Hydrogen economy - Opportunities and limitations

Leena Sivill, Marika Bröckl, Nikita Semkin, Antti Ruismäki, Henriikka Pilpola, Olli Laukkanen, Hannele Lehtinen, Saana Takamäki, Petri Vasara, Jenni Patronen

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Hydrogen economy - Opportunities and limitations

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Abstract

Hydrogen economy aims to reduce CO2 emissions in sectors and processes where utilising other solutions is particularly challenging. Such processes can be found in industries, aviation, maritime transport, and heavy-duty road transport.

The EU is currently preparing legislative changes to enable an increased implementation of hydrogen-based solutions. At the same time, countries in and outside Europe have been develoing their national hydrogen strategies. Thousands of projects are being established for the production and end-use of clean hydrogen in Europe alone.

Hydrogen economy provides an opportunity for Finland, as Finnish power generation has a relatively low carbon intensity and there is a stable national transmission grid for electricity available. Furthermore, Finland has vast potential for additional wind power, which could be utilised to produce hydrogen and electrofuels to meet domestic demand as well as for exports. On the other hand, the future supply and demand still remain highly uncertain in the international market. Strong competition is anticipated between different technologies and alternative locations for production.

Finland must ensure preconditions for industrial investments in the hydrogen economy, and create clear targets and an action plan for the hydrogen transition in different sectors. The development of the hydrogen economy can be supported, e.g., by easing the licensing of additional wind power construction, increasing hydrogen expertise, and supporting R&D activities in technologies, services, and collaboration. Electricity and hydrogen transmission infrastructures should be developed as a whole in preparation for the future needs while managing the related risks and costs. Alternative technologies and solutions must be considered along with the hydrogen-based solutions. In addition, conditions for fair competition must be ensured both domestically and internationally.

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Vetytalous – mahdollisuudet ja rajoitteet

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Tiivistelmä

Vetytaloudella tavoitellaan hiilidioksidipäästöjen vähentämistä aloilla, joilla muiden keinojen käyttö on erityisen haasteellista. Tällaisia kohteita löytyy mm. teollisuudesta, lento- ja meriliikenteestä sekä raskaasta tieliikenteestä.

EU valmistelee yhteisiä vetyratkaisujen yleistymistä mahdollistavia lainsäädäntömuutoksia. Samaan aikaan eri maat Euroopassa ja sen ulkopuolella ovat laatineet kansallisia vetystrategioitaan. Vedyn tuotantoon ja loppukäyttöön suunnattuja projekteja on pelkästään Euroopassa kehitteillä tuhansittain.

Suomelle vetytalous näyttäytyy mahdollisuutena, koska Suomessa on melko vähähiilinen sähköntuotantokapasiteetti ja vahva sähkön kantaverkko. Tämän lisäksi Suomessa on valtava tuulivoiman lisärakennuspotentiaali, jota voitaisiin hyödyntää vedyn ja sähköpolttoaineiden tuotantoon sekä kotimaan kysyntää että vientiä varten. Toisaalta kansainvälisen markkinan tulevaisuuden tarjontaan ja kysyntään liittyy suuria epävarmuuksia. Odotettavissa on tiukka kansainvälinen kilpailu eri teknologioiden ja tuotantopaikkavaihtoehtojen välillä.

Suomessa on varmistettava edellytykset teollisuuden vetytalouteen suuntautuville investoinneille ja luotava selkeät tavoitteet ja toimenpidesuunnitelma vetyratkaisujen käyttöönotolle eri sektoreilla. Vetytalouden kehittymistä voidaan edistää mm. tuulivoiman lisärakentamisen luvitusta helpottamalla, vetyosaamista lisäämällä ja TKI-toimintaa tukemalla niin teknologioiden, palvelujen kuin yhteistyön osalta. Sähkönsiirto- ja vedynsiirtoinfrastruktuureja tulisi kehittää kokonaisuutena tulevaisuuden tarpeisiin varautuen, mutta halliten kustannuksia ja riskejä. Vetyratkaisujen edistämistoimissa tulee ottaa huomioon vaihtoehtoiset teknologiat ja ratkaisut. Samoin on huolehdittava tasapuolisten kilpailuedellytysten toteutumisesta niin kotimaassa kuin kansainvälisesti.

Klausuuli	Tämä julkaisu on toteutettu osana valtioneuvoston selvitys- ja tutkimussuunnitelman toimeenpanoa. (tietokayttoon.fi) Julkaisun sisällöstä vastaavat tiedon tuottajat, eikä tekstisisältö välttämättä edusta valtioneuvoston näkemystä.

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Vätgasekonomin i Finland – möjligheter och begränsningar

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Referat

Vätgasekonomin syftar till att minska koldioxidutsläppen inom sektorer där andra metoder är särskilt utmanande. Dessa omfattar industri, luftfart, sjöfart och tunga vägtransporter.

EU förbereder gemensamma lagändringar för att möjliggöra användningen av vätgaslösningar. Samtidigt har länder i och utanför Europa utvecklat nationella väte-strategier. Tusentals projekt för produktion och slutanvändning av vätgas är under utveckling enbart i Europa.

För Finland är vätgasekonomin en möjlighet, eftersom Finland har en elproduktionskapacitet med relativt låga koldioxidutsläpp och ett starkt elnät. Dessutom har Finland en enorm potential för ytterligare vindkraftskapacitet, som skulle kunna användas för att producera vätgas och elbränslen för både inhemsk efterfrågan och export. Å andra sidan finns det stora osäkerheter om den framtida tillgången och efterfrågan på den internationella marknaden. Man förväntar sig en hård internationell konkurrens mellan olika teknoligier och produktionsanläggningar.

Finland måste skapa förutsättningar för industriella investeringar i vätgasekonomin och fastställa tydliga mål och en färdplan för införandet av vätgaslösningar inom olika sektorer. Utvecklingen av vätgasekonomin kan främjas t.ex. genom att underlätta tillståndsgivningen för ytterligare vindkraftsbyggnation, öka kunskap om vätgaslösningar och stödja FoI-verksamhet inom teknik, tjänster och samarbete. Infrastrukturen för överföring av el och vätgas bör utvecklas som en helhet, där man förutser framtida behov samtidigt som man hanterar kostnader och risker. Åtgärder för att främja vätgaslösningar bör ta hänsyn till alternativa tekniker och lösningar. Samtidigt måste man se till att det råder rättvisa konkurrensvillkor både nationellt och internationellt.

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Contents

Acronyms

CCS	Carbon Capture and Sequestration
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Sequestration
CEM	Clean Energy Ministerial
CfD	Contract-for-Difference
CH4	Methane
CO2/CO2e	Carbon dioxide/Carbon Dioxide equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
EC	European Commission
eFT	e-Fuels Technology
ET	Finnish Energy Industries Association
ETA	European economic zone (EU27, the UK, Norway, Iceland and Liechtenstein)
ETS	European Emissions Trading System
EU	European Union, Euroopan Unioni
GDP	Gross Domestic Product
ICAO	International Civil Aviation Organization
IMO	International Maritime Organization
IPCEI	Important Project of Common European Interest
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelized Cost Of Electricity
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
LPG	Liquefied Petroleum Gas
LUT	Lappeenranta–Lahti University of Technology
LVM	Finnish Ministry of Transport and Communications
MeOH	Methanol

MJ	Megajoule
MW/GW	Megawatt/Gigawatt
N2	Nitrogen
NECP	National Energy and Climate Plan
NH3	Ammonia
OECD	Organisation for Economic Co-operation and Development
PEM	Proton Exchange Membrane
POX	Partial Oxidation
PPA	Power Purchase Agreement
PtX/P2X	Power-to-X, production of synthetic fuels using electrolysis
RDI	Research, Development and Innovation
RED	Renewable Energy Directive
RFNBO	Renewable Fuels of Non-Biological Origin
SAF	Sustainable Aviation Fuel
SMR	Steam Methane Reformation
SNG	Synthetic Natural Gas
SOEC	Solid Oxide Electrolyser Cell
STTK	A Finnish employee organisation representing 12 trade unions
STUK	Finnish Radiation and Nuclear Safety Authority
T&D	Transmission and Distribution
TEM	Finnish Ministry of Financial Affairs and Employment
TUKES	Finnish Safety and Chemicals Agency
TWh	Terawatt-hour
UN	United Nations
VN	Finnish Prime Minister’s Office
VTT	VTT Technical Research Centre of Finland
WAM	With Additional Measures

Definitions

Carbon-Contract-for-Difference A funding mechanism that offer governments the opportunity to guarantee investors a fixed price that rewards CO2 emission reductions above the current price levels in the EU Emissions Trading System (ETS) in the contract period.

Drop-in fuel Liquid bio-based or synthetic hydrocarbons that are functionally equivalent petroleum fuels and are fully compatible with existing petroleum infrastructure

Fit-for-55 A set of proposals by the European Commission to revise and update EU legislation and to put in place new initiatives ensuring that EU policies are in line with the goal of cutting emissions by at least 55% by 2030

Fossil gas Natural gas or other gas prepared from fossil energy sources through a process where the resulting carbon dioxide is not captured and sequestrated

Fossil hydrogen Hydrogen prepared using fossil energy sources

Grey hydrogen Hydrogen prepared using fossil energy sources in a process where the resulting carbon dioxide is not captured and sequestrated

Power-to-Gas-to-Power Production of gas with electricity, storing of the produced gas, and the subsequent conversion of the stored gas back into electricity

Power-to-X Production of hydrogen or gaseous or liquid synthetic feedstocks or fuels using electrolysis (e.g., hydrogen, methane, other hydro carbon, methanol)

Clean hydrogen Hydrogen prepared using renewable or other emissions neutral (nuclear power) energy sources

Hydrogen economy An economic system where hydrogen produced with clean or low-carbon energy sources is used as an energy carrier or feedstock instead of fossil energy sources and feedstocks

Green hydrogen Hydrogen produced with renewable energy sources

Low-carbon hydrogen Hydrogen produced with fossil energy sources in a process where the resulting carbon dioxide is captured and sequestrated, or hydrogen produced with electrolysis using low-carbon electricity

FOR THE READER

Hopes for hydrogen economy are higher and more tangible than ever before. As soon as the EU-level legislation required by production and demand of hydrogen is complete, hundreds of publicly subsidised industrial-scale and demonstration-scale hydrogen projects will start in Europe and its near regions, with the applications ranging from industry and traffic to energy generation.

At present, we need to form a clear vision on the opportunities, limitations and challenges hydrogen economy brings to Finland. This report was launched in spring 2021 to meet the need for such information.

When the report was being drafted, the European Commission published its proposals for the Fit-for-55 and Hydrogen and Gas Market Decarbonisation legislative packages, which lay down the legislation needed for hydrogen as part of the EU's sustainable development programme. By the end of 2021, the EU Commission had been presented more than 1,500 hydrogen projects being developed in Europe. Meanwhile, Finland has continued to update its climate and energy strategy, established a domestic Hydrogen Cluster, continued research, launched new projects and opened public funding applications for hydrogen-related investments. Since these factors are in a constant state of change, this report had to be updated constantly in close cooperation and dialogue with the project group, steering group and the stakeholders.

The project group wishes to extend a warm thank you for all experts and organisations who participated in the interviews, surveys, workshops and seminars. We also wish to thank the steering group for its support, guidance and feedback during the project.
Concrete actions towards hydrogen economy proceed at all levels – this report describes a social framework and general guidelines for these efforts.

Leena Sivill, Project Manager

February 2022

1 Preface

> ***"The past is but the beginning of a beginning."***
>
> H.G. Wells

In the 2020s, hydrogen has become an essential part of the discussion on future energy and climate solutions. Internationally, carbon-neutrally produced hydrogen is seen as having a lot of potential especially in industry and traffic. Many countries have drawn up a national hydrogen strategy or roadmap or are currently working on one. The European Commission published its hydrogen strategy in June 2020 and is now promoting legislative proposals associated with the strategy.

Finland takes hydrogen into account in the preparation of Finland's national climate and energy strategy. This report, titled 'Hydrogen economy – opportunities and limitations', serves the preparation of the national climate and energy strategy and on a more general level, Finland's energy policy and energy technology policy.

This report investigated the following questions:

- What is the situation of hydrogen technology and hydrogen economy in the EU Member States and globally at present, in 2025, in 2030 and further on?
- What scenarios could be presented for the Finnish hydrogen economy (up to 2050)?
- What kind of cost forecasts and estimates are presented on hydrogen technology and how realistic are they?
- What is the potential scope of hydrogen business and reduction of emissions in Finland and Europe in 2030 or further on?
- What political measures on hydrogen economy have been presented in Europe or in the rest of the world?
- What are the strengths of Finnish research and industry, and what should they concentrate on in hydrogen economy?
- What limitations and problems exist in hydrogen and hydrogen economy?

The start of the report describes the role of hydrogen from the perspective of international climate and energy scenarios (Chapter 2). The report then describes the European Commission's goals on hydrogen and the situation of the EU legislation and subsidy programmes funded by the EU (Chapter 3). Chapter 4 looks at individual countries' hydrogen strategies and projects, although this information might become obsolete relatively quickly. After the international overview, the report looks at Finland's readiness to adopt hydrogen economy (Chapter 5). Chapter 6 reviews value chains and technologies of hydrogen economy from a Finnish perspective and presents some conclusions. Chapter 7 presents five scenarios, created in collaboration with stakeholders, on the production, end use and export potential of hydrogen in Finland. Some specific underlying factors are discussed in more detail in Chapter 8. Finally, Chapter 9 presents the conclusions of the report.

2 Role of hydrogen in climate and energy scenarios

[Chapter available in the original report in Finnish]

3 Hydrogen EU climate and energy policy objectives

[Chapter available in the original report in Finnish]

4 Hydrogen strategies, roadmaps and projects in different countries

[Chapter available in the original report in Finnish]

5 Finland's starting points in hydrogen economy

Summary

Hydrogen economy brings **opportunities** for Finland, both in terms of emissions reductions and business. Hydrogen might play a significant role in the reduction of greenhouse gas emissions in the Finnish industry, therefore, a **precondition** for hydrogen economy is a demand for hydrogen and a supply of hydrogen that is competitive compared to other solutions.

Finland's **strengths** include highly advanced decarbonisation of electricity generation, robust transmission networks and a significant potential for constructing low-carbon electricity production. Finland is also home to a significant number of demonstration-level and pilot projects and research projects that promote the generation of hydrogen innovations, expertise and ecosystems in Finland.

However, Finland also faces many **challenges and limitations** in hydrogen economy. Finland is not close to the potential primary markets. A comprehensive infrastructure for zero-emission hydrogen will emerge in areas that have lot of demand and industrial activity within a small geographical region, i.e. in the industrial areas of Central Europe or as a link between them. It is also unlikely that Finland has the resources to make as large public investments in hydrogen economy in absolute terms as many other European countries will make in the next few years. On the other hand, many of the challenges faced by Finland when developing its hydrogen economy are not unique – many other countries also need an enabling and supportive legislation and investments in infrastructure.

Finland is not geographically close to sources of natural gas or opportunities for geological storage which would support the production of Finnish blue hydrogen. Furthermore, the Finnish natural gas network covers only the southernmost parts of the country. Therefore, Finland is not an internationally attractive country for producing blue hydrogen even if blue hydrogen were more cost-competitive than other types of hydrogen.

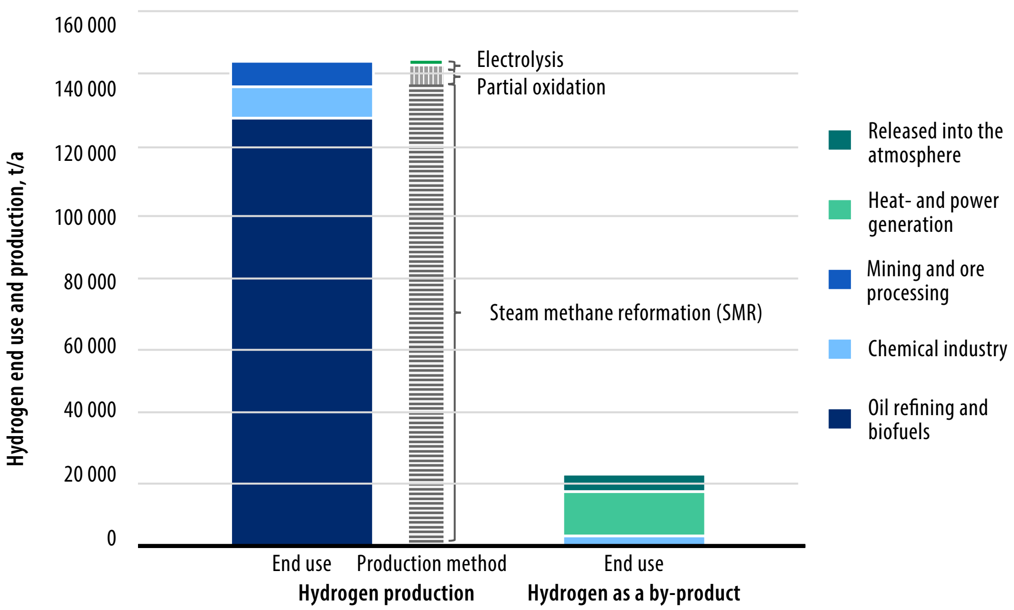
Hydrogen economy involves many **risks**. The solutions of hydrogen economy might not be a cost-effective method of achieving reductions in emissions, because the transfer to hydrogen depends strongly on political guidance and the associated requirements and applications vary considerably between industries. Relying on a transfer to a large-scale hydrogen economy might also delay the abandonment of fossil fuels (Ueckerdt *et al.*, 2021). Hydrogen economy also requires infrastructure investments that consume a lot of land area and feedstocks which might have a significant and widespread impact on nature and biodiversity (Pörtner *et al.*, 2021) .

The following sections describe the current state of hydrogen production, end-use and hydrogen projects in more detail and present the views of the Finnish stakeholders of hydrogen economy in spring 2021.

5.1 Current state of hydrogen production and end-use in Finland

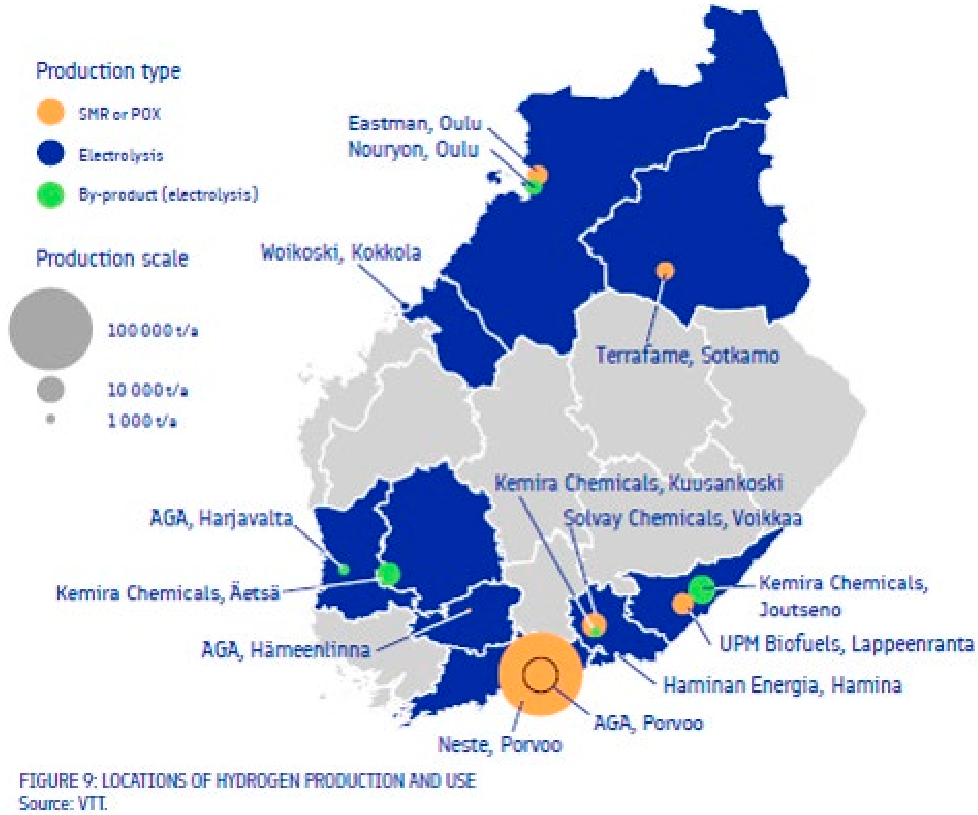
In 2020, Finland produced an estimated 145,000 tonnes of hydrogen (5 TWh) for industrial needs, which accounts for approximately 1.5 per cent of all hydrogen produced in Europe. In addition, hydrogen is also generated as a by-product in industrial processes. Twenty-three thousand tonnes (765 GWh) of such hydrogen was generated 2020, but statistics are incomplete in this respect. The most significant applications of hydrogen in Finnish industry are oil refinement and production of biofuels. Small quantities of hydrogen are also used in chemical industry (such as the manufacture of hydrogen peroxide) and in mining industry (Laurikko *et al.*, 2020).

Figure 1. Production and consumption of hydrogen in Finland (Laurikko et al., 2020)



Hydrogen production in Finland takes place mostly in chemical industry plants (see Figure 1 above). Almost two-thirds of hydrogen produced in 2020 was produced in the Neste's Porvoo refinery complex. Other significant producers of hydrogen in Finland are AGA that has a hydrogen production unit in the Porvoo refinery complex, Terrafame and UPM. Currently the most common method for producing hydrogen is reforming natural gas. The process separates natural gas into carbon and hydrogen and then oxidises the carbon into carbon dioxide. The end result is carbon dioxide and hydrogen. On the other hand, Woikoski Oy's Kokkola plant uses by electrolysis to manufacture hydrogen for industrial applications.

Figure 2. Consumption and production of hydrogen in Finland (Laurikko et al., 2020)



Hydrogen gets produced as a by-product in Finnish industry especially in the production of chlorates (electrolysis of NaCl). This by-product hydrogen is often used as a fuel in industrial boilers, manufacture of process gas or generation of heat for district heating purposes (Kauranen *et al.*, 2013). This hydrogen can also be sold for other industrial purposes. In such a case, the hydrogen is transported in steel cylinders, cylinder bundles or containers. By-product hydrogen might require purification, which increases its cost.

Except for the Woikoski plant in Kokkola, clean hydrogen manufactured by electrolysis is not produced on an industrial scale in Finland (see Figure 2). Outside industry, for example in transport, the use of hydrogen is very limited, due to insufficient infrastructure and the challenges involved in the commercialisation of clean hydrogen.

5.1.1 Hydrogen projects in Finland

Dozens of new investment projects associated with clean hydrogen and low-carbon hydrogen have been launched in Finland. Most of the projects are in a preliminary survey or preliminary planning phase which forms the basis for arranging funding and making investment decisions. The programmes mostly involve the production of clean hydrogen and using wind power as the source of energy.

Figure 3 shows examples of public hydrogen projects in Finland. The industrial-scale research project at the SSAB steel mill seeks to manufacture fossil-free steel by means of hydrogen reduction and clean electricity. In addition, southern Finland is home for several demonstration hydrogen projects on the production of synthetic natural gas (Q Power and Wärtsilä), production of clean hydrogen and utilisation in ferry transport (Flexens), synthetic methanol (Joutseno business consortium) and the production of clean and low-carbon hydrogen for the manufacture of oil and liquid biofuels (Neste). Some projects have already been granted public investment aid. The European Commission will publish a notification on its decisions on national projects that will be granted public funding through the hydrogen IPCEI process, perhaps in early 2022. The second hydrogen IPCEI financing round was launched in autumn 2021.

Figure 3. Examples of Finnish hydrogen projects in 2021

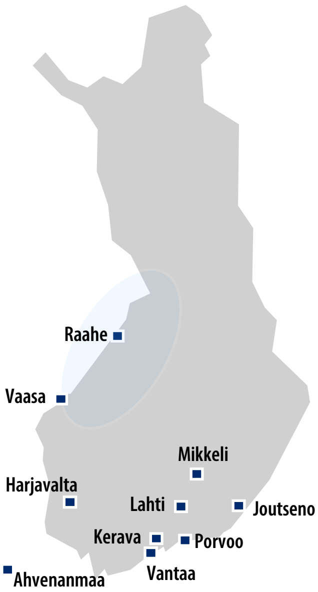
PtGtP
Renewable hydrogen prod.**
Location: Vaasa
Stage: Demonstration
Companies: EPV Energia, Vaasan Sähkö, Wärtsilä, City of Vaasa

Prizztech
Synthetic methane production
Location: Meri-Pori
Stage: Suitability study (20MW)
Companies: SSAB, LKAB, Vattenfall

P2X Solutions
Green hydrogen production**
Location: Harjavalta
Stage: Design 20MW
Companies: P2X Solutions

Green H2UB Green NorthH2 Energy
Hydrogen fuel production
Location: Naantali
Stage: Letter of intent
Companies: Turun Seudun Energiantuotanto; Green NorthH2 Energy (Elomaticin tytäryhtiö), Flexens

Ren-Gas
Renewable methane and hydrogen production
Location: Lahti
Stage: Feasibility study
Companies: Lahti Energia



Wärtsilä
Synthetic methane**
Location: Vantaa
Stage: Demonstration
Companies: Vantaan Energia, Wärtsilä

Flexens
Production and use of hydrogen in marine industry
Location: Åland
Stage: Pilot
Companies: Flexens

Both2nia
Hydrogen Valley
Location: Gulf of Bothnia FI-SE
Companies: Konsortio

Ren-Gas
Renewable methane and green hydrogen production
Location: Mikkeli
Stage: Feasibility study
Companies: Etelä-Savon Energia

Consortium
Synthetic methanol
Location: Joutseno
Stage: Demonstration
Companies: Finnsementti, Kemira, Neste, St1, Wärtsilä, Finnair, Shell

Soletair
Synthetic fuels production + CO2 recovery
Location: Joutseno
Stage: Demonstration
Companies: Soletair, LUT-yliopisto

Q Power
Synthetic gas production
Location: Kerava
Stage: Demonstration
Companies: Q Power, Keravan Energia

Neste
Clean and low-carbon hydrogen*
Location: Porvoo
Stage: Demonstration

* Subsidy EUR 88m from EU Innovation Fund 2021 ** Energy investment support granted in 2021

5.2 Stakeholders' views on the starting points of hydrogen economy

Key stakeholders were interviewed on the starting points and development needs of Finnish hydrogen economy before the scenario phase of the report was started. A total of 21 interviews were held with a total of 29 stakeholder representatives. The range of stakeholders was selected to cover all phases of the hydrogen value chain. Except for Finnish energy transmission companies (Fingrid Oy, Gasgrid Finland Oy), the views of companies were surveyed through industry associations, including employee associations. In addition, the project heard research institutions, independent experts and environmental organisations. For a list of the organisations and persons interviewed, please see Appendix 1.

The interviews were semi-structured and sought to elicit opinions on especially the following topics: a) opportunities and limitations on the consumption of hydrogen in Finland; b) opportunities for hydrogen export and hydrogen ecosystem in Finland; and c) research topics that are important for Finland in terms of hydrogen economy. Any other views expressed by the interviewees were also recorded.

After the round of interviews was completed, a joint discussion event was held in which the stakeholders could supplement their viewpoints and comment on the conclusions drawn from the interviews. The participants also asked supplementary questions.

5.2.1 Results of the stakeholder interviews

The following were considered Finland's competitiveness factors: **structure of the industry and the industry's commitment to climate actions, the energy system and robust electricity transmission infrastructure and other special characteristics of the Finnish society**. The stakeholders felt that the industry is committed to the government's carbon neutrality goal, and Finland also has clear industrial clusters that are familiar with the use of hydrogen.

A significant potential for wind power and utilising the latest onshore and offshore technology was seen as one of Finland's strengths. This was considered to increase the supply of renewable and competitive electricity for the industry and other sectors of the society. Other perceived strengths were **Finland's geographical location, availability of fresh water, bio-based sources of carbon dioxide, stable social conditions, good governance and the small number of operators, which makes networking easy and promotes string cooperation among industries**. The sector coupling opportunities in hydrogen production were considered significant, partly thanks to Finland's extensive district heating network.

Metal refining, chemical process industry, manufacturing industry, transport and the energy systems were seen as sectors in which demand for hydrogen was likely to increase in the future, although there were differences in opinions. The stakeholders were also asked which components in the hydrogen value chain they considered the most promising. The responses highlighted especially **solutions that connect the different parts of the value chain**, i.e. production optimisation solutions based on IT and AI, turnkey solutions and project management expertise. Other components considered promising were **hydrogen refining and energy production**.

The following sections present the stakeholders' views, grouped on the basis of how frequently a theme came up in the interviews and the level of consensus that prevailed on the opinions. This results in a four square: Consensus, Long-term Approach, Watershed or Under the surface (see Figure 4 below).

Figure 4. A four square of stakeholders' views

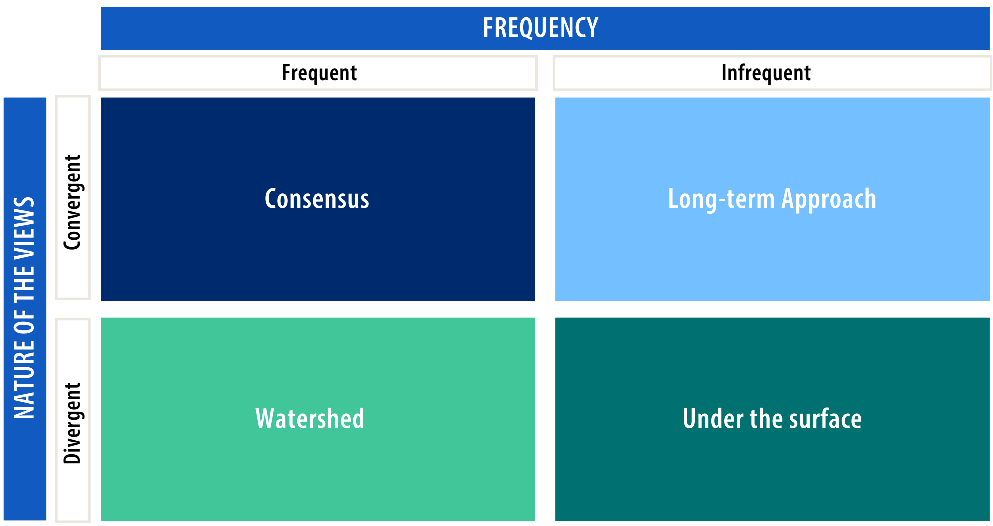


Figure 5 presents a four square on the views expressed in the stakeholder interviews. **Consensus** (top left quadrant) prevailed on the increasing role of hydrogen as part of the energy system of the future. Industry in particular was seen as a potential end user sector. Among the identified competitiveness factors was Finland's potential for constructing wind power which enables the production of competitive renewable electricity.

Figure 5. Stakeholders' views in a four square

NATURE OF THE VIEWS	FREQUENCY: Frequently	FREQUENCY: Infrequent
Convergent	• Hydrogen will play a significant role in the energy system of the future, but to what extent, is still unclear • Finland's absolute competitive advantage is competitive electricity generated by wind power • Industry is a good application for hydrogen	• Rather a systemic change, not a technological change • Electricity, hydrogen and natural gas must be as integrated system as possible • Security of supply factors should be considered more widely in the hydrogen debate • Hydrogen competence development is long-term work • Hydrogen safety issues should be a priority
Divergent	• Finland should export hydrogen vs. products and services of the hydrogen ecosystem vs. electricity • Finland has the opportunity to join the competition as part of the export of the hydrogen ecosystem • Finland's competitive position as part of the hydrogen economy ecosystem • Emphasis between hydrogen exports and imports and targeting investments to the needs of Finland vs. exports • "Colours" and "cleanliness" of hydrogen • The future of hydrogen fuels	• Finland should strive for a position as an exporter of hydrogen production technology • Funding allocation, risk sharing and the role of the public funder • Purpose and nature of regulation and taxation • The use of hydrogen should be minimized, the increase in its use is not an absolute value

Watershed (bottom left quadrant) presents themes that occurred frequently but elicited different opinions in the stakeholder interviews. Firstly, the stakeholders' opinions differed on Finland's potential export products associated with hydrogen economy. The views also differed on Finland's potential to attract hydrogen economy investments and catch up the lead of the Central European countries whose governments support hydrogen economy projects much more than Finland does. On the other hand, the stakeholders also emphasised that Finland has a large spectrum of strengths in hydrogen economy.

A wide range of dissenting opinions were voiced as well. Among the challenges faced by hydrogen economy in Finland were the currently limited co-operation between the industry and academic research, challenges associated with financing, a great need to develop the main grid and the limited possibilities for storing hydrogen. The production potential of synthetic fuels polarised the opinions. The stakeholders' views also differed on whether hydrogen should be valuated differently depending on its method of production. Some stakeholders would favour clean hydrogen only and emphasise the critical role played by the source of renewable electricity, whereas others would favour the importance of zero emissions irrespective of the origin of the electricity.

Long-term Approach (top right quadrant) summarises views that were expressed only rarely in the stakeholder interviews but which are nevertheless shared by the stakeholders. The stakeholders agree on the comprehensive nature of the hydrogen economy revolution and the importance on integrating the components of the energy system. The stakeholders also agreed on the importance of the security of supply, expertise, safety and security. The limitations of hydrogen storage were seen as an important research topic.

Under the surface (bottom right quadrant) presents themes that were expressed only rarely and in which the stakeholders' opinions differ. Opinions on large-scale issues, such as the funding of hydrogen investments, the role of public administration, regulation and taxation differed markedly among the stakeholder groups.

The stakeholder interviewees were also asked to identify research topics or themes that are important in terms of Finnish hydrogen economy. Numerous suggestions were received. Figure 6 presents the research topics proposed by the stakeholders. They are grouped in six categories: technology, markets, applications, regulation, infrastructure and other.

Figure 6. Categories of research topics and themes proposed by the interviewed stakeholders.

Hydrogen technology
- Can electrolysers be made in mass production?
- Alternative hydrogen production technologies, e.g., photocatalytic processes
- IT & artificial intelligence
- Basic research on hydrogen transfer

Infrastructure
- How to make electricity transmission affordable?
- How would hydrogen be stored, taking into account the Finnish climate and geology?
- Linking the gas and electricity systems
- How to maximise the flexibility of hydrogen production?
- Involving people in wind power construction decisions

Applications
- How can hydrogen be used in practice in metalworking processes?
- Basic research on the production and use of hydrogen, e.g., electrochemistry and various catalytic processes

Market
- How to support the emergence of a domestic hydrogen ecosystem?
- If all fossil fuels are replaced, how will infrastructure and supply-demand change?
- How is hydrogen production taxed?
- Utilization of the Mankala principle in the hydrogen economy?

Regulation
- How is regulation evolving in different market areas (Asia, Africa, USA)?
- In which direction should controls and regulation be taken?
- What type of policies are found effective around the world?
- Standardisation

Other
- Safety in the use of hydrogen, safety training, use of hydrogen outside industry, use and inspection of technology (TUKES)
- Basic knowledge base / scenario review
- Opportunities in food and fertilizer production
- Perceiving system change

Figure 7 below is an example created by AFRY on how the themes could be approached as research packages. This is simply a way to introduce a structure to the research topics, not to express an opinion on the actual implementation of the research projects.

Figure 7. AFRY's proposal based on the individual research topics presented by the stakeholders. The proposal consists of hypothetical research packages that combine several suggestions made by the stakeholders.

RESEARCH PROJECT 1:
World's safest hydrogen

- Safety in the use of hydrogen, safety training, use of hydrogen outside industry, use and inspection of technology (TUKES)
- Presentation of effective policy measures, examples from around the world, e.g., Ludwigshafen
- How would hydrogen be stored, taking into account climate and geology?
- Linking the gas- and electricity systems
- Standardization
- How to adjust the process?
- IT & artificial intelligence

RESEARCH PROJECT 2:
Optimally integrated energy system

- Circular economy
- Linking the gas- and electricity systems
- Renewable energy, control power
- Hydrogen transfer and storage
- IT & artificial intelligence

RESEARCH PROJECT 3:
The world's fastest emerging hydrogen ecosystem

- How to support and accelerate the emergence of the domestic hydrogen ecosystem?
- How is hydrogen production taxed?
- Utilization of the Mankala principle in the hydrogen economy
- IT & artificial intelligence
- Involving people in wind power construction decisions
- Hydrogen transfer and storage

World's safest hydrogen (1) could be a project package that would research the safety of hydrogen production, storage and consumption with a special emphasis on Finnish conditions and special characteristics. Examples of best practices could be sought both domestically and abroad.

Optimally integrated electricity system (2) would investigate how the components of the energy system could be connected to each other, including research topics on circular economy and ecological sustainability.

The world's fastest emerging hydrogen ecosystem (3) would be the most commercial of the project packages, investigating the development of the Finnish ecosystem from the perspective of the markets. The project could also evaluate tangible mechanisms for providing public support for the development of hydrogen economy. The project could also investigate the preconditions for social sustainability and acceptability.

5.3 Background information on how Finland prepares for hydrogen economy

Unlike other European countries, Finland does not have a separate hydrogen strategy. The role of hydrogen is acknowledged in the national energy and climate strategy that is currently being prepared, in the final report of the sector integration workgroup (Ministry of Economic Affairs and Employment, 2021), roadmap for fossil-free transport (Ministry of Transport and Communications, 2021) and Finland's Sustainable Growth Programme (Government of Finland, 2021b).

The Roadmap for fossil-free transport published by the Ministry of Transport and Communications in June 2021 acknowledges the significant future potential of hydrogen especially in heavy transport. On the other hand, the roadmap states that the most sensible option might be to use hydrogen in transport applications that do not require the construction of a nationwide hydrogen distribution infrastructure. An example of this are seaports. In the long term, the role of e-fuels and straight hydrogen in reducing emissions is seen highly important in modes of transport in which do not seem electrifiable at the moment. The Roadmap estimates that hydrogen will directly or indirectly replace 4 TWh of fossil energy by 2045.

As for transport, Finland has had distribution obligations in place for transport fuels since 2007 with the purpose of promoting biofuels that replace gasoline and diesel fuel in transport. (Act on the Promotion of Biofuels in Transport 446/2007). In 2021, the Act was amended to speak of the "promotion of renewable fuels" and natural gas was included as a transport fuel that will be replaced. The change creates preconditions to using hydrogen and e-fuels refined from it as renewable transport fuels.

The national hydrogen roadmap prepared by VTT Technical Research Centre of Finland and Business Finland assesses that the use of low-carbon hydrogen might increase especially in chemical industry's refining process, if the use of vegetable-based oils increases in the manufacture of renewable diesel (Laurikko *et al.*, 2020). The most promising development presented in the roadmap the increase of P2X production in areas in which surplus hydrogen and point sources of bio-based CO2 are available. An example of such areas is Joutseno, which could produce methanol from hydrogen generated as a side stream of the Kemira plant and by means of an electrolyser. The roadmap also assesses Finland's strengths, weaknesses, opportunities and threats considering the production of low-carbon hydrogen and an increase in its consumption (see Table 1).

Table 1. Finland's strengths, weaknesses, opportunities and threats in Business Finland's hydrogen roadmap (Laurikko et al., 2020)

STRENGTHS	WEAKNESSES
• wind power resources • robust transmission connections	• higher price of electricity compared to Sweden and Norway • no hydrogen expertise outside the industry • no experience on the use of hydrogen in transport
OPPORTUNITIES	**THREATS**
• existing fuel production • decarbonisation of currently consumed hydrogen • production of fossil-free steel • cutting logistics costs in the industry	• changes to / interpretations of RED II: that might have a negative impact on Finland • low price of fossil fuels and CO2 • delays in the upscaling of electrolyser production • high price of hydrogen technology

Finland's strengths identified in the roadmap are its potential for onshore and offshore wind power, robust electricity transmission network and a lot of experience on using hydrogen in the industry. Opportunities include fossil-free steel production, refining hydrogen into transport fuels and replacing currently used hydrogen by low-carbon hydrogen in the industry. On the other hand, factors identified as Finland's weaknesses include a higher price of electricity compared to the neighbouring countries, lack of experience in using hydrogen outside the industry and the lack of salt caves. The key threats identified by the roadmap are the poorly developing cost competitiveness of hydrogen technology and challenges in the upscaling of production which might form a bottleneck in the actualisation of investments.

The sector-specific low-carbon roadmaps published in 2020 identify hydrogen as a potential means of emissions reduction in several different roles, especially in metal refining and chemical industry (TEM, 2020b). **The low-carbon roadmap for chemical industry** states that low-emission production of hydrogen might reduce the current emissions originating from the production of fossil hydrogen (Vasara *et al.*, 2020a). There are several alternatives for producing hydrogen. Although the solutions vary strongly from case to case, the cost of emissions reductions achieved by Power-to-X technologies is estimated to be significantly higher than the costs of many other options. The cost comparison was made in the cost level of 2019. In the chemical industry scenarios (scope 1 and 2 emissions), the production of hydrogen by electrolysis is estimated to consume approximately 10 TWh of electricity per year in 2050. The production of hydrogen by electrolysis is estimated to reach significant levels in the early or late 2030s (scenarios 3 and 2, respectively). **The low-carbon roadmap for the technology industry** lists hydrogen as an alternative reducing agent in the production of fossil-free steel (Soimakallio, 2020). The transition to using hydrogen in steelmaking is expected to take place stepwise between 2025 and 2040. **The low-carbon roadmap for transport and logistics** estimates that hydrogen is one of the potential power sources especially in heavy transport (Vasara *et al.*, 2020b). However, widespread commercialisation of technologies that use hydrogen or synthetic fuels in passenger of freight traffic is not expected to take place before the 2030s. The roadmap assesses that the transition might even be quicker in heavy transport, but it requires investments in hydrogen infrastructure. Please note that the roadmap for transport and logistics did not investigate international maritime or air transport. **The roadmap for forest industry** estimates that the carbon capture and utilisation (CCU) technologies might play a role in carbon capture in the 2040s (Vasara *et al.*, 2020c). **The energy industry roadmap** is of the opinion that hydrogen will be one of the increasingly clean gases that are estimated to make strong headways especially in the 2030s in Europe. An increase in the production of hydrogen would result in a significant demand for electricity (Finnish Energy, 2020).

6 Value chains in hydrogen economy

[Chapter available in the original report in Finnish]

7 Hydrogen economy scenarios in Finland

Summary

The five hydrogen scenarios created for Finland describe alternative futures for Finnish industry, Finnish and international transport and heavy transport and the export of hydrogen and e-fuels.

In the scenarios, the production volumes of clean hydrogen vary between 3.7–7.9 TWh in 2030 and reach up to 6.4–132.9 TWh by 2050. The large differences are caused by assumptions made on the export of hydrogen and e-fuels: the minimum scenarios concentrate on domestic demand while the maximum scenarios also consider the export of hydrogen and/or e-fuels.

In the maximum scenarios, the required electrolyser capacity would reach up to 27 GW by 2050 and the required extra capacity of wind power to 53 GW (cf. 3.3 GW in 2021) with the required cumulative investments at slightly less than EUR 90 billion. Reaching the maximum scenarios would require that Finland remain extremely competitive in the international market and at the same time the international demand corresponds to or exceeds the energy scenarios presented by the European Commission.

In the minimum scenarios, the required electrolyser capacity would be between 0.5–1.3 GW by 2030 and would stay at that level in the smallest of the minimum scenarios. In the other minimum scenario, the capacity would rise to 2.6 GW by 2050. The necessary increase in wind power would be 1.1–5.2 GW and the investment costs would remain below EUR 6.2 billion.

From the perspective of Finland's carbon neutrality goal and national economy, **the most important end users of clean or low-carbon hydrogen are steel industry and oil and biofuel refineries**. If the steel industry implements carbon neutrality by other means than hydrogen reduction of iron ore, the domestic demand for hydrogen will be approximately 6.3 TWh less per year than with hydrogen reduction. Compared to the steel industry and oil and biofuel refineries, the potential demand for hydrogen and e-fuels in other Finnish industries and transport is small.

Finland's export opportunities are limited first and foremost by the trends in international demand and competition. Therefore, the production potential described in the maximum scenarios is difficult to reach.

The purpose of the hydrogen economy scenarios presented in this report is to **illustrate the opportunities and limitations faced by Finland in hydrogen economy**. The five scenarios describe alternative futures in which the domestic demand and export opportunities of hydrogen and e-fuels develop differently depending on the growth-limiting factors at play.

The most important growth-limiting factors in the scenarios are the availability of domestic onshore wind power, trends in the domestic demand for hydrogen and e-fuels, export of hydrogen made possible by a potential international hydrogen transmission line and the trends in the international demand of e-fuels. Domestic demand consists of the industry, Finland's domestic and international water and air transport and heavy transport. The use of hydrogen for energy production has not been taken into account since it is expected to remain marginal in Finnish conditions compared to the other end uses.

The scenarios were created in autumn 2021 in co-operation with the steering group and stakeholders (see the participants in Appendix 2). The initial values used in the scenarios are partly based on public sources and partly on assumptions on trends that were made in co-operation with the stakeholders.

The following sections present the primary assumptions and main results of the scenarios. Next, each scenario is discussed in more detail, including the key background factors that should be taken into account when assessing the development of hydrogen economy in Finland in the long term.

7.1 Assumptions and results of the scenarios

The main assumptions of the hydrogen economy scenarios are presented in Table 2 below. All scenarios assume that Finland will reach its carbon neutrality goal by 2035. The most significant differences between the scenarios arise out of the forecasted demand for hydrogen in steel industry, oil refining and export. The first two scenarios, titled 'No regret A' and 'No regret B', describe minimum domestic demand in the industry and transport. In alternative A, the steel industry implements carbon neutrality by other means than hydrogen reduction of iron ore, and the transfer to clean hydrogen in oil and biofuel refinement takes place slower than in scenario B. The 'Moderate' scenario describes a development in which the steel industry implements carbon neutrality by other means hydrogen, but the transfer to clean hydrogen corresponds to the 'No regret B' scenario. In addition, the 'Moderate' scenario involves significant exports of hydrogen and e-fuels. Due to international competition, however, the growth in the scenario is much less than what would be possible in terms of the availability of renewable energy. In scenario 'Maximum A and B', the potential for onshore wind power has been used to maximum extent for export of hydrogen and e-fuels. The 'Maximum A' scenario assumes a maximum volume of e-fuels without the export of hydrogen, while in 'Maximum B', the exports are divided between e-fuels and hydrogen gas.

Table 2. Primary assumptions in the hydrogen economy scenarios

Factor in the scenario	No regret A	No regret B	Moderate	Maximum A	Maximum B
Hydrogen and e-fuels for domestic and international transports are produced in Finland	yes	yes	yes	yes	yes
The steel industry reduces iron ore directly with hydrogen	no	yes	no	yes	yes
Oil refineries strongly emphasise clean hydrogen	no	yes	yes	yes	yes
Finland's market share of European e-fuels in 2050*	Small	Small	4%	Exports not limited by the demand in Europe	10%
Volume of exported hydrogen	no	no	Demand less than 25 TWh per year	no	The demand for hydrogen does not restrict the sizing of the hydrogen pipeline

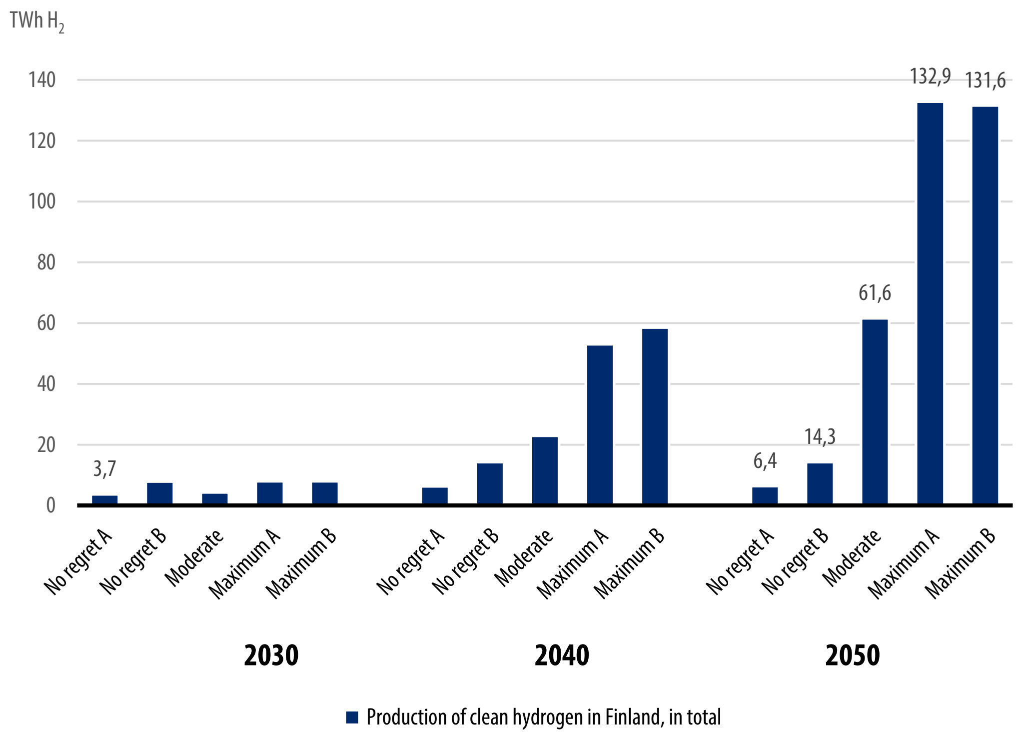
* Based on the size of the European e-fuel market in the European Commission's reference scenario 'MIX' (EC, 2020)

In the maximum scenarios 'Maximum A' and 'Maximum B', the exports are restricted only by the available onshore wind power capacity, which is expected to be 80 GW by 2050. The restriction above is based on the assumption that 100 GW of onshore wind power could be available for hydrogen production, of which approximately one fifth is not implemented due to technological or financial non-viability or other reasons. The estimate is based on AFRYs view on the wind power potential that is left when the extra wind power capacity required by the direct electrification of the society is subtracted from the theoretically available onshore wind power capacity. Although the above does not include offshore wind power, the same technological and financial requirements apply both to offshore and onshore wind power. As long as onshore wind power projects are more profitable than offshore wind power, hydrogen producers will prefer the former.

The minimum scenarios 'No regret A and B' and the maximum scenarios 'Maximum A and B' give rise to three questions: a) how much of the potential capacity for wind power could actually be constructed in Finland, b) would hydrogen and e-fuels manufactured in Finland be competitive in the international market in all situations and c) how would the demand for hydrogen and e-fuels develop as a whole in the international market. As a result of these questions, the minimum and maximum scenarios were supplemented by a fifth scenario, the 'Moderate', which illustrates a situation in which the development of hydrogen economy would initially be slower than in the maximum scenarios due to the fact that for the first ten years, the European countries will primarily concentrate on developing their domestic production and demand. In the long term, Finland's market share of exported hydrogen and e-fuels would remain lower than in the maximum scenarios due to international competition and the slow progress of the transmission infrastructure construction.

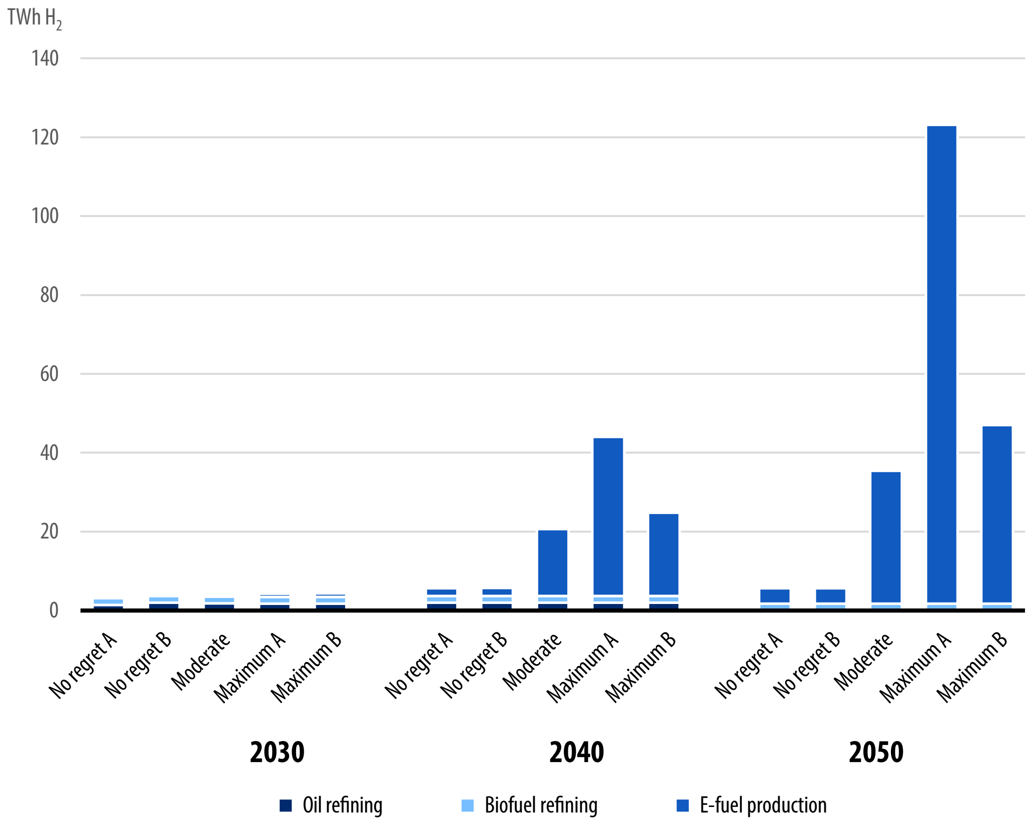
The scenarios lead to widely different hydrogen production volumes (see Figure 8 below). The 'No regret' scenarios that concentrate on domestic demand and alternative technologies represent only a fraction of the maximum scenarios in which the entire potential for wind power is realised. The figures in the 'Moderate' scenario represent less than half of the maximum scenarios, but are nevertheless many-fold compared to the minimum scenarios.

Figure 8. Development of total hydrogen production in the scenarios



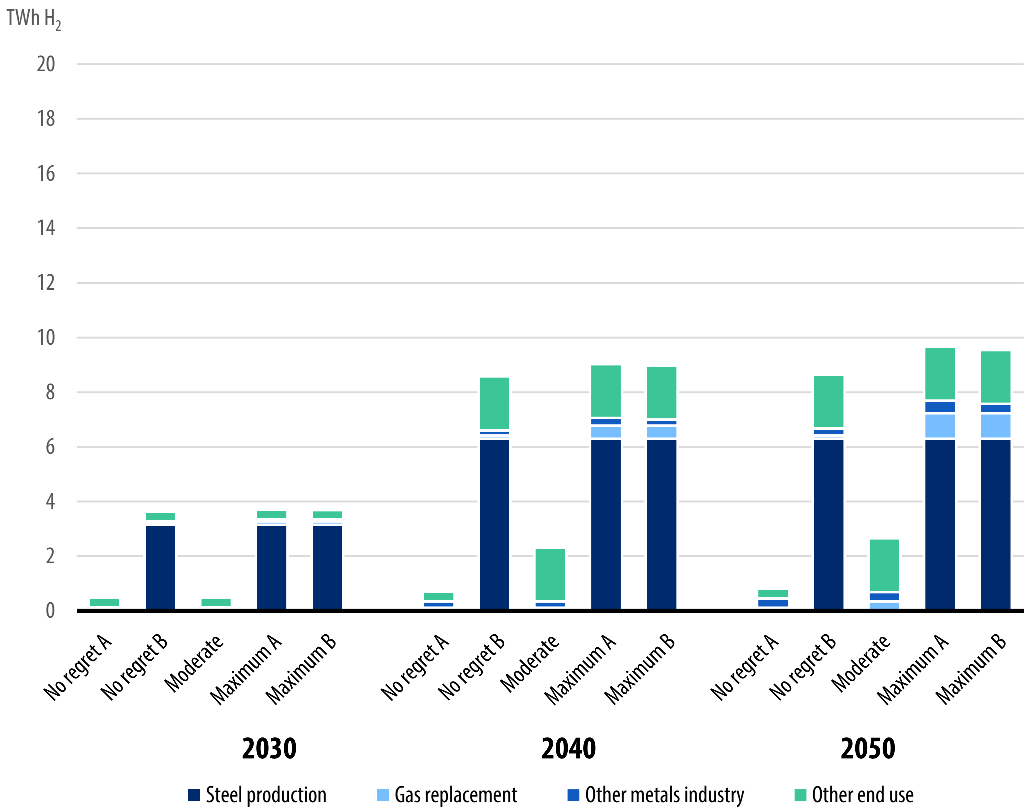
The production volume of e-fuels would be considerable in the 'Maximum A' scenario (see Figure 9 below), provided that an international market larger than Europe emerged for e-fuels, Finland were competitive in relation to its competitor countries and that no hydrogen gas were exported.

Figure 9. Quantity of hydrogen required for oil and biofuel refining and e-fuel production in each scenario



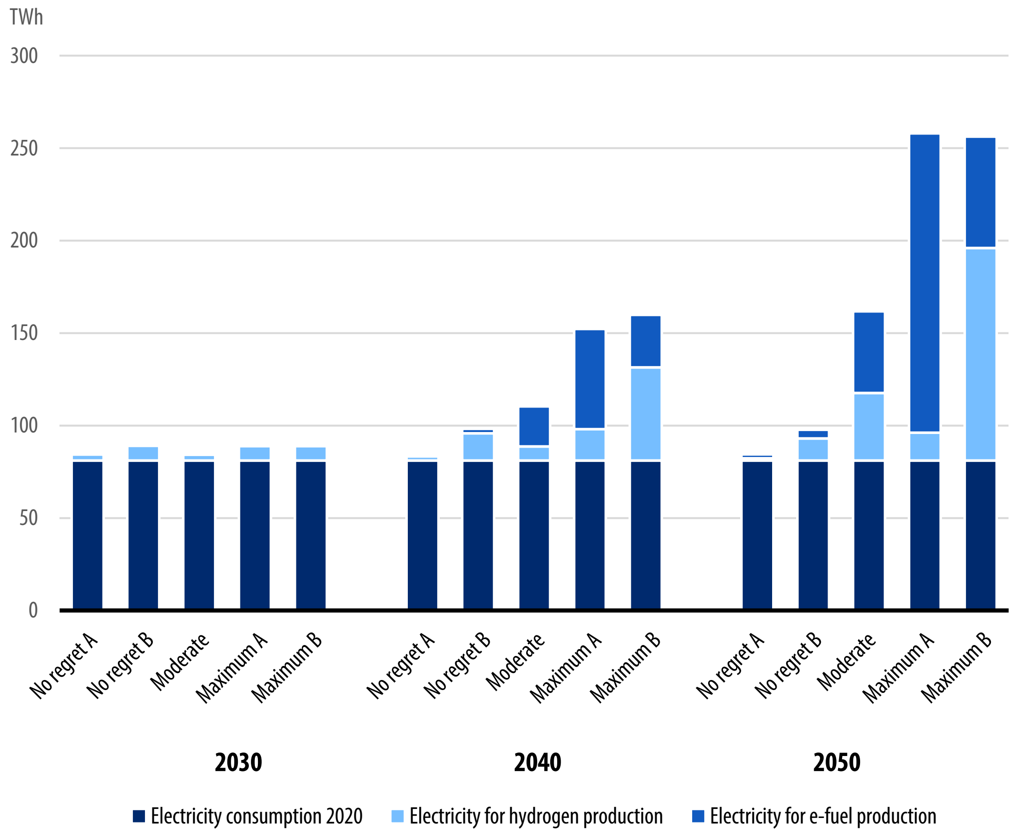
The demand for hydrogen in sectors other than fuel production is mostly determined by the demand of the steel industry (see Figure 10 below). Therefore, the demand will be strongly affected by the choice made by Finnish steel industry for producing carbon-neutral steel, i.e. hydrogen reduction or other methods.

Figure 10. The demand for hydrogen in other industries than fuel production is strongly dependent on the solutions chosen by the steel industry for producing carbon-neutral steel



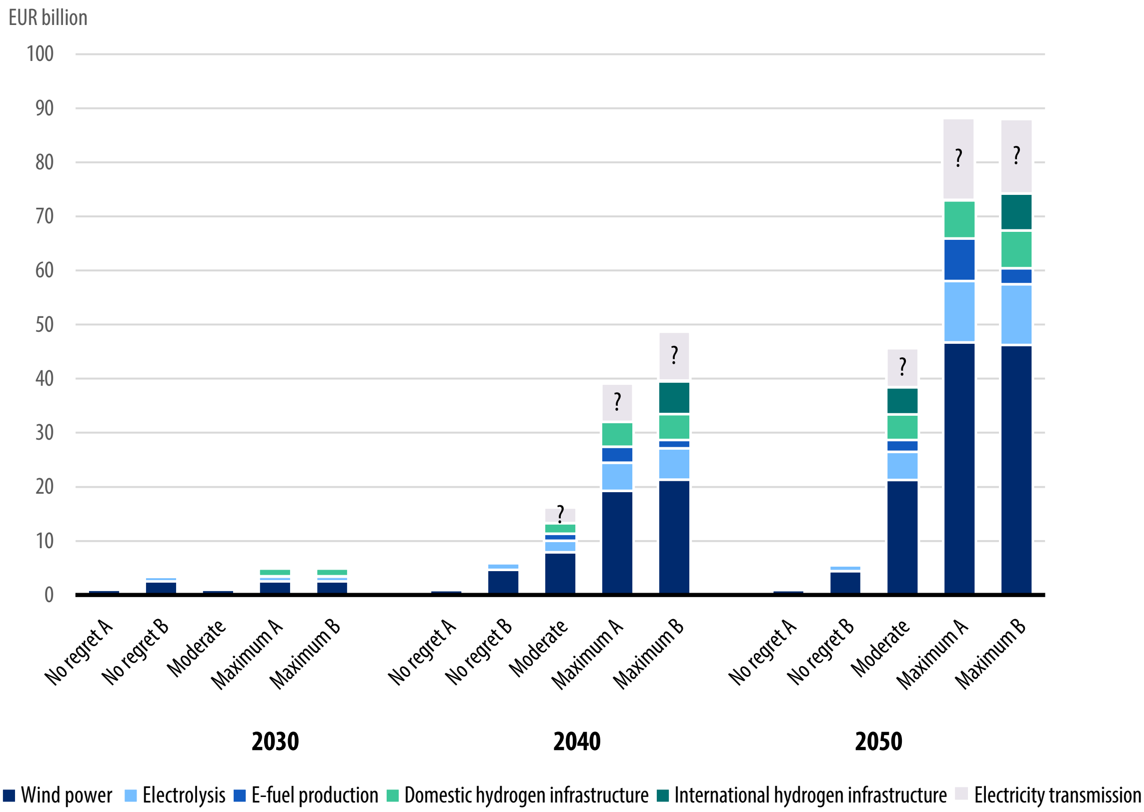
In all export scenarios, the impact of hydrogen economy in Finland's electricity consumption would be significant (see Figure 11 below). The 'Moderate' scenario would double the electricity consumption and the maximum scenarios would more than triple it from the present level.

Figure 11. The impact of the hydrogen scenarios on the demand of electricity in Finland



The export scenarios 'Moderate', 'Maximum A' and 'Maximum B' require significant investments in wind power construction – more than half of the total investments required by hydrogen economy would be associated with wind power (see Figure 12 below). The export scenarios also emphasise investments that need to be made in electricity transmission infrastructure and domestic and international hydrogen transmission infrastructure, whereas direct investments on the production plants of hydrogen and e-fuels would only amount to less than one-fifth of the total investment needs.

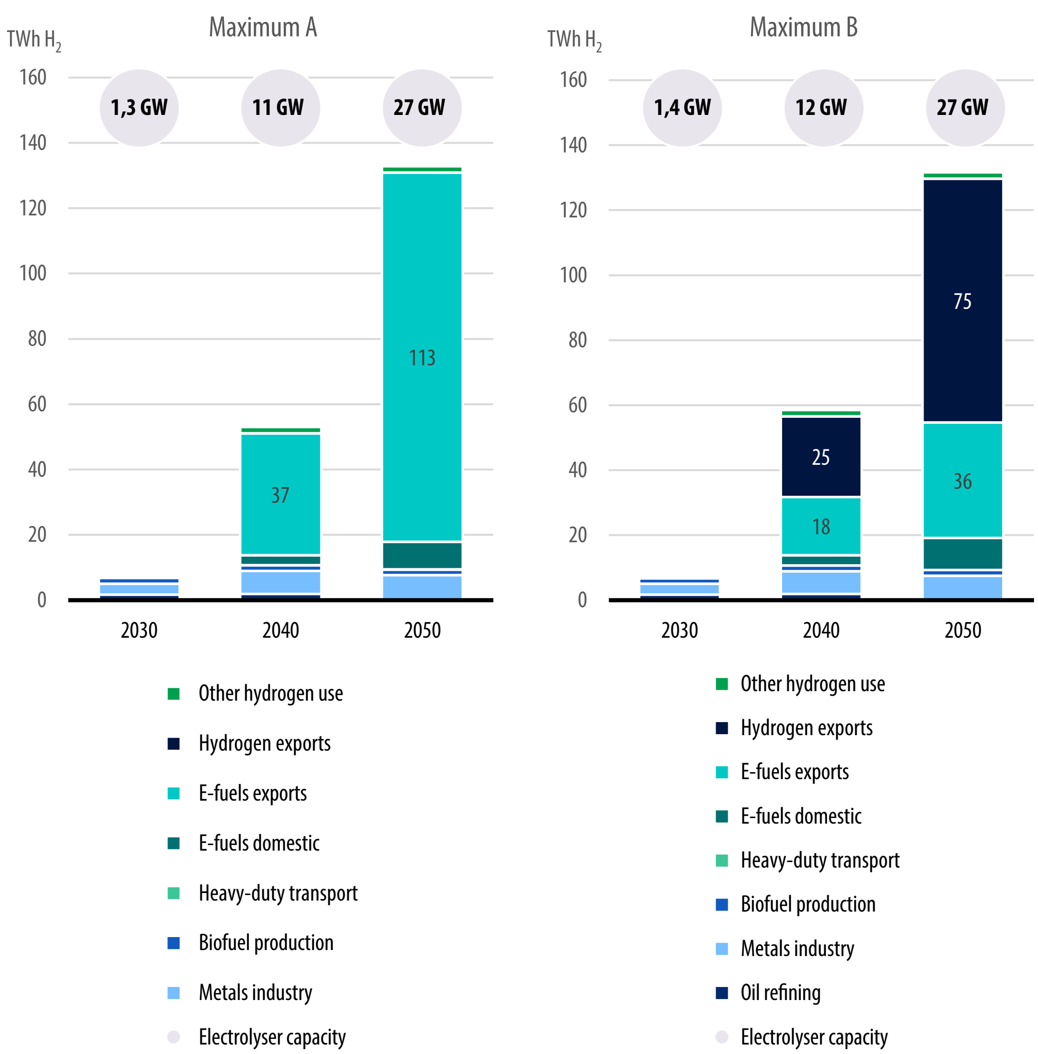
Figure 12. Costs of investments required by the hydrogen scenarios. NB! The necessary investments on the electrical grid have were not estimated, but their magnitude is based on Heikkilä (2021).



7.1.1 Maximum A and Maximum B

The electrolyser capacity required by the maximum scenarios would be 1.3–1.4 GW by 2030. The figure is based on the partial replacement of fossil fuels in the current hydrogen production, oil refinement and liquid biofuel production, hydrogen peroxide production, steel industry and other industrial end use of gases (see Figure 13 below).

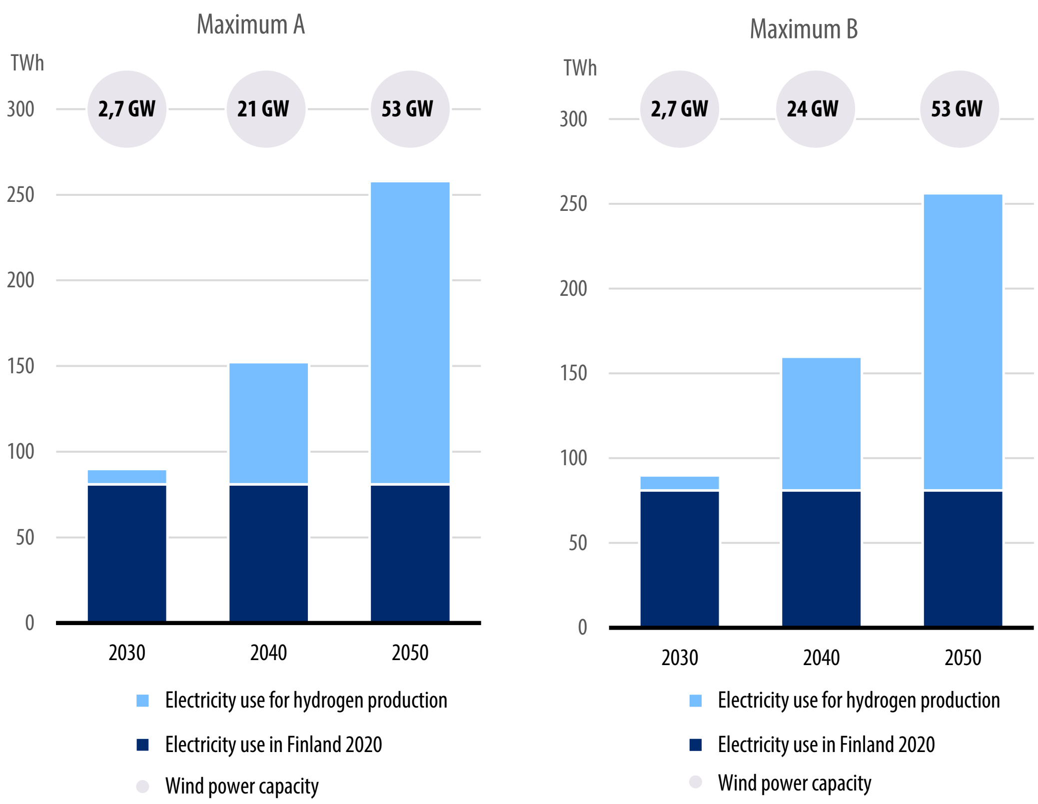
Figure 13. End use of hydrogen and the needed electrolyser capacity in scenarios 'Maximum A' and 'Maximum B'



In scenario 'Maximum A', strong investments would be made in the production of e-fuels by 2040, with the pace of investments accelerating even further towards 2050. In scenario 'Maximum B', the investments would consist of production of hydrogen and e-fuels and a large international hydrogen export pipeline by 2040. The volume of hydrogen exports will increase significantly up to 2050, as production reaches its maximum between 2040–2050. In 'Maximum B', the export of e-fuels remains approximately 10% of the European e-fuel market compared to the EU reference scenario MIX (EC, 2020a).

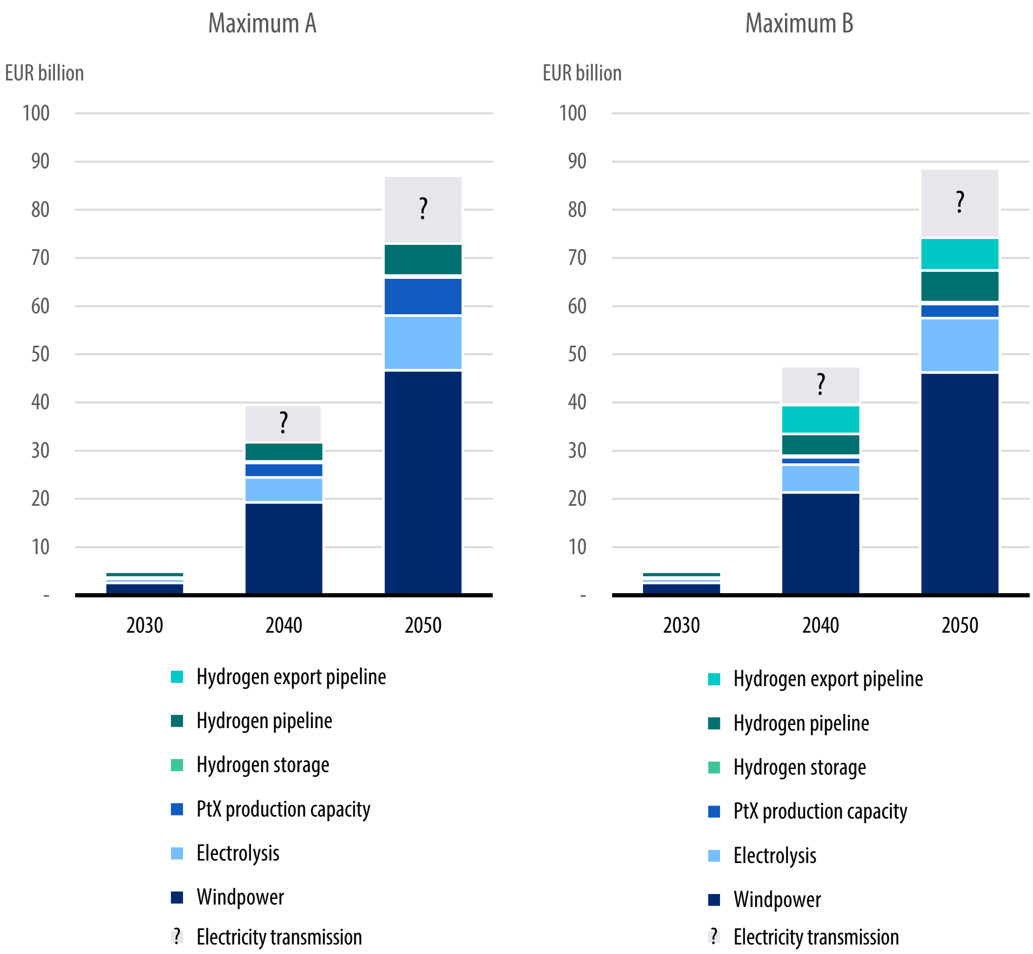
The wind power capacity required for hydrogen production would be 2.7 GW by 2030, increasing to 53 GW by 2050 (see Figure 14 below).

Figure 14. Consumption of electricity for hydrogen production and the required wind power capacity in scenarios 'Maximum A' and 'Maximum B'



The cumulative investment needed in the maximum scenarios would reach up to EUR 90 billion by 2050 (see Figure 15 below). More than half of the figure would consist of additional construction of wind power and approximately one-third would go to electricity transmission and hydrogen transmission networks. The rest of the investments would consist of production plants for hydrogen and e-fuel. The investment costs of hydrogen production plants also contain a storage capacity of 8 hours. The investment costs do not take into account the costs of investments needed in industrial processes, transport fleets and distribution infrastructure when the current fuels are replaced by hydrogen (for example, the process equipment required by the hydrogen reduction process in steelmaking, hydrogen burners, transport hydrogen distribution stations and hydrogen trucks).

Figure 15. Investment costs in scenarios 'Maximum A' and 'Maximum B'



The strengths, weaknesses, opportunities and threats associated with the maximum scenarios are shown in the Table below 3.

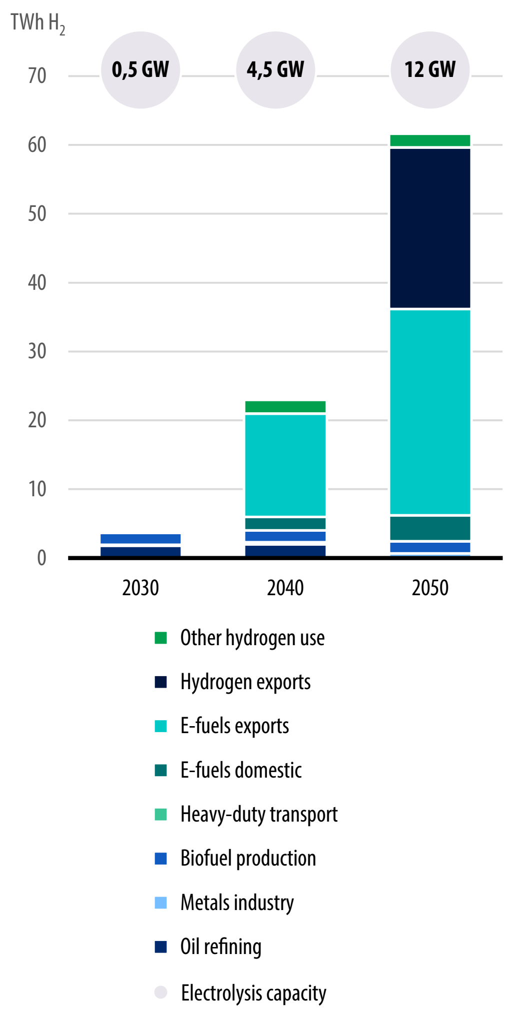
Table 3. Strengths, weaknesses, opportunities and threats associated with the maximum scenarios

STRENGTHS	WEAKNESSES
Enormous export potential that is developed to a maximum extent, on the condition that Finland has a continuous advantage on the market Brings significant investments and jobs into Finland The entire wind power construction potential is used to a maximum extent 'Maximum A' focuses on production chains that are valuable for the national economy, without the need to invest in an international hydrogen transmission infrastructure 'Maximum B' leverages the maximum production potential and exports the portion of hydrogen that cannot be sold to the international markets as e-fuel	Requires significant investments on both electricity and hydrogen transmission infrastructure, even though the development of the international market is unsure In 'Maximum A', the export potential of hydrogen is not utilised even though leftover potential remains from the production of biofuels In 'Maximum A', the technological and economical utilisability of biogenic CO2 might form a bottleneck to the production of methane, methanol and liquid hydrocarbons Large growth puts pressure on the availability of technologies, services and labour Finland's economy would be sensitive to international changes in hydrogen economy
OPPORTUNITIES	**THREATS**
Optimising the export investments and production of e-fuels and hydrogen as dictated by the market conditions If long-term forecasts indicate that an international hydrogen transmission pipeline is needed, the investment can be made later in 'Maximum A' A widespread hydrogen network enables the production locations of hydrogen to be distributed, which makes it easier to utilise waste heat, balance production and consumption and reduce the need to strengthen the electricity transmission network Biogenic CO2 can be utilised to meet the market demand, which brings CCU investments in Finland If wind power could be constructed affordably in larger quantities than those presented in the scenarios, the volume of exports could be even higher	An international e-fuel market does not emerge due to insufficient national and EU-wide incentives Competition on the global hydrogen and e-fuel market is so tough that production in Finland is not viable The necessary investments in wind power and infrastructure in Finland fail to meet the need (for example due to delays or excessive costs), resulting in lost export potential The development of infrastructure will be funded nationally, but Finland would not get a sufficient proportion of the gains If production costs in Finland increase more than in the competitor countries (for example the unit costs of additional wind power construction increase as Finland strives to achieve maximum wind power production), production is not economically viable

7.1.2 Moderate

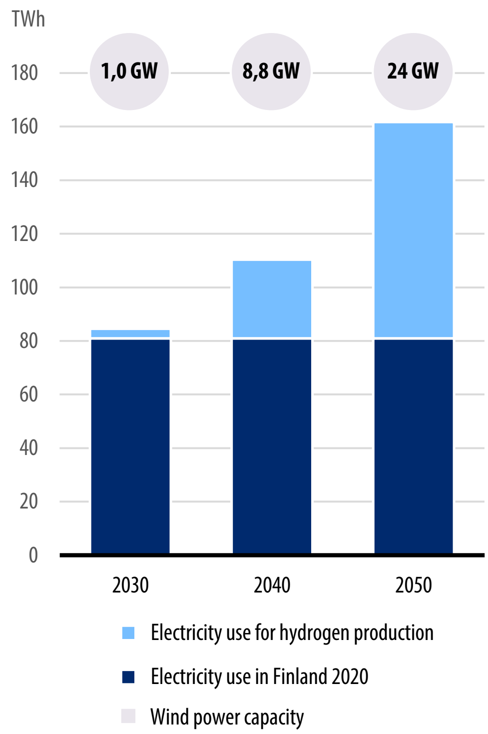
The 'Moderate' scenario starts slowly, corresponding to the trend in the 'No regret A' scenario up to 2030 (see Figure 16 below). The reason is that in this scenario, the international demand for hydrogen and e-fuels develops slowly, since European countries first concentrate on the development of their domestic production and demand in the 2020s and the steel industry adopts alternative solutions for carbon neutrality than hydrogen reduction of iron ore. The export of e-fuels then increases significantly by 2040 and continues to increase until it reaches a market share of 4% of the European e-fuels by 2050. The export of hydrogen gas starts after 2040 when the export pipeline to Germany is completed. The exported quantity is less than 25 TWh per year. The required total electrolyser capacity in Finland would be approximately 12 GW by 2050.

Figure 16. End use of hydrogen and the necessary electrolyser capacity in the 'Moderate' scenario.



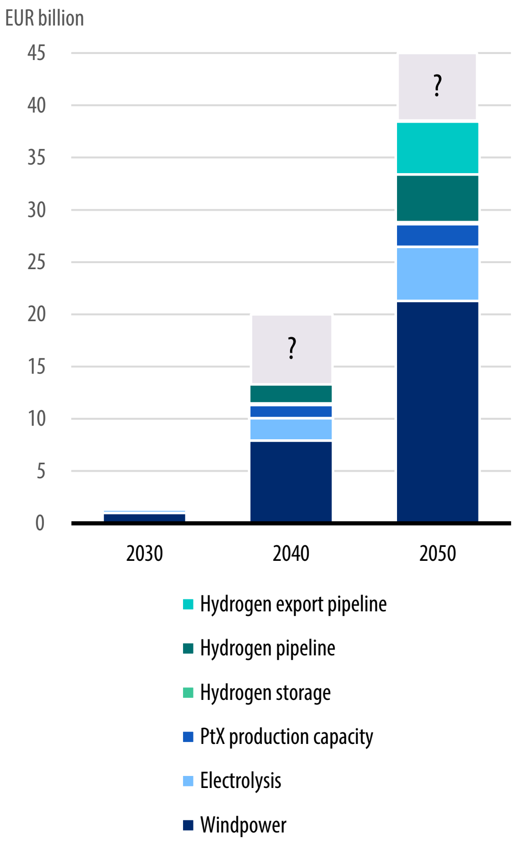
The additional wind power capacity needed would increase starkly from the 2030s onwards (see Figure 17 below) and would be approximately 24 GW by 2050.

Figure 17. Consumption of electricity for hydrogen production and the required wind power capacity the 'Moderate' scenario



The required cumulative investments would be approximately EUR 45 billion by 2050 (see Figure 18 below). Approximately half of this would be needed for additional wind power construction and a third would go towards constructing the necessary transmission infrastructure for electricity and hydrogen. The rest of the investments would consist of production plants for hydrogen and e-fuel. The conversion costs of the industry and transport sectors have not been taken into account in this scenario.

Figure 18. Investment costs in the 'Moderate' scenario



A SWOT analysis for the 'Moderate' scenario is shown in Table 4 below.

Table 4. Strengths, weaknesses, opportunities and threats in the 'Moderate' scenario

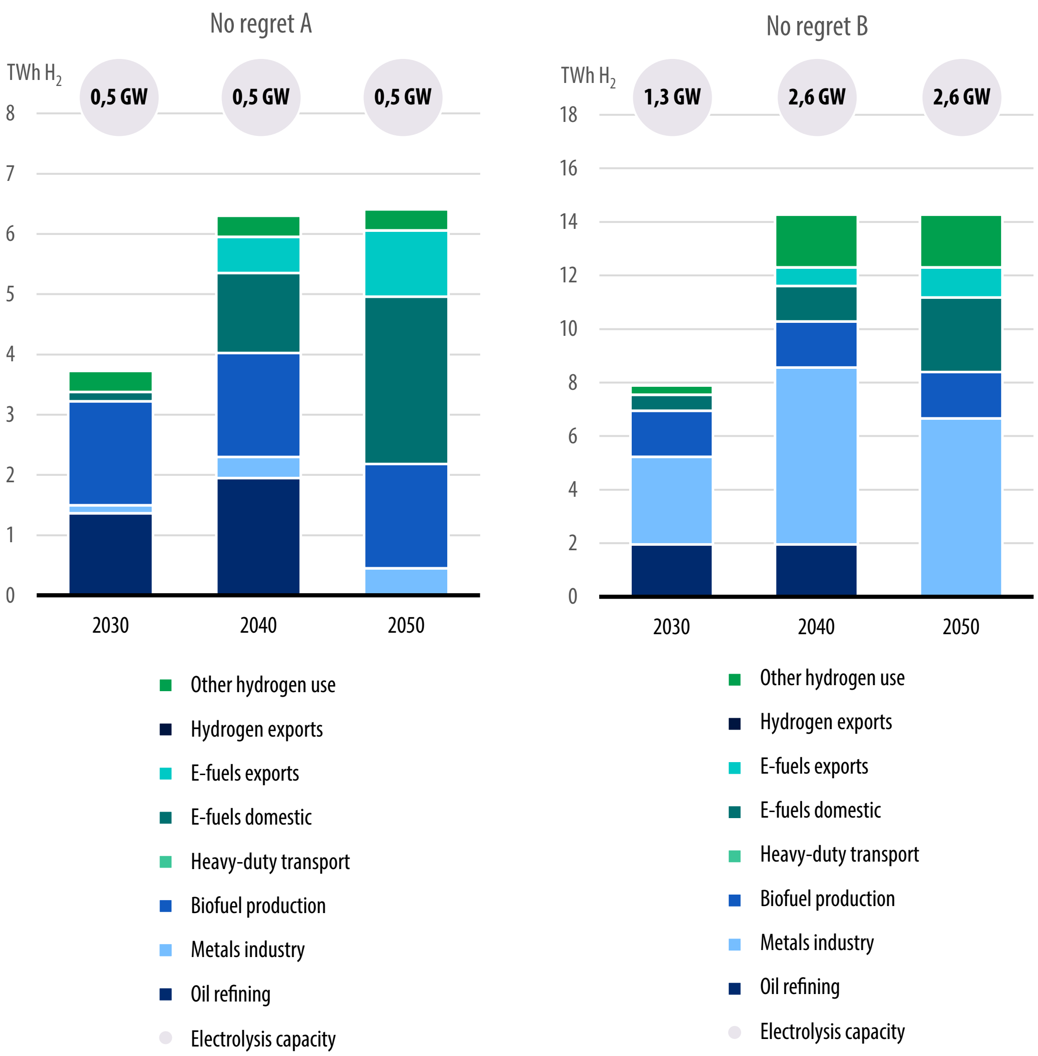
STRENGTHS	WEAKNESSES
Although initially slow, export volume reaches a maximum dictated by international competition A slow start ensures that Finland makes correct choices in technology and products while the international market is still seeking its shape Infrastructure is constructed with a long-term approach and as dictated by the needs at any given time. The inherent risks in hydrogen economy are kept at a manageable level	Finland cannot be a pioneer in hydrogen economy if Finland's exports increase slowly Higher investment costs in transmission infrastructure for electricity and hydrogen
OPPORTUNITIES	**THREATS**
Exports can be scheduled in different ways depending on the development of demand A hydrogen network enables the production locations of hydrogen to be distributed, which makes it easier to utilise waste heat, balance production and consumption and reduce the need to strengthen the electricity transmission network. Biogenic C02 can be utilised to meet the market demand, which brings CCU investments in Finland	If Finland fails to develop exports in the initial phase, Finland will not benefit from the pan-European growth phase and the available subsidies, which in turn might make later development impossible Investors might lose interest in Finland if Finland remains passive in the initial phase A slow start causes Finland to lose some of the export potential in the initial phase

7.1.3 No regret A and B

The minimum scenario 'No regret A' emphasises alternative technologies. The steel industry achieves carbon neutrality by other means than hydrogen reduction of iron, and oil refineries and liquid biofuel manufacture focus on the recovery of CO2. Electrolysis of hydrogen would remain at a pilot level at approximately 500 MW (see Figure 19). In the 'No regret B' scenario, the end use of hydrogen would be double compared to scenario A, to approximately 14 TWh per year. As for oil refining, the assumption is that half of the hydrogen would be produced by steam methane reforming equipped with CCS until

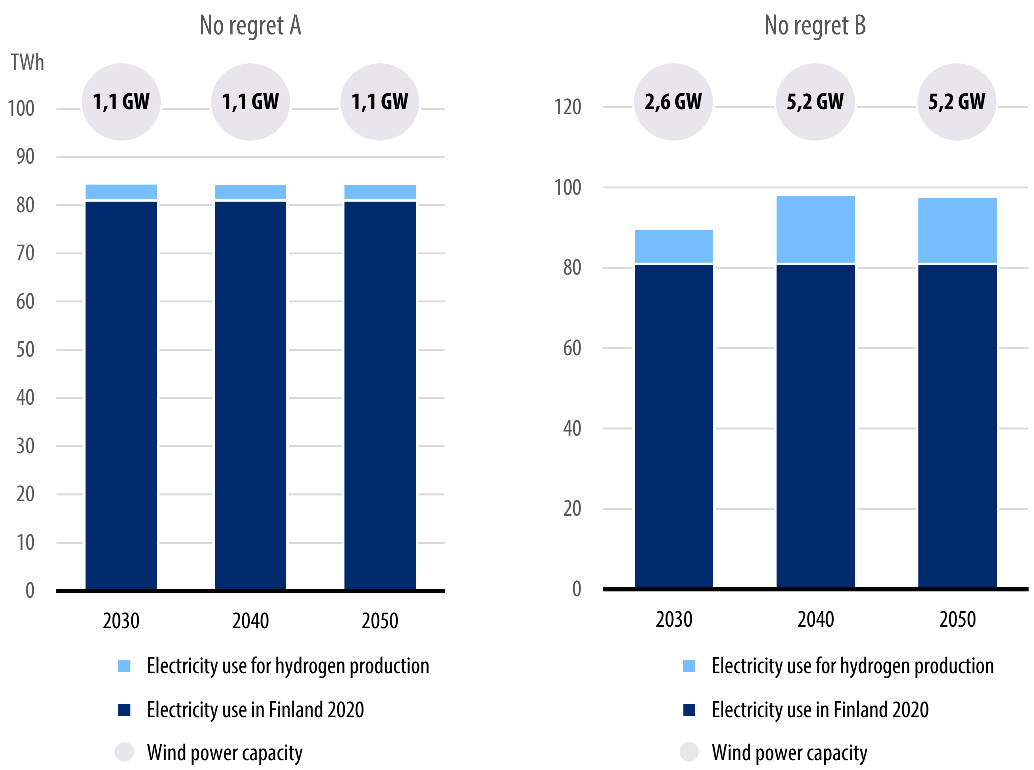
2040, after which all hydrogen would be produced by electrolysis. The existing oil refining capacity is expected to transfer to the production of e-fuels gradually, as the consumption of oil products reduces. In the 'No regret B' scenario, the required electrolyser capacity would be 1.3 GW already in 2030.

Figure 19. End use of hydrogen and the needed electrolyser capacity in scenarios 'No regret A' and 'No regret B'



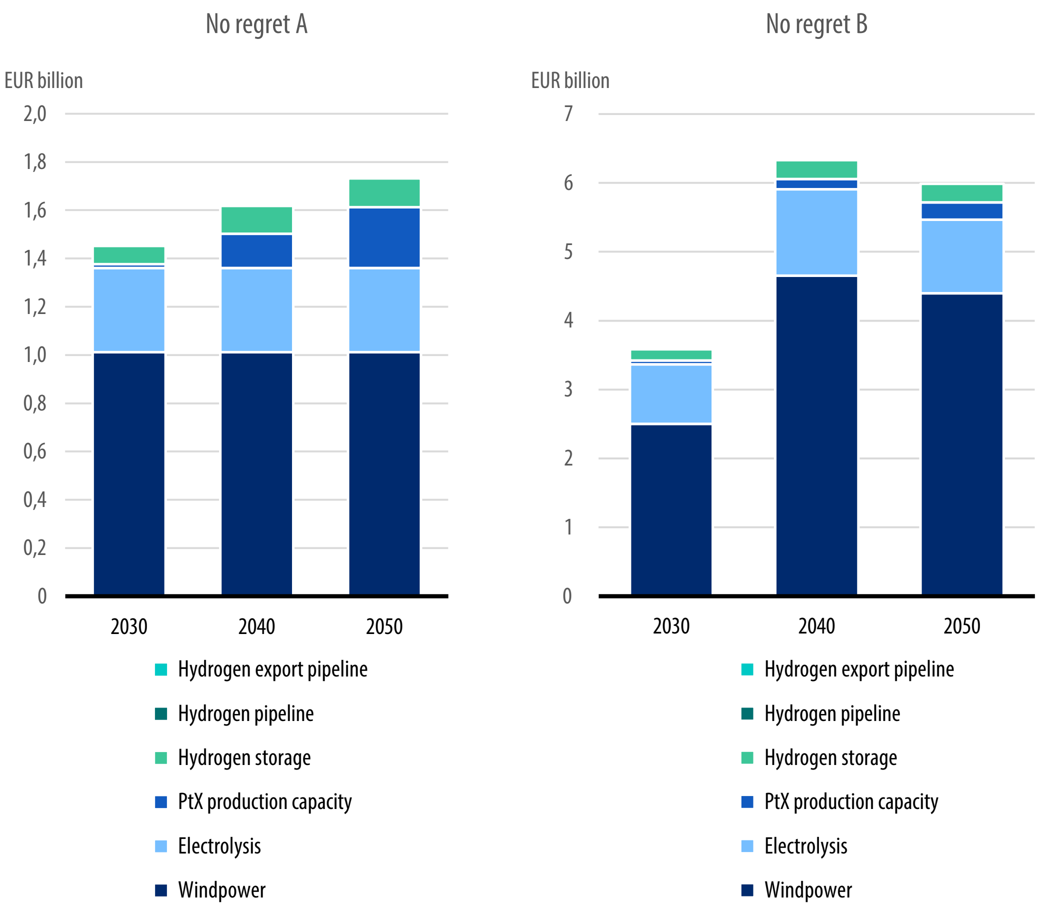
The required additional wind power construction capacity remains small in the 'No regret A' scenario (see Figure 20 below). In scenario B, the requirement is four times higher. Electricity consumption grows from the present level by 20% by 2040.

Figure 20. Consumption of electricity for hydrogen production and the necessary wind power capacity in scenarios 'No regret A' and 'No regret B'



The investments in the 'No regret' scenarios take place in the production of electricity and hydrogen (see Figure 21 below). No significant additional investments in the electricity transmission network and hydrogen transfer are needed.

Figure 21. The investment costs in scenarios 'No regret A' (left) and 'No regret B' (right)



A SWOT analysis for the 'No regret' scenarios is shown in Table 5 below.

Table 5. Strengths, weaknesses, opportunities and threats of the 'No regret' scenarios.

STRENGTHS	WEAKNESSES
If the progress of technology creates new solutions that are more efficient and sustainable than hydrogen, the production of hydrogen and the associated infrastructure does not need to be developed strongly High-risk investments are avoided	Export potential is not leveraged irrespective of how the technologies and markets develop Does not attract investments in Finland Finland would gain little expertise on an ecosystem that other countries are developing and thus also gaining expertise The possibilities for importing and storing hydrogen are not utilised since the necessary transmission infrastructure is missing Developing hydrogen economy for local needs might result in higher unit costs in production than in large-scale production that links several operators
OPPORTUNITIES	**THREATS**
Meeting domestic demand entirely by domestic production Instead of investing in hydrogen transmission pipelines, Finland would invest in the transmission of CO2 for the production of e-fuels or CO2 storage The production opportunities for e-fuels can be utilised depending on the market situation Exports can be developed later as necessary when uncertainties in international demand reduce over time	If Finland fails to develop exports at this stage, Finland will not benefit from the pan-European growth phase and the available subsidies, which in turn might make later development impossible If Finland fails to invest in hydrogen value chains or any other technologies, Finland's economy might not be able to keep pace with the other European countries

7.2 Conclusions on the hydrogen economy scenarios

The production of hydrogen and e-fuels in Finland might be limited to meet the domestic demand or might grow into an industry that exports its products to the international market. The production volumes in the scenarios vary wildly and depend on the export assumptions.

Finland's domestic demand and the demand of Finland's international transport can be met by an electrolyser capacity of 0.5–2.6 GW by 2050, depending on the which choices the steel industry and oil and biofuel refineries make to achieve carbon neutrality. The development of export depends heavily on international demand and Finland's competitiveness in the sector. In the export-driven maximum scenarios, the production of hydrogen might reach up to 130 TWh by 2050.

The stakeholders' comments on the maximum scenarios consider the full-scale utilisation of Finland's production potential as one of Finland strengths, but the stakeholders also acknowledge that uncertainties exist concerning demand and Finland's competitiveness. The 'Moderate' scenario is seen as more realistic than the maximum scenarios, but its slow initial start raises concerns: can Finland enter a growth track if the public aid in the initial phase is not utilised and no market share is gained at that time?

The minimum scenarios represent a future in which an international market is not created or Finland consciously neglects to utilise the export opportunities. Many stakeholders saw these minimum scenarios as a threat, even though in both scenarios, the domestic production would meet the domestic demand for hydrogen in the industry and transport.

7.2.1 Limitations of the scenarios

The hydrogen scenarios do not include the necessary investments in the electricity transmission network, since that would require detailed modelling of the networks. The need for additional investments in the electricity transmission networks referred to in the maximum scenarios is based on an estimate by Fingrid. It should be noted that in autumn 2021, Fingrid and Gasgrid launched a study on the relationship between electricity transmission networks and hydrogen transmission networks, including network scenarios. The study will complete by the end of 2022.

The hydrogen network investments modelled in the study are based on parts of the hydrogen network vision presented by Gasgrid Finland in the European Hydrogen Backbone report, since no concrete investments plans have been presented in public.

The hydrogen pipeline from Southwest Finland to Germany serves as an example of international exports in the scenario, but does not indicate an opinion that this very solution is superior to alternative solutions.

The scenarios do not take a stand on which e-fuels would be produced in Finland, since the fuel choices would depend on the companies' business strategies and the development of the future e-fuel market. Likewise, the study does not investigate the cost trends and emission reduction potatials of all alternative transport energy source solutions and does not therefore rank the solutions in an order of preference.

8 Background factors in the Finnish hydrogen scenarios

Summary

Hydrogen economy means an economic system in which fossil sources of energy or feedstocks are replaced by hydrogen that is produced by clean or low-carbon energy sources and serves as an energy carrier or feedstock.

A Finnish approach on hydrogen economy must be based on an understanding of Finland's starting points and available development paths, but also a prioritisation of what Finland should strive for and why. These factors would then serve as input for the necessary political measures.

Hydrogen economy represents an opportunity for Finland's economy. However, it also involves uncertainties, the largest of which are the development of international demand and Finland's competitiveness.

The primary social goal of hydrogen economy is to achieve the carbon neutrality goals in order to control climate change. Hydrogen economy also has an impact on the economy, since it requires changes in some value chains. Since Finland is a country that can produce more carbon-neutral energy than it needs, hydrogen economy offers more opportunities than limitations for Finland.

The development of Finnish hydrogen economy depends not only on the development of domestic demand, but also international developments on the market, technology and regulation. Most of the factors that affect the profitability, targeting and timing of investments in hydrogen economy are shared across all industrial activity. An attractive operating environment consists of predictability, an effective energy system, the availability of feedstocks required in production, skilled workforce, regulations and permits, that support and foster operation, and other factors that have a direct impact on economic indicators. Of course, geographical proximity to markets, key production inputs and products is an advantage. Safety of the operations and a broad public support are the foundation of any sustainable business. The hydrogen economy of the future must be built on a socially, ecologically and economically sustainable foundation.

The following sections discuss selected factors that will affect the development of Finland's hydrogen economy and that have affected the scenarios and their limitations presented in this report and the conclusions of this report. The first chapter describes what is meant by competitiveness. The following chapters describe in more detail the role of electricity in hydrogen economy, the international preconditions for the development of a hydrogen market and the availability of biogenic carbon dioxide in Finland. The final chapter presents some views on the impact of hydrogen economy on employment and the political tools available for hydrogen economy.

8.1 What does competitiveness mean in terms of hydrogen economy?

The competitiveness of an economy can be divided into short- and long-term competitiveness (Stenborg *et al.*, 2020). What is essential for hydrogen economy in the short term are **a change in investments** and **a change in net exports**, assuming on the basis of the hydrogen economy scenarios that a change in private and public consumption costs has little effect on hydrogen economy in Finland, since hydrogen economy does not affect households or the public sector directly.

Net exports depend on the success of products in the export market or against imports in the domestic market. Success in these areas requires cost competitiveness, i.e. **in the short term, competitiveness consists of keeping unit costs lower than in competing countries.** Industrial investments typically react with a delay to changes in price competitiveness. **As price competitiveness improves, industrial investments improve; as price competitiveness reduces, industrial investments reduces.** (Stenborg *et al.*, 2020)

In the long term, competitiveness stems out or an increase in productivity (Stenborg *et al.*, 2020). Productivity is affected by companies' ability to improve their technologies, processes and products to better meet the needs of the market and trends in demand, which maintains the companies' short-term competitiveness. Other factors affecting productivity are companies' ability to shield themselves against competition by patents or by concentrating on products that face little competition.

For Finland, the competitiveness of hydrogen economy stems from Finland's national starting points (see Chapter 5) and how the Finnish companies and public sector continue to build their competitiveness in relation to the demand. This can be influenced by political tools that affect the cost factors and foster social conditions that promote growth of productivity.

In the Finnish hydrogen scenarios, the primary cost factor in hydrogen economy is the price of clean electricity, followed by the transmission, storage and transport costs of electricity, hydrogen and e-fuels. Direct investments in production occupy a third place. In addition to influencing the cost factors, Finland needs investments in developing expertise on hydrogen value chains and especially building the technological and functional conditions that enable the end user sectors to transfer to hydrogen. This is where Finland has excellent opportunities to leverage its strengths and come up innovations in technology, design and services.

8.2 What is the most probable path to hydrogen economy?

As shown in Chapters 3 and 4, hydrogen projects are being developed strongly in Europe in the early 2020s. The number of published projects reaches many thousands, and unpublished projects up to many tens of thousands.

At the moment, hydrogen projects are mostly national and financed by national and EU aid, since at this phase, the projects are not yet competitive on market terms. It will take 2 to 3 years before EU-level legislation on hydrogen and e-fuel enters into force, depending on how the European Commission’s Fit-for-55 package, EU taxonomy and gas decarbonisation package proceed in the processing by the European Parliament and European Council and in the subsequent preparation of national legislation. The completion of an EU-level legislation is a precondition to the development of demand, which will require compelling legislation (distribution obligations, emissions trade, bans on use, definitions), elimination of obstacles (infrastructure, market mechanisms, education) and financial support (tax aid, investment aid, production aid).

The chapters below draw detailed conclusions on the data presented in this study and describe how the transfer to hydrogen is likely to happen in the Finnish transport and industry sector.

8.2.1 Transfer to hydrogen in transport

Hydrogen is suitable as a transport fuel as is (hydrogen engines, fuel cells) or refined into e-fuels (ammonia, methanol, methane, kerosene, diesel, gasoline). Air transport will most likely start using e-kerosene, long-distance maritime transport ammonia and methanol and heavy road transport hydrogen. All sectors will also develop solutions based on electrification and biofuels.

National and EU-level political tools can affect the speed of hydrogen transfer in drop-in transport fuels (i.e. fuels that can be used in existing technologies, such as kerosene, diesel, gasoline, methane and methanol in small proportions in a blend) already today and in 100% hydrogen-based solutions (100% methanol or ammonia) when commercial adoption becomes viable.

Finland is committed to reducing the emissions of domestic transport by at least 50% by 2030 and will reach a zero-emissions target in transport by 2045 (Ministry of Transport and Communications, 2021). The emissions reduction goals set by Finland for itself are more ambitious than the goals set in the EU Commission's Fit-for-55 package.

Critical factors in the development of Finnish exports of e-fuels are the national and EU-wide obligations set for the distribution of renewable transport fuels and e-fuels (including clean hydrogen) in air and road transport. This will determine both domestic and international demand for e-fuels in these sectors. Without a distribution obligation it is difficult to see how an EU-wide market could emerge for e-fuels, since the production costs of e-fuels are about three times as high as their fossil equivalents. Air transport within the EU will also be affected by a reform of the current emissions trade, which might not increase the use of e-fuels but rather the use of emissions compensation mechanisms. In Finland, the Act on Distribution Obligation (446/2007) was amended in 2021 to cover not only biofuels, but also all other renewable fuels in order to replace gasoline, diesel fuel and natural gas in transport.

Control of the emissions reductions in marine transport is based on the Fit-for-55 package's expansion of emissions trade to the intra-EU marine transport and partly to external marine transport. Therefore, marine transport will continue to have more freedom to reduce its emissions than shifting to use other fuels, even though the ReFuel Maritime initiative introduces stricter emissions limits to marine fuels. Marine traffic will use of drop-in fuels for a long time before propulsion solutions based on 100% hydrogen, methanol or ammonia are commercially available. **For air transport, the ReFuelEU Aviation initiative proposes a distribution obligation of sustainable fuels on the Member States' airports.** The obligation includes not only biofuels but also synthetic clean and low-carbon fuels (including e-fuels). The blending obligation will be 5% in 2030, of which 0.7% should be of non-biological origin. In 2050, the blending obligation will be 63%, of which 28% should be of non-biological origin.

In addition to EU, the international renewable fuels market is shaped by the UN agency International Maritime Organization (IMO), which strives to promote international co-operation on the reduction of greenhouse gas emissions in maritime transport by means of voluntary agreements, and International Civil Aviation Organisation (ICAO), which has 193 member countries. ICAO has established a Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), whose goal is to achieve carbon-neutral growth of in international air transport from 2020 onwards. Under CORSIA, the aircraft operators reimburse the growth of emissions in international air transport by purchasing CORSIA-approved emissions units from the carbon market. The units originate mostly from the emissions reduction projects of other sectors. The reimbursement obligation is calculated annually by comparing the emissions from the routes between the CORSIA member states to the emission average in 2019 (Traficom, 2022) .

Hydrogen distribution stations for heavy transport become necessary when or if fuel cell trucks are adopted in Finland for heavy transport. This might become relevant if EU legislation starts to demand it, hydrogen trucks start to operate internationally on routes that reach Finland or the price of hydrogen trucks becomes competitive compared to other propulsion alternatives. In air transport, the fuel would be synthetic kerosene, which will not require changes to the current distribution infrastructure. **The development of distribution infrastructure for waterborne transport requires investments when vessels start to transfer to 100% hydrogen-based fuels**.

8.2.2 Hydrogen transfer in the steel industry

Steel industry. Finland has two major steel industry plants. SSAB Raahe manufactures pig iron in two blast furnaces and refines it into steel in a steel plant. Outokumpu Tornio manufactures stainless steel out of recycled steel and ferrochrome.

On 28 January 2022, SSAB issued a press release stating that SSAB’s steel production will be fossil-free already by 2030. The Raahe factory will be reformed to use a so-called minimills production which uses electric arc furnaces and rolling mills. As a result, the blast furnaces will be decommissioned by 2030. A more detailed action and reformation plan is underway. The press release did not state the form of the feedstock to the Raahe plan. In this regard, both alternatives described in Finland’s hydrogen scenarios are still possible, but the current blast furnaces will be decommissioned earlier

Like SSAB, Outokumpu has set for itself emissions reduction targets and an action plan to reach them. The plan includes the replacement of fossil fuels and reducing agents with sustainable solutions (Outokumpu, 2021a). Recycled steel is melted in electric arc furnaces. The production of ferrochrome requires coke, and studies have been made on whether it can be replaced by biogenic carbon. As for Outokumpu’s processes, it is still unclear which sustainable technical solutions can be used, but research continues (Outokumpu, 2021b).

The conclusion is that the steel industry can transfer to carbon neutrality also by adopting solutions that do not need hydrogen. On the other hand, using hydrogen-based solutions might be possible, if they are competitive in Finland.

Refinement of oil and biofuels and production of e-fuels. In chemical industry, the transfer to hydrogen might mean using clean and low-carbon hydrogen to replace existing fossil hydrogen or new hydrogen-based production. The Neste Porvoo refinery is currently the largest consumer of hydrogen in chemical industry. Neste has not set a target year for carbon neutrality in its production. Neste has received EU funding for steering its current consumption of hydrogen at the Porvoo refinery towards green and blue hydrogen (Neste, 2021). One of the drivers behind the transfer to hydrogen is a change in the demand for end products, because as the transfer progresses, the demand for traditional oil refining products will decrease, but the demand for new products will increase. The production of e-fuels as a feedstock or transport fuel will start to grow when the EU legislation, national political measures and the situation on the target markets create the preconditions to exports and the construction of industrial-scale plants in Finland.

Other industry. Finland currently manufactures small quantities of hydrogen peroxide, which needs hydrogen. At present, that hydrogen is manufactured from fossil fuels (natural gas or heavy fuel oil). The alternative is to either equip the current process with CO2 recovery and storage or transfer to using clean hydrogen. Natural gas, LNG and LPG are used in industrial processes that require a high temperature, such as in the food industry, manufacture of construction materials, ceramics and glass industry and in some forest industry processes (such as infrared drying of paper and lime kilns). Most of the current consumption of fossil gases could be replaced by direct electrification or other renewable fuels, such as biogas. In applications where such alternatives are unsuitable, such as high temperature treatment of metals, it is possible to transfer to hydrogen if the combustion technology is altered. The challenges in this approach are additional costs associated with the procurement of hydrogen and hydrogen technologies, as well as safety aspects. **Therefore, research is needed on how fossil gases can be replaced with hydrogen in various specialised end uses.**

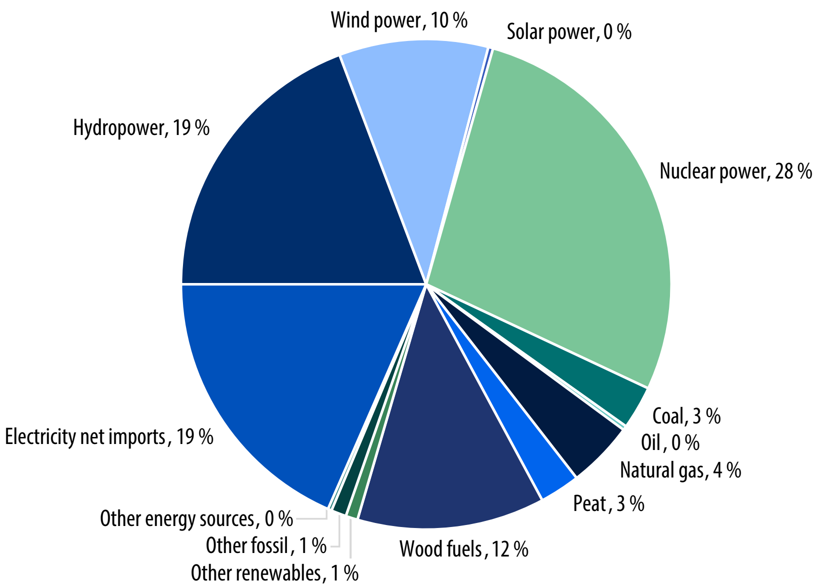
8.3 The role of electricity in Finnish hydrogen economy

As stated in Chapter 8.1, electricity and electricity transmission are key factors for a competitive hydrogen economy. **Finland has huge potential for additional wind power construction**, which is an important precondition for industrial-scale hydrogen production projects. The total capacity of wind power projects published by January 2021 is 21.3 GW (Finnish Wind Power Association, 2021). If realised, this would exceed Finland’s current electricity generation capacity, which is approximately 11.3 GW by the end of 2021 (Energy Authority, 2021).

In addition **new nuclear power plants are being constructed and planned in Finland**. Olkiluoto 3 (1.6 GW) will enter a trial run phase in January 2022 and will start regular production in June 2022 (YLE, 2021). The Hanhikivi 1 plant (1,2 GW) being planned in Pyhäjoki is expected to receive a construction licence in 2022 (Fennovoima, 2021). The discussion on whether nuclear power is allowed in the production of low-carbon hydrogen continues in Europe. Even if nuclear power does not meet the EU's requirements for the production of clean or low-carbon hydrogen, nuclear power nevertheless plays a significant role in Finland's progress towards its national carbon neutrality goal and also has an effect on the average CO2 emissions factor of electricity procured from the grid. Whether nuclear power is approved for hydrogen production is a deal-breaker especially for France that produces most of its electricity by nuclear power (WNN, 2021).

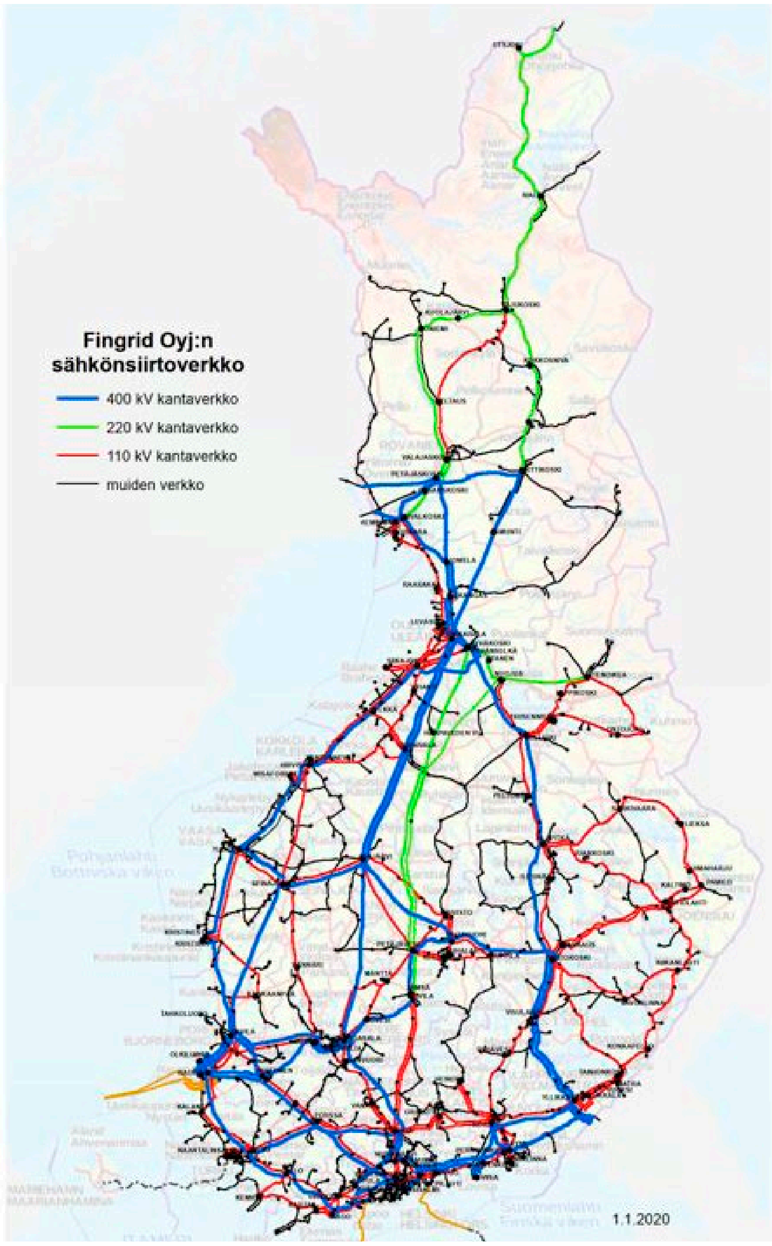
Finland's electricity generation is already heavily based on carbon-neutral sources of energy. For example in 2020, approximately 86% domestically procured electricity was based on renewable sources and nuclear power (see Figure 22 below). The share of carbon-neutral electricity generation will grow in the future also because electricity generation capacity based on fossil fuels is leaving the market and the use of peat will also dwindle.

Figure 22. Procurement of electricity by energy source in Finland in 2020 (Statistics Finland, 2021)



Finland's electricity transmission grid consists of approximately 14,400 km of power lines (see Figure 23 below). **Fingrid designs the main grid in accordance with section 40 of the Electricity Market Act, ensuring that the transmission capacity of the grid is sufficient to keep Finland as a single bidding zone in electricity trade** (excluding the Åland islands which belong to the Swedish bidding zone SE3) (Fingrid, 2021a). Fingrid is currently planning to invest approximately EUR 1.4 billion on the main grid by 2030. Based on Fingrid's network vision published in early 2021, the total investments might reach up to EUR 2.5 to 4 billion by 2035.

Figure 23. Fingrid's electricity transmission grid on 1 January 2020 (Fingrid, 2021b)



Finland's main grid is robust compared to Sweden, which is divided into four bidding zones due to north-south transmission constraints. This is a positive aspect for Finland, since Finland has less needs to strengthen its transmission network than Sweden. On the other hand, Sweden's strengths are its electricity generation capacity (a lot of wind power and hydro power) and the price of electricity on the market. For example in 2021, the market price of electricity in Northern Sweden was on average EUR 15/MWh lower than in Finland. A new cross-border connection, Aurora Line, between northern Sweden and Finland (800 MW from Sweden into Finland) will be completed in 2025, which will mitigate the price differences in the future. Differences in electricity prices might have an effect on the location chosen for hydrogen production plants and possible hydrogen pipelines between countries. On the other hand, the demand for electricity in Northern Sweden might grow significantly as the local steel industry starts to need hydrogen, in which case Finland's capacity to transmit electricity and/or hydrogen to Sweden might become important.

Fingrid's network vision states that if a significant amount of new electricity-intensive industry emerges in Finland or if Finland becomes an exporter of electricity or e-fuels, it is likely that the main grid needs more investments than planned. The primary uncertainty factor seen by Fingrid is the trend of electricity consumption in Finland, which is affected by the electrification of the end use of energy, development of industrial production and development of hydrogen production. Fingrid is currently co-operating with Gasgrid Finland to determine how the electricity system might be affected by large-scale weather-dependent generation of electricity combined with the production of clean hydrogen in Finland, and on the other hand the cases in which transmission of hydrogen along pipelines would be more cost-effective than locating hydrogen production near the end use sites. The study is expected to be completed by the end of 2022. Fingrid is also preparing a system vision in 2022 which will take into account the changes that are taking place in the electricity market.

The low-carbon roadmaps prepared by industries in 2020 highlighted a significant need for electrification, the impact of which on the electricity system was assessed in a study in 2021 (Forsman *et al.*, 2021. The study found that demand elasticity plays an important role as weather-dependent electricity generation increases. One of the elastic elements studied was the potential elasticity of hydrogen production. Storing hydrogen on site is not particularly cheap, and when local hydrogen generation is combined with industrial end use, shutdown of hydrogen production would cause interruptions in production and thereby major costs. The situation might be different should a hydrogen transfer system between multiple producers and end users be available, since the pipeline might be able to smooth out the fluctuations in hydrogen production and demand (depending on the size of the pipeline), although such a system would also involve investment costs. In the long term, the quicker and more flexible adjustability of PEM electrolysers compared to alkaline electrolysers might help in solving some of the challenges associated with the maintenance of the electrical system.

Approximately 70–90% of the total costs of a hydrogen production plant consist of electricity procurement costs. Therefore, hedging against price and volume risks in electricity procurement is of paramount importance in hydrogen production investments. Such hedges involve a range of arrangements, such as long-term Power Purchase Agreements (PPA), in which the purchase price and volume is agreed for 10 to 12 years in advance. Hydrogen producers can also purchase electricity at cost by purchasing entire power plants. Finnish energy producers may also operate under a special 'Mankala' principle in which a non-profit limited liability company may produce electricity for its shareholders at cost price. However, hedges like these do not make elasticity any less important: as long as there are significant price fluctuations on the electricity market, flexibility can bring added value to hydrogen producers even if the price of electricity were hedged to a large extent.

In practice, hydrogen producers would optimise their electricity purchase portfolio in line with the procurement policy of their company. Another component of the optimisation of short-term procurement is demand elasticity, the marginal cost of which is determined on a case-by-case basis and in accordance with the special features of each case.

In the long term, the prices in the PPAs can be expected to follow the long-term trends of electricity market prices. If Finland were to construct a lot of hydrogen production capacity for export, for example, it would increase the average electricity procurement costs if at the same time the financially most viable sites for wind power were already constructed. This also sets limits to growth because it would reduce Finnish companies' price advantage to competing countries. Likewise, when or if the proportion of wind power in Finland's electricity system becomes large, the volatility of market prices of electricity will increase, which will also be reflected in long-term agreements as a higher risk premium.

Swedish and Norwegian hydro power is highly regulable, although the share of weather-dependent production is growing in the Nordic electricity market. This means that the construction of hydrogen production plants in the Nordic electricity market cannot be based on the assumption that the price of electricity has a lot of low-price hours that the hydrogen generation plant could utilise. Furthermore, regulability of hydro power varies from year to year: the prices are higher in dry years than in years with plenty of water. The impact of abnormal years is visible in the market prices for 2 to 3 years after the abnormal season. This serves to further increase the need for hedges in hydrogen production investments.

From the perspective of Finland's electricity system, a significant growth in the share of wind power is more challenging for Finland than Sweden or Norway, since Finland has significantly less hydro power that can be used for regulation. As a result, Fingrid is investigating which assumptions can be made on the demand elasticity of hydrogen production and storage in Finland and what role would hydrogen transmission networks and the location of production and consumption play in it.

8.3.1 The need, opportunities and limitations of elasticity in hydrogen production and consumption

Hydrogen production plants that are connected directly to an industrial end user are usually equipped with a hydrogen storage that helps to smooth out short-term fluctuations in hydrogen production and demand. When the hydrogen produced is a by-product or grey hydrogen, the interim storage is typically rated for only a few minutes' worth of consumption. The pressure in interim storages is very high, 250–300 bar, in order to reduce the material costs (steel) of storage. Interim storage operations consume electricity, since hydrogen must be compressed to a pressure higher than required by the production and end use processes. Storage also causes losses, since hydrogen diffuses through steel.

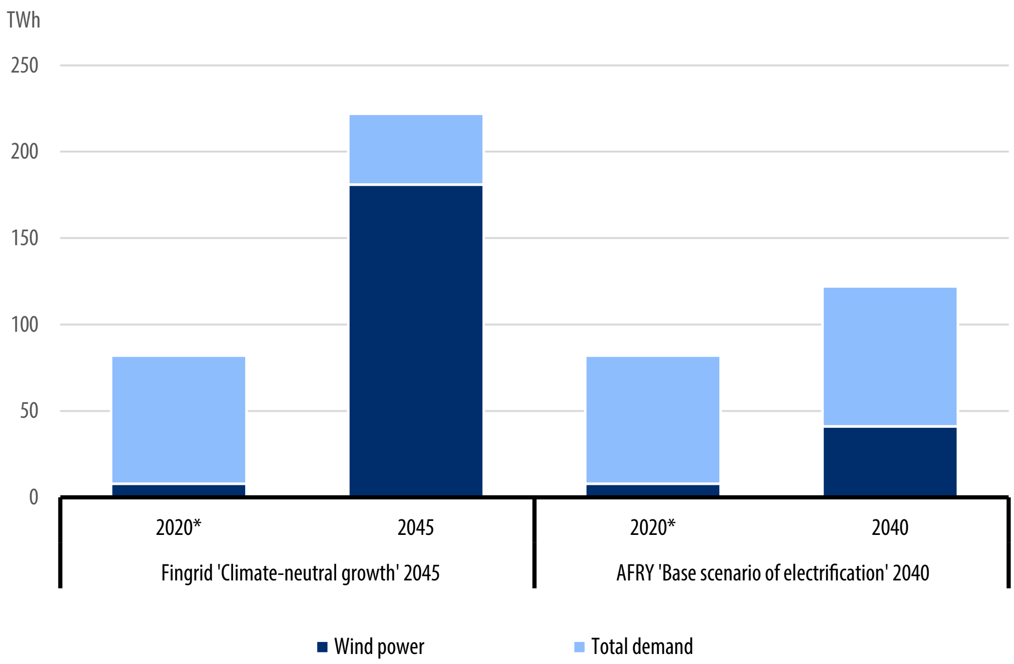
The above factors should be taken into account if there is a need to increase the size of the interim storages to enable consumption elasticity in electricity. Without interim storages, elasticity in the electrolyser plant would mean that the end user has to shut down their industrial production for the time hydrogen is not available. This would drive the marginal cost of consumption elasticity so high that consumption elasticity would become impractical. Therefore, the only way to implement consumption in elasticity in networked plants would be to increase the size of interim storages.

Long-term storage and transmission of hydrogen must take into account hydrogen's capability to diffuse through materials. While losses in natural gas networks arise mostly out of breakages or material damage, losses in hydrogen transmission networks also occur due to hydrogen diffusing through materials. This fact must be taken into account in the design long pipeline connections. There is currently no experimental evidence on the transmission losses in hydrogen transmission lines, but the losses can be expected to increase as higher transmission pressures are used. One source estimates a transmission loss of 0.77% per 100 km, which would mean a 14% loss in a 2,000 km transmission line (Mazza & Hammerschlag, 2004). Currently, experiments have been run only at pressures equivalent to distribution networks (3–4 bar) for mixtures of natural gas and hydrogen. Likewise, when hydrogen is stored in high pressure (250–300 bar in a steel vessel in industrial applications), significant hydrogen losses will occur, especially if the storage time is long.

Hydro power has traditionally acted as a balancing factor in electricity generation and price fluctuations in the Nordic countries, but the electrification scenarios show that demand might increase significantly and the electrical system cannot rely on the assumption that the existing hydro power generation is enough to balance the entire system in the future. In the long term, significant drivers will be the transmission connections being constructed in continental Europe and Great Britain, which means that the regulating potential of Nordic hydro power is distributed across a larger electricity market. We have already seen cases in which hydro power generation has been at a low level, which, combined with other drivers on the electricity market, has increased the price of electricity to a significantly high level. For example, in the second half of 2021, the monthly average of Finland's regional electricity price varied between 65 EUR/MWh and 193 EUR/MWh (Nordpool, 2022).

While demand increases, the primary new production capacity in the Nordic countries will likely be weather-dependent. In Finland, this means onshore wind power in particular, but also offshore wind power and solar panels (see Figure 24).

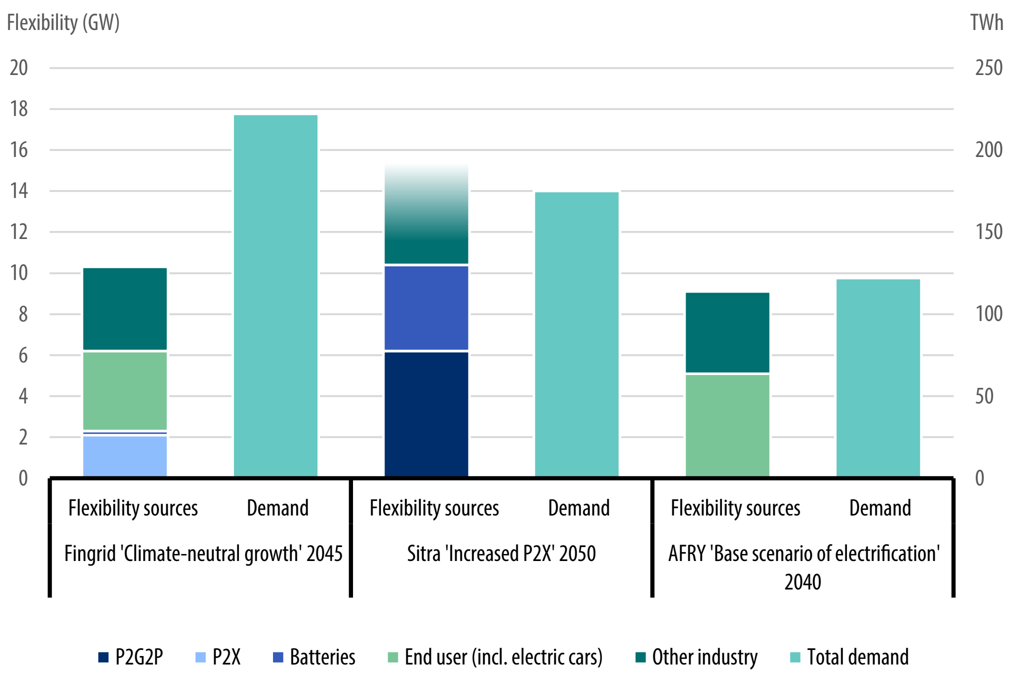
Figure 24. The share of wind power production in total demand in different scenarios in Finland (Fingrid, 2021a; Forsman et al., 2021, *2020 updated in accordance with the latest statistics: Statistics Finland 2022)



This means that while demand grows is linearly, the production that meets it is weather-dependent. To balance the entire system, Finland needs more flexible solutions, either flexible production capacity, demand elasticity or energy storages.

Three parties have recently published nationwide models of the electricity market: Fingrid (Fingrid, 2021a), AFRY (Forsman *et al.,* 2021) and Sitra (Roques *et al.,* 2021). Figure 25 illustrates the assumptions on total demand (TWh) and demand elasticity (GW) used in these models. All scenarios assume a significant amount of elastic demand from different sources. In Fingrid's 'Climate-neutral growth' scenario, elasticity comes from end users, mostly from electric vehicles and electric heating, the industry and P2X production. In Sitra's 'Increased P2X' scenario, elasticity comes primarily from batteries, P2G2P (Power-to-gas-to-power) production and elasticity in the industry, although the latter is not quantified in much detail. Sitra's scenario also assumes that new gas production capacity serves as a source of elasticity. AFRY's 'Basic electrification scenario' assumes that elasticity comes primarily from end users and the industry, including P2X production. In AFRY's scenario, the demand elasticity of the industry is not fully elastic, but rather 'peak-smoothing'.

Figure 25. Demand elasticity and total demand in different reports and scenarios (Fingrid, 2021a; Forsman et al., 2021; Roques et al., 2021)



It is worth noting that in all scenarios above, the need for elasticity grows significantly as wind power meets a large share of the demand. There is a significant number of sources of elasticity, but at the same time, all scenarios assume that the production of hydrogen participates in this elasticity even to a great extent. For electrolysis hydrogen, elasticity on the electricity market might mean either elasticity that limits demand, i.e. demand that reacts to price spikes by cutting consumption, or consumption that optimises price, i.e. demand that alters consumption on the basis of price signals. The first option is possible if the production capacity of hydrogen is higher than average demand and the demand can flex as necessary; the latter option is possible by overrating the electrolyser plant and constructing a hydrogen storage next to the electrolyser.

Electrolyser capacity and hydrogen storage are very expensive at the moment, and flexible production of hydrogen is not likely to be common in the initial phase of the transfer to hydrogen. Flexible hydrogen production might become more profitable in the future as hydrogen storage and production technologies evolve and wind power capacity increases.

In Finland, the need for elasticity can be partially achieved by increasing integration between sectors, especially between the electricity system and heating system. This would have two effects from the perspective of hydrogen and the electrical system;

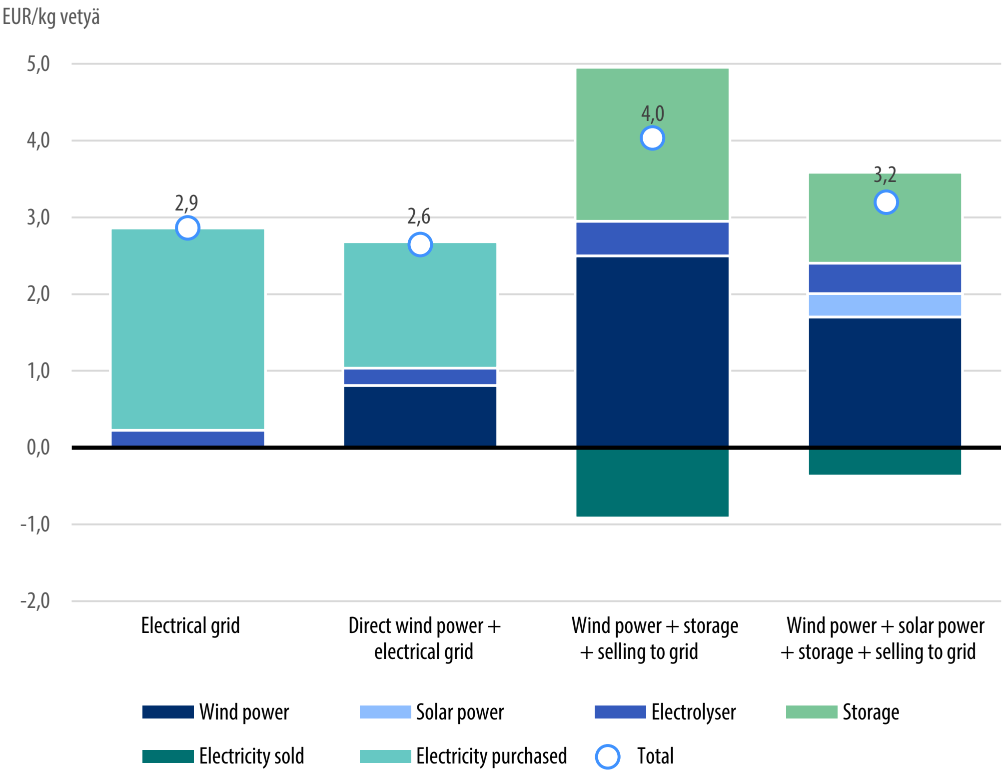
- Utilisation of waste heat – an electrolyser generates a significant amount of waste heat that could be used for district heating, among other thing. The utilisation is limited by the distance between the district heating networks and electrolyser plants and the seasonal variation in the demand for heating. It is likely that electrolysers will be located near the industrial plants that need hydrogen. In the more distant future, electrolysers might be placed near electricity generation plants. In such cases, the electrolysers might not be located near the district heating network, which reduces the potential to utilise waste heat.
- Electrification of heating – storing heat is usually cheaper than storing electricity. Electrification of heating could mean that district heating networks might play a role in smoothing out variations in electricity generation by storing generated heat when surplus exists and then utilising the stored heat when less renewable generation is available. This potential is limited by the total demand of district heating, storage technologies and the fact that demand for heating is highly inelastic.

8.4 Cost factors of hydrogen

The final price of hydrogen is affected by production costs and potential logistics costs. The production cost factors depend on the production structure. Potential production structures for electrolyser hydrogen are 1) an electrolyser connected to the grid, 2) an electrolyser connected directly to an electricity generation plant, for example as part of a wind or solar park, or 3) a combination of the above. The first production structure is the simplest: an electrolyser plant is located next to an industrial end user, for example. In the other options, the electrolyser is located at the electricity generation plant from which hydrogen is transferred to the end user by a pipeline. In other words, electricity transmission costs between electricity generation and the electrolyser are very low. The second and third option assume that future electricity generation will very likely be weather-dependent, in which case electricity generation must be smoothed out either by a hydrogen or electricity storage or by utilising the electrical grid and electricity markets. These factors will have a significant impact on the total cost of the hydrogen produced. This should be taken into account especially when calculating the total cost of hydrogen produced by renewable sources of energy, including the capacity required and the need for storage.

Figure 26 shows the impact these factors might have on the total costs. The results shown are based on an hourly-level modelling that seeks to minimise the total costs within the restrictions imposed by Finnish conditions in the future. In the first model, 'Electrical grid', hydrogen is produced by electricity at market price (~EUR 63/MWh). In the second model, hydrogen is produced by a combination of directly connected wind power and market-price electricity (alternatively, electricity generated by wind power is transmitted in the grid with very little extra cost). In the third model, hydrogen is produced entirely by wind power connected to an electrolyser, but the 'surplus' wind power could be sold to the electricity market. The fourth model is similar to the third, but it also uses solar power in addition to wind power. In all models, the final demand of hydrogen is the same and stays constant over time. The purpose of the comparison is to illustrate the combination of renewable sources of energy and hydrogen production.

Figure 26. Production costs of hydrogen in different production structures (the investment cost of an electrolyser in the models is set at EUR 490/kW)

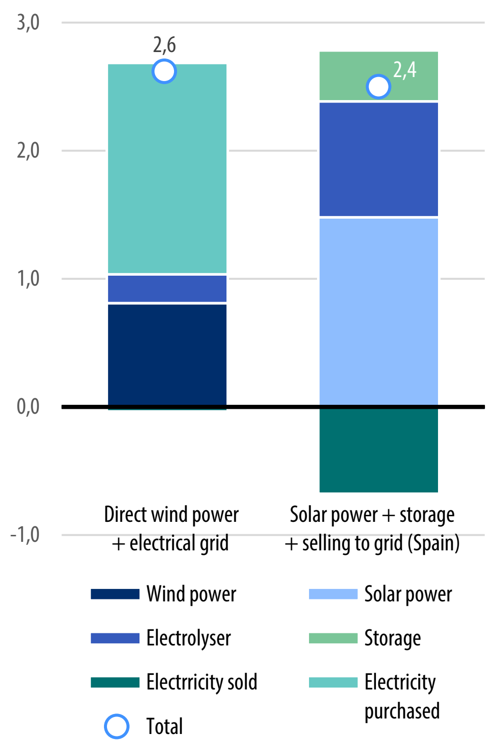


The first model indicates a relatively high price for hydrogen due to the relatively high price of electricity, although the price (EUR 63/MWh) is not unusually high on the Nordic electricity market. Relatively large savings can be achieved by combining wind power and the electricity market. If hydrogen were to be produced solely by wind power, significant overinvestments would have to be made on wind power, electrolyser capacity and storage capacity. The fourth model indicates that if the third model is supplemented by even a small amount of solar power, the price drops significantly.

The key observations that can be gleaned from the models are as follows: the electricity market will play an important role in the cost-effective combination of renewable energy sources and hydrogen production especially if the production is based on highly variable renewables, such as onshore wind power. Hydrogen production based solely on wind power might increase production costs significantly, and even a small amount of solar power might increase the viability of wind-power-driven hydrogen production.

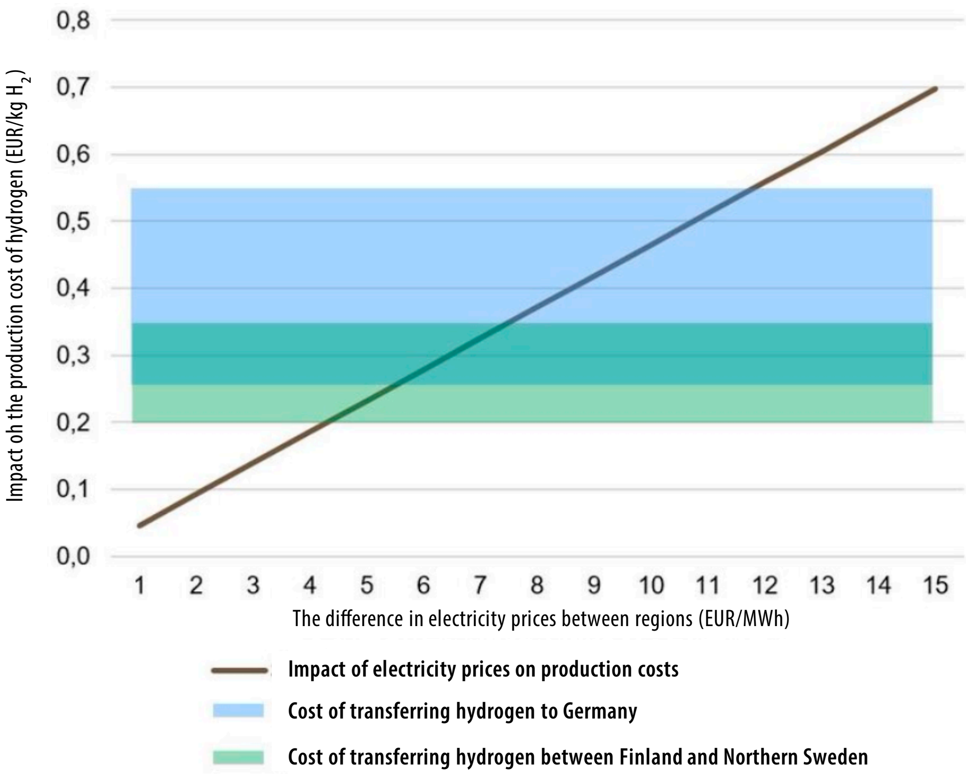
Figure 27 shows the results of similar modelling that compares Finland to another country, which in this case is Spain, where hydrogen would probably be produced by solar power. The figure compares the most cost-effective Finnish model to clean hydrogen produced in Spain by solar power. In the solar power example, hydrogen is produced solely by a solar power system connected to an electrolyser, but any surplus electricity can be sold to the grid at an assumed price of EUR 10 per MWh. It is worth noting that in the solar power example, hydrogen from an electrolyser that is almost 100% directly connected to electricity generation is relatively cost-effective compared to the previous example in which hydrogen production connected directly to wind power was not cost-effective. This suggests that in systems that rely heavily on wind power (especially onshore wind power), electricity market plays an important role in balancing production and demand, whereas in systems that rely on solar power, electrolysers connected directly to solar power are possible. It should be kept in mind that the insolation conditions in Spain are relatively constant, whereas some potential solar power areas (such as Middle East) suffer from sandstorms that might cause long production outages in solar power. A similar assessment was presented by EHB (2021), according to which the most cost-effective way of producing hydrogen in Europe is solar power in Spain.

Figure 27. Production costs of hydrogen in Finland and in Spain with different production structures.



The financial viability of hydrogen exports and competitiveness of exported hydrogen in the target country depend on several factors. A significant factor that affects cost competitiveness of electrolysed hydrogen is the cost difference in the price of electricity in the importing and exporting countries and the transmission cost of hydrogen between the areas. 28 below illustrates the maximum cost of hydrogen transmission in a pipe between two regions in order for the transmission to be financially viable given the difference in the cost of electricity between the regions. Transmission of hydrogen in a pipeline from Finland to Germany is estimated to cost EUR 0.26–0.55/kgH_2, depending on the export volume. The difference in the price of electricity should be EUR 6–12/MWh to make hydrogen produced in Finland cheaper than hydrogen produced in Germany.

Figure 28. An example of the difference in the price of electricity on the production cost of hydrogen between Finland and Germany and between Finland and Northern Sweden.



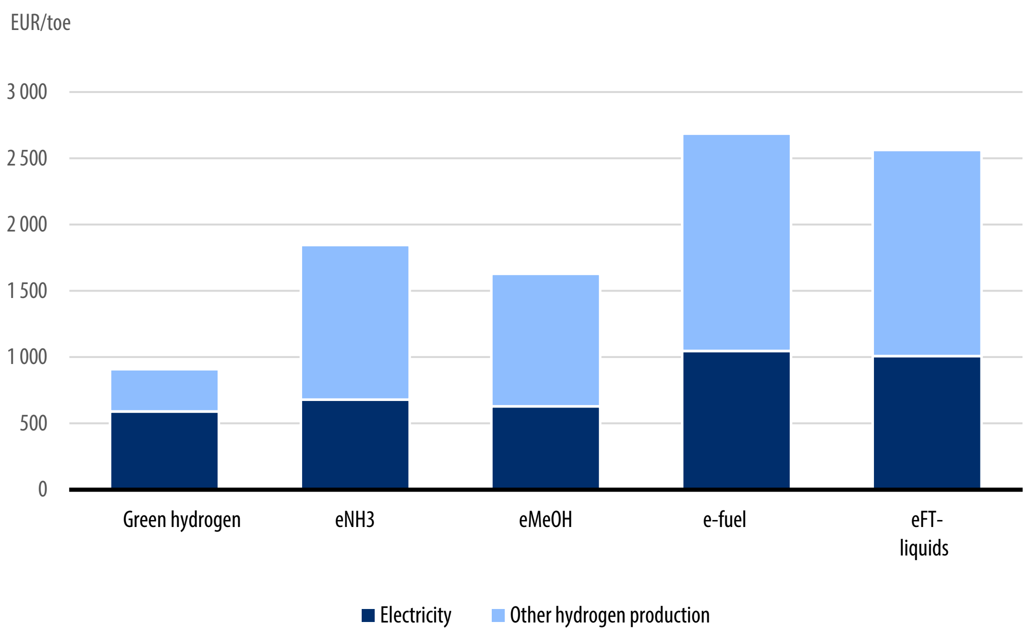
Since the transmission of hydrogen between Northern Sweden and Finland is estimated to cost EUR 0.20-0.35/kgH_2, transmission between the regions is profitable when the price difference is EUR 5–8/MWh. In recent years, the price difference between Northern

Sweden and Finland has varied between EUR 2–14/MWh, with the price being cheaper in Sweden (Nordpool, 2022).

The import and export of hydrogen is also affected by other factors than just the competitiveness of production costs. Among these factors is insufficient clean electricity capacity for domestic production of hydrogen, in which case hydrogen has to be imported elsewhere. Hydrogen pipelines between some areas, such as Finland and Northern Sweden, might enable a market in which the direction of hydrogen flow varies by the market situation and the wind power conditions at any given time. However, if one of the regions (for example Northern Sweden) has consistently better conditions and a lower average price of electricity, it is likely that hydrogen flows from that region to the region with more expensive electricity.

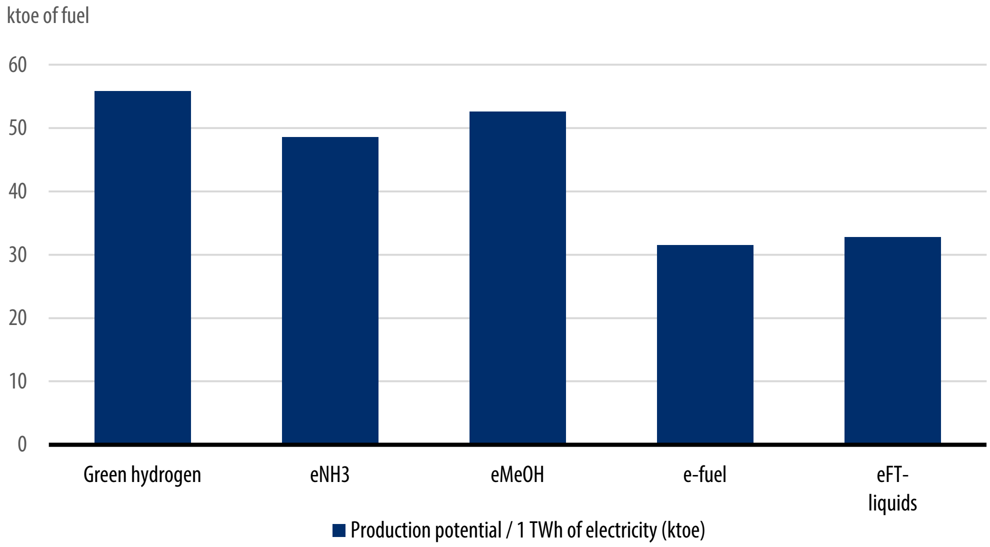
Figure 29 shows how the production costs of green hydrogen and four different e-fuels (synthetic ammonia, methanol, e-gasoline and other eFT liquids) are divided between electricity and other production costs. The figure is based on estimated production costs in 2040. If competitiveness of a country or region in e-fuels is primarily based on the availability of low-cost electricity, the greatest relative competitiveness is achieved in fuels in which electricity represents the largest proportion of production costs. Electricity represents up to two-thirds of the production costs of green hydrogen, whereas in the other e-fuels studied, its share is approximately 40%. Other production costs consists of investments in the production plant and other variable costs.

Figure 29. Share of electricity in the production costs of green hydrogen and some e-fuels in 2040.



If the production on e-fuels is limited by the availability of low-emission electricity, the production potential of e-fuels compared to the electrical energy available becomes essential. Figure 30 illustrates the production potential of different e-fuels from 1 TWh of electricity generation. The losses are highest in the most highly refined e-fuels, which means that less final product is obtained than green hydrogen, where the production losses are lowest. The amount of e-gasoline or eFT liquids that can be produced out of a given quantity of electricity generation is only 60% of the amount of green hydrogen.

Figure 30. Production potential of green hydrogen and some e-fuels out of 1 TWh of electricity generation.

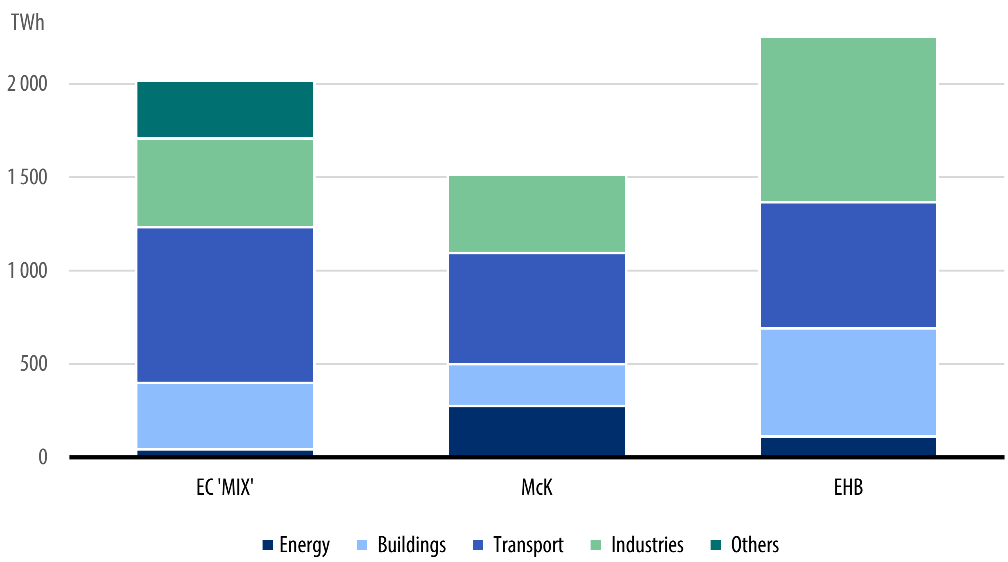


8.5 Development of an international market of hydrogen and e-fuels

The development of international demand for hydrogen and products refined from hydrogen contains uncertainties, as stated in Chapter 7.2. These include the speed at which demand develops in each country, the sectors in which the demand occurs, the trends in production capacity, export markets and production costs in each country and the market capitalisation of the international market for hydrogen and products refined from hydrogen. For Finland, hydrogen economy might be a significant export opportunity.

Many estimates predict that the demand for environmentally friendly hydrogen in the EU will rise to 1,500–2,000 TWh (see Figure 31). Some estimates are even higher, such as McKinsey (2021), who describes a hydrogen-focused scenario in which the European demand for hydrogen reaches up to 2,400 TWh per year. An interesting factor in terms of export potential is the distribution of demand between different products, because it will dictate which end products can be viably produced for export in Finland in the future. In all scenarios, transport fuels (including road, water and air transport) represent the largest category, up to one half of the total demand for hydrogen. Also in the scenario by EHB (2021), transport fuels represent a significant portion of the total demand, but the scenario considers the production of e-fuels as part of industrial demand. What this means for the export scenarios discussed in Chapter 7 is that a significant portion of the total exports should probably be e-fuels and other transport fuels.

Figure 31. Demand for hydrogen in Europe in different scenarios (EC, 2021; McKinsey, 2021; EHB, 2021)

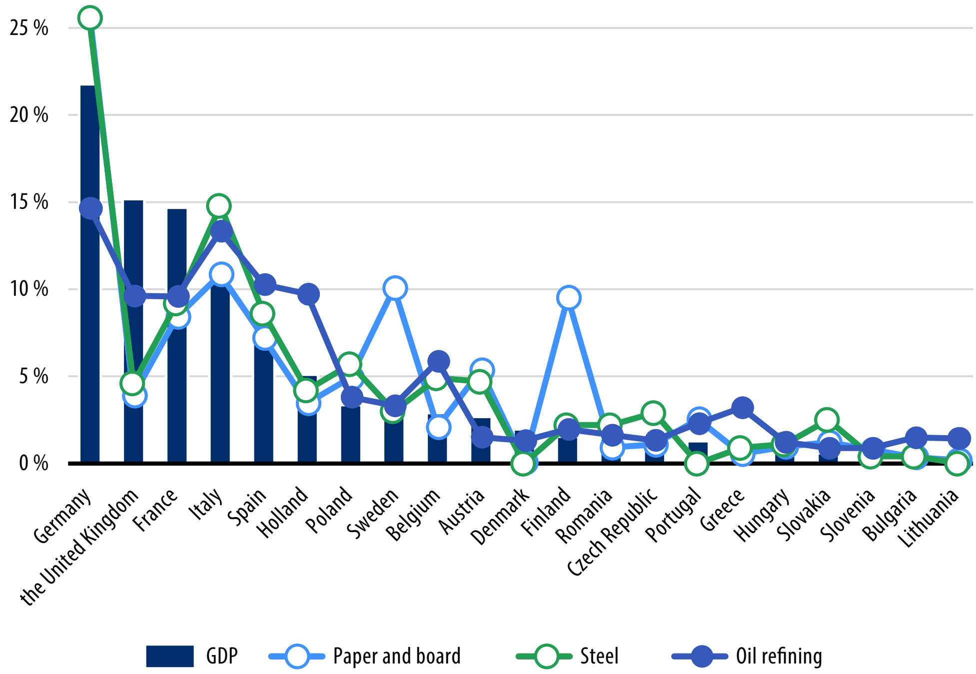


Production costs and production potential will have a significant impact on the type and production location of products that are supplied to meet the demand for hydrogen. Chapter 4 discusses the hydrogen strategies of various European countries in more detail. To sum up the chapter, most European countries have a hydrogen strategy whose objective is to increase exports EHB (2021) has studied the production potential and production costs of hydrogen in Europe. According to the EHB study and other studies, Europe has much more production potential than demand, since the production potential in 2050 is expected to be almost 4,000 TWh per year. The demand could primarily be met by hydrogen produced by solar power with a production cost of less than EUR 1.5/kg. Estimates on production potential have been presented by Kakoulaki *et al.* (2021) and other parties. Based on the studies, it seems that Europe has significantly more production potential for renewable energy than the forecasted demand for hydrogen. According to an estimate made by AFRY (see Chapter 8.4), hydrogen produced in Finland might nevertheless be competitive compared to hydrogen produced in Spain with solar power, for example. The differences in the outcome of the analysis are minor, which means that other factors, such as investment environments, permit processes and the electricity market might have a significant impact on investment decisions.

An international market might arise for products refined from hydrogen. According to an estimate by Roland Berger (2021), up to 40% of hydrogen used in Europe in 2050 might be imported from outside Europe. IEA (2019) has estimated that in many cases, local production will be the most cost-effective option, except if there is demand for the transported product as is. An example of such a product is ammonia which has potential for a future marine fuel. An assessment by EHB (2021) indicates the production of green hydrogen is more cost-effective in North Africa and other areas close to Europe than in Europe itself. EHB also assesses that the production of blue hydrogen in Norway or Russia might be very cost effective due to the extremely low price of natural gas, but verifying the origin of such hydrogen might be difficult.

The resulting balance between export and import will depend on the factors above, but other factors are also at play, such as the general investment environment, regulations, cost of capital, etc. Hydrogen and products refined from hydrogen will be bulk products, so the market structure of other bulk products might give clues to what the hydrogen market will be like. Figure 32 shows the share of some European countries of the GDP of the entire EU and their share of the market of selected basic commodities (steel, paper and cardboard, oil refining). The production, price formation and logistics of hydrogen will of course differ from the market of these products, but historically, few states 'punch above their weight' in basic commodities.

Figure 32. A comparison of the GDPs of some European countries and their respective share of the production of some industries in the EU and Great Britain (Eurofer, 2020; Eurostat, 2021; Fuels Europe, 2021; AFRY's databases)



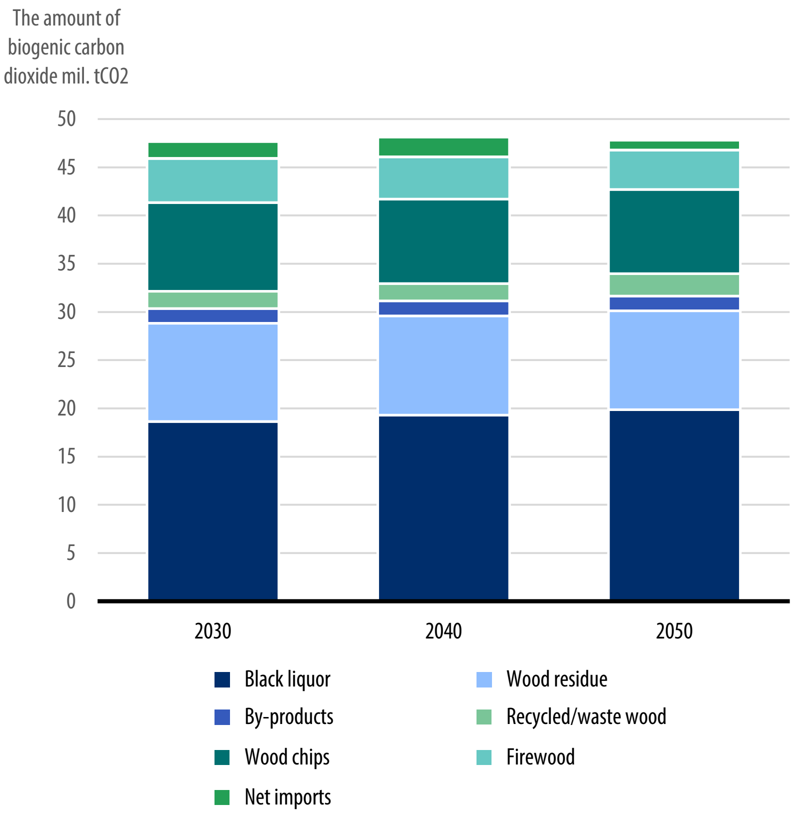
To summarise, the export of hydrogen and products refined from hydrogen is a significant potential for Finland. The demand of hydrogen will increase significantly in the future in Europe alone, and not all end users or countries are able to meet their demand by domestic production. Finland is probably capable of producing hydrogen competitively, but at the same time, Europe and the world have a significant amount of production potential for affordable hydrogen, which means that competition in hydrogen export will be tough and becoming an exporter country will not be easy.

8.6 Availability of biogenic CO2 in Finland

The manufacture of hydrocarbons and methanol from clean hydrogen requires biogenic CO2. Biogenic CO2 means CO2 obtained by burning or decomposing biomass. The availability of biogenic CO2 might restrict the types of biofuels that are commercially viable to manufacture in Finland.

Figure 33 below shows a gross estimate on the availability of biogenic CO2 in Finland, based on the consumption volumes of biomasses in the WAM scenario of the background report for the Climate and Energy Strategy (Lehtilä *et al.*, 2021) and the default emission factors of Statistics Finland for 2021[1]. In addition, small quantities of biogenic CO2 could be obtained from biogas burning and from the process in which biogas is refined into biomethane.

Figure 33. The availability of biogenic CO2 from biomass combustion, based on the use of biomasses in the WAM scenario of the Climate and Energy Strategy (adapted from Lehtilä et al., 2021)



The quantities of biogenic CO2 presented in Figure 33 above would be sufficient for producing methanol, methane and kerosene in all scenarios presented in this report. **In practice, the production of hydrocarbons and methanol would be restricted by the local technological and economic viability of biogenic CO2 and regulatory requirements.** The production capacity of industry and communities is partly located

1 The net import of wood in the WAM scenario consists of import of energy wood, which the model restricts to a maximum of 5 TWh (Lehtilä *et al.*, 2021).

in a densely built and inhabited urban areas, which means that captured CO2 should be transported to e-fuel production plants located further away. In addition, industrial-scale CO2 capture would mostly take place in large industrial plants.

During the transitional period, it might be cost-effective to source CO2 from both biogenic sources and fossil fuels or process side streams (if available), provided that the total consumption would be less than the supply of domestic biogenic CO2 and this utilisation would not prolong the use of fossil sources of energy. However EU regulation might not allow this for end products that are intended to be labelled clean or low-carbon.

8.7 Hydrogen transition in Finland and its impact on employment

Hydrogen transition will significantly increase the demand for labour, since the transition involves the entire hydrogen value chain from energy production to end use of products refined from hydrogen, including the export of products, technologies and services. The impact on employment is depends heavily on the volume of exports, while its lower limit is determined by the domestic demand for hydrogen and e-fuels.

The impact on employment would not be completely additional, since hydrogen transition also involves loss of jobs in value chains based on fossil fuels and feedstocks. **Nevertheless, the overall impact on employment in Finland would be additional and stem from the additional impacts of growth in export of hydrogen and e-fuels, steel and chemical industry products, technology and services**, although some jobs would be lost in parts of the current export value chains. On the other hand, the demand for labour in value chains associated with fossil fuels and feedstocks will inevitably diminish in the future, and hydrogen economy represent only one of the branches of sustainable economy in which the demand for labour will grow.

This study does not contain a quantitative estimate on the impact of hydrogen economy on employment, since it would require an in-depth study on the factors that increase and decrease the demand for labour in different sectors. However, the stakeholder interviews, workshops and surveys revealed the following areas that will increase the demand for labour in the hydrogen value chains and should therefore be taken into account when estimating hydrogen economy’s overall impact on employment:

- The lifecycle phases of investments associated with the production transmission (including transport, distribution, logistics) and end use of electricity, hydrogen and e-fuels: planning and design, construction, operation and decommissioning,
- The components of the hydrogen value chain: wind power (partly also bioenergy, solar power and nuclear power), electricity networks, hydrogen networks, production of hydrogen and e-fuels, new investments of industry that consumes hydrogen, storage of hydrogen and e-fuels, recovery, transmission and storage of CO2, distribution and end use of hydrogen and e-fuels in different sectors (air transport, maritime transport and heavy road transport) and export,
- Technology industry associated with hydrogen economy (investments, production, export),
- Design, consulting and maintenance services associated with hydrogen economy, RDI operations, financial services, educational services and other such services, and
- Indirect impact on employment in addition to direct impact on employment.

8.8 Stakeholders' opinions on political tools

During the scenario process, discussions were held with the stakeholders on a general level on the political tools needed in Finland to implement the transition to hydrogen. As the process was not directly associated with the preparation of the climate and energy strategy, the assignment did not involve making choices towards a specific goal or the processing of all viewpoints and means. As a result, the results below are not comprehensive and the responses focussed on the stakeholders' opinions:

- It must be possible to construct a lot of additional wind power.
- Finland's electricity transmission infrastructure must have sufficient capacity. Cost optimisation is needed on the construction of the electricity transmission and hydrogen transmission infrastructures. The needs to develop transmission infrastructure must be studies and obstacles to construction must be eliminated.
- Finland must have enough skilled labour for the design, planning and operation phases of hydrogen value chains.

- Ports must be ready to transport both liquid e-fuels and carbon dioxide.
- Finland needs investment subsidies.
- Finland needs to create demand, for example through distribution obligations and by reducing the carbon intensity of chemical industry products.
- Electricity from the grid must be clean (renewables, clean hydrogen and nuclear power).
- Investments in RDI activity must be made in areas that would foster the development of industry in Finland, development of technology and technology export.
- Hydrogen must be brought into the national climate and energy strategy and a national action plan must be established.
- University curricula and vocational training programmes must be updated towards hydrogen economy.
- Opportunities for retraining and supplementary training must be increased.
- Finland must develop national legislation required by hydrogen.
- The most important thing is to reduce emissions and not concentrate on the origin of the hydrogen.

9 Conclusions

This report presents an outlook on Finland's opportunities and limitations in hydrogen economy based on the emerging international hydrogen economy and the special characteristics of Finland. This chapter presents the key conclusions of the report.

9.1 A carbon neural society needs hydrogen economy

In the long term, hydrogen economy will become an integral part of the energy systems, industry, transport and economy of advanced carbon neutral societies. Hydrogen produced by clean and low-carbon energy sources might serve as an energy carrier and an intermediate feedstock in applications in which other solutions are not suitable.

The progress towards hydrogen economy requires focus, long-term commitment, comprehensive planning and political guidance that takes social needs into account, since this is the only way to ensure that the value chains become competitive and that the development of their components does not grind to a halt due to mutual interdependencies. The focus of the political tools and technical development affects the speed of the transition in a given end use sector. As a result, the **political tools must be designed carefully in order to achieve the desired results**, and not, for example, distort international competition of lead to undesirable results in terms of emissions reductions.

In the initial phase, production and end use will develop around local industrial centres. In the long term, the development towards carbon neutrality will **inevitably lead to the emergence of an international market for hydrogen and products refined from it**, just like for other commodities, since the starting points of developed countries differ in terms of hydrogen economy. The markets steer production and end use towards the most cost-effective solutions, although right now the size of the future market and other details are still uncertain.

9.2 Hydrogen economy will see rapid growth once the EU legislation completes

The role of hydrogen has been investigated in more detail in global (IPCC, IEA), regional (EU) and national climate and energy scenarios and by using these scenarios as a basis for roadmaps and strategies. The differences in the plans are significant due to the difference in national and regional starting points. In addition to industry and transport, hydrogen has been planned as a partial solution for heating buildings and balancing the electrical system as the production of weather-dependent renewable electricity increases. These supplementary areas are seen as important especially in countries that are currently dependent on natural gas (Germany, the Netherlands, Great Britain). Some countries have reported that they need to import large quantities of hydrogen (Germany, Japan, South Korea), whereas several countries have announced their intention to become exporters (such as Australia, Chile, Russia, Saudi-Arabia, Morocco, Namibia, Tunisia and Denmark).

Most of the hydrogen produced in the future will be clean hydrogen generated by electrolysis with solar or wind power. A competing technology is low-carbon hydrogen which is generated from natural gas and the generated CO2 stored. This production would use the existing production and transmission infrastructure of natural gas and production plants for fossil hydrogen. As a result, countries that produce a lot of natural gas and can store CO2 in large quantities in their vicinity (such as Great Britain and the Netherlands) are basing their solutions also on low-carbon hydrogen in addition to clean hydrogen. In addition, the Russian gas importer Gazprom has publicly stated that it is capable of delivering low-carbon hydrogen directly to Europe (Hydrogen Central, 2021), and at this phase, Germany is strongly promoting both ramping up its domestic production and production from regions close to Europe. As a result, **international competition on the hydrogen and refined products market will be fierce right from the start**, even though the growth phase will continue for the next 20 years.

Europe is leading the international development on hydrogen projects in terms of electrolyser capacity. The EU hydrogen strategy, wide-ranging public co-operation, financial support for hydrogen projects and the legislation being prepared have made Europe and its nearby regions an interesting development environment for hydrogen projects. As can be gleaned from public sources, there are thousands of industrial- and demonstration-scale projects underway on hydrogen production, refinement, transmission, distribution and end use in different sectors. The number of unpublished projects is estimated to be dozens of times higher. So far, only a few final investment decisions have been made, since the EU legislation is still being prepared and public funding has been granted to only a few ongoing projects.

Rapid growth in international hydrogen economy will being when the critical uncertainties associated with EU legislation have been solved. The European Union aims to reach carbon neutrality by 2050 and a 55% reduction in emissions compared to the 1990 level by 2030. The EU legislation package being prepared will lay down definitions on clean and low-carbon hydrogen, sustainable investments and regulatory conditions for the emergence of a hydrogen market with competition and an international hydrogen transfer infrastructure. In addition, the EU will allow state support for hydrogen projects under certain conditions and will grant loans for socially important infrastructure projects.

What comes to the political actions that Finland should take, **the key countries to monitor are Sweden, other Nordic countries and Germany**. Sweden's national hydrogen strategy sets a goal of 5 GW of electrolyser capacity by 2030 and 10 GW more by 2045. The strategy discusses financial incentives, RDI operations and the need to develop expertise, regulation and new value chains. Germany has earmarked EUR 7 million for projects that deal with the production of green hydrogen in Germany. The goal is to reach 5 GW of electrolyser capacity by 2030 and 5 GW more between 2035–2040. The state supports industry for example by 10-year Carbon-Contract-for-Difference agreements that help industries transfer to using low-carbon technologies. In addition, Germany invests EUR 2 billion on international co-operation projects with the goal of enabling the import of hydrogen into Germany. Of this sum, EUR 900 million has been earmarked for countries outside Europe. What comes to financial incentives, we should keep an eye on Great Britain which will probably introduce new financial incentives in early 2023. Also the Danish strategy is interesting in terms of hydrogen export. One of Denmark's traditional strengths is tight international co-operation to promote exports and Denmark's national interests. The Nordic countries have also launched cooperation on hydrogen economy at all levels, including research, business, transmission networks and political level (such as the Nordic Council of Ministers). For example, the preparation of a low-carbon roadmap for maritime transport between the Nordic countries starts as a four-year programme in spring 2022.

9.3 Finland's opportunities lie in high production potential for clean electricity and Finland's export industry

The starting point of the hydrogen economy scenarios presented in this study is that **Finland attains its carbon neutrality goal by 2035**, but this study does not take a stand on the transition to carbon neutrality in other respects than hydrogen and products refined from it. Finland's carbon neutrality goal can be implemented in different ways depending on the investment decisions of Finnish steel industry and chemical industry. Likewise, the emissions goals set by Finland for the transport sector can be met by various combinations of power sources and fuels.

From the perspective of Finland's carbon neutrality goal and national economy, **the most important end users of clean or low-carbon hydrogen are steel industry and oil and biofuel refineries**. Hydrogen is also needed in small quantities in other industries for replacing fossil gases. In addition, hydrogen and e-fuels are needed for heavy road transport and Finland's domestic and international air and water transport. However, these industrial and transport sector needs are low compared to the needs of the steel and chemical industry.

The domestic demand for hydrogen and e-fuels presented in the hydrogen scenarios only represents a part of Finland's entire production potential, since **Finland has a significant potential for additional construction of wind power**. It should be utilised by building more industry that is carbon-neutral and/or manufactures highly refined products in Finland. Above all else, Finland should **ensure that Finnish industry stays competitive** and only then create the conditions for meeting demand with Finnish for hydrogen and e-fuels. This prioritisation is necessary, since reaching the carbon neutrality goal requires major investments in steel and chemical industry. It would also ensure that industrial investments take place in Finland. The key factors for competitiveness in the production of hydrogen and e-fuels are mostly the same, but the development of exports requires a constant assessment of demand as the market changes.

E-fuels are more highly refined than plain hydrogen gas. However, it will take time for an international market to emerge for e-fuels/feedstocks. Compelling legislation (such as tightening emissions trade, distribution obligations) will also be needed, since the production costs of e-fuels are not competitive compared to their fossil counterparts. Therefore, it is likely that Finland has potential for export of hydrogen in addition to e-fuels. This would require the construction of an international export pipeline to Sweden, the Baltic countries and/or directly to Central Europe. However, as long as no such pipeline exists and fossil fuels are still used in Finland, hydrogen can be traded internationally by means of certificates of origin, although the hydrogen gas produced has to be consumed in Finland as a fossil fuel.

Hydrogen and e-fuel production plants should be closely integrated with industrial plants and energy generation for communities in Finland, since hydrogen electrolysis also creates oxygen and heat as by-products that can be utilised. Producing hydrocarbons and methanol from clean hydrogen also requires biogenic CO2 which is available from energy plants that burn biomass and from production facilities of the pulp and paper industry. In addition to the integration of production plants, **Finland must optimise the strengthening of electricity transmission networks and the construction of hydrogen transmission networks**. If wind power plants and hydrogen production plants are located far apart, significant investments have to be made on the electricity network. It is more economical to construct pipelines for transferring large quantities of hydrogen than strengthening the electrical grid. Hydrogen pipelines would help to smooth out the fluctuations in demand and production, but the challenge is whether the emerging production and demand volumes are large enough to warrant a construction of a hydrogen pipeline between them. Another way of approaching the challenges of selecting a physical location for hydrogen production, selecting a production technology or selecting a location for flexible capacity is to focus on the minimisation of the total costs of the transmission infrastructure. For example, CCS might be a solution in existing fossil hydrogen production plants if the transmission infrastructure has significant bottlenecks that would be too expensive to eliminate.

9.4 Challenges and limitations in the development of hydrogen economy

The transition of the industry and transport from fossil hydrogen and other fossil fuels and feedstocks to clean and low-carbon hydrogen still require a determined application of political tools, and the same goes for e-fuels. **Therefore, the highest risks in hydrogen economy are political, since hydrogen economy cannot be created without political guidance.** The size of the market for hydrogen and its derivatives and the rate of change of the market will depend on the focus of the actions. The incompleteness of the requirements concerning hydrogen and e-fuels and the upcoming changes to them create uncertainty throughout Europe. One of the risks for Finland is EU legislation if it fails to acknowledge the special characteristics of Finland or creates obstacles for competition. Among the critical questions for Finland's competitiveness are whether electricity generated by nuclear power or biomasses is allowed in the production of hydrogen, whether low-carbon hydrogen and natural gas are accepted as interim solutions and what kind of requirements are set for fuels generated with renewable electricity, including additionality of electricity procurement, balancing of electricity generation and consumption and what requirements are set for the origin of hydrogen imported into the EU from outside the EU, including the verification of the origin.

One of the risks is that political tools might promote solutions that are not good for sustainability. At present, the recovery of carbon dioxide in the production of fossil hydrogen is more profitable than the production of clean hydrogen, even though clean hydrogen is a better solution for the climate in the long term. **Sustainability should be approached comprehensively by investigating the lifecycle emissions of the entire energy system and end use sectors**. Direct electrification is always a preferred choice compared to hydrogen and products derived from it. Furthermore, the total efficiency of e-fuels is always poorer than that of hydrogen. Hydrogen should not be mixed with natural gas or refined into other products if it can replace fossil fuels directly. E-fuels can also drive biofuels from the market if the political control fails to pay attention to how much of each fuel type is needed. For example, the Nordic countries have highlighted synthetic methane as a good choice for an e-fuel, since its production costs are among the lowest of the e-fuels and the current natural gas technologies are directly available for the distribution chains of synthetic methane (Wråke *et al.*, 2021). However, this should be carefully investigated in context, including the electrification of transport, end consumption of biogas in industry and transport, the goal of reducing the use of all fossil fuels, the leakage risk of methane (the emission factor of methane leaking directly into the atmosphere is 25 times that of CO2) and the costs of methane from the perspective of the entire energy system.

The export opportunities of hydrogen and e-fuels are restricted first and foremost by the development of international demand and competition, and the current lack of hydrogen transmission connections. There are several countries in Europe and its nearby regions that seek to become exporters of hydrogen and e-fuels. Even though Finland has great potential for additional wind power construction, it does not guarantee that Finland can actually gain the corresponding share of the international market. Projects are developed by companies, and the investors who finance these projects make the decision on which country the projects are located in. In addition to electricity procurement, the investment decisions are affected by several other factors, such as the availability and procurement cost of utilities, construction costs, taxes and subsidies, the location and logistics of the production plant in relation to demand, the possibility to make long-term offtake agreements, the climate and energy policy, economy and cost-competitiveness of the country of location in the long term, opportunities for scaling the production, etc.

International competition involves market risks in price, supply and demand. For example, the competitiveness of hydrogen and e-fuels against their fossil counterparts is strongly affected by the price trends of emission allowances. In addition, international competition might start to favour imports from other countries than Finland. This might happen if EU widely approves the import of blue hydrogen from outside the EU.

Among the risks in a wide-scale export of energy products (electricity, hydrogen, e-fuels) is that it weakens the competitiveness of Finland’s domestic industry by driving up the costs of energy procurement. In hydrogen economy, Finland is already affected by competition that comes from within Europe and outside Europe. As a result, the export of energy products might turn out to be a low-margin business in the long term, which is why the comparison should be made against the production and supply costs of competing exporter countries instead of the production costs of the target market.

Hydrogen economy also involves risks for the energy system, such as a failure to design the entire system in a timely manner or match its components to each other, which would drive up costs and emissions, thereby reducing Finland’s competitiveness or that bottlenecks in the energy system restrict growth. Therefore, it might be a good idea to supplement the political tools with measures that help Finland find the most effective locations for production, storage and end use in view of the entire energy system.

End use of hydrogen involves technical risks and safety risks. For example, the transition to hydrogen in maritime transport depends on how the technology associated with methanol and ammonia develops. Technological development might also result in heavy road transport becoming electric, which further increases the uncertainty in the forecasts for future demand for hydrogen. Large-scale production, storage and transport of hydrogen also involves questions on safety and losses, since hydrogen diffuses through steel and can react explosively.

9.5 Political tools needed by Finland

Based on the hydrogen economy scenarios presented in this study, the following things are essential for the competitiveness of Finnish industry and Finnish exports in hydrogen economy:

a) **market price of electricity in Finland remains low** and the obstacles for constructing electricity transmission connections between Finland and Sweden and inside the countries are eliminated,

b) **additional construction of wind power faces as few obstacles as possible**,

c) **the construction of industry and industrial-scale hydrogen and e-fuel production plants faces as few obstacles as possible**,

d) the Finnish **transmission infrastructure for electricity and hydrogen is built cost-effectively and proactively to meet the need, including solutions that might reduce the need for constructing transmission infrastructures**, and

e) alternatives for constructing international hydrogen transmission pipelines are investigated in more detail.

Constructing international transmission connections for hydrogen gas required co-operation between countries to survey the available options. **An independent cost-benefit analysis must be carried out on the options of international transmission infrastructure of hydrogen from the Finnish perspective**, including the necessary investments on the Finnish electricity and hydrogen transfer networks. Investment decisions cannot be made until it has been demonstrated that a long-term need for transmission pipelines exists and private and/or public funding is available. This also involves the allocation of costs and risks between the parties and which parties would benefit from the investments. Furthermore, Finland should also investigate scenarios in which a pipeline between countries would result in imports into Finland, since the competitiveness of Finnish industries requires that they use the most cost-effective sources of hydrogen. Getting EU funding for a cross-border pipeline requires that **the project can be demonstrated to bring European-wide social benefits**.

One of Finland's **special characteristics is its ability to integrate the production of hydrogen and e-fuels with the forest industry and energy production for communities by means of biogenic CO2 and oxygen and heat that are generated as a by-product in electrolysis**. Many other European countries cannot use biogenic CO2 and recovery of heat for district heating as widely as Finland. Taking advantage of this special characteristic requires close collaboration between companies in order to develop best models for implementation and operation.

Heavy transport in Finland should concentrate on using electricity, biofuels and hydrogen as motive powers, as recommended by most international sources. In road transport, electrification must be prioritised. In heavy transport, hydrogen has better energy economy than synthetic methane, when the fleet based on fuel cells or hydrogen internal combustion engines is available. Physical biogas has to be consumed locally, whereas biofuels and e-fuels can also be exported. Political tools should promote the development of a distribution infrastructure that is based on electricity, biofuels and hydrogen and the transfer to new motive powers in heavy transport fleets.

Based on the above, the role of Finland's government in promoting hydrogen economy is as follows:

- To create clear short-term and long-term national goals and a concrete action plan for hydrogen economy.
    - To co-operate with the sectors in order to create a roadmap for hydrogen transition in that particular sector; the primary goal of this co-operation is to identify the actions needed to eliminate bottlenecks for development of the sector.
    - To create a national export promotion strategy for hydrogen economy products produced sustainably in Finland (such as steel industry products, chemical industry products, including hydrogen and e-fuels, other products and products associated with hydrogen economy).

- To look after Finland's national interests by promoting Finland's competitiveness and international carbon neutrality goals. This should take place by direct co-operation between countries and by ensuring that Finland is a member in the co-operation bodies and associations that influence the development of the hydrogen economy sector.

- To promote the availability of educated workforce needed for hydrogen economy (universities, polytechnics, vocational schools, further education).
- To remove obstacles for construction needed by hydrogen economy, such as additional wind power, industrial investments and the necessary transmission, storage and distribution infrastructure.
- To exercise political control in order to ensure that the development of Finland's energy infrastructure considers the electricity transmission, natural gas transmission, LNG and biogas infrastructure and future hydrogen transmission networks as a whole, including security of supply and reliability of delivery. The energy system must be developed holistically into a system in which both the production and consumption of hydrogen are elastic and resources are used efficiently. As for hydrogen, the location of hydrogen production with relation to the infrastructure is also a question that can be politically controlled by different means.
- To promote of hydrogen economy indirectly through state-owned enterprises and affiliated companies in their respective business areas and via public procurements.
- To enable the transition to hydrogen by supporting investments and production associated with hydrogen projects. This means a range of targeted measures to ensure that the solution is cost-effective for the society and leads to actual reductions in emissions.
- To identify the most important RDI topics for Finnish hydrogen economy (such as steel industry and other metal industry, chemical industry, maritime industry, electronic and electrical industry, energy industry, forest industry, energy transmission and transport infrastructures) and to promote RDI activities and networking on hydrogen economy by means of public subsidies, funding and networking services (Finnvera, Climate Fund, Business Finland, Academy of Finland, state research institutions, universities and polytechnics).

9.5.1 RDI activities must focus on technologies and innovations that are essential for Finland's competitiveness

Finland must invest in RDI activities by granting direct subsidies for the development of technology and services and by engaging in actions that promote networking between companies and research institutions domestically and internationally. In Finland, RDI should take place under research programmes that focus on **technologies**

and innovative services in which Finland will likely be competitive (this could be implemented via leading companies in hydrogen economy which have a network of partners in Finland) and emerging technologies which are not intensively researched internationally at the moment. In particular, replacing fossil fuels by hydrogen and its derivatives in marine transport and metal industry requires a lot of research and development in processes and technologies. **Pilot and demonstration project** can bring experimental evidence required by the commercialisation of new technologies.

Hydrogen economy will bring a need for new types of procurement chains and cooperation between companies in industry, transport sectors and the construction of energy infrastructure. **Co-operation networks** (clusters, ecosystems) focusing on different sectors are important platforms for co-operation and information exchange both domestically and internationally, since they set joint goals and action programmes for the hydrogen transition in each sector. Hydrogen economy also involves the **development of new operating models** as companies integrate their operations. **The results of publicly funded RDI operations should be, as far as possible, public and of interest to all companies in the sector**.

RDI operations can also be approached through thematic programme packages to ensure that Finland develops **new expertise** required by hydrogen economy. Examples of such themes are safety and standardisation aspects of hydrogen economy which were identified in the stakeholder interviews.

As the operations move towards practical applications, i.e. industrial-scale investments, commercial operations and looking after interests, political control of hydrogen economy needs to start using other methods than just RDI instruments.

9.5.2 Recommendations for further research

Finland needs political decisions on the goals of the development of a Finnish hydrogen economy and the measures to be taken to reach those goals. It is likely that several supplementary studies are needed in order to specify the measures at a sufficiently concrete level, as this report only presents general outlines and examples of measures taken in other countries. Examples of areas warranting further study are targeted measures that support hydrogen transition in different end use sectors in Finland, development needed in education and measures to promote international exports.

Research is also needed on how to align the components of the energy system effectively, including the location of hydrogen production, end use and flexible capacity in relation to the transmission infrastructure. Finland's development efforts in hydrogen economy could also look into possibilities for co-operation with Sweden, Germany and the Baltic countries. Finland's infrastructures for the transmission of electricity, natural gas, LNG, biogas and hydrogen must be developed in parallel, in accordance with actual needs and cost effectively. This development requires independent cost-benefit analyses from a Finnish perspective, preferably even before the transmission network owners start presenting their proposals for investments.

Appendices

Annex 1. Stakeholder engagement

Interviewed organisations and their representatives

Organisation	Interviewed persons
Aalto University	Annukka Santasalo-Aarnio
Business Finland	Helena Sarén
Climate Leadership Coalition	Jouni Keronen, Juha Turkki
EK	Matti Kahra
Energy Industries	Jukka Leskelä
Fingrid	Jussi Jyrinsalo, Mikko Heikkilä,
Gasgrid Finland	Olli Sipilä
Greenpeace	Kaisa Kosonen, Olli Tiainen
Climate Panel	Peter Lund
Finnish Chemicals Industries	Mika Aalto, Sami Nikander
LUT University	Petteri Laaksonen
Forest Industries	Ahti Fagerblom, Jyrki Peisa, Antti Tahvanainen
University of Oulu	Timo Fabritius
STTK	Antti Koskela
SAK	Lauri Muranen
Sitra	Oras Tynkkynen
VTT	Antti Arasto
Technology Industries	Kimmo Järvinen, Mervi Karikorpi, Martti Kätkä
Hydrogen Cluster	Outi Ervasti, Sakari Kallo, Matti Malkamäki, Simo Säynevirta

Annex 2. Stakeholder experts in scenario workshops

Jukka Leskelä and Pekka Salomaa, Finnish Energy Industries

Outi Ervasti, Simo Säynevirta and Matti Malkamäki, Finnish Hydrogen Cluster

Antti Arasto and Peter Lund, Climate Panel

Timo Ritonummi, Harri Haavisto, Juho Korteniemi, Jyrki Alkio, Bettina Lemström, TEM

Saara Jääskeläinen,LVM

Petteri Laaksonen, LUT

Tiina Koljonen, VTT

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