market terms. Finland's advantage compared to the rest of Europe is affordable clean electricity that can be produced in extremely high quantities.

Figure 7 illustrates the scale of investments in the production of clean hydrogen by 2030 and 2040 in the different scenarios. Most of the investments go to the generation of renewable electricity that is required to produce clean hydrogen. These investments will reach approximately EUR 10–15 billion by 2030 and around EUR 30–50 billion by 2040. The investments in electricity generation equal the electricity consumed by electrolysis, which would primarily be produced by Finnish onshore wind power (see 3.2, Figure 5). Investments in domestic energy transmission are a fraction of the presented costs. The assessment of investments in energy transmission will become more specific in the modelling of the final scenarios of the joint project.

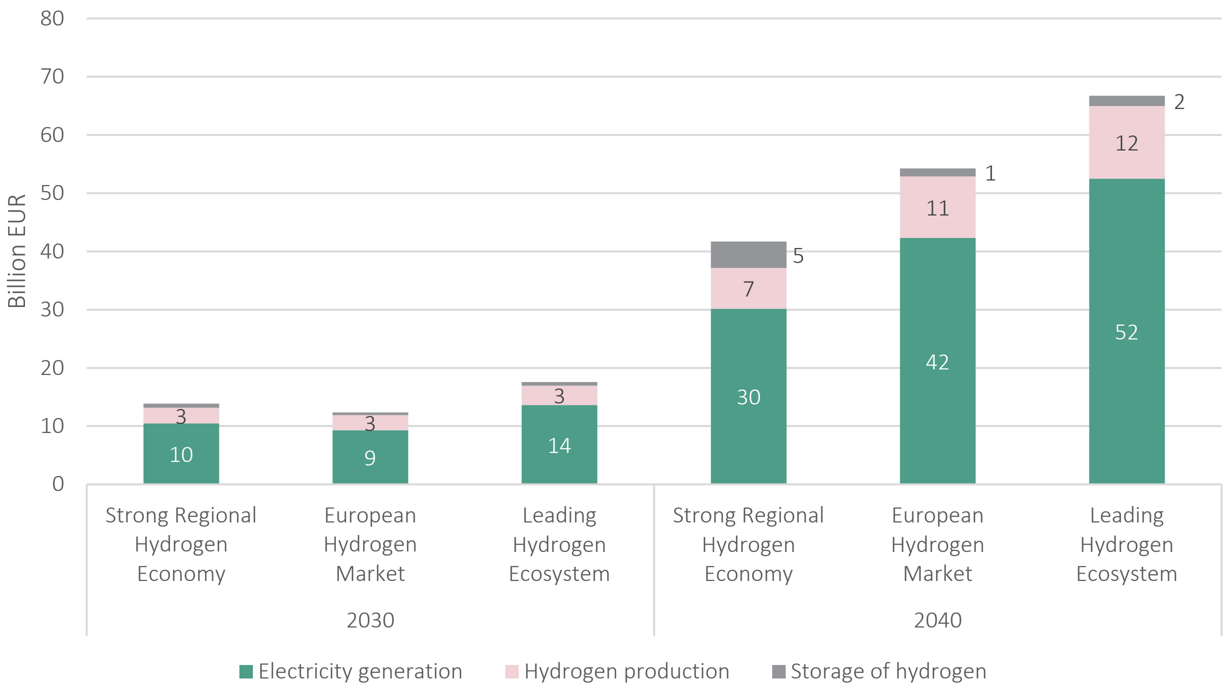

Figure 7 An estimate of cumulative investments in the production of clean hydrogen in Finland by 2030 and 2040

Investments in hydrogen production and storage by 2030 will be in the order of EUR 2–3 billion and will increase to a total of approximately EUR 10–15 billion by 2040. The majority of these investments take place in electrolysis (see capacities, Figure 4), but the magnitude of investments required for rock caverns is also significant (see capacities, Figure 6). This is particularly evident in the *Strong Regional Hydrogen Economy* scenario, in which significant investments of almost EUR 5 billion are made in domestic storage and EUR 7 billion in electrolysers. The magnitude of the investments does not take into account any additional investments in the hydrogen economy value chains (e.g. P2X downstream chain), which further highlights how investments in transmission infrastructure have a multiplier effect on the emergence of new industries. The benefits of the value chains will be assessed in the future phases of the joint project.

The development of hydrogen storage is subject to significant uncertainties, for example in the construction costs of hydrogen storage facilities and technical solutions. A range of storage solutions already exists for natural gas, but large-scale storage facilities for hydrogen are still in the pilot phase. In Sweden, for example, a rock cavern is being piloted for hydrogen storage in the HYBRIT project[22]. In their joint project, Fingrid and Gasgrid are also investigating in more detail the costs of various hydrogen production and storage solutions and the P2X downstream chain.

4.2 Investments open the door to a multibillion-euro hydrogen market

Large investments in the production of clean hydrogen will enable Finland to participate in the multibillion-euro market for clean hydrogen in the EU (Figure 8). The price of competitive clean hydrogen is estimated to be EUR 2.5/kg in 2030, falling to around EUR 2/kg by 2040[23]. At these prices, the value of Finland's clean hydrogen production is EUR 1.5–2.5 billion annually in 2030, rising to as much as EUR 4–8 billion by 2040. In addition to the above estimate, Finland generates added value by further refining hydrogen into P2X products such as e-fuels, the value of which is clearly higher than the value of hydrogen production alone.

Figure 8 Estimated annual value of Finland’s clean hydrogen production (excluding the added value of P2X products)

[22] https://fuelcellsworks.com/news/ssab-lkab-and-vattenfall-started-building-a-rock-cavern-storage-facility-for-storing-hydrogen/
[23] Five Hydrogen supply corridors for Europe in 2030, p. 115 (EHB, 2022)

When assessing Finland's potential as a hydrogen exporter, it is important to take into account the EU's objectives for a clean hydrogen market. The estimated size of the EU hydrogen market in 2030 is approximately 670 TWh[24] and in 2040 approximately 1,300 TWh[25]. Accordingly, Finland's market share in the EU market for clean hydrogen and processed hydrogen (incl. Finland) in the scenarios is 3–5% in 2030 and 5-10% in 2040 (Figure 9). Finland punches above its weight in the scenarios compared to other EU countries, thanks to the excellent availability of clean and affordable electricity.

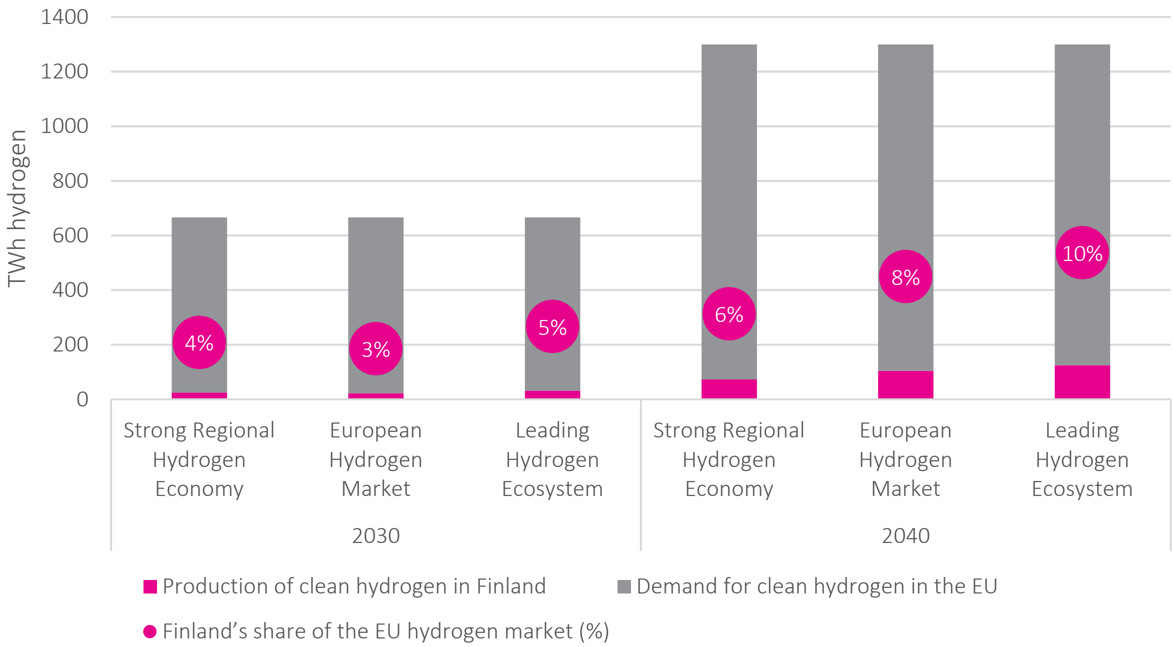

Figure 9 The share of pure hydrogen produced in Finland in the 2040 EU hydrogen market in the scenarios

[24] Based on the EU's REPowerEU plan, taking into account both the EU's 10 Mt production target and the 10 Mt import target by 2030 (European Commission, 2022)
[25] Based on the scenarios in the Development Plan for European Electricity and Gas Network Operators. Note: the scenarios do not take into account the impact of the REPowerEU plan, against which the estimated hydrogen demand appears low. (ENTSO-E, ENTSOG, Ten Year Network Development Plan 2022)

5 Transmission infrastructure enables investments in Finland

Based on the draft scenarios, the production of clean hydrogen is affordable in Finland, which makes it profitable to produce and also export hydrogen gas or P2X products to other parts of Europe, where demand is expected to grow enormously. In all scenarios, hydrogen transmission infrastructure will enable the transmission of hydrogen gas in a pipeline between Finland and Northern Sweden in 2030. In addition, the *European Hydrogen Market* and *Leading Hydrogen Ecosystem* scenarios assume that a hydrogen pipeline is constructed between Finland and Central Europe by 2040. The chapters below discuss in more detail what kinds of transmission infrastructure development needs exist within Finland in each scenario.

5.1 The need for energy transmission will grow many-fold from the present level

A large part of Finland's electricity consumption is located in the south, while a significant part of the growth potential for renewable electricity production lies in the north. The scenarios in Fingrid's network vision[26], published in 2021, identify the need to expand the north-south power transmission capacity step by step in the long term. Since the scenarios in Fingrid's network vision were published, the need for power transmission has only increased, and the placement of hydrogen production and renewable electricity generation will have a critical impact on the need for transmission.

Most of Finland's existing wind turbines are located in Ostrobothnia and Lapland, while Southern and Eastern Finland have only a few. In Southern Finland, the potential of wind power resources is constrained by the higher population density, among other things. In Eastern Finland, on the other hand, the constraint is created by radar surveillance, which limits the areas in which wind farms can be constructed and their size. This, in turn, reduces the interest of operators in developing wind power. Due to these constraints, most new wind power projects are located in Western and Northern Finland.

In Finland, hydrogen is currently used in the chemical industry, especially in Southern Finland[27], and hydrogen production is largely concentrated in the vicinity of the demand facilities. The main drivers in the scenarios are the emergence and location of new industry and the replacement of current consumption with clean hydrogen. A large proportion of the Finnish hydrogen projects announced so far are in the southern parts of the country[28], for example in Vantaa and Porvoo, as well as on the coast of the Bothnian Bay[29]. Currently, hydrogen is mainly produced close to the site of consumption, but in the energy system of the future, the production and use of hydrogen may be located in different geographical areas if the hydrogen infrastructure develops accordingly, enabling hydrogen transmission. Therefore, the geographical location of hydrogen production and consumption is one of the most significant uncertainties in the scenarios.

The production clusters of clean hydrogen require renewable electricity, which is why their location in relation to the generation of renewable electricity determines the need for energy transmission within Finland. The need for electricity transmission will increase if the electrolyser is located close to the end

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[26] Network vision (Fingrid, 2021): https://www.fingrid.fi/globalassets/dokumentit/fi/sahkomarkkinat/fingrid_verkkovisio.pdf
[27] Business Finland, National Hydrogen Roadmap for Finland: (Laurikko, et al., 2020)
[28] Prime Minister's Office, Hydrogen economy – Opportunities and limitations, (Sivill, et al., 2022)
[29] https://www.both2nia.com/fi

consumers of hydrogen. Finland's internal hydrogen transmission infrastructure would enable the electrolyser to be located close to renewable power production, in which case energy could be transmitted as hydrogen. The hydrogen transmission infrastructure would also allow hydrogen downstream processes to be placed close to CO_2 emission sources that are used as raw material for P2X products.

The hydrogen infrastructure could also enable hydrogen production to be located close to cities that can utilise waste heat from hydrogen production in their district heating networks. This would increase the need for electricity transmission from the wind farm clusters to urban consumption centres.

5.1.1 Location of hydrogen consumption and renewable electricity generation in Finland

Figure 10 shows the distribution of electricity generation and consumption in Finland in 2030 and 2040 in the scenarios. In the figure, Finland is divided into northern and southern regions at Central Finland. The cross-section is used to describe the necessary energy transmission within Finland. In the figure, the electricity demand corresponding to the demand for hydrogen is illustrated according to the assumed location of the hydrogen demand, meaning that hydrogen would be produced by electrolysis near where it is consumed. The demand for hydrogen also takes into account exports from the northern region to Sweden and from the southern region to Central Europe. In this context, ‘renewable electricity generation’ refers to onshore and offshore wind power and solar power.

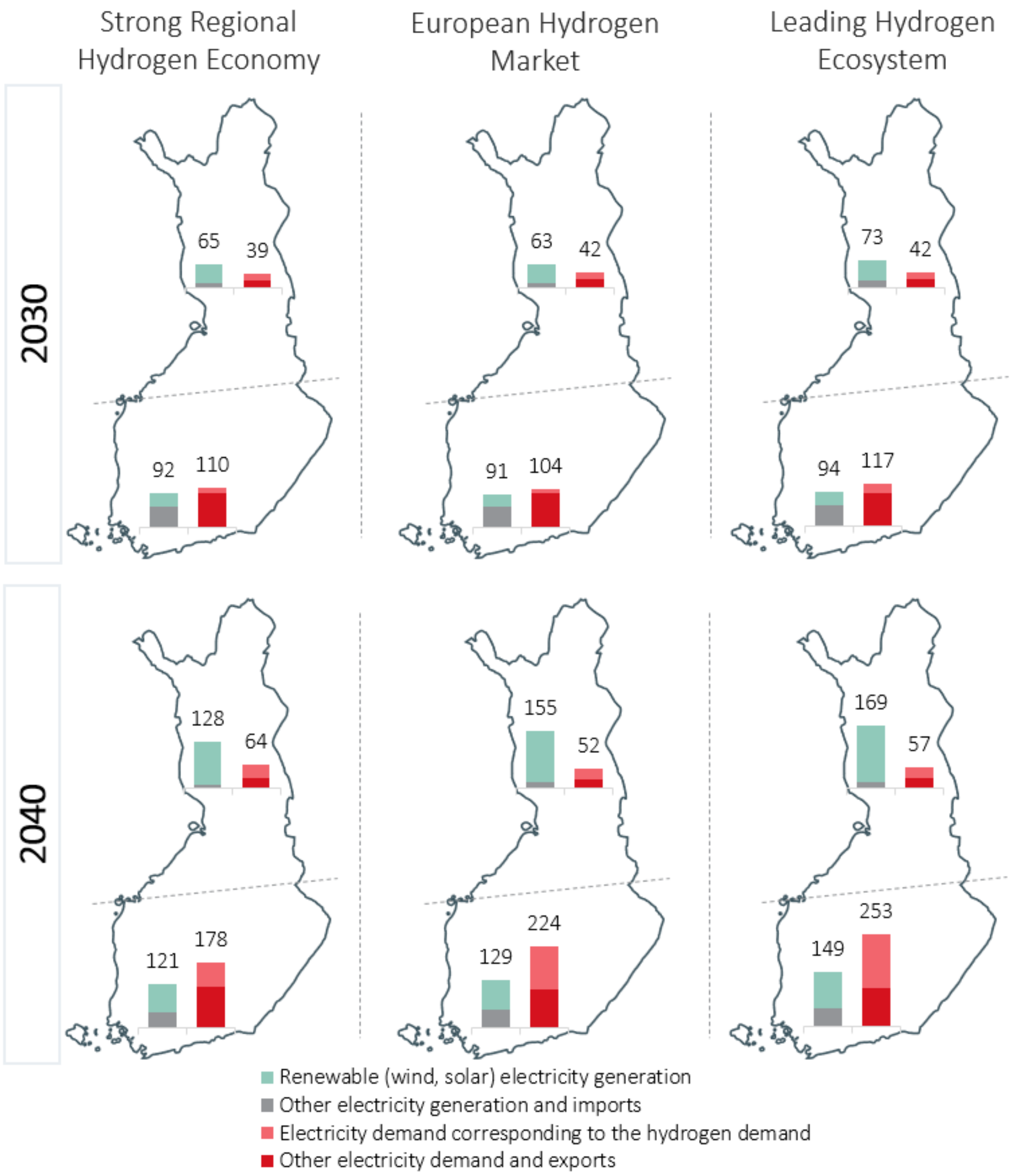

Figure 10 Location of electricity generation and consumption in Finland in scenario years 2030 and 2040

In 2030, the demand for hydrogen will increase fairly equally between the northern and southern regions. The growth in the north is driven in particular by the consumption of hydrogen in the steel industry and exports to Northern Sweden, while in the south, the demand increases as the existing industrial plants replace grey hydrogen and as the production of e-fuels increases. In the *European Hydrogen Market* scenario, there are more exports to Northern Sweden and less domestic production of e-fuels, which is why demand is concentrated in Northern Finland

In all scenarios, however, the majority of new renewable production will be built north of the cross-section, resulting in a surplus in the area, while the south will have a deficit due to high consumption of electricity. As a result, all scenarios indicate the need to transmit energy from the north to the demand facilities in the south.

By 2040, the production of e-fuels at production plants in the south and/or the export of hydrogen gas via a hydrogen pipeline from Southern Finland to Central Europe will shift the focus of hydrogen demand to Southern Finland in all scenarios. Renewable onshore and offshore wind power will be built, especially in the northern half of the cross-section, which will increase the surplus in the area. A large surplus in the north and a deficit in the south will lead to a very great need to transmit energy from north to south.

When looking at the scenario figures, it is also worth noting that the restrictions imposed by radar surveillance in Eastern Finland are assumed to be resolved, which means that onshore wind power can be built more freely in Eastern Finland, too. This enables the maximum utilisation of Finland's onshore wind potential. The geographical diversification of wind power also improves profitability, since local variations in windiness improve the profitability of wind power investments. It also lessens the variability of wind power, since production is dispersed to areas with different wind conditions.

5.1.2 Assessment of the energy transmission required within Finland in each scenario

Figure 11 provides an estimate of the energy transmission needs between Northern and Southern Finland in the scenarios. At present, the energy transmission need is 10 TWh, which will more than double by 2030. By 2040, the need for energy transmission will increase many times over: to a minimum of 60 TWh and a maximum of up to 100–115 TWh. The higher transmission need in the two last scenarios stems from the need to export hydrogen in large quantities via the pipeline that runs from Southern Finland to Central Europe.

As shown in the figure, energy can be transmitted either as electricity or as a combination of hydrogen and electricity. The proportions are based on an assumption that the production of renewable hydrogen consumes electricity from north and south onshore and offshore wind farms and solar power in proportions corresponding to their output. This way, the production of hydrogen can leverage the benefits of the geographical distribution of electricity generation, reducing the variability in production. The transmission of renewable electricity for the production of hydrogen is shown in the figure as transmission of energy that can be either electricity or hydrogen, based on the location of the electrolysers. The remaining electricity output is used in other demand facilities, which means that it is transmitted over the main grid.

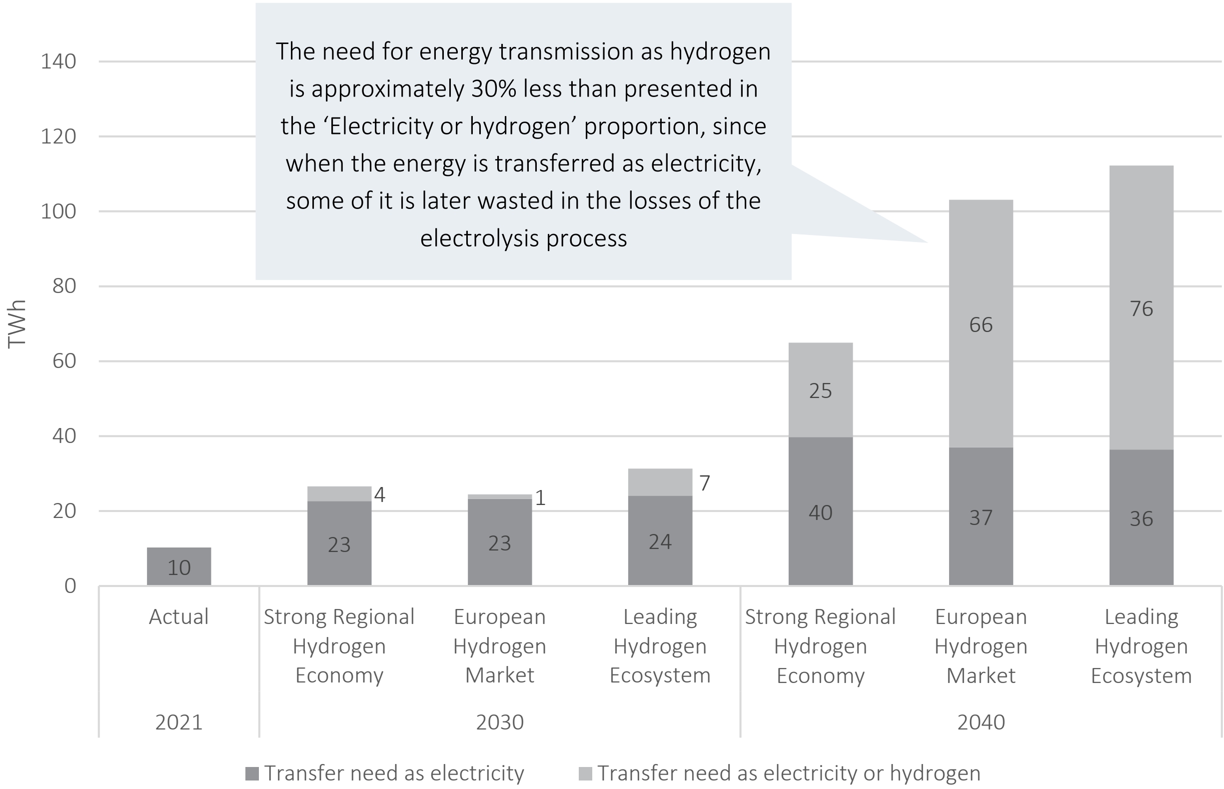

Figure 11 Estimate of Finland's internal energy transmission needs (through Cross-section Central Finland[30])

The location of hydrogen production plants will have an effect on whether the energy is transmitted as electricity or hydrogen. For example, an electrolyser connected to a northern wind farm could produce clean hydrogen that is transferred to a demand facility in the south. Similarly, the electrolyser may be located near the demand facility far from electricity generation, in which case the transmission is carried out as electricity. However, when energy is transmitted as electricity, a larger amount of energy is needed, since 30% of the electricity is wasted in the losses of the electrolysis process. On the other hand, most of the losses can be utilised as waste heat, which can encourage the placement of electrolysers close to large cities and their district heating networks, for example. This contributes to the construction of hydrogen infrastructure.

All scenarios assume that the Nordic Hydrogen Route pipeline connection will be in use between Finland and Sweden from 2030 onwards. Based on the pipe sizes used in the Bothnian Bay Hydrogen Valley research report[31], the pipeline connection can transfer 7.2 GW of hydrogen. In addition, the *European Hydrogen Market* scenario and *Leading Hydrogen Ecosystem* scenario contain a pipeline connection built from Finland to Central Europe by 2040, with a transmission capacity of 13 GW of hydrogen based on the European Hydrogen Backbone[32] study.

[30] The Cross-section Central Finland is shown in the map images above
[31] Bothnian Bay Hydrogen Valley – Research Report (Karjunen et al., 2021)
[32] Extending the European Hydrogen Backbone (EHB, 2021)

The extremely high-volume energy transmission from Finland to Central Europe outlined in the scenarios (56–67 TWh of hydrogen is equivalent to 80–96 TWh of electricity) is only possible via hydrogen pipes or as products. Transmitting an equivalent net amount of energy as electricity over the same period at maximum load would require almost 19 GW of electricity transmission capacity, which is not possible in a system like the present one.

6 Please give us feedback

Fingrid Oyj and Gasgrid Finland Oy would like to receive stakeholder feedback on the draft scenarios outlined above.

Feedback can be sent from the publication day of this report. Please provide your feedback by 19 August 2022. To send your feedback, use the Microsoft Forms form at:

https://forms.office.com/r/jaGKz7r0FM

The form first asks you to provide some background information about you and your organisation to help the processing of the answers. You can give feedback on the draft scenarios on the next page of the form. The final fields are free-text fields for open feedback.

The feedback will serve as input for refining the scenarios in autumn 2022, along with the results of the studies carried out in the joint project. The studies and scenarios also assess the impact of various value chains and development paths in the hydrogen economy on the development needs of gas, electricity, and a potential hydrogen transmission system. The final report of the project will be completed at the end of 2022, and a joint stakeholder event will be held in connection with the publication.

In spring 2021, Finland's gas transmission grid operator, Gasgrid Finland, and its electricity transmission system operator, Fingrid, began work to identify opportunities for the hydrogen economy to thrive in Finland and to clarify the role of energy infrastructure as an enabler of the hydrogen economy. The collaboration was followed up in tangible form by a research and development project jointly run by Gasgrid and Fingrid. The new project is being executed as part of HYGCEL, a wide-ranging research project consortium consisting of several Finnish companies and research institutes. On 28 October 2021, Business Finland awarded a grant for the joint project between Fingrid and Gasgrid, as well as for the larger entity.

Gasgrid Finland Oy is a state-owned company that acts as the gas transmission system operator with system responsibility in Finland. We offer our customers safe, reliable and cost-effective transmission of gas. We develop our transmission platform, services and gas markets actively and in a customer-focused way to promote carbon-neutral energy and the raw materials system of the future. For more information, see: www.gasgrid.fi

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