HYDROGEN STUDY OF THE BAY OF BOTHNIA

Final Report

ABSTRACT

This report presents the methodology adopted and results obtained in the hydrogen study of the Bay of Bothnia. The study took place from May to June 2021.

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1 Introduction

Climate change mitigation has proven to be the modern-day's biggest challenge. Due to this, targets have been adopted and strategies are being developed by nations in order to contribute on climate change mitigation. EU targets to be carbon-neutral by 2050, while Finland has set the same target by 2035. Sweden targets to be carbon neutral in 2045 at the latest.

The Green Deal presented by European Union in 2019 identifies clean hydrogen as a priority area for achieving carbon neutrality by 2050.[1)] Lately, the ambitious climate targets and possibilities offered by hydrogen have initiated extensive discussions on transition to hydrogen economy in Europe. Traditionally, hydrogen has been used in oil refining and chemical industry. There is, however, a large potential for the use of hydrogen in other industries as well, such as steel and other metals production. Furthermore, hydrogen and its derivatives play an important role in the Power-to-X concept which allows storage of electrical energy in various forms.[2)] The use of hydrogen could enable significant CO_2 emissions reduction provided it is produced in a low-carbon manner. Low-carbon production of hydrogen from non-fossil sources requires large amounts of electrical energy. It yields that, if hydrogen (along with electrification) is used for decarbonisation of industries, traffic, shipping etc., the demand for sustainable/low-carbon power will increase dramatically in the future.

Dedicated hydrogen production in Europe is appr. 9.8 Mt/a in total (less than 9% of the global production). Almost all hydrogen is produced from fossil raw materials. Majority of the produced hydrogen is consumed in oil refining (30%) and production of ammonia (50%). Including methanol production (5%) and metals industry (3%), these four sectors are responsible for appr. 90% of the total hydrogen consumption in Europe.[1)] In Finland, dedicated hydrogen production is appr. 140-150 kt/a, while the by-product hydrogen is produced appr. 22-24 kt/a.[2)] In Finland, most of hydrogen is also consumed in refining and chemical industry. Currently, Finnish steel industry consumes only a couple of hundreds of hydrogen tons/a. SSAB has announced that they will abandon the carbon-intensive BF-BOF route by 2040 and adopt hydrogen-reduced iron as the main raw material. Provided that the plan will realize, appr. 150 kt/a of hydrogen is needed for iron reduction. This is roughly as much as the total production volume in Finland today. As SSAB steel plant is located at the Bay of Bothnia, it follows that there will be an enormous increase in the demand of green hydrogen in the future.

Suitable conditions for wind power and plans to extend the wind power production in the area offer a prerequisite for producing low-carbon hydrogen in the area. Due changes in the weather conditions, there are fluctuation in wind power production. Therefore, there is low-cost electricity available at times when the supply is higher than demand. Hydrogen or its derivatives could offer a possibility to storage electric energy when excess, low-cost electricity is available. This, however, affects the net efficiency greatly as the original form of energy is converted multiple times. Furthermore, it includes that the challenges in storing hydrogen are solved. Due to decrease in efficiency during multiple conversion(s), it is probable that electrification is preferred in those application where it is possible. However, there are also applications where hydrogen is needed as such.

In this study, a questionnaire study for the companies and municipalities in the area of the Bay of Bothnia was carried out for mapping the hydrogen related activities and plans. Some of the participants were also interviewed after the questionnaire. The main goals were:

- An up-to-date assessment of the companies' and organizations' plans related to hydrogen economy (planned activities during 2020s, overall schedule for the transition)
- An up-to-date assessment of the restrictions for transition to hydrogen economy in general and of the specific restriction in different part of the value chain
- Description of the research needs
- Description of the expertise research organization has to offer

The questionnaire was planned in cooperation with University of Oulu, VTT, Educational Consortium OSAO, Oulu University of Applied Sciences (Oamk) and BusinessOulu. The study was commissioned by Oulu Innovation Alliance and funded by Council of Oulu region and City of Oulu and City of Raahe.

2 Hydrogen production

Today, vast majority of a global hydrogen production is based on the use of fossil raw materials (natural gas, coal, oil). Fossil-based hydrogen production has a considerable carbon footprint unless equipped with carbon capture and utilization/storage (CCUS) technology. However, there are low-carbon options for the hydrogen production as well. In terms of sustainability, hydrogen is typically classified depending on the technology and raw materials as presented in Table 1.

Table 1. Typical classification of hydrogen.[1,3]

Type of hydrogen	Description
Grey hydrogen	Produced typically from natural gas by steam-methane reforming at a cost appr. €1.5/kgH_2. This production process results in emissions of 10-30 kgCO_2/kgH_2.
Blue hydrogen	Produced as grey hydrogen, but the CO_2 is captured and stored permanently. Production cost is appr. €2/kg. Emissions are appr. 5-15% of those in the production of grey hydrogen.
Green hydrogen (or renewable hydrogen or clean hydrogen)	Produced by electrolysis of water with renewable electricity. Reported cost vary between €2.5/kg to €8/kg depending on the source. No GHG is emitted during the process
Turquoise hydrogen	Produced by pyrolysis of natural gas, with solid carbon as a side product. Technology is still at an early stage of development.

2.1 Fossil-based technologies

Currently, almost all hydrogen is produced from fossil raw materials globally.[1)] The mostly used technologies are: 1) steam reformation (SMR) of methane, 2) partial oxidation (POX) of methane and 3) coal gasification. Globally appr. 95% of hydrogen is produced using these technologies with natural gas or coal as the raw material.

Hydrogen produced from fossil raw materials is called *grey hydrogen*. Production of grey hydrogen yields substantial CO_2 emissions: Depending on the raw material and technology, the emissions fall into the range of 10-30 $kgCO_2/kgH_2$.[1)] With the CCUS technology it is possible to significantly lower the CO_2 emissions. Hydrogen produced in this manner is called *blue hydrogen*. Production of blue hydrogen cannot be done totally emission-free: CO_2-capture efficiencies are expected to reach 85–95% at best, which means that the other 5–15% is leaked. It must be noted that the emissions of blue hydrogen do not include up-stream emissions of the supply chain of natural gas. The escape of methane into the atmosphere in different parts of supply chain increases lifetime emissions. Furthermore, if the increased need of hydrogen will be covered with blue hydrogen it would increase the need of natural gas and, hence, the absolute upstream emission would increase substantially.[2)]

2.2 Low-carbon production technologies

There are also low-carbon methods for hydrogen production. Water electrolysis and photocatalysis enable production of hydrogen without CO_2 emissions. There are few different technologies for water electrolysis, some of them are already commercially available. Photocatalysis is still quite immature technology but basic research regarding photocatalysis is gaining momentum. In the NATIONAL HYDROGEN ROADMAP for Finland[2)], it has been evaluated that water electrolysis will the employed technology for producing low-carbon hydrogen in the near term.

2.2.1 Water electrolysis

In practice, water electrolysis is a method that currently can respond to the demand of clean hydrogen in the large scale. The use of water electrolysis in hydrogen production requires large amounts of electricity. Thus, the question on the availability of clean hydrogen in the future boils down to the availability of clean electricity and also availability of water electrolysis technology.

There are three electrolyser technologies available: 1) Alkaline electrolysers (AEL), 2) Polymer electrolyte membrane electrolysers (PEM) and 3) Solid oxide electrolysers (SOEC). Table 2 presents data on electricity consumption, efficiency and CAPEX of different technologies now and in the future. In the near term, AEL and PEM will be the applied technologies for water electrolysis. SOEC is not yet commercially available but under development.

Table 2. Technological and economical features of different water electrolyser technologies.[1-2)]

Technology	**Alkaline**			**PEM**			**SOEC**		
Time window	**Today**	**2030**	**Future**	**Today**	**2030**	**Future**	**Today**	**2030**	**Future**
Electricity consumption (kWh/kgH_2)	50–51			55–58			40–41		
Electrical efficiency (%, LHV)	63-70	65-71	70-80	50-60	63-68	67-74	74-81	77-84	77-90
CAPEX (USD/kW_e)	500-1400	400-850	200-700	1100-1800	650-1500	200-900	2800-5600	800-2800	500-1000

2.2.2 Photocatalysis

Photocatalytically produced hydrogen from water is considered as the cleanest and most promising energy vector of the future. The photocatalytic hydrogen production can be realized in two major ways: 1) via direct water splitting (direct scission of water into H_2 and O_2), and 2) via reforming of organics in either a liquid or a gas phase. Currently, the low quantum efficiency of the photocatalytic materials in hydrogen production is limiting the practical application of the technology on a large scale. The low hydrogen production rates are partly associated with limitations in band gap excitation and recombination of the charge carriers in semiconductor photocatalysts. The other solar-driven hydrogen production systems are photovoltaics-assisted electrolysis (PV-E), and photoelectrochemical cells (PEC), but photocatalysis is predicted to be the most cost-effective of these methods.[4-5)]

3 Low-carbon electricity production

Sustainable hydrogen production requires large amounts of low-carbon electricity (wind and solar power, nuclear power etc.). Table 3 contains a preliminary data of the total electricity consumption and production along with imported electricity in Finland in 2020. As it can be seen, appr. 57% of the supplied electricity was low-carbon power (hydropower, wind power, solar power and nuclear power). In terms of green hydrogen, the work on the EU taxonomy for defining the allowed energy sources for green hydrogen production is still uncompleted. For instance, there are still open questions on how the hydropower and nuclear power (and also bioenergy) will be positioned in the EU regulation. However, wind power is certainly part of the taxonomy which, in terms of hydrogen economy, favours the Bay of Bothnia due its suitable conditions and extending wind power capacity.

Table 3. Electricity production in Finland in 2020.[6)]

	Quantity (GWh)	Share of total electricity supply (%)
TOTAL ELECTRICITY CONSUMPTION	81072	100.0
1 ELECTRICITY PRODUCTION	66123	81.6
1.1 Hydro power	15608	19.3
1.2 Wind power	7970	9.8
1.3 Solar power	256	0.3
1.4 Nuclear energy	22358	27.6
1.5 Hard Coal	2317	2.9
1.6 Oil	227	0.3
1.7 Natural gas	3549	4.4
1.8 Peat	2155	2.7
1.9 Wood fuels	10032	12.4
1.10 Other renewables	640	0.8
1.11 Other fossil fuels	811	1.0
1.12 Other energy sources	200	0.2
1.13 Other fuels	..	..
2 NET IMPORTS OF ELECTRICITY	14949	18.4

In Sweden majority of electricity is produced by nuclear power and hydropower. Wind power is a significant source of electricity and it is expanding its share of the total electricity production in the future. Table 4 presents the electricity production by source in Sweden in 2019. It can be seen that the share of hydropower, wind power, solar power and nuclear power produced in Sweden is appr. 85% of the total electricity supply.

Table 4. Electricity production in Sweden in 2019.[7)]

	Quantity (GWh)	Share of total electricity supply (%)
TOTAL ELECTRICITY CONSUMPTION	174700	100.0
1 ELECTRICITY PRODUCTION	165629	94.8
1.1 Hydro power	64969	37.2
1.2 Wind power	19847	11.4
1.3 Solar	663	0.4
1.4 Nuclear power	64334	36.8
1.5 Conventional thermal power	15816	9.1
1.5.1 CHP in industry	6716	3.8
1.5.2 CHP in public steam ant hot water works	8924	5.1
1.5.3 Condensing steam power	168	0.1
1.5.4 Gas turbines and others	9	0.0
2 NET IMPORTS OF ELECTRICITY	9070	5.2

3.1 Wind power

3.1.1 Finland

At the end of 2020, the total wind power capacity was 2.5 GW in Finland and the production totalled 7.8 TWh of electricity corresponding to appr. 10% of total electricity consumption. In addition, there are sizeable investments for building new wind power capacity. According to Finnish Wind Power Association[6)], there are 240 on-shore projects and 9 off-shore projects on-going in different stages comprising 18.5 GW and 2.8 GW of new wind power capacity, respectively. If all the projects were to realize, it would tenfold the wind power capacity in Finland. The projects that are fully permitted or under construction will increase the capacity by appr. 6 GW, by 2023 the cumulative capacity is prognosed to increase to 5 GW, presented in Fig. 1. According to Fig. 2, the annual wind power production will total almost 16 TWh in 2024, i.e. production will be roughly doubled in comparison to 2020 in the next few years. Of the reported projects 2/3 will locate in the Bay of Bothnia.

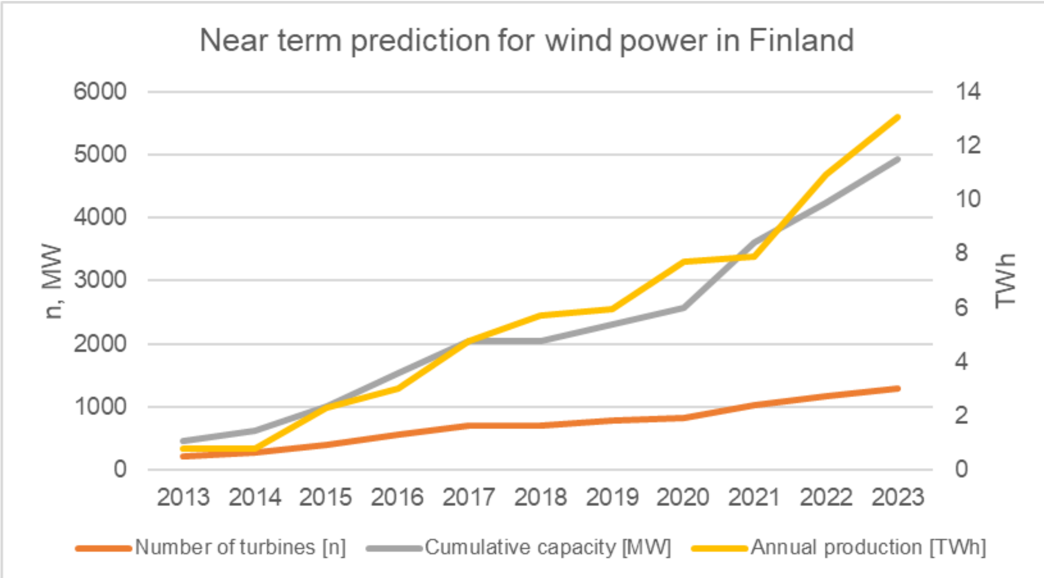

Figure 1. Prognosis of the number of turbines, the cumulative wind power capacity and annual production in Finland in 2021-2023.[8)]

3.1.2 Sweden

In Sweden, the total wind power capacity was 10 GW at the end of 2020 and the total wind power production was 27.5 TWh. As in Finland, the wind power production is increasing strongly in Sweden in near term (2021-2024). A prediction for annual production varies from 44 to 54 TWh in 2024 while the cumulative capacity is going to reach appr. 17 GW. In the northern most part of Sweden where this study locates, the projects signed or under construction will increase the wind power capacity by 1.21 GW in 2021-23.[7)]

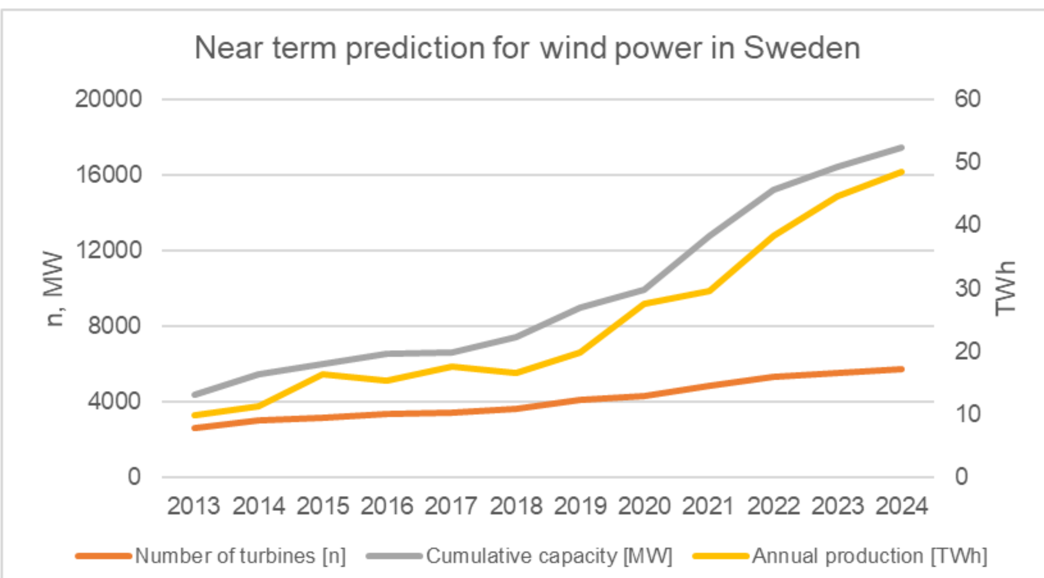

Figure 2. Prognosis of the number of turbines, the cumulative wind power capacity and annual production in Sweden in 2021-2024.[9)]

3.2 Solar power

3.2.1 Finland

The scale of electricity production by photovoltaic (PV) power generation is much smaller in comparison to wind power generation in Finland. According to the annual report of the International Energy Association[10)], the total installed grid-connected PV capacity was appr. 300 MW in Finland in 2020. The report states that there is no specific national strategy nor objectives for photovoltaic power generation in Finland. Instead, solar PV is mainly considered an energy technology that can be used to enhance the energy efficiency of buildings by producing electricity for self-consumption.

3.2.2 Sweden

In Sweden, the cumulative grid-installed PV power was 714 MW in 2019. The PV power capacity has been in rapid increase during the last few years, but it still plays a very small role in Swedish electricity production with 0.7 TWh annual production in 20219 which represented 0.4% share of the total production. However, it has been estimated that the potential for electricity produced by roof-mounted solar cells in Sweden amounts to over 40 TWh per year.[10)]

3.3 Hydropower

3.3.1 Finland

Hydropower is a significant form of renewable energy in Finland. In 2020, the total hydropower capacity was over 3 GW. Finland's 400 power plants more than half are hydropower plants. The electricity generated through hydropower totalled 15,6 TWh in 2020 which was appr 19% of the total production.[6)] The potential of extending the hydropower capacity is quite limited. However, hydropower plants have a very important role as load following plants. Therefore, in renewable energy system hydropower can used for balancing the fluctuation typical for wind and solar power generation.

3.3.2 Sweden

In Sweden hydropower is the major form of electrical energy. In 2019, 65 TWh of hydropower was produced representing appr. 37% of the total production.[7)] Sweden has 1800 hydropower plants and 600 regulating damns, although 203 over 10MW plants produce 93% of all hydropower and almost all regulatory power.[11)]

3.4 Nuclear power

3.4.1 Finland

Finland has four nuclear reactors in operations in two nuclear plants. The nuclear reactors produced appr. 28% (22.4 TWh) of the electricity in the country in 2020 being the largest source of electrical energy.[6)] The reactors are among the most productive in the world with the capacity factor of 95%. The existing nuclear power capacity under operation totals 2.8 GW. Fifth reactor (Olkiluoto 3, 1.6 GW) is under construction and commercial operation is scheduled to start in 2022. Sixth reactor (Hanhikivi, 1.2 GW) is planned. If all the projects are realized, it would increase the total nuclear power capacity to 5.6 GW. Hanhikivi locate in Bay of Botnia area and would increase low carbon electricity production in the area.

3.4.2 Sweden

In Sweden, nuclear power provided 37% of the electricity (64.3 TWh) in 2019.[7)] Today, there are 6 reactors in 4 plants in operation with capacities varying from 990-1400 MW with the total capacity of 6.9 GW.[12)] The nuclear power production is concentrated to the southern part of Sweden.

4 The hydrogen study of the Bay of Bothnia

4.1 Geographical area

Fig. 3 shows the geographical area the study was subjected to. The companies that were contacted for the study for the most part locate to this area. The municipalities indicated in the map were also contacted. In addition, some companies outside the geographical area, that were considered having a strategic importance in transition to hydrogen economy in Finland and at the Bay of Bothnia, were contacted.

Figure 3. Geographical area in the study.

4.2 Methodology

The study was carried out as a web-based questionnaire for the companies and municipalities in the area. For obtaining participants, appr. 70 companies and 12 municipalities were contacted directly. In addition, the questionnaire was distributed via Finnish Wind Power Association and Akraamo as well as LinkedIn. The companies that were contacted directly were chosen by recognizing them as a current or potential future actor in the hydrogen value chain. In total, 37 organizations answered the questionnaire. Participants are presented in Table 5. The questionnaire was implemented using Webropol 3.0 online analysis and survey tool.

Furthermore, participant's willingness for taking part in an additional interview was asked in the questionnaire. Overall, 16 organizations were interviewed. Unfortunately, due to a tight schedule in the project we couldn't interview all the willing organizations.

As for the public organizations (municipalities), only one organization participated in the study. Also, the participation activity in Sweden was quite low with only two companies taking part in the questionnaire.

Table 5. Participated organizations in the study.

Company/organization	**Interview**
Air Liquide Finland Oy	No
ALTEN Finland	No
Aurelia Turbines & vetyklusteri	Yes
Bet-Ker Oy	No
Eastman	No
Fortum	Yes
Freeport Cobalt	Yes
Freeport Cobalt Oy	Yes
Gasgrid Finland Oy	Yes
Gasum	No
Iin kunta	Yes
Kemijoki Oy	Yes
Kemin Digipolis Oy	No
Kemira Chemicals Oy, Oulun Tehdas	Yes
Kiertokaari Oy	No
Korsu Oy	No
Liftlink Oy/Hooli Stevedoring Oy	No
Linde	No
Liquid Wind	No
Metsä Group	No
Neste	No
Nouryon Finland Oy	No
Oilon Technology Oy	No
Oulun Energia Oy	Yes
Oulun Satama Oy	No
Outokumpu	Yes
P2X Solutions	Yes
Pentti Hämeenaho Oy	No
Presteel Oy	No
Raahen Satama Oy	Yes
Ramboll Finland Oy	Yes
Rejlers Finland Oy	No
ReNext Generation Oy	No
Rovaniemen kaupunki/Napapiirin Energia ja Vesi	No
SSAB	Yes
St1	Yes
Storaenso	No
Wärtsilä	Yes

5 Results

The questionnaire was divided into four categories:

Category	Purpose
1. General questions	To clarify plans, schedule, conditions and barriers for transition to hydrogen economy
2. Production of hydrogen	To clarify in more detail the current status, future plans, schedule, barries etc. related to the current/planned position in the hydrogen value chain
3. Transport and storage of hydrogen	
4. Use of hydrogen	

The general questions were aimed for all respondents. Given the relevance, the respondents could choose to which of the following, value chain-based categories they answer.

5.1 SWOT Analysis

As a result of the questionnaire and interviews, a number of strengths, weaknesses, opportunities and threats were recognized related to transition to hydrogen economy in the area (Fig. 4). As for the strengths, there already is production of hydrogen in the Bay of Bothnia which could contribute for a kick-starting in the wider use of hydrogen. There are also significant new opportunities for using hydrogen including hydrogen-based steelmaking. The increase in the production of wind power in the near term improves the availability of low-carbon energy for green hydrogen production. Finngrid's investment plan on power grid is further improving the outlook as hydrogen production using electrolysis requires substantial amount of electrical energy. Another encouraging aspect revealed in the study was that safety issues were not considered an insurmountable obstacle at any part of the value chain.

Weaknesses include poor availability of green hydrogen at the moment. Transfer and storage infrastructures are not sufficient at the moment. This part of the chicken-egg problem related to hydrogen economy: production of green hydrogen doesn't exist because there is only limited use of hydrogen (demand), infrastructure is lacking because there is not need for it due small demand etc. Furthermore, some industrial players have found it difficult to get large enough amounts of hydrogen for larger experiments. This might slow down the transition if it is not possible to do suitable tests due to difficulties in supply.

Transition to hydrogen economy includes lots of opportunities. Firstly, hydrogen offers a significant possibility for reducing CO_2 emission in many industries. There is a strong political support for hydrogen economy in national and EU levels which enhances realizing the potential. Large enterprises are showing genuine interest towards hydrogen and many of them have on-going or planned RD&I activities on the topic. Furthermore, there are opportunities related to integration: 1) Large amount of O_2 and heat are produced as side streams in the hydrogen production by electrolysis which could be exploited; 2) Hydrogen and its derivatives can be used for the storage of electric energy (P2X). EU's Recovery and Resilience Facility (RRF) funding instrument provides funding opportunities for RD&I projects related to hydrogen economy.

Threats related to hydrogen economy include uncertainties in the EU regulation, high production cost of green hydrogen and the chicken-egg problem. As for the EU regulation, uncertainties in, e.g., classification of hydrogen and taxonomy, were recognized as a threat for the transition. The classification of hydrogen (i.e. the "color coding") was considered unclear. The taxonomy related to suitable energy sources in green hydrogen production is still under preparation: it is unclear how, e.g., hydropower and nuclear power will be positioned in the taxonomy. Production costs (and, thus, the price of the end-product) of green hydrogen are currently much higher in comparison to that of fossil-based hydrogen. The danger is that high costs will hinder the demand and market for green hydrogen is not going to be formed. The chicken-egg problem is another threat that can possibly prevent the transition or delay it substantially. Market prospects understandably have an effect on investments on hydrogen production. At the moment, the demand for green hydrogen is quite low. On the other hand, availability of green hydrogen (with a fair price) affects the transition from fossil-based alternative to green hydrogen. And in between, the lack of suitable transfer and storage infrastructure further complicates the situation.

Based on the SWOT analysis, it can be concluded that the Bay of Bothnia has a significant potential in relation to hydrogen economy. There are RD&I and business opportunities in every part of the value chain. The reception from the companies has been very enthusiastic and promising. Furthermore, 2021 saw the kick-off of BotH2nia, an international network for building a large-scale hydrogen economy around the Bay of Bothnia. The area has also been noted on the EU level as a very potential location from the hydrogen economy point of view.

Strengths	**Weaknesses**
• Significant new opportunities for using hydrogen in the area • Production of hydrogen already takes place in the area • Availability of renewable energy is increasing in the future • Solid power grid and announced investment for further improvement of the grid (2 billion € by Fingrid) • Safety related issues can be solved	• Poor availability of green hydrogen due to limited production at the moment • Transfer and storage infrastructure is insufficient • Availability of hydrogen (e.g. for industrial experiments) is difficult in general
Opportunities	**Threats**
• Hydrogen offers a significant reduction potential for CO2 emission • Strong political support • Genuine interest and investments by large enterprises • Opportunities for integration (useful sidestreams: heat, O_2) • Sectoral integration (storage of electric energy) • RRF funding opportunities	• Uncertainties related to regulation (taxonomy, REDII) • High production costs of green hydrogen • Chicken-egg problem prevents the progress (no production, no use/no use, no production)

Figure 4. SWOT analysis of the results of the questionnaire and interviews.

5.2 Prospect for the hydrogen economy

According to the questionnaire results 67% of respondents have an existing plan for hydrogen or synthetic fuel related business (Fig. 5). However, it revealed that only 31% have a plan for the transition to hydrogen economy (Fig. 7). It could be concluded that hydrogen related business is widely planed among the respondents, but most players are in very early stages in the transition to hydrogen economy. This emerged in the interviews as well: transition is a chicken-egg problem. The lack of hydrogen production prevents the use and vice versa. This further bolstered by the missing infrastructure for transfer and storage. Some actors are planning activities in multiple parts of the value chain and more than half have plans related to hydrogen production or use (Fig. 6).

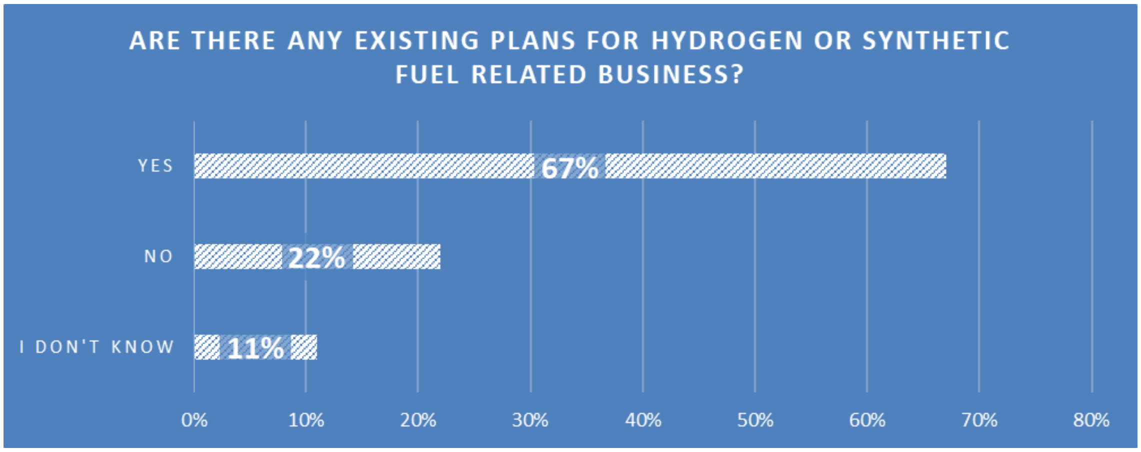

Figure 5. Respondents' opinion on hydrogen and synthetic fuels related business.

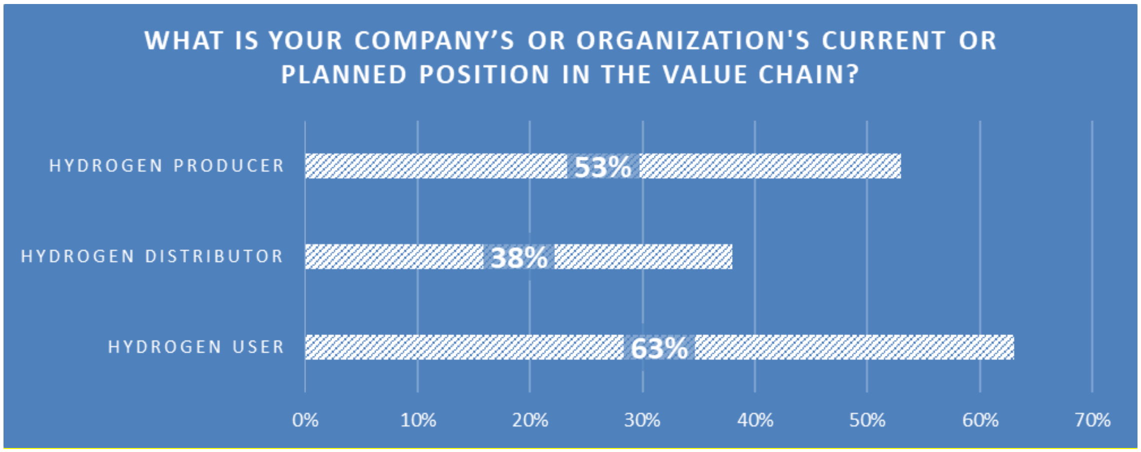

Figure 6. Respondents' position in the hydrogen value chain.

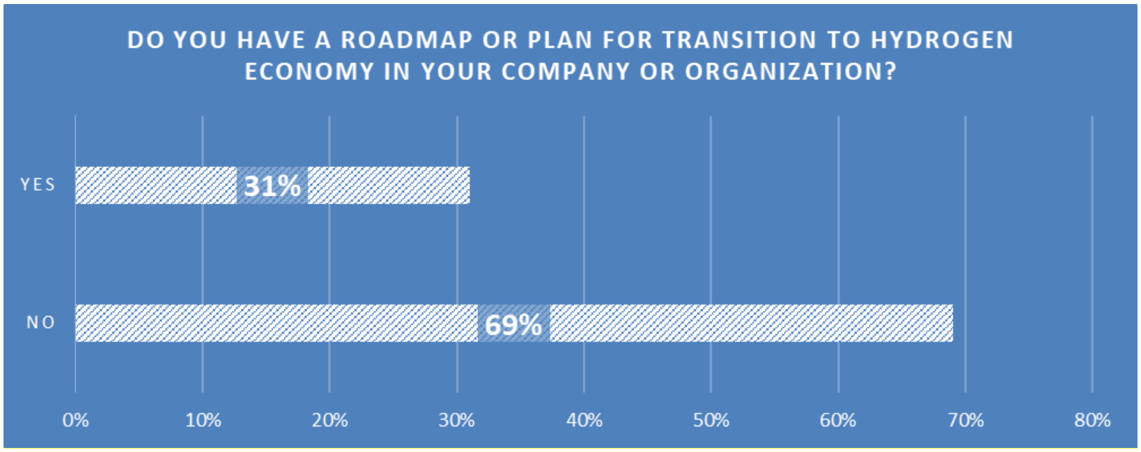

Figure 7. Roadmap situation for the transition to hydrogen economy.

Most of the organizations estimated that the overall transition to hydrogen economy takes 10-15 years (in 2030s at the earliest). For some, the transition takes longer, to 2040-50. Metsä Group is planning to be fossil-free by 2030, Neste by 2035. SSAB has announced it will be a completely fossil-free company by 2040, Fortum targets the same by 2050.

As for the intermediate goals in transition, the level of planned actions varied strongly. Many organizations are observing how the situation develops and making assessments without any clear investment plan. This due to the uncertainty in relation to availability of hydrogen, economic feasibility of using hydrogen and (low) efficiency of current technology. At the largest, the intermediate goals contain demonstration scale projects (SSAB, St1) in 2020s and up-scaling to industrial scale in the following decade(s). SSAB is planning to build a demonstration plant to Malmberget for producing hydrogen-reduced iron (H_2-DRI) and hydrogen with electrolyser capacity of 400-600 MW by 2026. P2X Solutions has announced that their first industrial scale hydrogen production plant is targeted to be operational already in 2024. Hycamite has announced that building their pilot plant for producing turquoise hydrogen will begin in 2022. Aurelia Turbines aims to develop turbines fuelled by 100% hydrogen within a few years. Wärtsilä is currently developing 100% hydrogen fuelled engines.

Lowering CO_2 emissions includes a variety of actions in addition to utilization of hydrogen. Over 90% of the organizations reported having a plan for reducing industrial CO_2 emissions (Fig. 8). The actions include improving energy efficiency, favoring low-emission products, circular economy, gradual transition to carbon-neutral raw materials etc. As for utilizing industrial CO_2, 36% of the organizations are planning to utilize produced CO_2 (Fig.9). The plans include utilizing CO_2 for producing synthetic fuels/other carbon-containing product as well as making preliminary assessments on capturing produced CO_2 provided that there are suitable end-users.

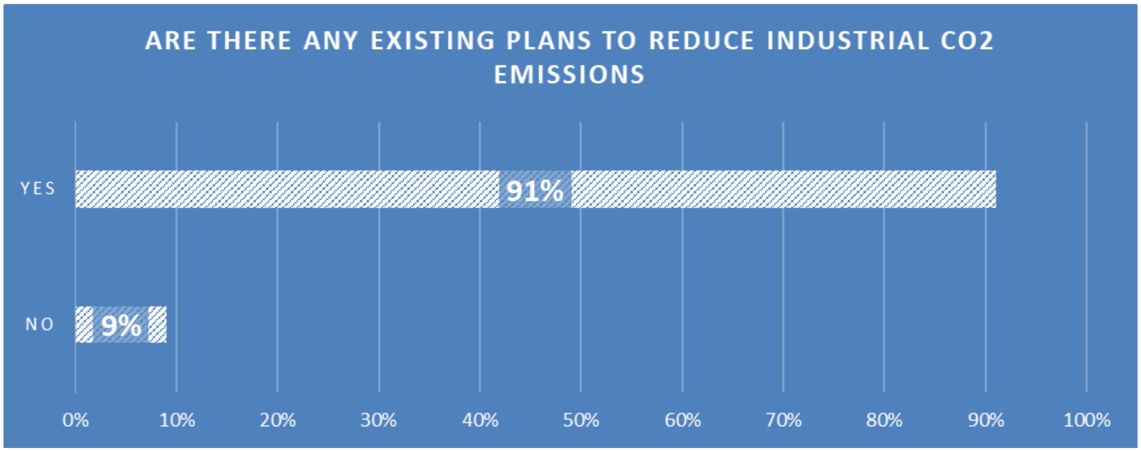

Figure 8. Position in reducing industrial CO_2 emissions.

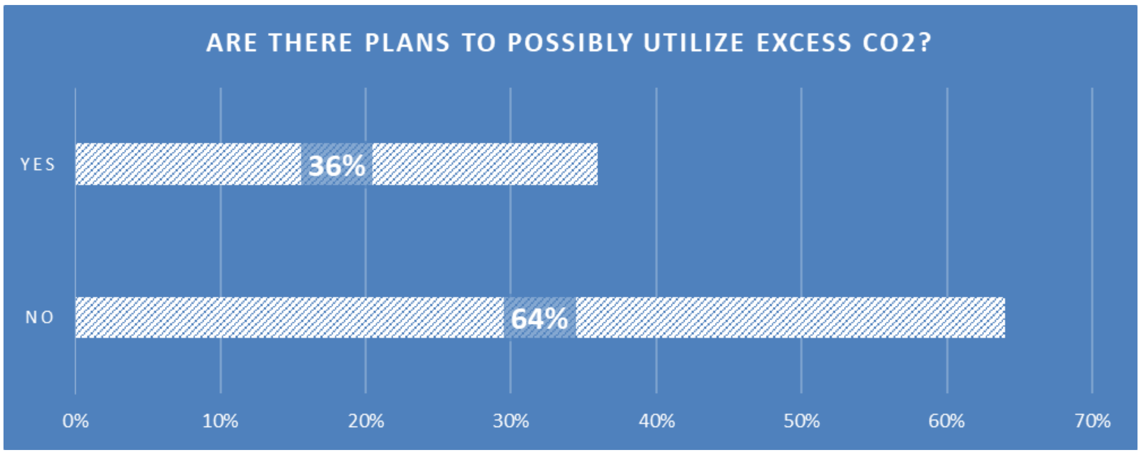

Figure 9. Position in utilizing excess CO_2.

Prerequisite for hydrogen economy is the availability of renewable energy. In general, the situation with the electricity grid is considered good or at least decent for the current situation. However, in the questionnaire it arose that if transition to hydrogen economy was to realize, the main grid must be strengthened especially if large wind parks are to be connected into it. SSAB's plans in Sweden and Finland require building of new power lines: 400 kV and 130 kV lines in Sweden and 400 kV in Finland. Fingrid has announced its willingness to invest 2 billion euros on expanding and strengthening the main grid during this decade.[13)] In the interviews, it was noted that although the investment on the main grid is well-founded in many ways, it should be also considered how the hydrogen and electricity production are situated in relation to each other. As for the local electricity generation, 92% of the organizations reported that there is local electricity production in the area (Fig. 10). Although there already is low-carbon energy available (Fig. 11), most of the respondents considered that there is a need for more renewable energy in their area (Fig. 12). There are also plans to build new electricity generation in the area (Fig. 13).

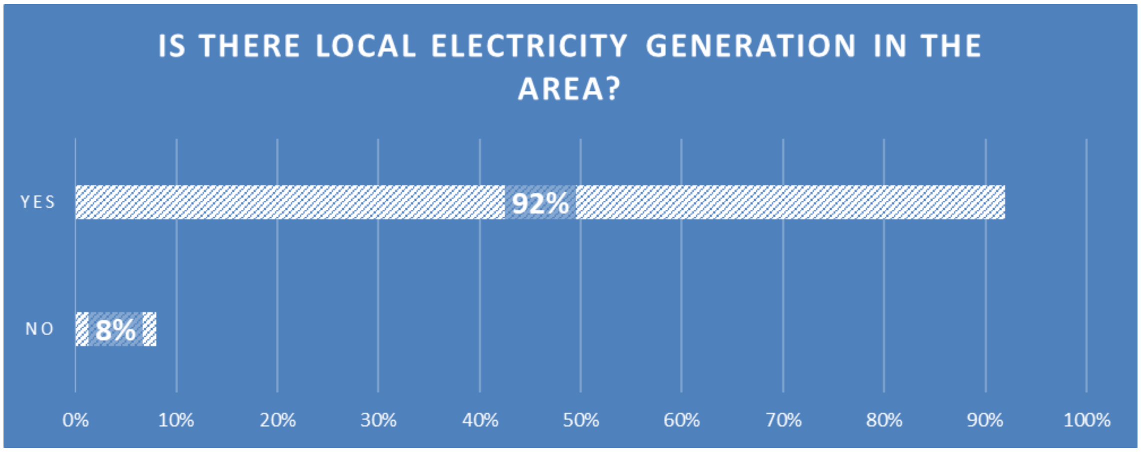

Figure 10. Situation for local electricity generation in the respondent's local area.

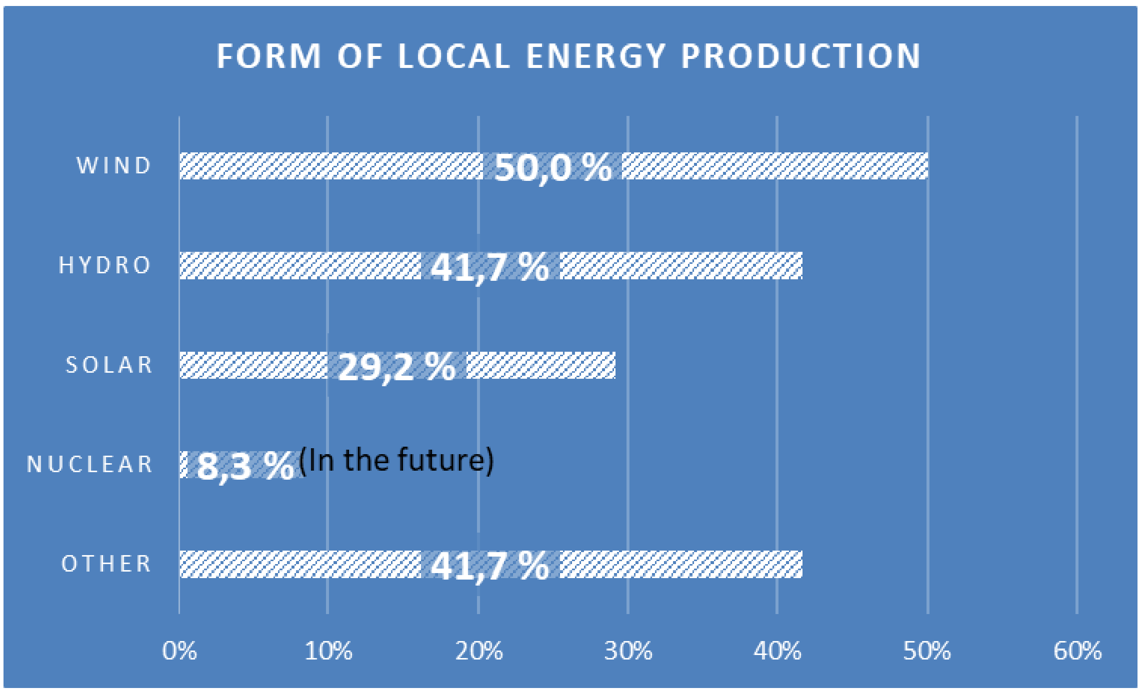

Figure 11. Form of local electricity production in the respondent's local area.

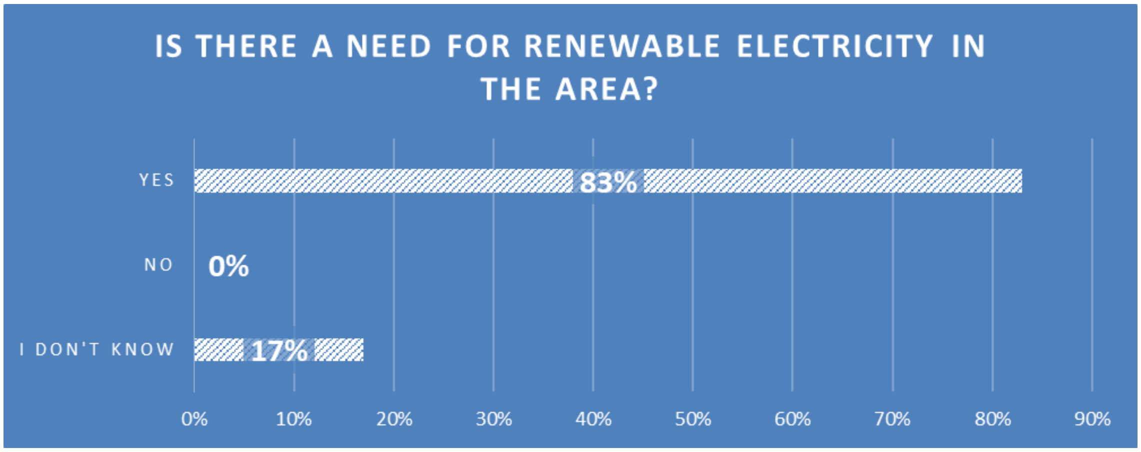

Figure 12. Need for renewable energy in the repondent's local area.

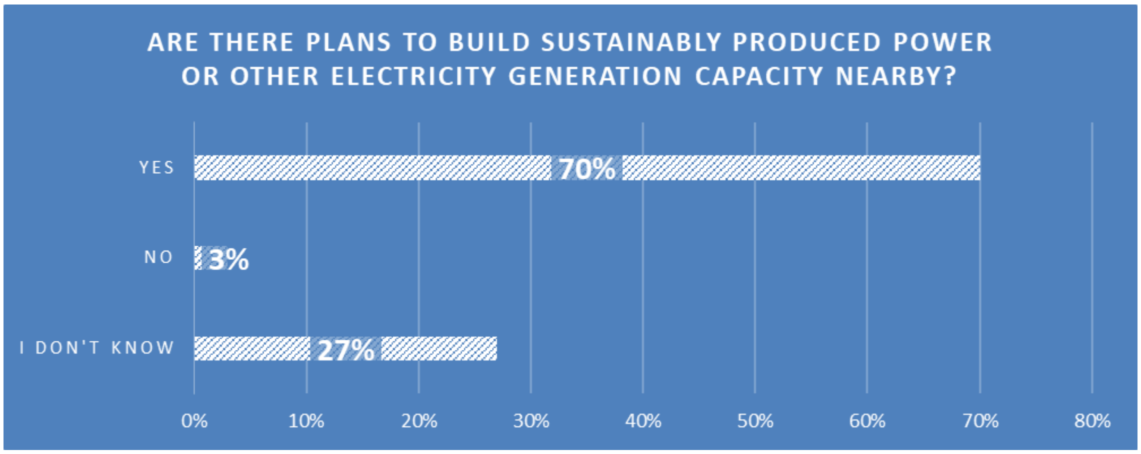

Figure 13. Plans for building new power generation in the repondent's local area.

A quite common conception was that the first step in the transition to hydrogen economy is the development of industrial *hotspots*, i.e., the production and use of hydrogen take place near to each other. If the electricity is also produced in the same location, the main grid is not needed for transferring electricity to hydrogen production. This could be an appealing option as the price of the product would not be affected by the electricity transfer price. However, in general it is not realistic to assume that electricity production, hydrogen production and usage of hydrogen will take place in the same location. It follows that, in addition to strengthening the main grid, a major progress in the transfer and storage infrastructure of hydrogen is needed. Possible hotspots recognized in the Bay of Bothnia in Finland were: Kokkola, Raahe, Oulu and Kemi/Tornio (Fig. 14).

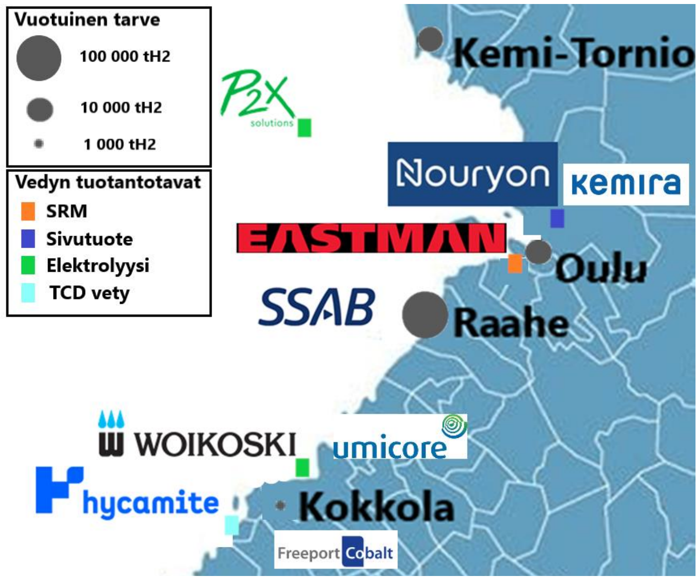

Figure 14. Possible hydrogen hotspots recognized in the Bay of Bothnia (Finland).

5.3 Production of hydrogen

The scale of production of hydrogen in the area of the Bay of Bothnia is tens of thousands of tons per year at the moment. There are three active companies in the area that produce hydrogen: Woikoski (Kokkola, electrolysis), Eastman (Oulu, methane steam reforming) and Nouryon (Oulu, by-product from chlorine production). In the questionnaire, 8 companies informed that they are planning to produce or they already produce hydrogen. Planned/current production volumes of all companies are thousands of tons per year. All companies did not disclose the volumes, but the scale of total production volume will remain the same at least in the short term. Both dedicated and by-product hydrogen are/will be produced (Fig. 15).

Majority of the respondents are planning to produce green hydrogen (Fig. 16). Hydrogen is mainly produced for industrial use and production of synthetic fuels. As for the plans during 2020s, the level of concreteness was variable. P2X Solutions announce that they are planning to build a green hydrogen production plant to Harjavalta. Provided that the plan realizes, the plant should be ready in 2024.

Plans in the short-term (2021-26) and medium-term (2026-30) are described in Table 6. Many of the respondents are in an observing position at the moment, i.e., they have interests towards producing hydrogen but for multiple reasons (uncertainties in legislation and regulation as well as overall progress of the situation) they have no short-term activities or investments coming. On the other hand, there are actors that are launching RD&I activities and even production (P2X Solutions) is planned to begin during the next 5 years. Concrete activities and investments as well as expanding the production are mostly planned for the latter half of 2020s.

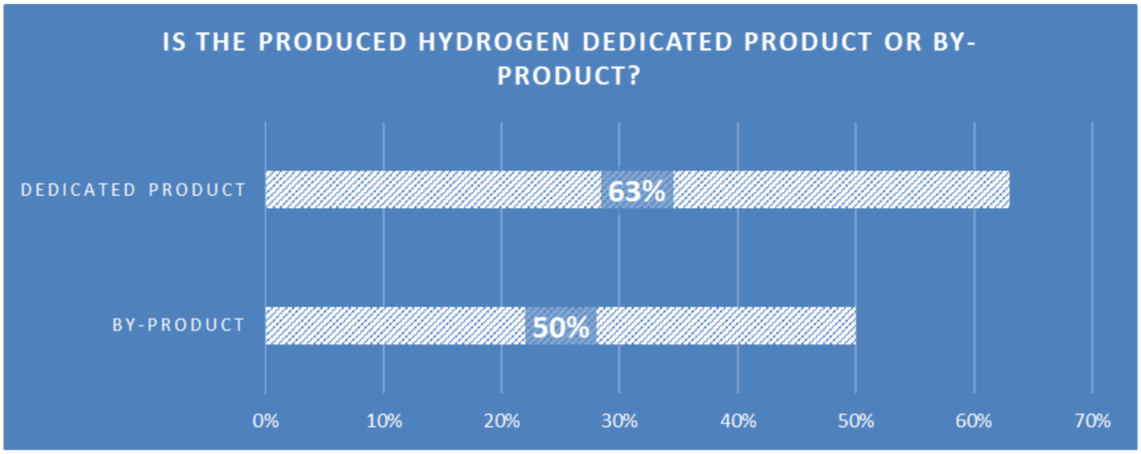

Figure 15. Type of hydrogen production among the current and future producers.

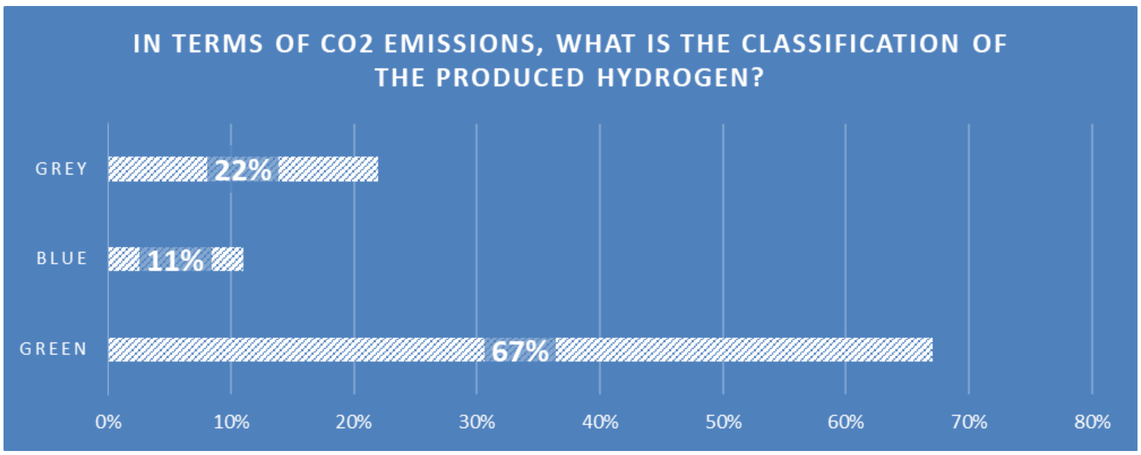

Figure 16. Classification of produced hydrogen among the current and future producers.

Table 6. Planned actions for hydrogen production in short and medium term.

Planned actions for hydrogen production	
2021-2026	2026-2030
• Assessment of the situation and observation of the development • RD&I activities • Launching the production	• Implementation of technology • Investments on green hydrogen • Expanding the production

5.4 Transport and storage of hydrogen

According to the study, in the hydrogen value chain the biggest uncertainties were related to transport and storage of hydrogen. Large scale storage of hydrogen is not possible at the moment due to the lack of storage facilities. Longer storage of hydrogen would require pressurized storage which increases the costs. Furthermore, there is no transfer infrastructure available for distributing larger amounts of hydrogen.

Pipeline transfer is seen the most preferable choice for hydrogen distribution in the questionnaire (Fig. 17). Building a transfer infrastructure, however, is a time-consuming process and a large investment. In the short-term, the solution for transporting hydrogen will be ship, road, and railway transport. As for the storage, most respondents were unaware if there are suitable existing facilities available. Only 17% reported that there are possible storage facilities in their area (Fig. 18).

Development of the larger transfer pipeline is considered to start from the hotspots: in the longer term as the demand of hydrogen increases, the hotspots will be connected by hydrogen pipeline leading to a wide-ranging transfer infrastructure.

Storage of hydrogen could be useful as a short-term (hours or days) buffer, e.g., in situations where there is a disturbance in the normal hydrogen supply.

Planned activities during 2020s for hydrogen transfer and storage are presented in Table 7.

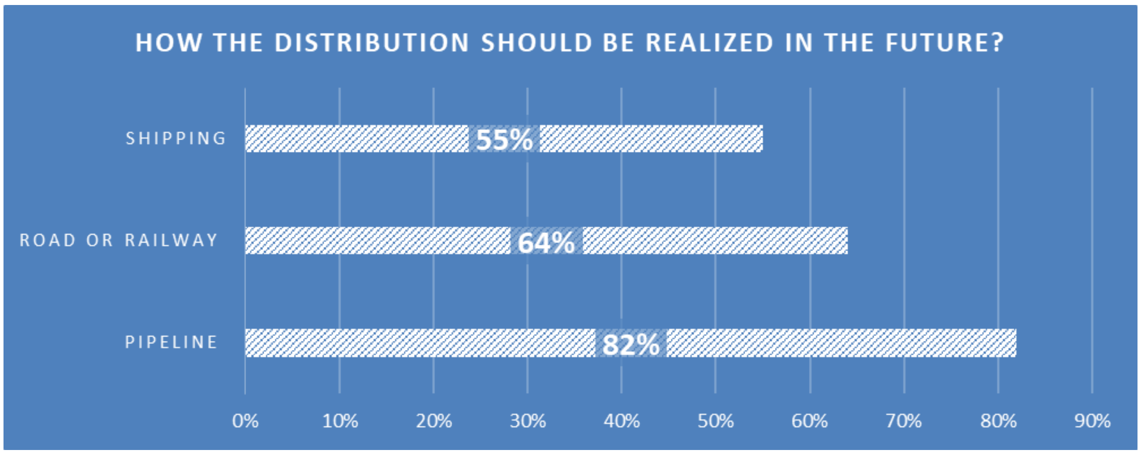

Figure 17. Respondent's opinion on how distribution should be realized.

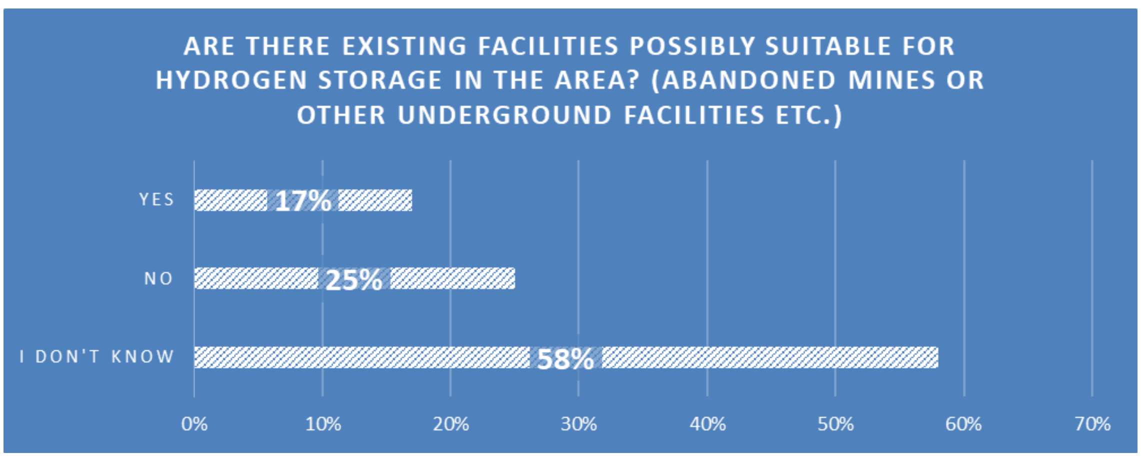

Figure 18. Situation regarding suitable storage facilitied in the respondent's local area.

Table 7. Planned actions for hydrogen transportation and storage in short and medium term.

Planned actions for hydrogen transportation and storage	
2021-2026	2026-2030

• Assessment of the market situation and observation of the development
  ○ Potential of the hydrogen economy
  ○ Needs by customers and markets
• Planning activities
• Preliminary actions and activities
  ○ Development of knowhow
• Funding assessment
	• Planning of construction
	• Expanding the activities and investments
	• Possibly first hydrogen pipelines

5.5 Use of hydrogen

Regarding the use of hydrogen, 11 companies answered that they are using or they are planning to use hydrogen. As for the required infrastructure, most of the respondents don't have suitable infrastructure available for using hydrogen (Fig. 19). Most respondents would prefer that hydrogen production takes place in the same location as the use (Fig. 20).

For the companies currently using hydrogen, the scale of use is tons per year. The estimated needed annual volumes in the future vary from thousands to over hundred thousand tons. In the questionnaire, availability of excess hydrogen was mapped: only 19% of the respondents replied that there are companies producing excess hydrogen in their area (Fig. 21). The interest towards using synthetic methane or methanol was clarified as well: 39% of the respondents replied that they are using or planning to use synthetic methane or methanol (Fig. 22).

Planned activities during 2020s for hydrogen use are presented in Table 8.

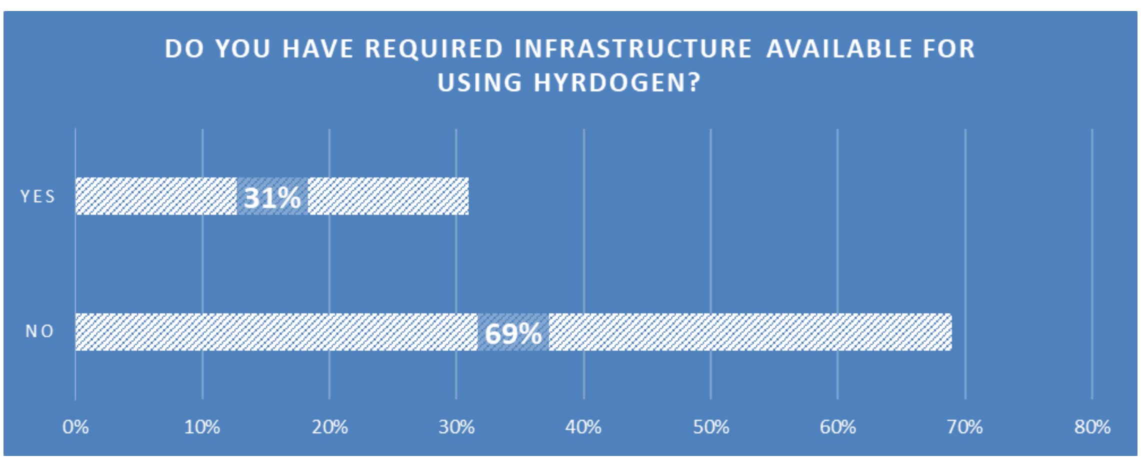

Figure 19. Situation regarding required infrastructure for using hydrogen among the respondents.

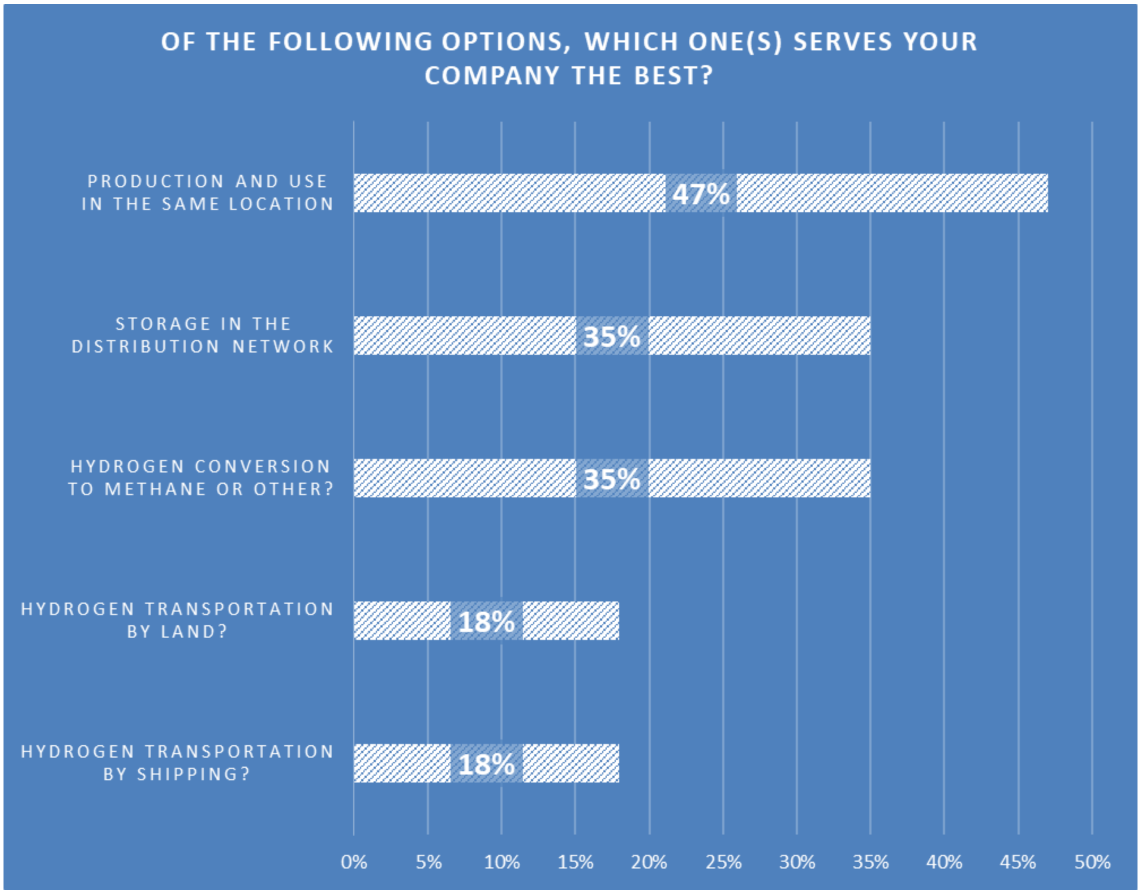

Figure 20. Logistic preference for hydrogen among hydrogen users.

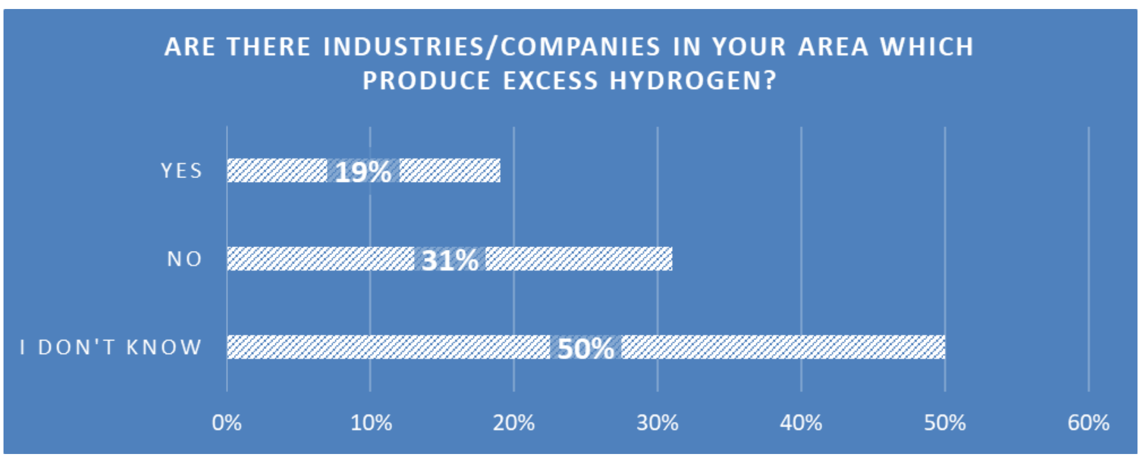

Figure 21. Availability of excess hydrogen.

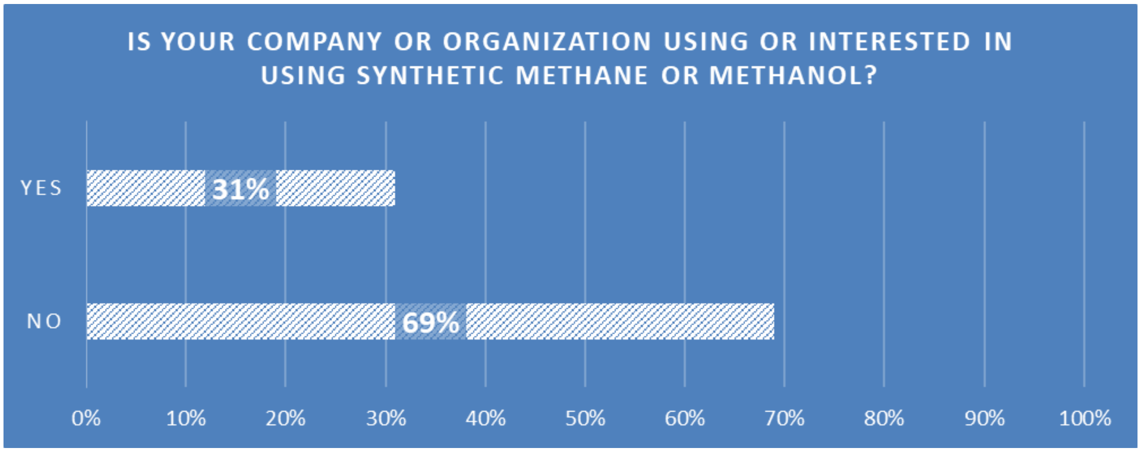

Figure 22. Interest towards synthetic methane and methanol among hydrogen users.

Table 8. Planned actions for hydrogen use in short and medium term.

Planned actions for the use of hydrogen	
2021-2026	2026-2030
• First investments on use of green hydrogen • Development of turbine and engine technology suitable for hydrogen • Demonstration plant for hydrogen based steelmaking • Planning of actions	• Expanding of investments • Transition to use of the hydrogen if techno-economically viable • Demonstration scale production of synthetic fuels

5.6 Restrictions and obstacles

The majority of respondents were of the opinion that there are restrictions or obstacles now or in the near future in hydrogen production, transport/storage and use (Fig. 23). The most restrictions or obstacles (78%) were seen in hydrogen transport and storage. Table 9 shows the most common restrictions and obstacles which were raised up in the questionnaire and in the interviews. The responses received are mostly related to regulatory and technical-economic matters. Currently, the EU regulation relating to taxonomy and hydrogen classification is still pending and seen as an uncertainty in hydrogen production and utilization sectors. For example, if existing water or wind power is not accepted as energy for the manufacture of green hydrogen, it is suspected that the transition to the hydrogen economy and the generation of projects will slow down. In addition, there is legislative ambiguity regarding synthetic fuels as well as safety related to transer, production and use of hydrogen.

In the techno-economic issues, the price and transmission of green electricity are seen as one of the significant factors in the cost of green hydrogen. The price of green hydrogen could be influenced, for example, through the taxation of transfer fees. Price as well as efficiency of electrolysis equipment are seen as obstacles now and in the near future, but at the same time it was considered likely that in the long term the prices of electrolysis equipment will fall and the efficiency will improve, which would favorably affect the cost of green hydrogen.

Fiscal guidance was generally seen to play a significant role in the transportation in hydrogen economy. Fiscal guidance could be used, for example, for building infra for hydrogen. Profitability of the hydrogen business may also be affected by taxation of replacement products (e.g., natural gas). The elimination of multiple taxation, e.g., in the manufacture of hydrogen, so that the taxation of raw materials (e.g., electricity) or the final product (hydrogen) is abolishing would also contribute to the cost of hydrogen. In the hydrogen use in the transport sector it is unclear what kind of propulsion taxes will the vehicles have and what kind of fuel taxes will there be in addition to VAT. Since it is unclear to what extent and how taxation will be used and what kind of impacts taxation will have on profitability, companies are forced to make assumptions and take risks.

Among the technical issues, the storage of hydrogen directly in large scale was seen challenging, in Finland, where there are no salt mines suitable for storaging hydrogen like in Central Europe. A carbon fibre tank can be used to store hydrogen, in which hydrogen is stored at high pressures, but that is not seen as an economical solution in the large scale. One possibility might be to find out the suitability of stone caves in Finland to store hydrogen on a large scale. Hydrogen piping can be used for hydrogen storage purposes in certain scale as well. In addition, conversion of hydrogen to synthetics fuels or chemicals could be a useful solution in large scale. For that purpose, CO_2 can be used as a raw material. Technology for that is already available even if research and development is still needed.

While there are still open questions regarding the safety of hydrogen use, for example, in terms of regulations regarding the transfer of hydrogen, the common view was that safety matters were not considered to be an obstacle to the transition to hydrogen economy. Safety matters of hydrogen are very important, and solutions are typically more expensive than for existing fuels and chemicals, but they are technically solvable. There is already a lot of experience in the use of hydrogen for example in oil refineries and chemical industries, which can be exploited.

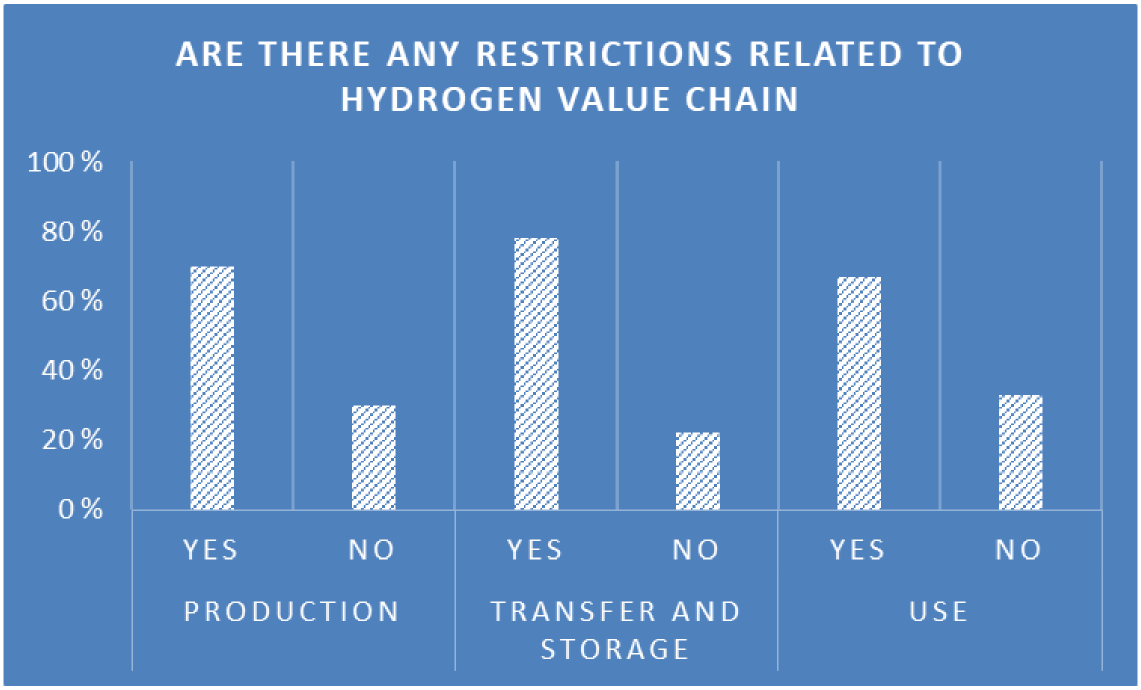

Figure 23. Respondent's opinion on restrictions related to hydrogen value chain.

Table 9. Restrictions or obstacles now or in the near future in hydrogen production, transport/storage and use.

Hydrogen production	- Technical-economic issues:
	  - Taxation
	  - Availability and price of clean electricity, transfer prices
	  - Price and availability of technology
	  - Efficiency of electrolysis equipment
	- Legal ambiguity in various industries (hydrogen production and use, transport, etc.)
	- Incomplete EU regulation (taxonomy, hydrogen classification)

Transport and storage of hydrogen	- Security, production and transport legislation is not up to date - Slowness in infra development and construction - Deficiencies in large-scale storage (cf. Central European Salt Mines) - Regulation as regards safety ambiguous (e.g. safety distances)
Hydrogen use	- Price and availability of green hydrogen - The price of the final product (hydrogen-based vs. fossil alternative) - Legislative ambiguity on synthetic fuels - Incomplete EU regulation (taxonomy, hydrogen classification)

5.7 Research needs

In the questionnaire and interviews it was asked what kind of research and development are needed in hydrogen value chain. Quite much research needs were general or concept level topics showing how early phase the transition to hydrogen economy is, as can be seen in Table 10. On the other hand, it appeared from the responses that many technical solutions relating to the hydrogen production or use are already existing or they are under development.

In the production of hydrogen, improving the efficiency of electrolyzes was raised up in the many responses. The efficiency would be desired to be increased from the current (50-60%) to 70% or even 80%, in which case the effect on the price of hydrogen would be significant. Under that topic, there is a lot research and development ongoing. The study of the integration and synergies of hydrogen economy, such as the use of heat and oxygen from electrolysis or exploitation of hydrogen generated as an industrial by-product are one of the key factors to the transition to hydrogen economy. Catalysis development in the low carbon hydrogen technologies like photocatalysis is still needed.

Transport and storage of hydrogen involves uncertainty and open issues, and with it there are a lot of research needs. Finland is seen as a potential hydrogen exporting country and research, actions and networking were hoped to map out and promote this issue. In particular, the construction of a transmission network for hydrogen export to abroad is seen to be critical. The development time for infra projects is long, so the development of the network must be started about 10 year beforehand. In Finland where is no salt mines, storing of hydrogen in the large scale as such is challenging. Therefore, research in hydrogen storage in Finland and especially comparative study to storage pure hydrogen and its derivate products such as ammonia, synthetic methane and higher hydrocarbons, and methanol were seen important. Material engineering research from the point of view of hydrogen transport was arised. Topic of this research area are for example suitable piping material and recycling of carbon fiber tanks used to store hydrogen.

Research needs in the use of hydrogen are mainly related to different application areas of hydrogen. Only optimization of hydrogen use, and recycling and purification of hydrogen are not application related topics. The development of P2X technologies were specifically mentioned, one example being biological and small scale catalytic methanization utilization in biogas refining technology.

Table 10. Research needs based on the questionnaire and interviews

Hydrogen economy / integration and synergies	-	Review of legislation alternatives (eg., effect of increasing the price of emissions trading) enabling a short hydrogen economy transition
	-	Optimal distribution infra and scalability of production with respect to consumption and storage
Hydrogen production	-	Techno-economic review
	-	The possibilities and impacts of various methods to produce hydrogen (electrification needs, raw material adequacy and demand for by-products)
	-	Improving the efficiency of electrolysis technology
	-	Demand and utilization of by-products (e.g., heat and oxygen)
	-	Development of catalysts and catalytic processes for hydrogen production from different hydrogen-containing streams
Transport and storage of hydrogen	-	Total comparison of different transport channels
	-	The potential of Finland as a hydrogen exporting country
	-	Hydrogen storage development and logistic
	-	Best solutions for storing hydrogen: pure hydrogen or derivate product (e.g., ammonia, synthetic methane and hydrocarbons, methanol)
	-	Material engineering research from the point of view of hydrogen transport and storage
Hydrogen use	-	Optimization of hydrogen use
	-	Recycling and purification of hydrogen
	-	Development of different technologies like P2X, turbines and internal combustion engines
	-	Modeling of combustion in internal combustion engines
	-	Steel: hydrogen reduction, use of hydrogen as an energy source, e.g., in billet heating furnaces + effects on product quality

6 Hydrogen research in the research and education organizations

This study was done in cooperation with the following research and education organizations: University of Oulu, VTT, Oulu University of Applied Sciences (Oamk) and Educational Consortium OSAO. Current and future hydrogen research and education activities and plans were mapped for these organizations using the following questions:

1) What kind of hydrogen-related research or activities do you have at the moment?
2) Research themes related to hydrogen in the near future?
3) Investing on hydrogen research, €-denominated volume, financiers (national, EU etc).

Table 1111 shows that the University of Oulu and VTT currently have several hydrogen-related activities in the whole hydrogen value chain. Oamk has actions in the School of Engineering and Natural Resources relating to the hydrogen use and the role of OSAO is to gather the knowledge relating to hydrogen economy and act when needed. In the near future (Table 12), the University of Oulu and VTT continue to work on the existing research topics. In addition, VTT is putting more investments on electrolysis research. It is important for the University of Oulu, Oamk and OSAO to take into account the transition to hydrogen economy in their education. Oamk and the University of Oulu will have the common new vehicle testing laboratory environment (NUVE-LAB) at the Linnanmaa campus site and hydrogen will be one of the energy sources used in the laboratory environment. Therefore, actions related to planning and use of the new laboratory are marked to both organizations in Table 1111 and 12.

The investment in hydrogen research at the University of Oulu and VTT is several million per year. The main sources of funding for them are EU projects, Business Finland, business orders and self-financing. Currently, Oamk has one project where hydrogen is as a part of the overall implementation. The strategy of Oamk focuses on low-carbon solutions, so more investment in the hydrogen sector will be directed. OSAO does not have ongoing hydrogen related projects. OSAO participates in the Bay of Bothnia project network and thus might find RD&I funding appropriate to the hydrogen theme in the future.

Table 11. Hydrogen-related research and activities at the University of Oulu, VTT, Oulu University of Applied Sciences (Oamk) and Educational Consortium OSAO.

Organization	Category	What kind of hydrogen-related research or activities do you have at the moment?
University of Oulu	Hydrogen production	- Modelling, development, and characterization of photocatalysts for photocatalytic hydrogen production - Research and development of methane pyrolysis - Develop a thermochemical method that utilizes biogas in hydrogen production - Release of hydrogen from liquid hydrocarbon carriers, development of catalysts and study of stability - Photocatalytic hydrogen manufacturing from the organic load of wastewater and industrial side streams
	Hydrogen use	- Reduction reactions in iron, ferro alloys and non-ferrous metals production - Optimization of Hydrogen Fuel Cell Systems - Research relating to P2X technology: Techno-economic and environmental reviews for small scale P2X plants, and exploitation of P2X technology in Laanila industrial park area - Manufacture of fuels and chemicals (CH_4, MeOH, DMC, HCOOH) from hydrogen - Participating in planning and utilizing of the new vehicle testing laboratory environments with Oamk and companies
	Transport and storage of hydrogen	- Steels in hydrogen storage (tanks, etc.) - Steels in hydrogen transport (pipelines, etc. + tanks in vehicles) - Steels in reactors in hydrogen plant
	Whole value chain	- Sustainability assessments (LCA and MCA) in hydrogen utilization
VTT	Hydrogen production	- Research related to the manufacture of pure hydrogen (electrolysis systems, materials, components, control systems, etc.) - Research on the quality of hydrogen: 1) How do hydrogen pollutants affect the performance and lifetime of the fuel cell system? 2) What are the relevant limits for hydrogen pollutants? 3) How can the pollutants be determined and ensure the quality of hydrogen?
	Hydrogen use	- Structure, control, diagnostics, materials, components of fuel cell systems - Modeling of fuel cells and electrolysis from component level to entire systems - Fuel cell applications (e.g., ships, vehicles, machinery, stationer use) - Hydrogen safety issues and risk management - Use of hydrogen in the manufacture of synthetic fuels and chemicals
	Whole value chain	- Technical economic analysis of hydrogen production, logistics, storage, use
Oamk	Hydrogen use	- School of Engineering and Natural Resources: Possibility to use hydrogen as a fuel is taken into account in the planning of new vehicle testing laboratory environment; Thesis and project work about hydrogen economy done/ongoing, the implementation of fuel cell testing environment in the hybrid laboratory during the academic year 2021-2022
OSAO	Whole value chain	- Follow up actively hydrogen-related activities for example by participating in the Hydrogen Study of the Bay of Bothnia.

Table 12. Research themes related to hydrogen in the near future at the University of Oulu, VTT, Oulu University of Applied Sciences (OAMK) and Educational Consortium OSAO.

Organization	Category	Research themes related to hydrogen in the near future (by 2026)
University of Oulu	Whole value chain	- Continue to work on the existing research topics - Transition to hydrogen economy will be considered in planning and updating of education - Using hydrogen as one energy sources in the new vehicle testing laboratory (NUVE-LAB) environment - A virtual model for utilizing a fuel cell in the vehicle (Mobilab) will be realized
VTT	Whole value chain	- In addition of current research topics, more invest in electrolysis research
Oamk	Whole value chain	- Using hydrogen as one energy sources in the new vehicle testing laboratory (NUVE-LAB) environment - In the energy sector, teaching more hydrogen related issues will be raised up - Supporting of the companies with RD&I actions
OSAO	Mainly hydrogen use	- If needed, developing new learning environments to ensure professional competence (basic degree, vocational degree, and specialized vocational training). For example, use of hydrogen as a fuel brings new technical skills needed in vehicle application.

7 Summary

In this study, numerous companies and organizations were contacted for carrying out a questionnaire study and interviews on the respondent's possible plans related to hydrogen economy. The study was directed mostly to companies and organizations in the area of Bay of Bothnia in Sweden and Finland but also some strategically important companies outside the geographic area were included. In total, 37 companies replied to questionnaire and 16 of those were interviewed in addition.

According to the results, it can be concluded that hydrogen and hydrogen economy are widely considered as vital factors in decarbonization of many industries and society in the future. There is a big potential for hydrogen economy in the Bay of Bothnia: there already are hydrogen producers and users in the area. Going from south to north, suitable locations for hydrogen hotspots (production and use are located in the same place) can be recognized in the area as well including Kokkola, Raahe, Oulu and Kemi-Tornio area. Prerequisites for green hydrogen production are satisfied as the availability of clean energy is good: wind power capacity will increase substantially in the near term. Furthermore, investments on improving the power grid is a promising sign for electricity-intensive hydrogen production and electrification of other industries. Hydrogen related business is widely planned but most companies are lacking roadmaps for the transition to hydrogen economy. Schedules for transition to hydrogen economy vary between 10 and 30 years.

At the moment, green hydrogen production is very limited nationally (and globally). However, new investments have been announced for near-term in Finland. Transfer and storage of hydrogen is considered the most problematic part of the hydrogen value chain. In the near-term, the solution for transportation will be shipping as well as road and railway transportation. Construction of the fixed transfer infrastructure (pipeline) will take place at the latter part of 2020s at the earliest. As for the use of hydrogen, the use will take place in the production of synthetic fuels and as a raw material in different industries. Estimates for the needed annual volumes vary between 1000 and 150 000 t.

Transition to hydrogen includes a variety of restrictions and obstacles. Restriction related to production include techno-economic issues (taxation, availability and price of clean energy, efficiency and availability of electrolysis technology). As for the transfer and storage, the slowness of building suitable infrastructure might become an obstacle along with deficiencies in large-scale storage of hydrogen. In the use of green hydrogen, the availability and price form the largest restriction at the moment. This also affects the price of the end-products (e.g., in steelmaking) which can hinder the transition from fossil alternative to hydrogen-based production. In every part of the value chain the legislation and regulations (safety, taxonomy, hydrogen classification) were considered to be somewhat ambiguous and/or out-of-date.

Research needs were also mapped in the study. The research is needed widely from techno-economic studies to legislation and regulation. Regarding hydrogen production, tecno-economic review is needed on the possibilities and impacts of various methods of production of hydrogen (electrification needs, raw material adequacy and demand for by-products). Development of technology (efficiency of electrolysis technology, development of catalysts) for hydrogen production needs additional studies and innovations. Regarding transfer and storage, the comparison of different transport channels is needed. The potential of Finland as a hydrogen exporting country should be examined. Hydrogen storage development and logistic is needed as well, including best solutions for storing hydrogen: pure hydrogen or derivate product (e.g., ammonia, synthetic methane, hydrocarbons, methanol). Furthermore, material engineering research from the point of view of hydrogen transport and storage is important. As for the use, optimization of hydrogen use is needed along with studying possibilities of recycling and purification of hydrogen. Development of different technologies (power-to-X to utilize hydrogen and secondary CO_2; turbines and internal combustion engines) was considered important. In steelmaking, hydrogen reduction, use of hydrogen as an energy source, e.g., in billet heating furnaces + effects on product quality are vital topics.

Relating of the use of hydrogen, the results revealed that most actors are still in very early stages in the possible transition and concreteness of plans and activities vary greatly. Most concrete plans for the use of hydrogen in the new applications by 2030 include demonstration plant of hydrogen-based steel production (by 2026), demonstration level plant for synthetic fuels production, development of 100% hydrogen-operational engines and turbines, pilot plant for producing turquoise hydrogen and operational green hydrogen production plant (by 2024).

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