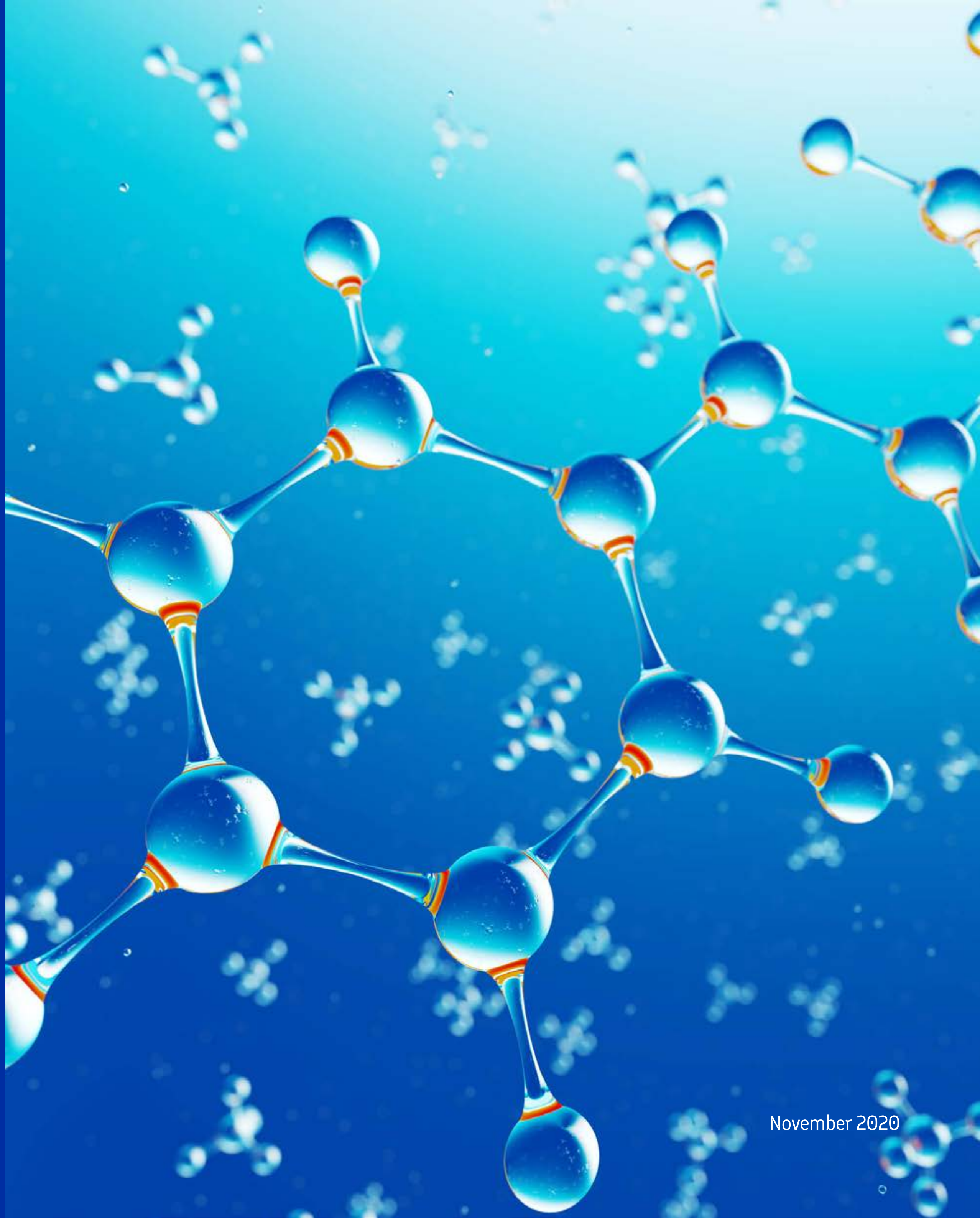
BUSINESS
FINLAND

NATIONAL HYDROGEN ROADMAP

for Finland

Juhani Laurikko, Jari Ihonen, Jari Kiviaho, Olli Himanen, Robert Weiss, Ville Saarinen, Janne Kärki, Markus Hurskainen



November 2020

ISSN 1797-7339
ISBN 978-952-457-657-4

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A Short Preface

Hydrogen has been used as an industrial chemical for more than 100 years. Today, hydrogen is used to manufacture ammonia, and hence fertilizers, as well as methanol and hydrogen peroxide, both vital feedstocks for a wide variety of different chemical products. Furthermore, in oil refineries, hydrogen is used for the processing of intermediate products, as well as to increase the hydrogen contents of the final products that are used propel the vehicles.

However, hydrogen has recently achieved new attention for its capabilities in reducing carbon emissions to the atmosphere. Producing hydrogen via low or totally carbon-free ways, and using this "good" low-carbon hydrogen to replace hydrogen with a larger carbon footprint, we can reduce carbon emissions. Furthermore, using renewable electricity and captured carbon, we can synthesise many such chemical products that are currently produced from fossil raw materials. This "Power-to-X" (P2X) is often seen as the eventual incarnation of the hydrogen economy.

In addition, the progress in technology both in hydrogen fuel cells, and in polymer electrolyte electrolysers alike, has increased their efficiencies. Furthermore, production costs of renewable electricity by wind or solar power have lowered significantly. Thus, cost of "good" hydrogen has also decreased markedly, and production volumes are expected to increase rapidly.

For these reasons, many countries have raised interests in "good" hydrogen, and have created roadmaps and strategies for their involvement in hydrogen. Hydrogen plays a key role also in combating climate change and reaching Finland's national goal of carbon neutrality by 2035. In recent years, many clean hydrogen and P2X production methods have developed significantly and become commercially viable.

This report was produced by a team of VTT experts on hydrogen and hydrogen-related technologies. The focus is in an outlook for low-carbon H_2 production, H_2 utilization for green chemicals and fuels, as well as storage, transport and end-use, especially during the next 10 years in Finland in connection to renewed EU regulations.

This roadmap is expected to serve as the knowledge-base for further work, such as shaping the hydrogen policy for Finland, and determining the role of hydrogen in the national energy and climate policy.

GLOBAL AND EU OUTLOOK

Reasons for **high interest in low-carbon hydrogen**

To prevent climate change, there is urgency to radically lower emissions. Otherwise, major climate impact, such as more extreme temperatures, rising sea levels, and significant biodiversity losses will be the consequence. Furthermore, according to FCH JU, hydrogen is an efficient tool to enhance energy efficiency, and if produced without significant carbon emissions, reduce fossil fuel use and decrease CO_2 emissions. Hydrogen can also enable renewables to provide an even greater contribution. It has the potential to help to cope with variable output from renewables, like solar photovoltaics (PV) and wind, and it can store electricity over days, weeks or even months with modest costs. Hydrogen can also transport energy from renewables over long distances from regions with abundant solar and wind resources. This is why hydrogen is currently enjoying a renewed and rapidly growing attention in Europe and around the world.

Yet today, hydrogen represents only a modest fraction of the global and EU energy mix, and is still largely produced from fossil fuels, notably from natural gas or from coal, resulting in the release of 70 to 100 million tonnes CO_2 annually in the EU. For hydrogen to contribute to climate neutrality it needs to achieve a far larger scale and its production must become fully decarbonized.

According to European Commission, large-scale deployment of clean hydrogen at a fast pace is key for the EU to achieve a higher climate ambition, reducing greenhouse gas emissions in a cost effective way. Moreover, Europe is highly competitive in clean hydrogen technologies manufacturing and is well positioned to benefit from a global development of clean hydrogen as an energy carrier, combined with EU's leadership in renewables technologies.

According to IEA, this is a moment of unprecedented momentum for hydrogen. Hydrogen has seen several waves of interest in recent history, none of which fully translated into rising, sustainable investment. However, this time could be different as hydrogen is increasingly a staple of mainstream energy conversations in almost all regions, with a diverse group of countries and companies all seeing hydrogen as having a potentially valuable and wide-ranging part to play in the future of energy, as well as feedstock for industrial production.

Global and EU hydrogen market and selected national cases

The global demand of hydrogen is growing fast and it has grown to be currently more than threefold the level in 1975. The production and supply of hydrogen for industrial use is a major, global business, and it is forecasted to grow even faster than before.

According to IEA the total demand for hydrogen in 2018 was is about 115-120 million tonnes in pure and in mixed gas.

In different sources, somewhat dissimilar figures for the global hydrogen production and consumption are reported. There are two main reasons for this. Firstly, hydrogen is produced as part of a mixture of gases as well as in pure form. Secondly, by-product hydrogen, produced in internal processes and consumed in oil refineries, is also counted for the total hydrogen amounts. This on-site by-product hydrogen production, which meets one-third of refinery hydrogen demand, is not always counted. Instead, only hydrogen production in external, dedicated processes is reported.

According to IEA the total fuel used for hydrogen production corresponds 6% of global natural gas and 2% of global coal consumption. Furthermore, the share of coal may not decrease as coal gasification is routinely used as hydrogen production unit in new refineries in China. Totally, the dedicated production of hydrogen causes 830 $MtCO_2$/yr emissions according to same report. It is worth noting that less than 0.7% of current hydrogen production is from renewables or from fossil fuel plants equipped with CCUS.

It is worth noting that **less than 0.7%** of current hydrogen production is from **renewables or from fossil fuel plants** equipped with CCUS.

Global hydrogen industry today is large, with many sources and uses.

However, most hydrogen is produced from gas in dedicated facilities, and the share of renewables is currently very small

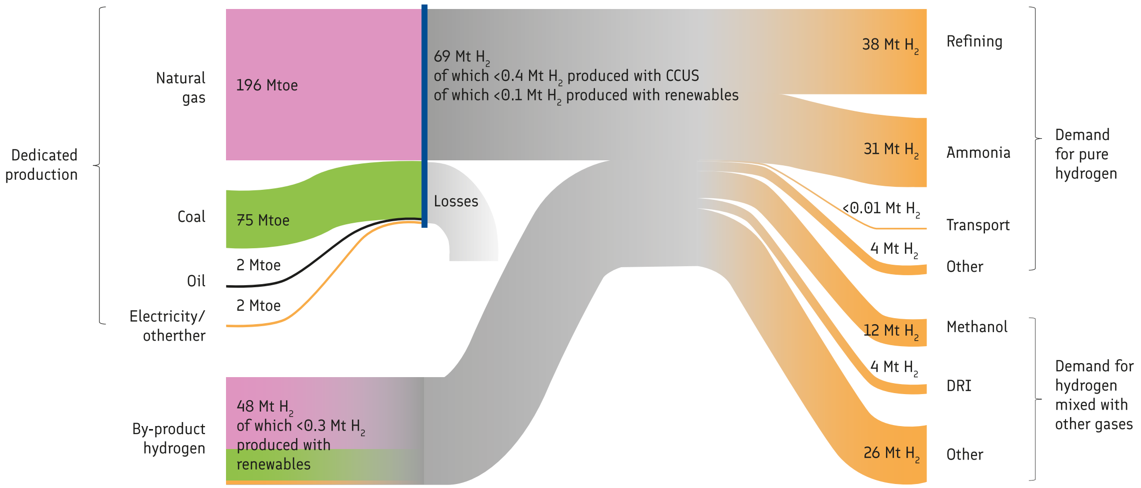


FIGURE 1: GLOBAL HYDOREN PRODUCTION AND USE
Adapted from: The Future of Hydrogen for G20. Seizing Today's Opportunities, IEA 2019

In a recent IEA report the production as well as use of hydrogen is also well illustrated, as shown in Figure 1. The most important difference compared to many other reports is that hydrogen used for oil refining is actually larger than hydrogen used for ammonia production, when on-site by-product hydrogen production and use in refineries is also included.

One frequent miscommunication is the amount of hydrogen that is produced by water electrolysis. When hydrogen production figures are shown it is often not distinguished, which part of the electrolysis is water electrolysis and which part is brine (sodium chloride) electrolysis, where hydrogen is a by-product.

According to IEA electrolysis currently accounts for 2% of global hydrogen production, but there is a significant scope for electrolysis to provide more low-carbon hydrogen.

Hydrogen consumption in EU

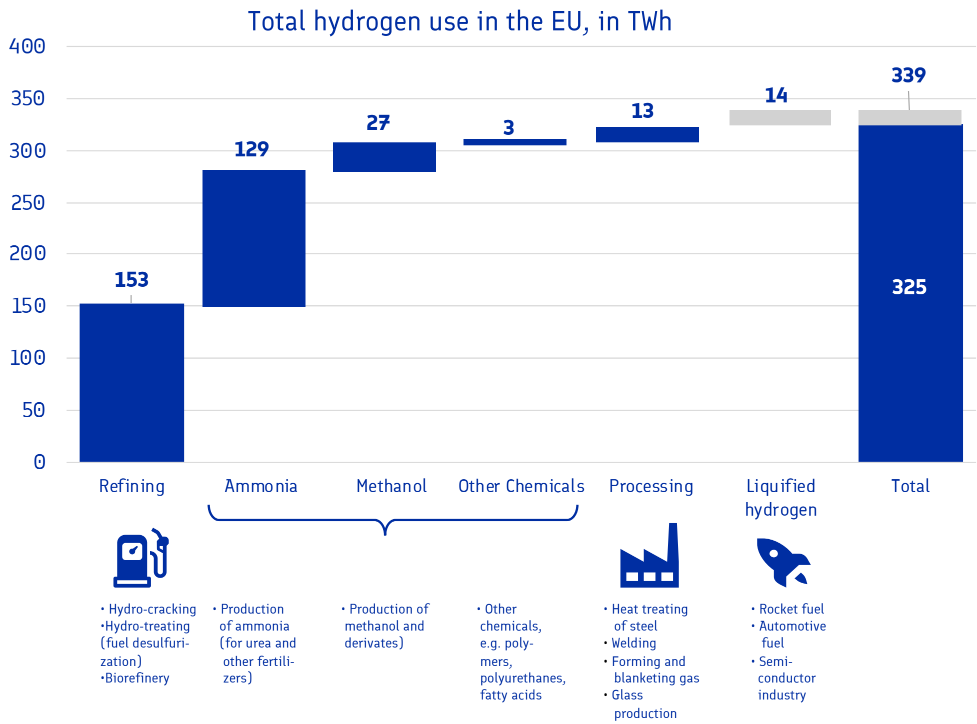


FIGURE 2: TOTAL HYDROGEN USE IN EU (2015 FIGURES)
Adapted from FCH JU Hydrogen Roadmap Europe, 2019.

In EU hydrogen consumption was 339 TWh (about 10 Mt) in 2015, according to Fuel Cells and Hydrogen Joint Undertaking. This includes by-product hydrogen from refineries. The use of hydrogen for refining as well as ammonia production dominates. It is worth noting that this amount is less than 10 % of the current global use.

We calculated that producing the 200 TWh, which is dedicated, pure H_2 production with clean electricity would equal 300-350 TWh of new, clean electricity generation, which is about 10% of total present electricity consumption in EU.

An ambitious scenario for hydrogen deployment in the EU to achieve the 2-degree target will require substantial increase in carbon-free power generation, increased energy efficiency, and the deep decarbonisation of transport, buildings, and industry. It is estimated by FCH JU that hydrogen could provide up to 665 TWh (6%) of energy in the EU by 2030. In addition, hydrogen could provide up to 24% of total energy demand, or up to 2250 TWh of energy in the EU by 2050, see Figure 2.

TABLE 1: HYDROGEN USE IN EU AND SOME MS (2015 FIGURES)

Area	Hydrogen use		Total final energy use	
	TWh, total	MWh/ capita	TWh	H_2 share
EU28	325	0.633	14 100	2.3 %
Germany	55	0.656	2 475	2.2 %
Netherlands	32.5	1.897	571	5.7 %
Norway	7.5	1.383	217	3.4 %
Finland	5	0.902	281	1.8 %

Projected hydrogen demand in EU for 2030 and 2050

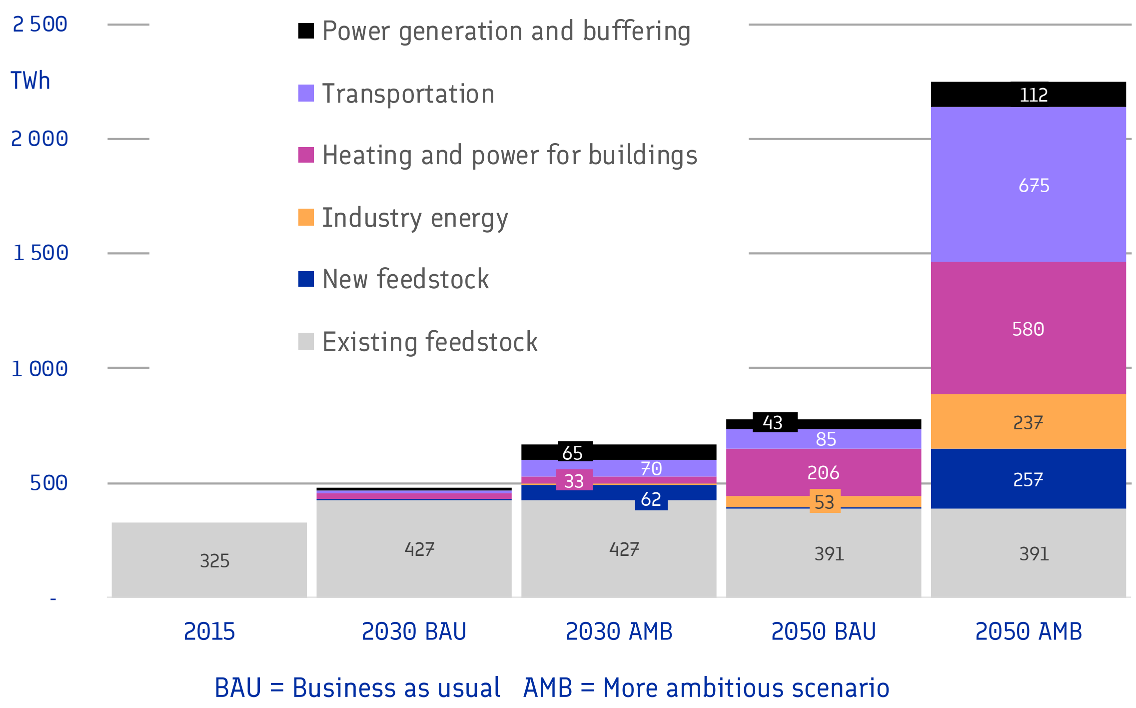


FIGURE 3: EXPECTED GROWTH OF HYDROGEN USE IN EU BY 2030 AND 2050
Adapted from: A Hydrogen Strategy for a Climate-Neutral Europe, European Commission, 2020

According to Fuel Cells and Hydrogen Joint Undertaking, the electricity need for generating approximately 2250 TWh of hydrogen in Europe in 2050, represents roughly a quarter of the EU's total energy demand.

Furthermore, FCH JU calculates that this amount would fuel about 42 million large cars, 1.7 million trucks, approximately a quarter of a million buses, and more than 5 500 trains. Furthermore, it would heat more than the equivalent of 52 million households (about 465 TWh) and provide as much as 10% of building power demand.

Moreover, in industry, approximately 160 TWh of hydrogen would produce high-grade heat and another 140 TWh would replace coal in steelmaking processes in the form of direct reduced iron (DRI). Additionally, 120 TWh of hydrogen combined with captured carbon or carbon from biomass would also produce synthetic feedstock for 40 Mt of chemicals in 2050.

According to the hydrogen strategy of the European Commission for a climate-neutral Europe, many indicators signal that we are now close to a tipping point. Every week new investment plans are announced, often at a gigawatt scale. Between November 2019 and March 2020, market analysts increased the list of planned global investments from 3.2 GW to 8.2 GW of electrolysers by 2030 (of which 57% in Europe).

Regulatory framework for hydrogen in EU

By far the most important regulation in Europe for future hydrogen market is the recast version of the renewable energy directive known also as RED II.

According to RED II, renewable hydrogen is accepted both as transportation fuel and as intermediate products for the production of conventional fuels, when each Member State must fulfil the minimum share (14% by 2030) of renewable energy within the final consumption of energy in the transport sector. Renewable hydrogen itself is one of "renewable liquid and gaseous transport fuels of non-biological origin" (ReFuNoBiOs), when used in vehicles. These fuels are liquid or gaseous fuels, which are used in the transport sector other than biofuels or biogas, and the energy content of which is derived from renewable sources other than biomass. Other ReFuNoBiOs include mostly fuels synthetized using renewable hydrogen.

The use of renewable hydrogen as intermediate product, instead of fossil fuel based hydrogen, would enable transport fuel producers a cost-effective way to increase renewable contents of conventional fuels, compared to other alternatives. While this increase in renewable energy content of diesel or gasoline would typically be modest (< 1 %) the total volumes for electrolytic hydrogen production are large. Based on FCH JU and IEA reports the dedicated hydrogen production for oil refineries in Europe is about 100 TWh (as LHV), which is 160-170 TWh as electricity production needed for hydrogen production.

In practice, this possibility of replacing natural gas based hydrogen production by electrolytic hydrogen can lead to massive demand of renewable hydrogen for oil refineries. The increased production and use of renewable hydrogen in oil refineries, produced by large centralised water electrolysis, would also improve the supply of fuel cell grade (ISO 14687:2019) hydrogen, and hydrogen from these centralised production units could also be transported to hydrogen refuelling stations (HRS).

However, roll-out of HRS falls within another directive on Alternative Fuels Infrastructure (AFID) that calls plans from MS to build infrastructure for alternatives . Third important directive regarding hydrogen is the Clean Vehicles directive (CVD), concerning public procurements of vehicles and transport services, and requiring zero-emission vehicles.

Critical questions concerning **acceptable renewable electricity**

There are number of open questions and interpretations in RED II directive concerning electricity, which is accepted as renewable for the production of renewable hydrogen. In general, the restrictions for the accepted electricity come from the fact that the use of already built renewable electricity production capacity for hydrogen production would increase greenhouse gas emissions from electricity production, as the increase of demand in renewable electricity would be covered mainly by fossil fuel in most European countries.

However, as electricity production is included in the EU Emissions Trading System (EU ETS), the emissions on the EU ETS level would not increase unless this would lead to increased import of electricity from countries which are not part of the EU ETS.

The explanation and rules given in RED II directive mentions that hydrogen can be counted as fully renewable when A) the electricity production is in production at the same time as hydrogen production and B) the electricity production is located of the same side in respect of possible grid congestion.

On the other hand, the average share of electricity from renewable sources in the country of production, as measured two years before the year in question, shall be used to determine the share of renewable energy for produced hydrogen.

However, electricity used for renewable hydrogen production obtained from a direct connection to an installation generating renewable electricity may be fully counted as renewable electricity, if it comes into operation after, or at the same time as hydrogen production, and it is shown that grid electricity is not used for production of renewable hydrogen.

Furthermore, the details, delegated to the Commission, will have a major importance for the sourcing of electricity for hydrogen production. Especially important will be the possibility to sell electricity for the market, when all produced electricity is not needed for the hydrogen production. For example, if electricity market price is high, hydrogen-consuming industry can use stored hydrogen and sell contracted renewable capacity to the market. This applies for both electricity obtained by power purchase agreements as well as electricity obtained from direct connection to an installation generating renewable electricity.

Another major question is how a grid congestion is defined, and in case there is a grid congestion, how is reduction in contracted renewable generation unit calculated or is it reduced all together?

Upstream methane emissions are very important for the carbon contents of the SMR hydrogen

In order to distinguish between different production methods of hydrogen, use of different colours to describe the production method and carbon footprint of hydrogen have been introduced. The most common terms are green, blue and grey hydrogen.

Grey hydrogen is based on the use of fossil fuels. Grey hydrogen is mainly produced via the steam reforming of natural gas. Carbon dioxide emissions of grey hydrogen are between 10 and 22.5 kg CO_2/kg H_2, depending on which fuel is used (natural gas, oil or coal). These are global average values and may differ significantly from region to region. Especially for natural gas the supply chain emissions can be significant and should be taken into account in calculations, as explained below. Most of the global merchant hydrogen is classified as grey.

Blue hydrogen is hydrogen which is also based on fossil fuels, but produced using carbon capture and storage (CCS). This means that most of the CO_2 produced in the process does not enter the atmosphere. However, there are several challenges: supply chain losses of methane, limited CO_2 capture rate, and release of CO_2 from storage. There is no consensus about CO_2 levels that blue hydrogen should reach.

With currently demonstrated capture rates, CO_2 emission of blue hydrogen would be about 2 kg CO_2/kg H_2. However, this does not include "upstream" supply chain emissions of natural gas. According to IEA, methane emissions are the second largest cause of global warming and IEA has collected a database for emissions for natural gas production. The global average of supply chain emissions would add about 2 kg CO_2/kg H_2. However, emissions for marginal natural gas are significantly higher, and if the increased hydrogen production is covered by marginal natural gas, emission levels will be much higher than 2 kg CO_2/kg H_2. As a conclusion, supply chain emissions should also be taken into account when calculating emissions of blue hydrogen.

New possible use of low-carbon hydrogen

According to the recent reports and roadmaps, several emerging applications for low-carbon hydrogen are envisaged and their prerequisites are being developed.

Market deployment of fuel cell cars has not been widespread mainly due to the infancy of the hydrogen refuelling network. However, for heavy road transport the availability of low-cost hydrogen may become a critical factor, as present and near-future battery technology cannot support long-range operations. Rail, shipping and aviation are also promising applications for clean hydrogen as the energy vector. Furthermore, petro-chemical industry that today produces and uses large amounts of fossil-based hydrogen in the production of current transportation fuels, and that can be replaced with low-carbon hydrogen.

In chemical industry, ammonia and methanol production based on green hydrogen is also technically viable already today, but the cost of low-carbon hydrogen does not yet meet the strict cost targets, when producing bulk products like these. On the other hand, wide process development and a paradigm change is needed for iron production, where hydrogen could replace the use of CO_2 with dramatic reductions in carbon emissions, and hence substantial global climate benefits.

Moreover, hydrogen is also an enabler to deploy more variable renewable power in the transition to tomorrow's energy systems. The flexibility benefits, electricity demand growth benefits and growing shares of renewables that can be achieved, create new compelling motivations to consider hydrogen as a solution in transition towards a fully renewable and emission-free power.

Eventually, power-to-X (P2X) is seen as the ultimate incarnation of the hydrogen economy, as by using renewable electricity and (captured) carbon, different "e-fuels" can be produced and used within the existing fuel logistics and refuelling infrastructure, as well as in present-day combustion engine powered vehicles. Furthermore, many such chemical products that are currently produced from fossil raw materials can be made totally fossil-free. It could also allow renewable energies be used also in far-off places where it's currently not viable because of non-existent grids or a low requirement for electrical energy.

New possible use of low-carbon hydrogen

Low-carbon hydrogen can technically be used to replace present use of fossil-based hydrogen in chemical industry producing ammonia, methanol and hydrogen peroxide. However, in these cases the cost of hydrogen is a highly sensitive issue, and today's cost projections for low-carbon hydrogen do not meet the strict cost targets, yet.

On the other hand, the renewed RED II directive creates an interesting class for renewable hydrogen, as hydrogen can be used to replace fossil-based hydrogen in the production of transportation fuels. Here, the cost target for hydrogen is different, because the competing product is not fossil hydrogen, but HVO and other possible alternatives that can be utilised to the target of 14% renewable energy contents in transportation fuels EU-wide by 2030.

Use of hydrogen in fuel cell electric vehicles (FCEV) has not taken such progress as anticipated. The main obstacle being the limited HRS network density, allowing the vehicles to be used in quite limited geographical areas. Moreover, this situation has led the automakers that have focused and committed in this technology to seek new applications for their fuel cells in heavier vehicles, especially in long-range and heavy payload applications, where battery power is not at its strongest.
One of the most potential new major uses of clean hydrogen is production of steel. Steel sector currently makes up about 7 % of global CO_2, and major part of the emissions result from the use of coke in the blast furnace for reduction of iron ore. One major pathway towards fossil-free steel making is to use hydrogen for direct reduction of iron ore (H-DR).

Power-to-X (P2X) refers to a number of electricity conversion, energy storage, and reconversion pathways that utilize electric power and allow the decoupling of power from the electricity sector for use in other sectors (such as transport or chemicals). Linked with P2X, carbon capture and utilization (CCU) is referred to as a family of technology concepts utilizing captured CO_2 as a feedstock for other processes, to produce materials, transportation fuels or to be utilized as a process medium e.g. carbon chemistry products and other products.

However, some CCU applications exist, where hydrogen is not needed, like the production of precipitated calcium carbonate, other carbonates and heat transfer fluids. Furthermore, in some CO_2 conversion processes hydrogen demand is limited, or hydrogen can be applied to boost bio-based processes where CO_2 is released as a by-product. An example of such a process is the production of hydrogen-enhanced biofuels, where hydrogen is used to convert CO_2 formed as a by-product of biomass processing.

New possible use of low-carbon hydrogen

Group	Product	Stage of development	Addressable market size	Number of developers	Potential for CO_2 mitigation
Mineralization	Cement	Medium	High	Medium	High
	Building materials	Medium	High	Medium	High
	Waste carbonation	High	High	Medium	High
Chemical intermediates	Methanol	Medium	Medium	High	Medium
	Formic acid	Low	Medium	High	Medium
	Syngas	Low	Medium	High	Medium
Fuels	Methane	Medium	High	Medium	Medium
	Diesel	Low	High	Medium	Medium
	DME	Low	High	Medium	Medium
Polymers	Polyols	Medium	Medium	Low	Medium
	Polycarbonates	Medium	Medium	Low	Medium
	Cyclic carbonates	Low	Medium	Low	Medium
	Sodium acrylate	Low	Medium	Low	Medium
	Acrylic acid	Low	Medium	Low	Medium

High	Medium	Low
High TRL (up to 9), market is a mature market, number of developers >50, prolonged abatement of CO_2	Medium TRL (up to 7-8), market is a developing market, number of developers 10-50, abatement of CO_2 by replacing concentional feedstocks	Low TRL (up to 6), addressable market size is unclear number of developers <10, minimal CO_2 mitigation

FIGURE 4: OUTLOOK OF CCU APPLICATIONS WHERE CO_2 WITH HYDROGEN CAN BE USED AS FEEDSTOCK
Adapted from: Kristin Onarheim, Antti Arasto, Ilkka Hannula, Janne Kärki, Juha Lehtonen, Pasi Vainikka (2017). CARBON CAPTURE AND UTILISATION The role of carbon capture and utilisation in transitioning to a low-carbon future, Discussion Paper, VTT.

Figure 4 gives an overview about the development and market outlook of CCU applications where CO_2 with hydrogen can be used as feedstock.

On the other hand, in most CCU conversion processes the demand for hydrogen is high, meaning that significant cheap, low-carbon electricity capacity is required to cover the needs of high-volume production of CCU-based products.

In addition to indirect electrification in the transport and energy sector, most of the organic chemicals as well as common large-scale chemical intermediates such as methanol, ethylene, propylene and BTX (benzene, toluene, xylene) aromatics, which are important building blocks for sustainable end products, can be synthesised from carbon dioxide and hydrogen.

The drivers for bulk energy products and high-value chemicals and materials are different. The market drivers for energy and fuel products are mainly based on the need for new sustainable fuels as a result of legislative pressures, such as various mandates and subsidies. Production of chemicals and materials is mainly based on the higher market value of these products compared to fuels providing better profitability. Even though the production cost of a CCU-based product is often higher than the cost of the displaced fossil-based product, the profitability of CCU can be improved by applying green premiums to the product price, improving the properties of a CCU-based product or the reputational enhancement that green products can provide.

Rapid scaling-up is projected for **renewable hydrogen demand in EU**

Can the industries keep up with it?

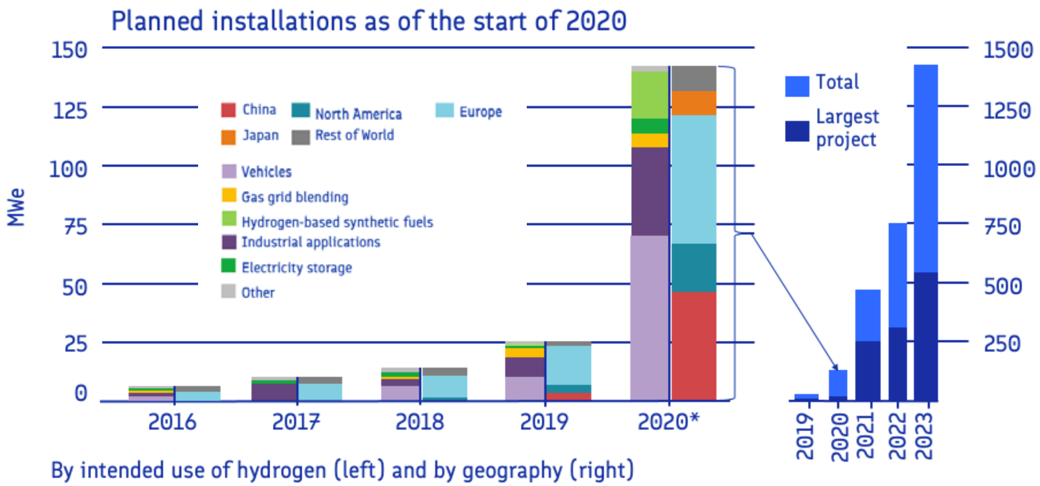


FIGURE 5: CAPACITY OF INSTALLED ELECTROLYSERS FOR HYDROGEN PRODUCTION by commissioning year, location and intended use of hydrogen.Source of data: IEA Hydrogen Database, 2020.

The production of green hydrogen by electrolysis requires large amounts of additional low carbon electricity and electrolysers as well as compressors and storage technologies. From these the availability of electricity and electrolysers are the most critical items for increasing green hydrogen production.

The availability and price of electrolysers is another critical question. Even, the total amount of water electrolysers currently in operation is an open question. According to FCH JU, annual hydrogen production amounts to 0.87 Million tons corresponding to 5500 MW of electrolysers with continuous operation. However, according to IEA the operational capacity was 170 MW in 2019, and less than 0.1% of dedicated hydrogen production globally comes from water electrolysis. IEA is also maintaining the database for the new electrolyser projects, and these are shown in Figure 5.

Consequently, the needed scale-up for annual electrolyser production to reach European Commission's targets is 100 to 200-fold, and within just few years. While the technology has been tested in last 10 years with good results, the level of scale-up is very large, and requires significant investments, too. Furthermore, the consequences concerning quality, lifetime and cost reductions are currently unknown. Also, a single failure of one manufacturer in quality control may have a significant negative impact in the progress of the whole industry.

Near-term low carbon hydrogen production will be done by commercial alkaline and polymer electrolyte electrolysers

Most likely, the near-term low carbon hydrogen production will be done by commercial alkaline and polymer electrolyte electrolysers (AEL and PEMEL), operating at low temperatures (60-90 °C) with electricity need 55-60 kWh/kgH_2.

However, much more efficient (<40 kWh/kgH_2) solid oxide electrolysers (SOEC, operating at 700-800 °C), are developed and currently reaching early commercial stage. SOEC has also potential to reach sufficiently low cost for the installed capacity.

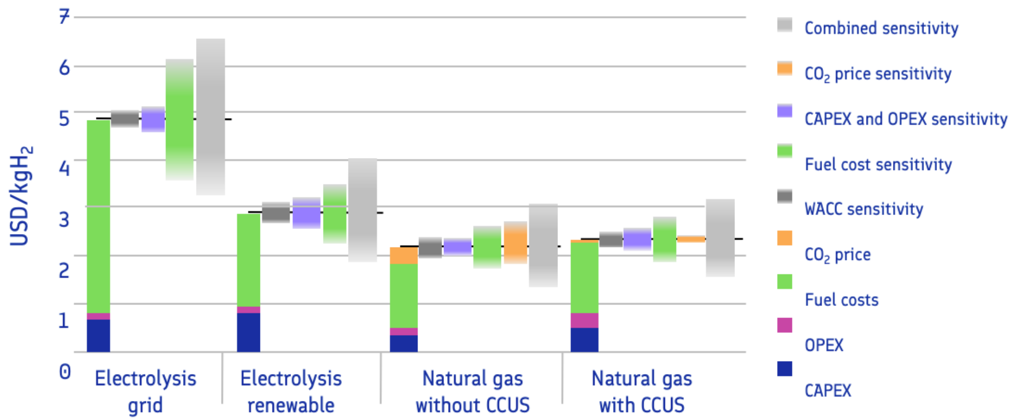
Benefits of high operation temperature of SOEC's are originating from lower activation losses at lower current densities and further on leading to lower power consumption during hydrogen production. In addition to having potential for very high alternate-current (AC) to H_2 total system efficiency (80-90%), SOEC technology is also reversible: the same system can work both as a fuel cell and an electrolyser depending on power generation and grid stabilisation needs. Consecuently, SOEC has the capability for co-electrolysis of steam and CO_2, which enables more efficient power-to-X, if integrated as part of some industrial processes.

TABLE 2: SOME MAIN CHARACTERISTICS OF DIFFERENT ELECTROLYSER TECHNOLOGIES: TODAY, 2030 AND LONG-TERM FORECAST

Type of technology	Alkaline electrolyser			PEM electrolyser			SOEC electrolyser		
Timeframe	Today	2030	Long-term	Today	2030	Long-term	Today	2030	Long-term
Electrical efficiency (%, LHV)	63-70	65-71	70-80	56-60	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

Notes: LHV = lower heating value; m2/kWe = square metre per kilowatt electrical. No projections made for future operating pressure and temperature or load range characteristics. For SOEC, electrical efficiency does not include the energy for steam generation. CAPEX represents system costs, including power electronics, gas conditioning and balance of plant; CAPEX ranges reflect different system sizes and uncertainties in future estimates.
Adapted from The Future of Hydrogen for G20. Seizing Today's Opportunities, IEA 2019.

The cost of hydrogen depends on a multitude of operatives



Notes: WACC = weighted average cost of capital. Assumptions refer to Europe in 2030. Renewable electricity price = USD 40/MWh at 4 000 full load hours at best locations; sensitivity analysis based on +/-30% variation in CAPEX, OPEX and fuel costs; +/-3% change in default WACC of 8% and a variation in default CO_2 price of USD 40/tCO_2 to USD 0/tCO2 and USD 100/tCO_2.
More information on the underlying assumptions is available at www.iea.org/hydrogen2019. Source: IEA 2019. All rights reserved.

FIGURE 6: HYDROGEN PRODUCTION COSTS WITH DIFFERENT TECHNOLOGIES BY 2030

There is a relatively large uncertainty about the future cost of low-carbon hydrogen, but the consensus is that acceptable cost for current and near-term applications is somewhat over 2 €/kg, while for some future uses (like e-fuels) the cost should be under 2 €/kg to make them viable. The hydrogen for transportation, however, has different cost targets. The acceptable cost for hydrogen delivered to a vehicle can be 2-4 times more (4-8 €/kg), according to IEA.

The cost of hydrogen is different in different parts of the world, as depicted in Figure 6. The lowest cost of hydrogen is found in places, where very cheap natural gas is available. This has a consequence that some hydrogen consuming industry (e.g. methanol production) has been located to the vicinity of cheap natural gas. There are huge regional variations in hydrogen production costs today, and their future economics depend on factors that will continue to vary regionally, including prices for fossil fuels, electricity and carbon. Natural gas without CCUS is currently the most economic option for hydrogen production in most parts of the world, with costs being as low as 1 USD/kgH_2 in the Middle East, says IEA.

The dominating cost factor in electrolysis is naturally the cost of clean electricity. In addition, the capacity factor (full-load hours) of the electrolysis is a major cost item. The outlook is that the specific investment cost of electrolysis will be reduced by upscaling, improving the manufacturing process (automation), substituting high-cost materials and using different technologies.

Regarding clean hydrogen production, significant room for electrolysis technology improvement still exists, including reduced capital cost, enhanced lifetime and durability as well as increased system efficiency. Efficient system integration of P2X side-streams (heat, steam, oxygen, grid services) are essential in enabling profitable plant operation and business models.

HYDROGEN IN FINLAND

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Hydrogen production today

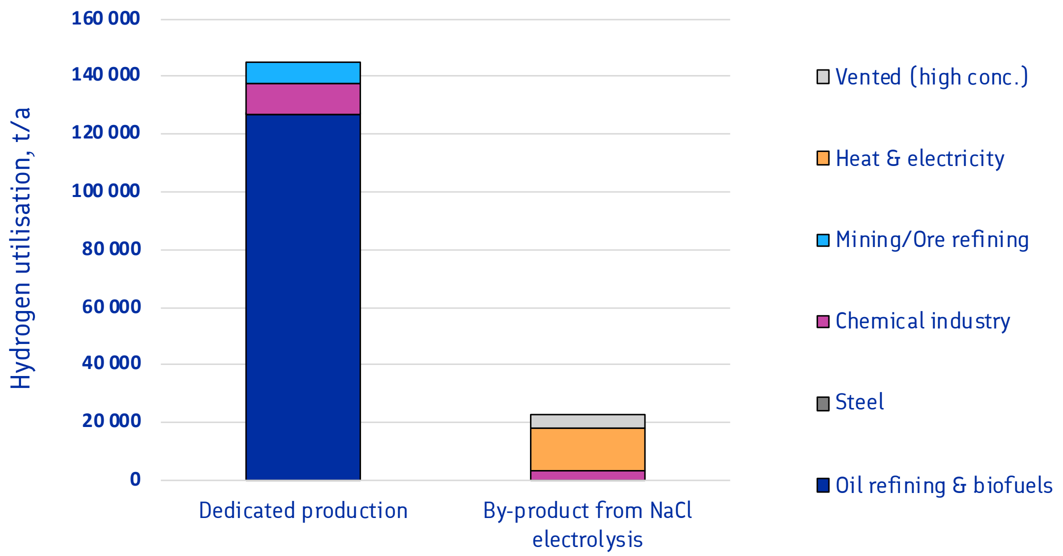


FIGURE 7: CURRENT HYDROGEN PRODUCTION IN FINLAND
Includes both dedicated production and by-product hydrogen. Hydrogen generated and used in refinery operations is not included.
Source: VTT.

Total dedicated hydrogen production in Finland is estimated to be 140 000–150 000 t/a (4.7–5.0 TWh), and 99 % of the dedicated hydrogen is produced via either steam reforming or partial oxidation of fossil fuels and <1 % is produced via water electrolysis.

In addition, 22 000–24 000 t/a (730–800 GWh) of by-product hydrogen is generated during sodium chloride electrolysis. Furthermore, significant amounts of by-hydrogen is generated during oil refining but this hydrogen is consumed in other oil refining steps and thus it has less importance and it is not included. Data for this type of by-product hydrogen is not publicly available.

As much as 88% of the dedicated hydrogen is used in oil refining and biofuel production, where hydrogen is used e.g. for hydro-cracking and hydro-treating. The rest is used in chemical industry for production of hydrogen peroxide (7 %) and in the in the mining and ore refining sectors (5 %), where hydrogen is used for production of hydrogen sulphide, reduction of cobalt and in nickel and copper refining. Today, only a couple hundred tonnes of hydrogen is used in the steel sector for preventing oxidation of steel.

By-product hydrogen from NaCl electrolysis is mostly used to generate process steam, district heat and to a lesser extent also electricity (via Rankine cycle) at the chlorate and chlor-alkali plants. This hydrogen – together with the hydrogen that is nowadays just vented into atmosphere – could be used in more valuable applications in the future.

Hydrogen use

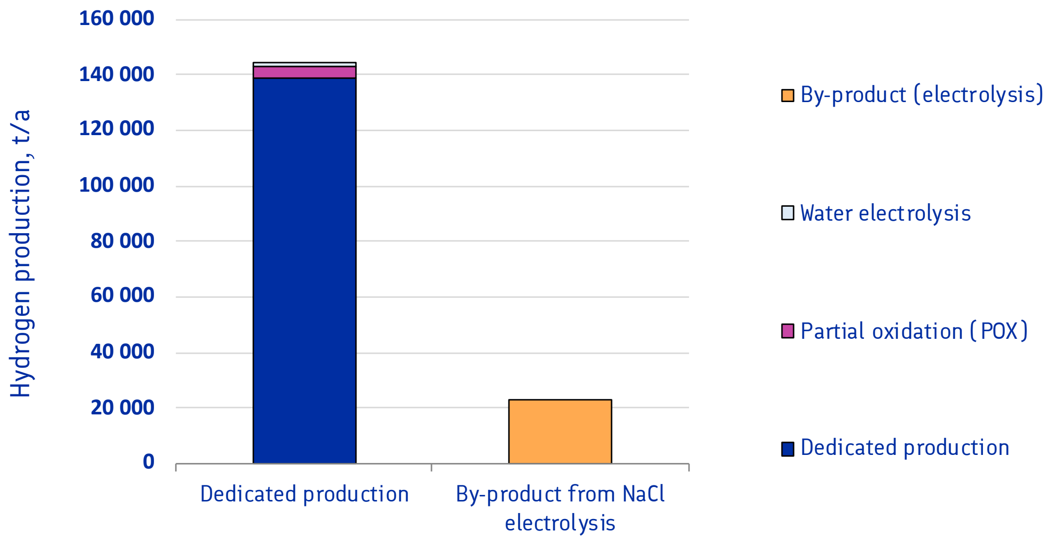


FIGURE 8: CURRENT HYDROGEN USE IN FINLAND
Includes both dedicated production and by-product hydrogen. Hydrogen generated and used in refinery operations is not included.
Source: VTT.

As much as 88% of the dedicated hydrogen is used in oil refining and biofuel production, where hydrogen is used e.g. for hydro-cracking and hydrotreating. The rest is used in chemical industry for production of hydrogen peroxide (7%) and in the in the mining and ore refining sectors (5%), where hydrogen is used for production of hydrogen sulphide, reduction of cobalt and in nickel and copper refining. Today, only a couple hundred tonnes of hydrogen is used in the steel sector for preventing oxidation of steel.

The second largest hydrogen consumer is UPM BioVerno production plant in Lappeenranta. The current biofuel production capacity is 130 000 t/a, which was estimated to correspond to 7 800 tonnes of hydrogen per year, based on their permits.

By-product hydrogen from NaCl electrolysis is mostly used to generate process steam, district heat and to a lesser extent also electricity (via Rankine cycle) at the chlorate and chlor-alkali plants. This hydrogen – together with the hydrogen that is nowadays just vented into atmosphere – could be used in more valuable applications in the future.

A few tonnes of by-product hydrogen from chlor-alkali electrolysis is used for production of hydrogen chloride and sodium borohydride and used in sweetener production.

Mapping of current **hydrogen production and use**

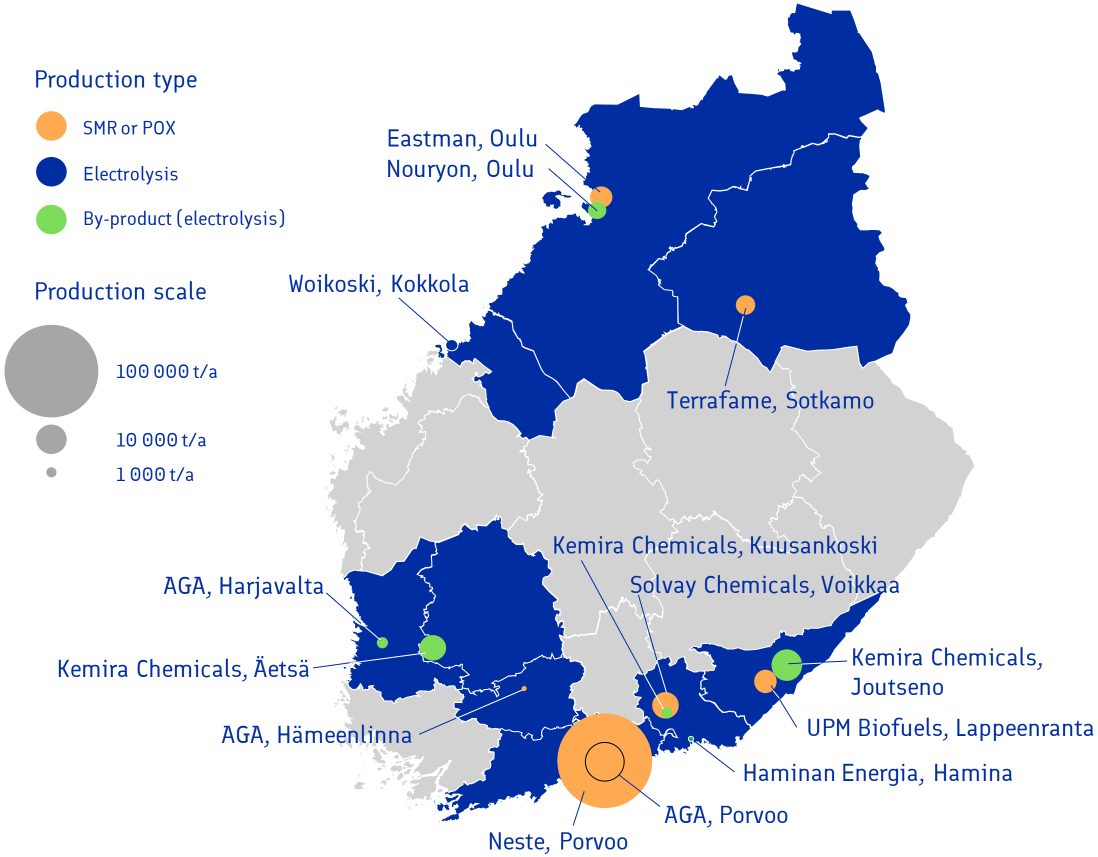


FIGURE 9: LOCATIONS OF HYDROGEN PRODUCTION AND USE
Source: VTT.

Figure 9 shows the geographical distribution of hydrogen production plants and their annual hydrogen outputs. There are only a dozen dedicated hydrogen production sites in Finland. In addition, a few sites generate high purity hydrogen as a by-product.

By far the largest hydrogen producers and consumers in Finland are Neste Oyj refineries in Porvoo and Naantali. However, in Naantali refinery by-product hydrogen from dehydrogenation and aromatization of cycloalkenes covers the total hydrogen demand, and thus no dedicated production is required. Therefore, Naantali refinery is not shown in the map. Furthermore, Neste has announced that it will close down the site in a few years time.

Regarding the locations of the current use of hydrogen, they are mostly located in south to south-eastern Finland, whereas the expected production sites for new wind power are mostly in the north. This is important not only due to the long transmission distance and losses, but also due to the shortage in north-to-south grid capacity creating a congestion referred in RED II.

Cost-estimates for low-carbon hydrogen production

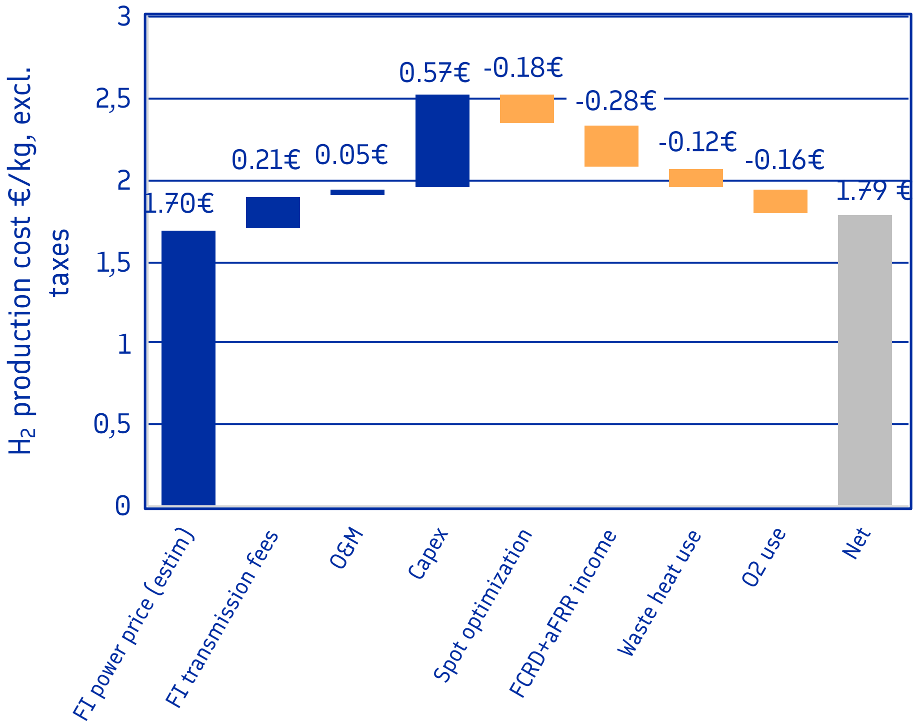
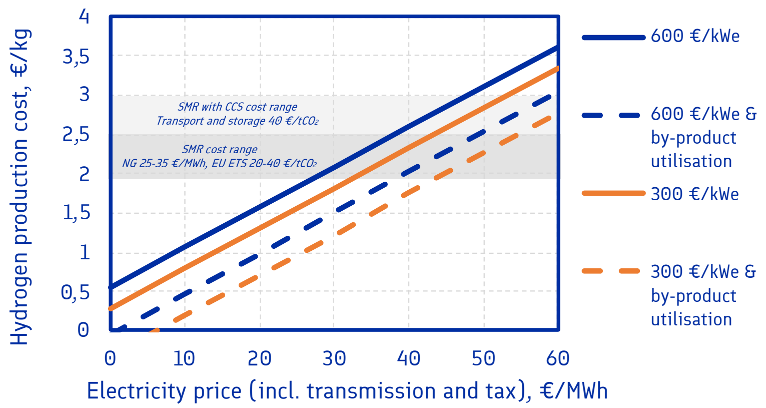


FIGURE 10: COST ESTIMATE FOR ALKALINE ELECTROLYSER BASED HYDROGEN PRODUCTION
based on 600 €/kW overall specific investment, 2020-2030 power price futures, transmission costs and O&M costs (blue bars) with 8000 h/a operation. With cost decrease from spot market optimization (cutting the most expensive 760 hours of the year) and the additional income from grid services, waste heat and oxygen utilisation (orange bars) the total cost is around 1.8 €/kg excluding taxes. Source: VTT.

The dominating cost factor in electrolysis is the cost of clean electricity. In addition to the electricity cost, the capacity factor (operation hours) of the electrolysis is a very important aspect for the cost of low-carbon hydrogen. The outlook is that the specific investment cost of electrolysis will be reduced by upscaling, improving the manufacturing process (automation) and substituting high-cost materials in electrolysis technologies. Efficient system integration of P2X side-streams (heat, steam, oxygen, grid services) are also essential in enabling profitable plant operation and business models.

Figures 10 to 13 present cost ranges for green hydrogen production in Finland with different assumptions and key economic parameters. Figures 11 to 13 also highlight the cost comparison to SMR based hydrogen production from natural gas. In the calculations 65% efficiency based on lower heating value (LHV) of hydrogen was considered for water electrolyser. The specific investment costs include also cost for installation, building, piping and grid connection (default investment is based on FCH 2024 alkaline electrolyser target 480 €/kW + 120 €/kW for building and localisation). The economic lifetime of the electrolyser was selected for 20 years with a WACC of 8% and fixed operation and maintenance costs were considered as 4% of total investment including also the stack replacement costs.

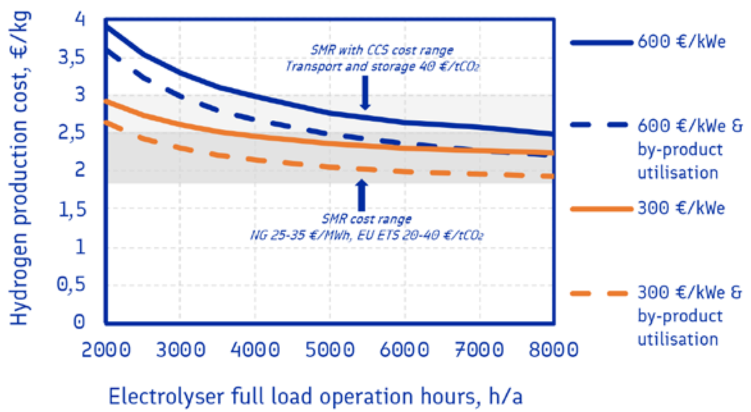


Hydrogen production cost estimates based on 600 €/kW and 300 €/kW electrolyser specific investments with and without by-product utilisation and grid stabilization with 8000 h/a operation assumption. The grey areas highlight the SMR-based hydrogen production costs with and without CCS.

FIGURE 11: COST ESTIMATE FOR ALKALINE ELECTROLYSER BASED HYDROGEN PRODUCTION
Hydrogen cost depending on electricity price. Source VTT.

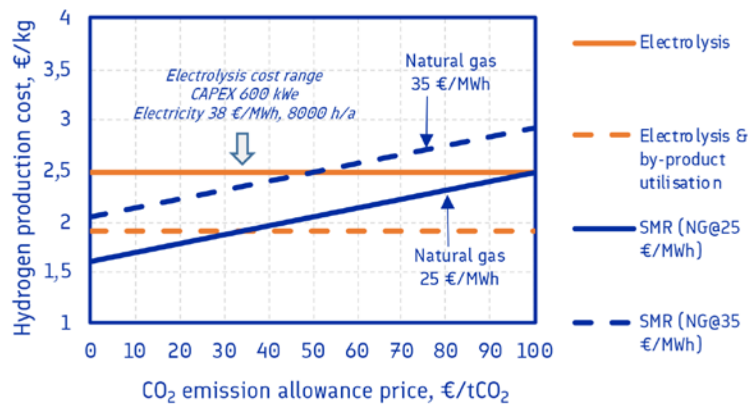
As a sensitivity analysis it was assumed that oxygen could be sold with 20 €/tn price and 50% of the low-temperature heat with a price of 20 €/MWh from the electrolysis. From the grid services a fixed income of 8.34 €/MWh, H_2 was considered in the sensitivity analysis.

From Figure 11 it can be seen that green hydrogen production costs are higher than SMR based hydrogen with the electricity price of 30 to 45 €/MWh depending on the assumptions. However, green hydrogen will become quickly more cost competitive if CCS is needed for the SMR or the price of EUA allowances increase from used default value of 20 €/tn.



Hydrogen production cost estimates based on 600 €/kW and 300 €/kW electrolyser specific investments with and without by-product utilisation and grid stabilization assuming 38 €/MWh total electricity price. The grey areas highlight the SMR-based hydrogen production costs with and without CCS.

FIGURE 12: COST ESTIMATE FOR ALKALINE ELECTROLYSER BASED HYDROGEN PRODUCTION
Hydrogen cost depending on electrolyser operating hours. Source VTT.



Hydrogen production cost estimates based on SMR using natural gas prices 25 and 35 €/MWh. The orange area highlights electrolysis based hydrogen production costs 600 €/kW electrolyser specific investments with and without by-product utilisation and grid stabilization assuming 38 €/MWh total electricity price and 8000 h/a operation assumption.

FIGURE 13: COST ESTIMATE FOR ELECTROLYSER BASED HYDROGEN PRODUCTION
Hydrogen cost depending on CO2 allowance price. Source VTT.

Storage and transport of hydrogen

Storage and transport of hydrogen are important parts for the total economy of producing and using low carbon hydrogen and can essentially affect the price. The use of hydrogen storage enables the use of less expensive electricity, which has a very large importance if electrolyser capital cost is reduced.

In Finland there are no suitable geological formations for inexpensive hydrogen storage such as salt caverns. It seems that only lined rock caverns (LRC) is possible in Finland. However, when hydrogen storage is used for daily or weekly storage, the cost of LRC is not excessive compared to salt caverns. In addition to LRC pipeline storage would be possible in Finland. In the literature, cost for hydrogen pipeline storage is high, but based on few small projects. As a summary, the cost of large-scale hydrogen storage in Finnish conditions is difficult to make and more research and demonstration projects would be needed.

In Finland there are no hydrogen pipeline infrastructure, excluding smaller pipelines in industrial sites between two companies (from Nouryon to Stora Enso in Oulu and from Borealis to Neste in Porvoo). However, as the use of natural gas in Finland has decreased by 50 % during the last 15 years, part of the natural gas transmission pipelines could be repurposed for the hydrogen transport, but more detailed studies for this will be needed.

Hydrogen transport by tube trailers is very cost-efficient in Finland compared to most of other European countries. The weight limit for ADR transport is 68 tonnes, while for non-ADR transport it is 76 tonnes. The length limit for vehicles is 34.5 meters. These limits allow around 2000 kg as payload, while in many older studies 200-300 kg are assumed.

In Finland **gas transport in tube trailers is exceptionally cost effective** since the limits for truck dimensions and weight are actually the largest in Europe.

Possibilities for **low-carbon hydrogen utilization**

The current use of hydrogen in chemical and refinery industry is expected to remain or even increase. Especially, the use of hydrogen in refinery industry could increase, if more vegetable oils will be used as feedstock for producing HVO, as these oils need to be hydrotreated. The energy contents from hydrogen in this type of final product is about 10 %.

There are also possibilities for major increases in biofuel production and refinery capacities, because according to the environmental impact assessment (EIA) for a new HVO production unit, Neste is planning the expansion of their biofuel production, and one of the potential locations is their current site in Kilpilahti, Porvoo. The exact size is not known, but according to EIA 48,000 tonnes of H_2-rich gas is needed annually, and the size of steam methane reformer (SMR) given in the document is 130 MW.

Furthermore, the expansion of UPM BioVerno production plant in Lappeenranta, if proceeded, will increase the site production to 180,000 tonnes/year.

Also, a potentially new field of industrial hydrogen utilisation in the next 10 years can be P2X-chemical production. The most promising locations are the places with currently unused by-product hydrogen, and sites where free concentrated and clean CO_2 streams are available. One P2X option is currently under pre-feasibility study. This is methanol production in Joutseno using by-product hydrogen from Kemira factory and some additional hydrogen from an electrolyser.

In addition, SSAB's HYBRIT process is based on direct reduction of iron ore using fossil free energy and hydrogen which is produced by electrolysis. The plan is that during 2030-2040 the blast furnaces in Raahe steel mill will be replaced with electric arc furnaces. This would require a significant amount of clean hydrogen production, but the exact amounts are not yet known.

Utilization of hydrogen for **green chemicals and fuels**

Synthetic hydrocarbons by P2X are an essential element in the global energy system to achieve net-zero fossil carbon dioxide emissions. CCU and P2X are under an intense RD&D phase, and the field is steadily growing also in Finland. Higher value CCU applications including specialty chemicals and polymers have higher potential to commercialise first. VTT is developing a BECCU-process where 100 % of polyol carbon is originating from carbon dioxide and sustainable hydrogen. In addition, high value carbon-based materials, such as nanotubes and graphene, could be produced with green electricity by using CO_2 as a raw material, which is being studied at Lappeenranta University LUT.

Furthermore, energy company St1 and Q Power have launched a joint project for developing a novel way of making synthetic biomethane from carbon dioxide and hydrogen. In the pilot project, Q Power's biological methanation technology utilises the carbon dioxide recovered from the production of waste-based ethanol at St1's biorefinery. Currently, biomethane is already in traffic and transportation as biogas, and in liquefied form in shipping.

Moreover, Vantaan Energia and Wärtsilä are conducting a feasibility study for a Power-to-Gas facility at Vantaa Energy's waste-to-energy -plant. This facility would produce carbon-neutral synthetic biogas using carbon dioxide emissions and electricity generated at the waste-to-energy plant. Once feasible, the parties intend to continue joint development of the project towards a commercial-scale pilot project.

In addition, a Finnish company Solar Foods has created a new way to produce natural protein by using renewable electricity and air. The protein is produced from soil bacteria fed with hydrogen from water electrolysis.

Another Finnish start-up company, Soletair Power, is developing direct-air-capture of CO_2 aiming to produce synthetic renewable fuels with electrolytic hydrogen and captured CO_2.

Use of **hydrogen in steel** and cement **industry**

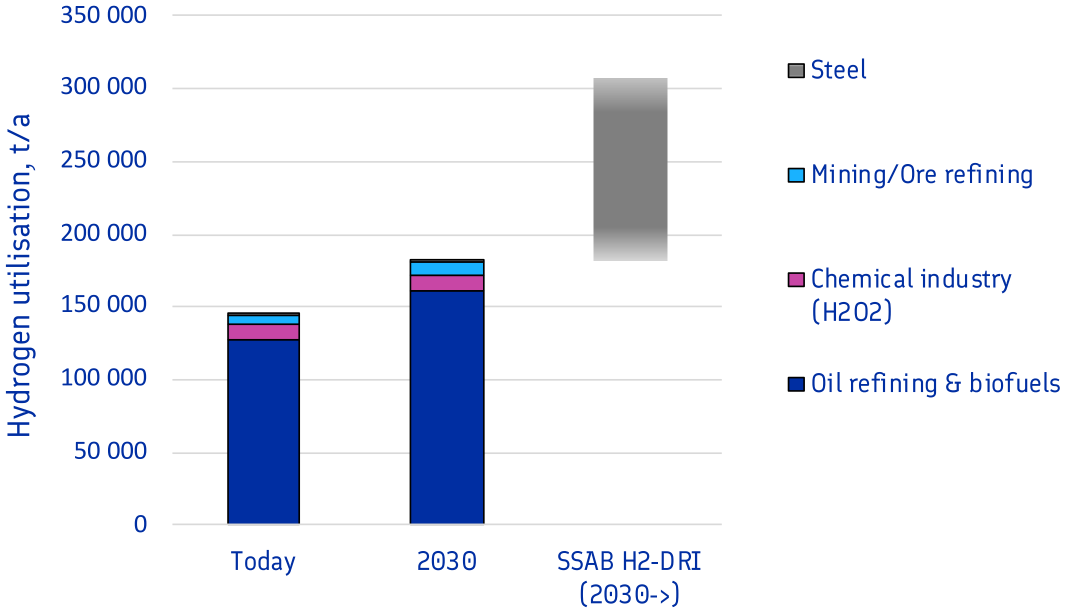


FIGURE 14: ESTIMATES FOR HYDROGEN USE FOR 2030 AND BEYOND.
Hydrogen use in various industrial sectors, present and new. Source VTT.

SSAB has publicly communicated a plan that during 2030-2040 the blast furnaces in Raahe steel mill will be replaced with electric arc furnaces. This would require an estimated 100 000 to 120 000 m3/h of hydrogen gas, which would correspond to 450-550 MWe electrolyser input, if produced with electrolysis. This would add about a third on top of the current production and use of hydrogen.

There are significant opportunitities for producing power-to-X fuels also in Finland, even before 2030, but only if the production cost level in Finland is competivive. If competitive cost level is reached, hydrogen use in the power-to-X production can reach the same order than all other use combined.

Direct **use in heavy transport** and logistics

Use of hydrogen in fuel cell electric vehicles (FCEV) has not taken such progress that was anticipated ten or even five years ago. The main obstacle being the limited HRS network density, allowing the vehicles to be used in quite limited geographical areas. Furthermore, the current market offering of the industry is restricted just to four different vehicles, and that may not satisfy the needs of the buying customers.

Moreover, this situation has led the automakers that have focused and heavily committed in this technology, also to invest in production capacity of fuel cell power units to support the rising production of FCEV cars. However, when the market has not taken the upward trend, these production investments are now in jeopardy.

Consequent, both Toyota and Hyundai are now seeking new applications for their fuel cells in other, heavier vehicles, especially in applications, where battery power is not at its strongest. This entails long-range and heavy payload applications, because of easy scalability of the fuel cell power, higher power needs are easily catered with using several FC-units in parallel, assisted with a battery to buffer the input/output.

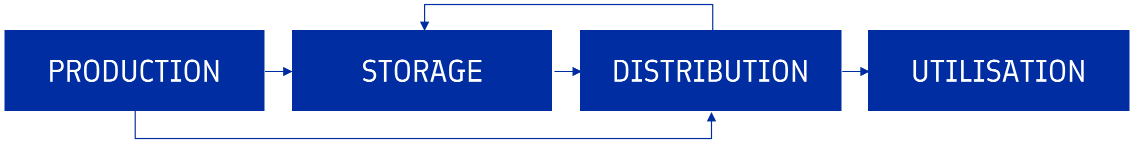
Even if FC power has been successfully demonstrated in urban bus applications across the globe, the battery-electric bus with its apparently more simple energy supply system, has succeeded to become the mainstream in shifting the urban public transport into a sustainable pathway. Therefore, the application fields where long range and high payload - or better yet, both - are essential, hydrogen FCEV has its prime stage to shine.

Catering captive fleets with hydrogen supply is also less demanding. Thus, the use of hydrogen in transport applications should begin with captive fleets, where the baseload of a HRS can be calculated beforehand, and shifted to commissioning of a correctly-dimensioned HRS. With these demonstrations and pilot-sites acting as local nucleus, the enlargement of the HRS for wider use could gradually begin, supporting more vehicles and a larger operative area.

In Finland, there are some potential cases, where sustained heavy transport between two fairly close locations takes place, and those should be carefully considered as primary pilot cases for hydrogen FC power in transport.

Key industries and ecosystems in Finland **reflecting the value chain**

A general-level value chain for a sustainable H_2 landscape consist of four parts: Production, Storage, Distribution and Utilisation.



Furthermore, regarding methods for clean hydrogen production, hydrogen made with water electrolysis using electricity made with renewables is the most sustainable option. All other hydrogen production methods, mainly based on utilisation of fossil fuels, would need effective CCU/CCS addition to achieve even partial carbon-neutrality. Therefore, renewable electricity generation and distribution needs to be added in the general level of the hydrogen value chain, when considering green hydrogen production and business potential connected to that.

Moreover, the storage and distribution part attain different technology options, such as pressure vessels or underground caves, as well as chemicals (liquid organic hydrogen carriers, LOHC), whereas in the distribution phase both on-road transport and pipeline options are possible. Especially, it is important to point out that pipelines can be utilized, both for hydrogen distribution and storage, or at least a buffer.

The options for hydrogen utilisation comprise six main avenues: Refining, Industrial chemicals & P2X, Power generation & storage, Steel production, Zero emission transport and Exportation. However, we do not foresee that Finland could produce so much low-carbon hydrogen that exportation could take place.

Also, other important actors are providers of infrastructure, technology and components, as well as maintenance, which are needed for maintaining many supportive activities throughout the entire hydrogen logistics chain. The substantive full value chain needed for green hydrogen from renewable electricity generation to utilisation is presented in Figure 15.

We have added also in the graph some key Finnish companies that are already working with hydrogen or have potential to do so in the near future. The listing is not comprehensive, but more like showing that there are already existing Finnish companies for all levels in hydrogen value chain, but there is also lot of space for new potential business opportunities.

Finland has a **well populated value chain for hydrogen**

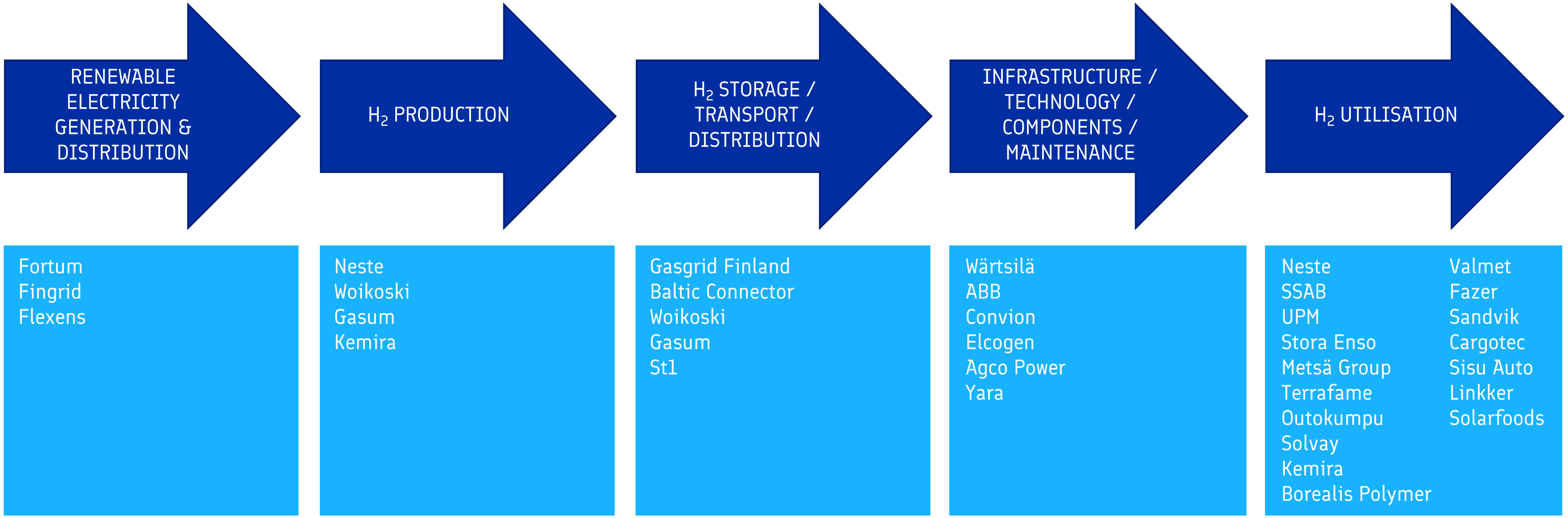
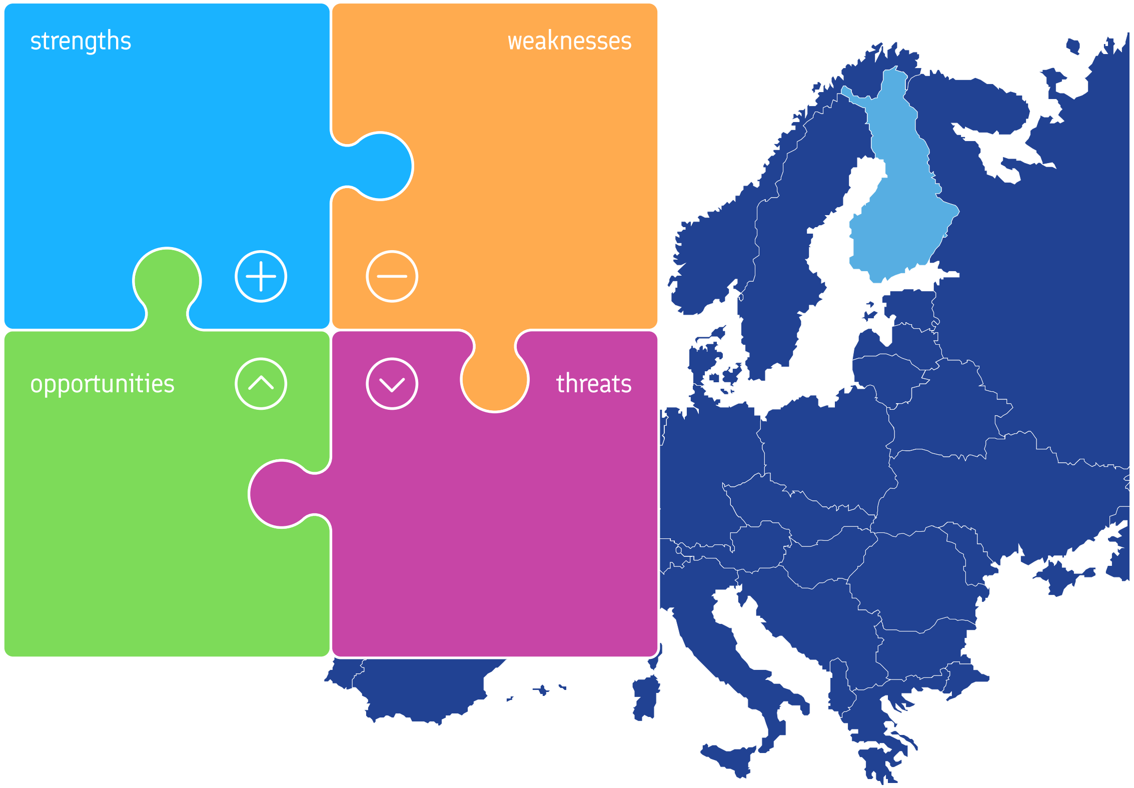


FIGURE 15: FINNISH HYDROGEN SUPPLY CHAIN AND EXAMPLES OF POTENTIAL COMPANIES. Source: VTT.

We have added also in the same figure some key Finnish companies that are already working with hydrogen or have potential to do so in the future. That listing is not comprehensive, but more like showing that there are already existing Finnish companies for all levels in hydrogen value chain, but there is also a lot of space for new potential business opportunities.

During the preparation of this report, a questionnaire was also sent out to these companies in order to chart their present activities and future plans regarding hydrogen

SWOT



A traditional SWOT analysis was performed to assess the strengths, weaknesses, opportunities and threats that Finland has regarding the growth of the production and use of low-carbon hydrogen.

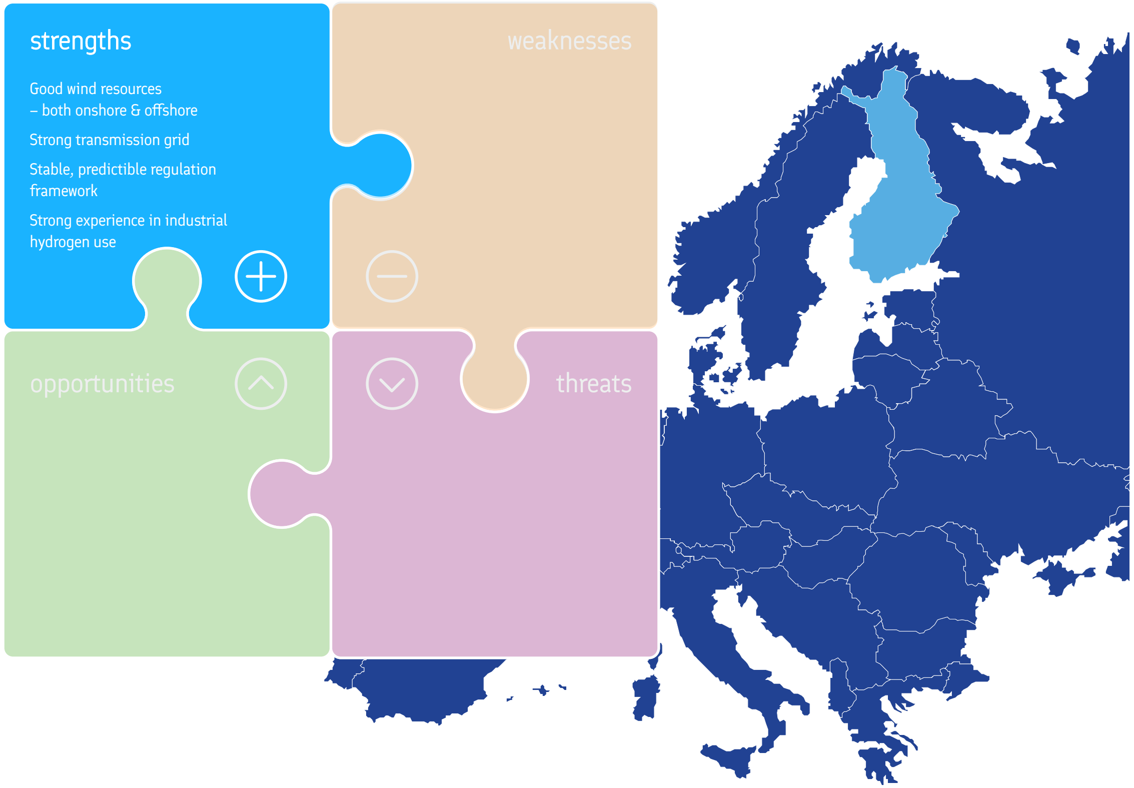
Finland has several assets, like strong electric grid and potential reserves to build new renewable wind power, both offshore and onshore. Furthermore, we have a full value chain of hydrogen production and use already in place, as well as long legacy and strong experience in using hydrogen as an industrial chemical.

There are also some assets missing that are worth noting. Some are spun from the geological formation of our bed-rock, and thus cannot be broken easily. However, some scarcities can be fulfilled with money and pure ingenuity that Finnish people are famous to have a lot.

Despite the bright picture that almost all roadmaps on hydrogen paint, nothing is for sure, and this is true also for Finland. There are crucial issues that can turn down the whole endeavour, and we should be aware of those. We need to be especially aware of those that we cannot control ourselves.

Finally, we found that there are quite many opportunities also for us to seize, and those can offer the first stepping-stones for our journey towards a future, where low-carbon hydrogen is an essential part of the energy system, and an enabler for wide use of renewable energy without excess carbon emissions.

Strengths



Good wind resources – both onshore & offshore

Finland has good wind resources both offshore and on-shore that allow increasing the production of renewable electricity that is the most important cornerstone for pro-duction of low-carbon hydrogen.

Strong transmission grid

The Finnish electricity grid is already now fairly strong, and the on-going undertakings shall strengthen it furt-her, especially in increasing the North-South transmis-sion capacity. This has crucial effect on the usability of the upcoming wind power in the north, and projected use of low-carbon hydrogen in the south and south-east.

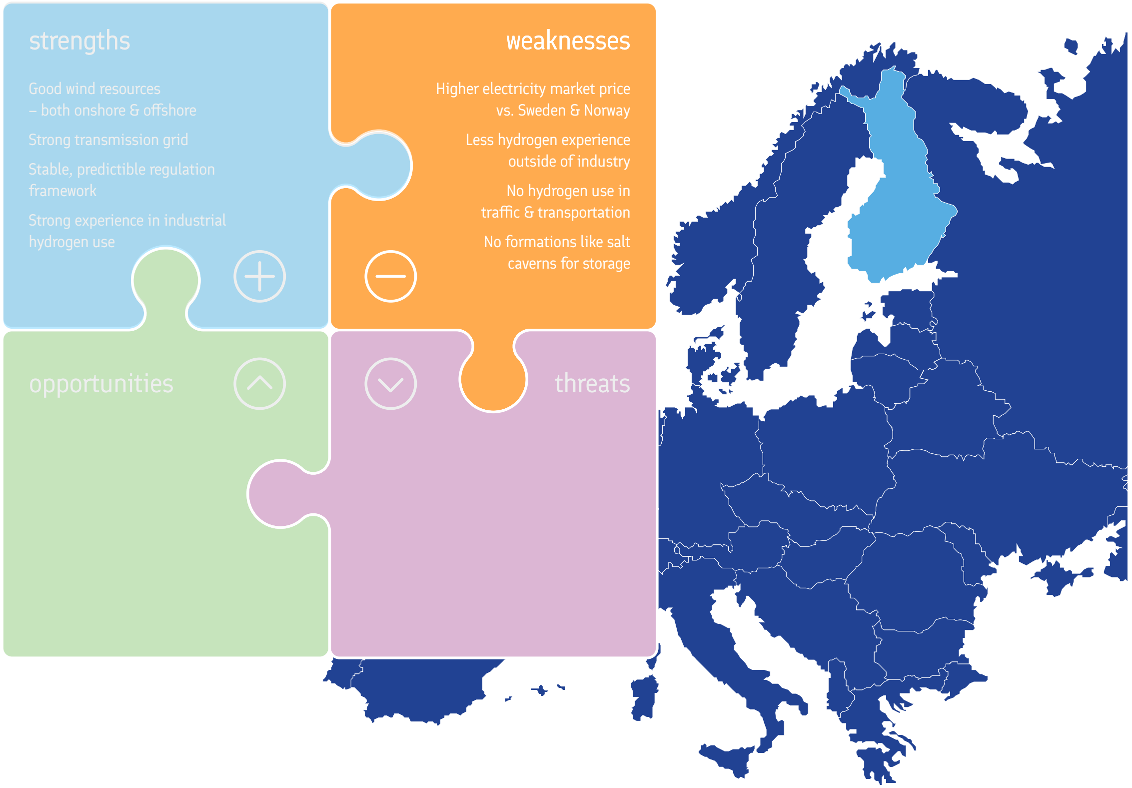
Stable, predictible regulation framework

Finland is a Member State of the European Union, and it has also stable national legislation framework regarding energy issues.

Strong experience in industrial hydrogen use

Finland has fairly strong tradition in industrial use of hydrogen, and many companies that already now form a complete hydrogen value chain. This founds a solid base for further activities in creating future ecosystems based on low-carbon hydrogen production and use

Weaknesses



Higher electricity market price vs. Sweden & Norway

The Finnish grid is part of the Nordpool, together with Norway and Sweden, that have large amounts of low-cost hydropower. However, due to limitations in cross-border connectivity, electricity import is throttled, and thus market-based price in Finland is usually higher.

Less hydrogen experience outside of industry

Although there is strong industry and long tradition in hydrogen use, outside this professional base the experience is less strong, and large knowledge gaps related to the characteristics of hydrogen can be seen.

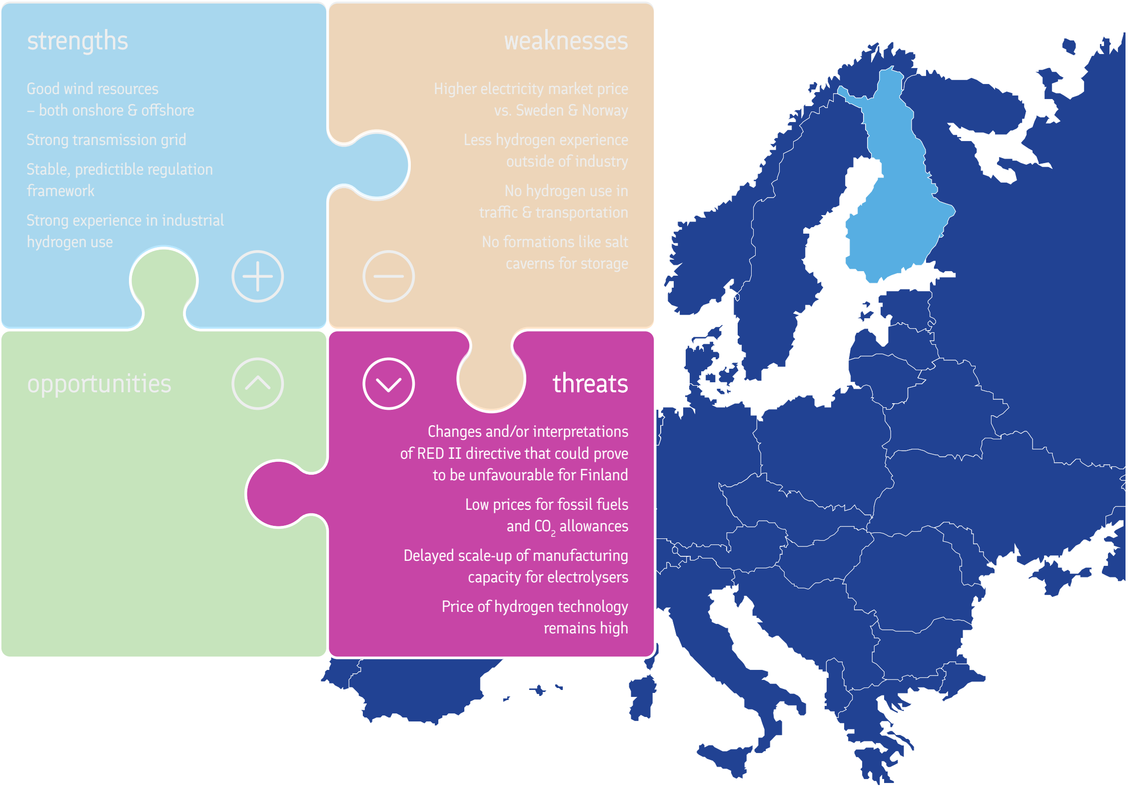
No hydrogen use in traffic & transportation

There is no present use of hydrogen in road transport, and no hydrogen refuelling infrastructure, despite the fact that there is a Finnish company that offers such technology to global market.

No formations like salt caverns for storage

Largely, Finland has very solid and hard bedrock terrain, with no hollow formations like the salt caverns that are quite common in other parts of Europe. This does not give any favourable way to build underground storages for hydrogen with reasonable costs, as everything must be purposefully excavated.

Threats



Changes and/or interpretations of RED II directive that could prove to be unfavourable for Finland

Because a large part of the proposed new use of low-carbon hydrogen is based on the particular value created by the RED II directive, interpretations in open questions or even larger changes could jeopardise the future endeavours based on that aspect.

Low prices for fossil fuels and CO_2 allowances

If the price of carbon in the emissions trade sector continues to remain low, and the use of fossil fuels continues, market for low carbon hydrogen does not grow as anticipated, despite the good prognosis.

Delayed scale-up of manufacturing capacity for electrolysers

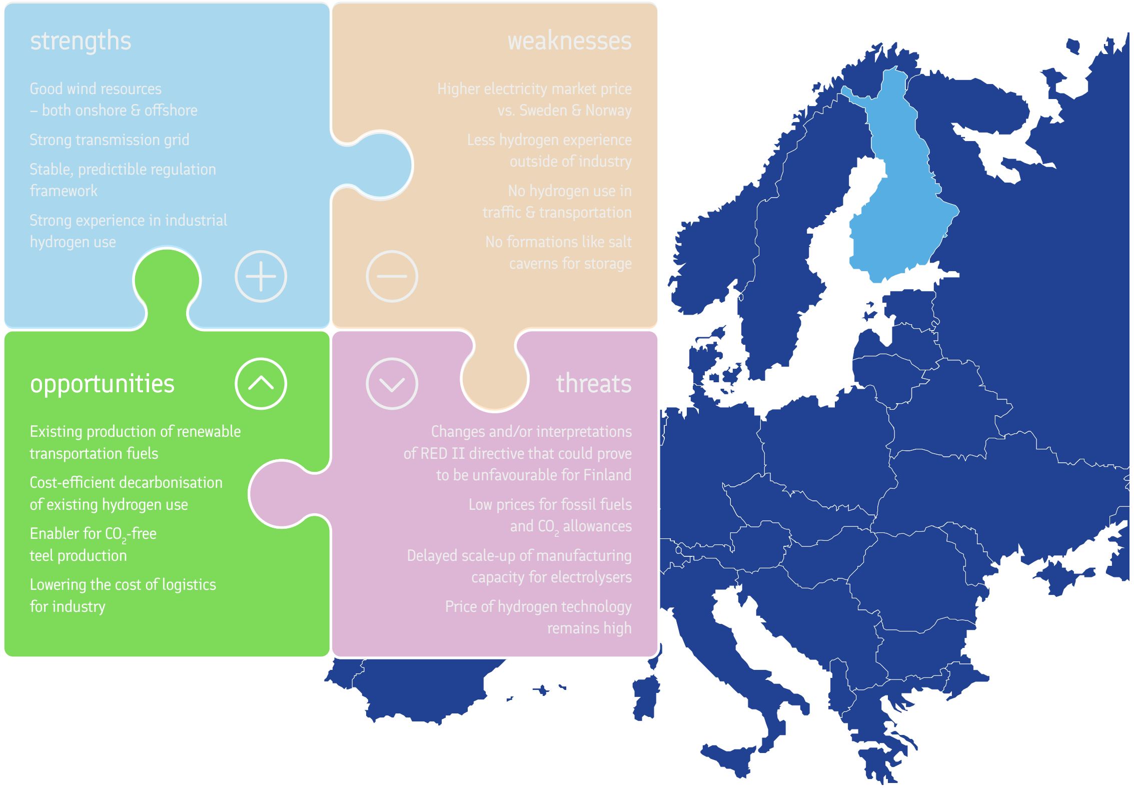
The projected growth in the demand of electrolysers is so extortionate that the supply industry may not succeed in scaling up the manufacturing capacity. This can seriously delay the market growth of low-carbon hydrogen

Price of hydrogen technology remains high

Should the scaling-up of manufacturing resources fail, prices for technology may remain high, with negative effects on the willingness to invest.

However, it is worth noting the latter three threats are not specific for Finland, but affect all globally.

Opportunities



Existing production of renewable transportation fuels

Finland has a fairly large fuel refinery industry, and presence of the global market leader of HVO type of renewable diesel production, as well as one other, but smaller company. Both are also planning to increase capacity. This creates a favourable position for using low-carbon hydrogen to replace fossil-based hydrogen, and "making the green even greener".

Cost-efficient decarbonisation of existing hydrogen use

Although market price for electricity in Finland is higher than in Sweden and Norway, it is still favourable enough to offer a reasonable basis for low-carbon hydrogen production, and kick-off decarbonisation of the fossil-based industrial hydrogen.

Enabler for CO_2-free steel production

The SSAB steel factory in Raahe, with the company's own initiative to "reinvent steelmaking", offers a unique case for increasing significantly the demand for low-carbon hydrogen with simultaneous and huge cut-down in CO_2 emissions.

Lowering the cost of logistics for industry

The Finnish heavy industry offers some potential cases, where sustained heavy transport between two locations takes place. Those could act as pilot cases for hydrogen FC power in heavy transport applications with a cost-cut aspect along with sustainability.

Key findings and recommendations

Based on the results of the interviews and the expertise knowledge VTT's personnel, a list of key findings and recommendations for advancing low-carbon hydrogen production and use in Finland was developed. Those are presented separately for each main part of the hydrogen value chain.

As some of the fundamental prerequisites like adding new renewable electricity production, strengthening of the electric grid or building large, underground hydrogen storages take considerable time, it is most important to focus on this kind of topics, and issue timely actions.

The list of recommendations are mainly for different R&D&D actions. However, equally important is to make necessary adjustemenst in different laws and regulations (e.g. Electricity Market Act) so that the large scale hydrogen production, transport and use can take place in the most efficient way.

For start, the main focus in the recommendations is how to increase the production and industrial use of low-carbon hydrogen, as this is easiest to made with national actions.

On the other hand, the incease of hydrogen use in different heavy transportation applications is more dependent on the international development of the offerins of the hydrogen fuel cell technology.

Furthermore, the selected recommendations for promoting the industrial use of low-carbon hydrogen will lower the production and transportation cost of hydrogen, which is a prerequisite of cost efficit use of hydrogen in heavy-duty road traffic and maritime applications.

Production

A fundamental prerequisite for clean, low-carbon hydrogen production is availability of electricity that meets the targets for both renewability and carbon emissions, but more so also regarding cost and price. This shifts the attention more on the investments in large-scale, industrial electrolysis installations.

Recommendations regarding hydrogen production are as follows:

- Hydrogen production using low carbon electricity should be promoted. Additional renewable and low carbon electricity production in Finland is needed, as well as strengthening cross-border and internal electricity transmission capacity.
- In Finland, the utilisation of by-product heat from electrolysis is an opportunity. The development of technologies for optimising this, as well as the development of solid oxide electrolysis technology are important for both hydrogen production in Finland as well as for technology export.
- Fossil fuel based hydrogen production can be gradually replaced by tax policy and with suitable incentives (e.g. Energy aid). The work can be started by hybridising the existing fossil fuel based hydrogen with electrolysers and short term local hydrogen storage.
- The total potential for green hydrogen production in Finland is between 100 kt and 150 kt in 2030 without new use in industry or traffic. Most of the hydrogen would be produced in the same location as now. In some new industrial locations can large scale hydrogen production start, if economic conditions for producing new products, such as P2X –fuels or carbon-free steel, are good enough.
- The most potential options for H_2 villages and valleys are places where electrolytic production of hydrogen is taking place for industry, as electrolytic hydrogen is required for hydrogen transport applications.

Storage and transportation

Concerning Finland, the two main near-term options for distribution of hydrogen appears to be gaseous hydrogen transport in tube trailers and dedicated hydrogen pipelines. However, hydrogen transmission in pipelines is meaningful only, if volumes are large, or some additional benefits can be gained.

Recommendations for hydrogen transportation are the following:

- Prerequisites for hydrogen distribution should be improved by enabling more cost-efficient transport of hydrogen in tube trailers, and by starting to build the first hydrogen pipelines.
- The use of green hydrogen mostly in large industrial facilities favours hydrogen supply chain (HSC) solutions, which consist of centralised electrolyser units and transport of hydrogen to smaller consumers first by hydrogen tube trailers. Later on pipelines can be combined with hydrogen tube trailers.
- It should be studied, if first hydrogen pipelines could be built already by 2030. This would enable large hydrogen storage facilities and improve security of supply for hydrogen users.
- The weight limit for ADR transport in Finland is 68 tonnes, while for non-ADR transport it is 76 tonnes. It should be studied, if weight limits in ADR transport could be increased to 76 tonnes when gaseous fuels are transported.
- It is recommended that investment for improved hydrogen transport are supported (e.g. Energy aid), as this would enable gradual build-up of hydrogen supply chain as well as better utilisation of existing by-product hydrogen.

Energy conversion and storage

The role of hydrogen in Finland as energy storage can be supported by developing large scale hydrogen storage solutions such as lined rock caverns (LRC) and pipeline storage solutions. For large scale use of hydrogen the cost of storage is one of the key parameters and these technologies should be demonstrated in suitable locations.

The main value as energy storage comes from the fact that hydrogen for industry can be produced with electrolysers, when electricity price is low, and production can be quickly shut down, when there is a shortage of production capacity.

In Finland, the maximum amount of hydrogen that can be blended in natural gas transmission grid is limited to 1% due to customer requirements. However, larger amounts of hydrogen can be blended for single customers and this applies both for natural gas delivered by pipeline as well as LNG.

The role of chemical hydrogen carriers in Finland can be considered uncertain. The most advanced chemical carriers are liquid organic hydrogen carriers (LOHC) such as methylcyclo-hexane. These are developed mostly for long-distance large-scale hydrogen transport and storage. While there may not be immediate need for LOHC in near future in Finland, the international development should be followed carefully.

Recommendations for Hydrogen in the area of energy conversion and storage are:

- Research and development of such storage options that are particularly feasible, like pipe-line storage or lined rock caverns, should be initiated and reinforced.
- Demonstration of the first, most-promising industrial-scale storage for hydrogen should be supported.
- Build-up of the first large-scale industrial hydrogen storage ought to be advocated.

Industrial use

In principle, clean low-carbon hydrogen could replace fossil-based hydrogen in all industrial use, if it would be cost-competitive. Thus, the industrial use of low-carbon hydrogen should be supported by tax policy as well as investment subsidies (e.g. Energy Aid), taking into account the direct positive net effects for carbon emission reduction, but also indirectly for the national economy, when imported energy, mainly natural gas, would be replaced by indigenous renewable electricity.

The decisions about tax changes concerning electricity and energy taxes by Finnish government in 2020 are supporting the replacement of fossil fuel based hydrogen by green hydrogen. The suitable level of support should be evaluated, taking into account effects of national economy and competiveness of the industry.

Recommendations for Hydrogen in industrial use:

- Study the effects of future cost and market developments for the Finnish industry, and determine how to ensure the competitiveness of the industry in a rapidly changing international operating environment.
- Support the use of hydrogen in P2X applications and other new hydrogen-related applications enabled by short-term cost development and regulations.
- Study what would be the impact of replacing imported chemicals like ammonia and methanol with equivalents produced with indigenous renewable electricity for the national, macro-economy.

Mobility and fuel cells

The Finnish manufacturing industry is profoundly dependent on heavy transport and logistics regarding raw materials, but also of intermediate and finished products. Furthermore, there are some potential cases, where sustained heavy transport between two locations takes place. Those should be carefully considered as primary pilot cases for hydrogen FC power in heavy transport applications. In these demonstrations, both sustainability point-of-view and cost-competitiveness should be taken into consideration. With these pilot-sites acting as local nucleus, the roll-out of HRS for wider use could progressively begin, gradually supporting more vehicles and a larger area.

It is also worth noting that if hydrogen use in marine applications begin to make progress, Ahvenanmaa could become an excellent test area. This archipelago region has lots of wind power opportunities to support low-carbon hydrogen production, as well as a fleet of small vessels in local use, and larger ships like car ferries in day-to-day transit operation and harbour visits, offering platforms for various different applications regarding both propulsion and on-board electricity generation.

Recommendations for hydrogen in mobile applications:

- Follow closely the widening market offering of hydrogen-fuelled heavy transport vehicles and working machinery.
- Study the potentials of hydrogen use in selected candidate cases for heavy transport vehicles and mobile machinery, and ensure that the effects of particular conditions of Finland, especially climate, are considered.
- Sponsor and patron small-scale demonstration projects that could lead into widening use of hydrogen in transport sector, taking into account both the sustainability point-of-view and cost-competitiveness.
- Develop step-by-step scenarios and roll-out timelines in connection with international developments in the field of HRS and filling stations.
- Follow the progress in hydrogen use for marine applications.

Overarching issues

There are some overarching issues regarding all novel production and use of hydrogen in Finland. Some are related to the European regulation and national legislation, and some are related to Finnish climate and geographical conditions.

Furthermore, as the use of hydrogen starts to widen from its current use as an industrial chemical, it will involve more people with less hands-on experience and knowledge in hydrogen safety. Therefore, using all existing resources that entail risk-assessment and support safe deployment of hydrogen use, should be widely publicised.

Recommendations regarding the overarching issues:

- Closely follow the development and possible revisions of the RED II directive, as the changes may have substantial consequences.
- Ensure that all national Degrees and Codes of conduct regarding e.g. safe use of hydrogen does not preclude the enlargement of the use of “higher value” and “good hydrogen”.
- Communicate effectively and widespread that all safety aspects of hydrogen use are “in good hands”, and no roots of concern should spur.
- Consider the need of raising the characteristics and status of hydrogen in all levels of public education, and its presence in the curricula.
- Consider the need of raising the characteristics and status of knowledge on hydrogen in all levels of public education, and its presence in the curricula.
- Initiate and continue an inventory of industries and their volumes that will need/use hydrogen in the future, such as emission-free production of steel and low-emission battery chemicals.
- Support recommendations of the integration of hydrogen into national and regional energy, industrial and transport policies.
- Foster all new use of H_2 and suggestions for demonstrations and pilot projects to gain practical operating experience, especially during the winter season.

Summary and conclusions

Hydrogen enjoys now a high degree of interest by a variety of different stakeholders. This is due to multiple reasons, mostly related to reducing carbon emissions to mitigate climate change. Still, we need to say that this is not the first time hydrogen has been promoted up to the point of a hype. Yet, all previous inceptions have fainted, and not led to a sustained flux of investments and growth in hydrogen use.

Nonetheless, we are currently confronted with even more aggressive global outlook in the rise of production and use of carbon-free hydrogen. To make all this happen, many EU countries have announced investments in billions to scale up the electrolytic hydrogen production. Also the significant lowering in the price of renewable electricity from wind or photovoltaics has made clean hydrogen economically viable, and many countries have given it a major role in their future energy and climate policies.

Regarding the outlook for Finland to increase clean hydrogen production and use, the basics are quite strong. Finland has good wind resources, both offshore and onshore, allowing increase in the production of renewable electricity, essential for production of low-carbon hydrogen. We have also a fairly strong electricity grid to support increased transmission of power. In addition, we already have a full and working value chain for hydrogen, and decades of experience in large-scale industrial use of hydrogen.

On the offset, we do not have formations like salt caverns that allow to build underground storages for hydrogen with reasonable costs. However, we do have a natural gas pipeline that could in the future store and carry also hydrogen. Furthermore, transport of hydrogen by truck is very cost-effective, as much higher total vehicle mass is allowed in Finland, compared to the rest of Europe. The large heavy long-distance transport sector in itself offers a case worth studying the possibilities of hydrogen-powered fuel cells to act as a zero-emissions power source, as due to the high unit masses and long transport distances, battery electricity is not a strong contender.

Regarding opportunities for clean hydrogen use, Finland offers a solid ground, because we have a fairly large (per capita)

Summary and conclusions

refinery and biofuel industry using today fossil-based hydrogen. Both could use clean hydrogen in the way that the current Renewable Energy Directive (RED II) prescribes. However, the value of this market is still unpredictable and strongly dependent on the open interpretations or revisions of this Directive. Also the production capacity and cost/price curve of other liquids that can be used to fulfil the requirements for renewable contents of transport fuels have their own itinerary. If positive, they may leave less room for hydrogen.

On the other hand, a major steel manufacturing company that has plants in Sweden and Finland has efforts to reform their steel-making process. This move will effectively cut down carbon dioxide emissions of their steel production to nearly nil, and create a huge demand for clean hydrogen. On its own, this endeavour for the Finnish plant alone would create about 30% increase in today's hydrogen production and use. However, for sure this will not take place before 2030, so it does not offer any counterbalance for the elusive market created by RED II, but rather can act as the next step.

Eventually, creating a "hydrogen economy" - widely touted as the ultimate goal - is not a spectator sport, where a few do something, and the rest of us just sits on their seats and watch. No. We all can, and to make this endeavour succeed, we all need to act. Gradually we can start to form the right kind of teams and find the playing fields, where growth starts to happen. And progressively, skills - and trust on those skills - shall improve, and then we have a trajectory that points upwards. Clearly, hydrogen offers for Finland great opportunity to create wide range of new businesses throughout the entire hydrogen value chain.

Finally, every journey starts with the first steps. Preferably, from the very beginning, you should know where to aim, and how to get there most efficiently. For this journey, this is our roadmap.

FURTHER READING IN THE GLOBAL AND EU CONTEXT

The Future of Hydrogen for G20. Seizing Today's Opportunities. International Energy Agency IEA, 2019.
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A Hydrogen Strategy for a Climate-Neutral Europe. European Commission, 2020.
https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

Hydrogen Roadmap Europe. Fuel Cells and Hydrogen Joint Undertaking (FCH JU), 2019.
https://www.fch.europa.eu/publications/hydrogen-roadmap-europe-sustainable-pathway-european-energy-transition

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