NEXT NORDIC GREEN TRANSPORT WAVE - LARGE VEHICLES

Large-scale hydrogen use in Nordic industry 2020-2030

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Next wave - about the project

Electrification of the transport sector already began and the Nordic countries, specifically Norway and Iceland, have taken major steps resulting in battery electric vehicles (BEVs) already accounting for a substantial percentage of the total sales. The world is looking towards the Nordics as they are providing global examples for success. However, little is happening regarding larger vehicles as battery solution still are not able to provide heavy-duty users (e.g., buses, trucks and lorries) the mobility they need.

Fuel cell electric vehicles using hydrogen as a fuel can solve this. The project focuses on providing infrastructure for a large-scale deployment of trucks, buses and lorries. The goal is to further stimulate the global technological lead, which the Nordic countries have by stimulating the very first hydrogen infrastructure roll-out for larger vehicles while at the same time map how the infrastructure build-up needs to be done, so that the transition to hydrogen vehicles can happen smoothly. Such roll-out will also benefit the use of hydrogen for trains and the maritime sector. Furthermore, in addition of sourcing the hydrogen as a by-product from the industry, in the Nordic region we have the unique opportunity to produce the hydrogen in a green manner exploiting renewable electricity production.

Already, Nordic industries have taken international lead in the field of hydrogen and fuel cells and a unique cooperation exists between "hydrogen companies" via the Scandinavian Hydrogen Highway Partnership (SHHP) cooperation. Jointly they have marketed the Nordic platform for hydrogen and, at the same time, paved the way for vehicle manufacturers to deploy such vehicles in the Nordic countries. When it comes to hydrogen, the Nordics have globally leading companies both within the infrastructure and the fuel cell business. The project therefore sets forward four key activities in a unique project where technical innovation and deployment strategies are intertwined.

The project will deliver an analysis on large-scale transport of hydrogen with mobile pipeline, a description of the innovation and business potential for a roll-out of FC-buses in the Nordic region, as well as a coordinated action plan for stimulating the FC truck demand and a prospect for utilising hydrogen in heavy-duty equipment. Finally, the project will contribute to national and Nordic hydrogen strategy processes even providing input to a possible Nordic Hydrogen Strategy.

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Summary

There is a different level of industrial production and use of hydrogen in Nordic countries. Norway and Finland, are the largest producers and consumers of hydrogen. In Sweden the amounts are slightly less, but there are large number of industrial sites with significant production and use of hydrogen. In Denmark and Iceland current use of hydrogen is at a lower level.

In all Nordic countries there are significant possibilities for expansion of hydrogen use for new applications and for replacing current fossil fuel-based hydrogen production by low carbon hydrogen.

Background

The global dedicated hydrogen production of 70 million tonnes (Mt) per year is almost entirely served by fossil fuel-based hydrogen production methods; 76% from natural gas and almost all the rest (23%) from coal. Electrolysis currently accounts for only 2% of the global hydrogen production – and only 0.1% origin from water electrolysis, the rest being brine electrolysis for sodium chlorate and chlor-alkali industry. As a result, the global hydrogen production is responsible for carbon dioxide (CO_2) emissions of around 830 Mt of CO_2 per year, equivalent to the CO_2-emissions of Indonesia and the United Kingdom combined (IEA, 2019).

Today, just about the entire dedicated hydrogen production is used as an input factor/feedstock for various industrial processes. Hydrogen is used in large quantities for chemical product synthesis, especially to form ammonia (55% of the annual hydrogen production) and methanol (10%). Refineries, where hydrogen is used for the processing of intermediate oil products, is another main field of application (25%), leaving only 10% of the global hydrogen production for other applications such as float glass production, fat hardening, protection gas, and mobility (Shell, 2017).

Also in the Nordic countries, large amounts of hydrogen are being used. While the hydrogen used for mobility in the Nordic region traditionally has exploited electrolysis-based hydrogen, greenhouse gas emissions resulting from hydrogen production for industry are large also in the Nordic countries since most of the hydrogen used is obtained from fossil fuels being feed directly into industrial processes.

In general, renewable/green electricity is available at scale and at a reasonable low market price in the Nordic countries. Thus, green hydrogen production by electrolysis can become a viable near-term option for replacing current fossil fuel-based hydrogen production. In addition, with the stated need for environmental policy shifted toward greener alternatives ("The green shift") and the increased renewable electricity production capabilities of the region in mind (especially with regard to wind power), there's an opportunity now to support/prepare the ground for Nordic companies (new and already established industries) to take leading positions in the green hydrogen market.

When produced at scale, which will be needed in order to supply heavy-duty hydrogen vehicle fleets like trucks and buses, green hydrogen (hydrogen produced on the basis of renewable energy) will become cost competitive with both grey hydrogen (hydrogen produced from fossil fuels without CCS) and even blue hydrogen (hydrogen produced from fossil fuels with CCS) (Nel Hydrogen, 2020). Furthermore, the use of green hydrogen in traffic is also promoted by EU directives such as the RED II directive and the Clean Vehicle directive, extending the Nordic "home market" to the whole of Europe.

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Photo: Jack Redgate, Pexels

Denmark

Hydrogen production in Denmark

Denmark is not characterised by large scale industrial use of hydrogen. There are currently three companies that are using hydrogen at an industrial scale, as well as a large bulk of minor consumers which are not relevant in this context.

Use of hydrogen power at an industrial level in Denmark

Refinery industry

Equinor Refining Denmark AS

At its location in Kalundborg, Equinor has a production capacity of 473,000 m^3 of hydrogen per day (around 1.75 tonnes per hour). This number is from 2008 and should therefore be approached with caution. However, based on the fact that the production capacity and operation procedures have not changed significantly over the years at this refinery, we believe that the numbers are a fair indication. We do however not have precise information about the actual production of (green) hydrogen at the Equinor refinery. The mentioned number is provided by our colleagues at Hydrogen Europe.

A/S Dansk Shell Refinery

The A/S Dansk Shell refinery consumes 35t of hydrogen a day at its refinery in Fredericia. The refinery has a capacity of 3.4 Mt crude oil per year. At its refinery in Fredericia, A/S Dansk Shell converts the crude oil to liquid gas, jet fuel, fuel oil, gasoline, diesel, biofuels, petrol and heating oil. Half of it is shipped out via the Fredericia harbour terminal and the rest is driven to costumers in Denmark.

Sintex

Sintex is located in Hobro, Denmark. Sintex works with powder metal applications, and uses hydrogen in their production process, but is currently not willing to disclose how much hydrogen is being used.

Announced projects 2020-2030

Several new production facilities are currently on its way in Denmark. The largest in scale are:

GreenLab Skive: 12 MW

At GreenLab Skive they are focussing on production of hydrogen. Together with a series of partners, GreenLab will create the world's first largescale facility for production of green hydrogen and methanol. Renewable energy will be converted to other forms of energy and stored for later use such as sustainable fuels for heavy transport and the process industry. The project entails (among other things) the establishment of a 10 MW methanol plant and a 12 MW electrolysis plant. Electrical power will come from a local 80 MW hybrid wind/ PV plant.

HySynergy: 20 MW

In a joint project, Shell and Everfuel have announced to produce and use up to 20 MW green hydrogen, meant to be utilised by the heavy transport sector. The project is called HySynergy and aims to install a large Power-to-X facility. The installed Power-to-X facility will have an electrolysis capacity of 20 MW, but the ambition is to reach 1 GW before 2030. The hydrogen production will run on green power and will produce hydrogen to store the green energy – which then can be used in the transport sector or be refined to other fuels.

H2RES: 2 MW

In a joint project Ørsted, Everfuel and partners will utilise wind power of two windmills at Ørsted's facility in Avedøre in favour of providing electrofuels (e-fuels) for heavy transport.

The purpose of the project is to demonstrate how energy production from offshore wind can be utilized to produce renewable hydrogen through electrolysis in an integrated system, where the hydrogen will subsequently be used as fuel for zero-emission fuel cell based commercial heavy-duty transport. The electrolyser plant will have a 2 MW capacity.

Green fuels for Denmark: 1.3 GW

Ørsted, A.P. Moller - Maersk, DSV Panalpina, Copenhagen Airports, DFDS and Scandinavian Airlines have brought together the demand and supply side of sustainable fuels in a partnership with the concrete vision to develop a new hydrogen and e-fuel production facility as soon as 2023. When fully scaled-up by 2030, the project could deliver more than 250,000 tonnes of sustainable fuel for busses, trucks, maritime vessels, and airplanes every year. Production would potentially be based on a total electrolyser capacity of 1.3 GW, which would likely make it one of the world's largest facilities of its kind.

Future use and production of green hydrogen: perspectives 2020-2030

Denmark is potentially facing a very large increase of the production of green hydrogen. Production capacity estimates vary but are expected to reach 1 GW installed capacity in 2030. There is a need and an increasing demand for green hydrogen in heavy duty transport and the political climate is willing to support the schemes leading up to this transition.

The exact scale of hydrogen demand is obviously difficult to project, but in recent studies it is assumed, that at least 10 PJ will be used for hydrogen production in 2030. Policies promoting green hydrogen are being intensified on the national level in Denmark as part of a national climate strategy. This strategy is currently being formed by the government and will likely have a major impact on the development of both hydrogen production and consumption in the near future.

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Photo: Nagy Szabi, Unsplash

Finland

The largest hydrogen producers and consumers in Finland are Neste Oyj refinery and biofuel production plant in Porvoo (Neste) and oil refinery in Naantali. In addition to these, there are four hydrogen production sites which have capacity between 4,000 and 6,000 tonnes per year.

Chemical and refinery industry with integrated HVO production

The largest hydrogen production location in Finland is the oil refinery in Porvoo (40 km from Helsinki), where hydrogen is produced in large scale (> 100 kt/year) using natural gas and steam methane reforming (SMR). Hydrogen is produced by Oy Linde Gas AB (previously Oy AGA AB).

In addition to separate production units, there is refining process (dehydrogenation and aromatization of cycloalkenes) which produces more hydrogen that all other hydrogen production processes together (20-22 tonnes) as well as some other minor sources of hydrogen, which includes some hydrogen bough from nearby polymer production factory (Borealis polymers). The total consumption of hydrogen can assumed to be in the range of 250,000 tonnes per year based on the thesis of Luosujärvi (Luosujärvi, 2012), while the total production capacity is more than 250,000 tonnes per year. However, the published total CO_2 emission levels for the annual hydrogen production by separate hydrogen production units (Neste Oyj and Oy Linde Gas AB) has been slightly less than 900,000 tonnes/year[1]. Assuming CO_2 intensity 10 kg (CO_2)/kg(H_2) this would be slightly less than 90,000 tonnes of hydrogen per year.

Neste has also a refinery in Naantali. However, hydrogen for Naantali refinery is produced only in refining process (dehydrogenation/aromatization of cycloalkenes) (Aluehallintovirasto, 2016). This is also a drawback, as hydrogen production process disturbances can affect seriously the production of other units in refinery.

1 http://www.paastolupa.fi/listemissionreports

The current use hydrogen in chemical and refinery industry is expected to remain or increase. The use hydrogen in refinery industry could increase if more vegetable oils will be used as a raw material and these oils need to be hydrotreated (HVO as final product). Energy content of hydrogen in the final product is about 10%.

As an example on possible increases in biofuel/refinery activities, Neste is planning expansion of biofuel production and one of the potential locations is Porvoo[2]. Neste is starting environmental impact assessment EIA for new NEXBTL (HVO) production unit named Porvoo Capacity Growth project. 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 (AFRY Finland Oy, 2020).

The major increase in renewable hydrogen use on Finland may take place if NG-based hydrogen in refineries is substituted by renewable hydrogen produced by electrolysis. The reason for this is the Renewable Energy Directive (RED II).

Hydrogen is accepted as fuel 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. It is a renewable fuel of non-biological origin in RED II directive (European Commission, 2018), which states in page 104 that "*renewable liquid and gaseous transport fuels of non-biological origin' means liquid or gaseous fuels which are used in the transport sector other than biofuels or biogas, the energy content of which is derived from renewable sources other than biomass*";. In practice, hydrogen produced using renewable electricity is the only commercially available option.

In addition, hydrogen is accepted when it is used as intermediate products for the production of conventional fuels as it is written in page 125: *For the calculation of the minimum share referred to in the first subparagraph, Member States: (a) shall take into account renewable liquid and gaseous transport fuels of non-biological origin also when they are used as intermediate products for the production of conventional fuels;*. In practice, this possibility can lead massive production of renewable hydrogen for oil refineries improving the supply of fuel cell grade (ISO 14687) hydrogen, also in liquid form.

Biofuel production (separate units)

In Finland, the largest biofuel production unit, which consumes hydrogen is UPM BioVerno production plant in Lappeenranta. According to the environmental permit, the estimated hydrogen consumption is about 6,000 tonnes/year, as based on that total biofuel production is 100,000 tonnes/year, as 12,000 tonnes/year was given for production capacity 200,000 tonnes/year (Etelä-Suomen aluehallintovirasto, 2011). However, exact figures for hydrogen consumption or biofuel production were not published.

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2 https://www.ymparisto.fi/fi-FI/Asiointi_luvat_ja_ymparistovaikutusten_arviointi/Ymparistovaikutusten_arviointi/YVAhankkeet/NEXBTLlaitoksen_rakentaminen_Porvoon_Kilpilahteen/NEXBTLlaitoksen_rakentaminen_Porvoon_Kil(56591)

In January 2020, UPM has submitted application for increasing the capacity from 130,000 tonnes/year to 180,000 tonnes/year (UPM Kymmene Oyj, 2020). In that application it is mentioned that the capacity has been increased to 130,000 tonnes/year with improvement in process in year 2018.

Based on the capacity 130,000 tonnes/year the current use of hydrogen would be 7,800 tonnes/year and the future maximum use would be 10,800 tonnes/year. This would make the UPM BioVerno production plant clearly the second largest hydrogen consumer in Finland. In case of production expansion, the daily capacity would exceed 25 tonnes/day and hydrogen production by SMR would be included in emission trading system.

Hydrogen peroxide production

Hydrogen peroxide is produced in Finland in two locations. Kemira is producing hydrogen peroxide in Oulu and Solvay is producing hydrogen peroxide in Kuusankoski.

In Oulu hydrogen for hydrogen peroxide is currently produced by partial oxidation of heavy fuel oil so that produced CO is used for formic acid production. The amount of hydrogen produced is about 4,000 tonnes/year based on the hydrogen peroxide production capacity of 65,000 tonnes/year (Ympäristökeskus, 2006). In 2016, Kemira announced that it has increased production capacity, but exact figures were not presented[3]. The updated maximum amount (82,000 tonnes/year) as well as production data for years 2016-2018 (78,348-81,599 tonnes/year) can be found in the new environmental permit (Pohjois-Suomen aluehallintovirasto, 2020b). The maximum daily capacity for hydrogen consumption is 14.4 tonnes/day corresponding 5,256 tonnes per year. However, the exact figures for hydrogen consumption are not given for Kemira.

However, based on the year 2019 of CO_2 data the plant capacity in Oulu was not fully utilised in 2019 and it can be estimated that current hydrogen production and use was 2,000-3,000 tonnes per year[4]. However, this is probably due to process changes, as heavy fuel oil is being replaced by LNG in hydrogen and CO production (Pohjois-Suomen aluehallintovirasto, 2020a). This will increase hydrogen production significantly.

Also Solvay consumes about 4,000 tonnes of hydrogen yearly in their hydrogen peroxide production (maximum capacity 85,000 tonnes/year, corresponding 6,070 tonnes/year hydrogen) in Kuusankoski (Etelä-Suomen aluehallintovirasto, 2016). Here, hydrogen is produced by steam methane reforming.

[3] https://www.kemira.com/company/media/newsroom/releases/kemira-continues-to-invest-in-the-growing-market-for-bleaching-chemicals-after-successful-ramp-up-of-the-new-capacity-in-oulu-finland/

[4] http://www.paastolupa.fi/listemissionreports

Oher chemical production

The largest other use of hydrogen is production of hydrogen sulphide by Terrafame Ltd in Sotkamo. In the past, hydrogen consumption has typically been 3,000-4,000 tonnes per year, but in 2018 and 2019 the need has been ~4,500 tonnes/year, as the nickel production in both these years was increased to about 27,440 tonnes/year. For maximum amount of nickel production in environmental permit (30,000 tonnes/year), the corresponding hydrogen need is 5,000 tonnes per year. The need for hydrogen at the mine may be increasing up to 6,200 tonnes/year due to the expansion of their bioleaching capacity (Pöyry Oy, 2017).

Potential new uses in industry

A potentially new field of industrial hydrogen utilisation the next 10 years can be so-called P2X-chemical production. The most promising locations are the places with currently unused by-product hydrogen and sites were 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 electrolyser[5].

Potential new uses in traffic

Potential new hydrogen applications in traffic in Finland is highly uncertain. There have not been any official announcements for fuel cell buses or other applications. There is a target of 20 hydrogen refuelling stations in Finland by 2030 (Liikenne- ja viestintäministeriö, 2017). The implementation of Clean Vehicles Directive (European Commission, 2019) may also accelerate the use of hydrogen as there is a requirement for zero emission heavy vehicles in the directive. However, now it seems that the electric buses will be the preferred solution.

A summary for the current and expected use for 2020-2030 in Finland

A summary of large-scale hydrogen production is given in *Table 1*. The accumulated annual hydrosgen production from the large-scale units is about 110,000-120,000 tonnes. Neste refinery in Porvoo is the major location accounting for about 80% of the total. Some of the figures are based on reported hydrogen production figures in environmental permits, while some are based on production data for chemicals or data for CO_2 emissions.

[5] https://www.lut.fi/web/en/news/-/asset_publisher/lGh4SAywhcPu/content/feasibility-study-on-synthetic-fuels-pilot-plant-in-joutseno-started

The development in hydrogen employment and production methods until 2030 will depend on various factors including:

- The future electricity market price and wind power production cost in Finland.
- The level of electricity tax for industry.
- The level of taxation of fossil fuel used as feedstock for hydrogen production.
- Consequences: A change from fossil-based to renewable-/electricity-based hydrogen production becomes more interesting.

One interesting fact is that several of the smaller hydrogen production units (Terrafame, Solvay, UPM) are not included in the emission trading system[6], as their hydrogen production capacity is less than the 25 t(H_2)/year threshold defined by Finnish law[7]. This means that CO_2 reductions in these hydrogen production facilities are in non-ETS sector, which is more costly to decarbonise.

Table 1. Summary of large-scale hydrogen production and use in Finland, updated from (Hurskainen, 2019). For refineries internal hydrogen production by gasoline reforming is not included

Company	Plant/site	Annual hydrogen production in recent years		Maximum annual hydrogen production		Hydrogen production process	Use of hydrogen
		t/a	GWh/a	t/a	GWh/a		
Neste Oyj	Kilpilahti oil refinery	~90,000 (2018 and 2019)	~ 3,000 (2018 and 2019)	118,680	3,956	SR (natural gas, refinery gas)	Oil refining (hydrocracking, hydrotreating.)
Oy AGA Ab	Kilpilahti oil refinery			34,400	1,147	SR (natural gas)	Oil refining (hydrocracking, hydrotreating.)
Terrafame Oy	Sotkamo nickel mine	~4,500 (2018 and 2019)	128	5,000	128	SR (propane)	Production of H_2S which is used for precipitation of metals as sulphides
Solvay Chemicals Finland	Voikkaa, H_2O_2 plant	~4,000 (2008-2013)	166	6,070	202	SR (natural gas)	Hydrogen peroxide production
UPM Biofuels	Lappeenranta Biodiesel plant	-	-	7800	260	SR (natural gas)	Hydrogen treatment of tall oil to produce liquid biofuels
Eastman Chemical Company	Oulu, Formic acid plant (+Kemira H_2O_2 plant)	Clearly less than 5,256 (2019)	Clearly less than 175 (2019)	5,256	175	POX (heavy fuel oil)	"By-product H_2" from partial oxidation of heavy fuel oil and LNG is delivered to Kemira Chemicals for production of hydrogen peroxide while CO is used to synthesize formic acid by Eastman
Oy AGA Ab	Harjavalta Industrial park	1,143-1,420 (2010-2013)	38-47.3 (2010-2013)	1,500	50	SR (naphtha)	-
Oy AGA Ab	Hämeenlinna, SSAB	-	-	225	7.5	SR (natural gas)	Prevention of the oxidation of the steel products at high temperatures
Woikoski	Kokkola, Industrial park	-	-	1,320	44.0	Electrolysis	Freeport Cobalt: reduction of cobalt

6 http://www.paastolupa.fi/listemissionreports
7 https://www.finlex.fi/fi/laki/ajantasa/2011/20110311

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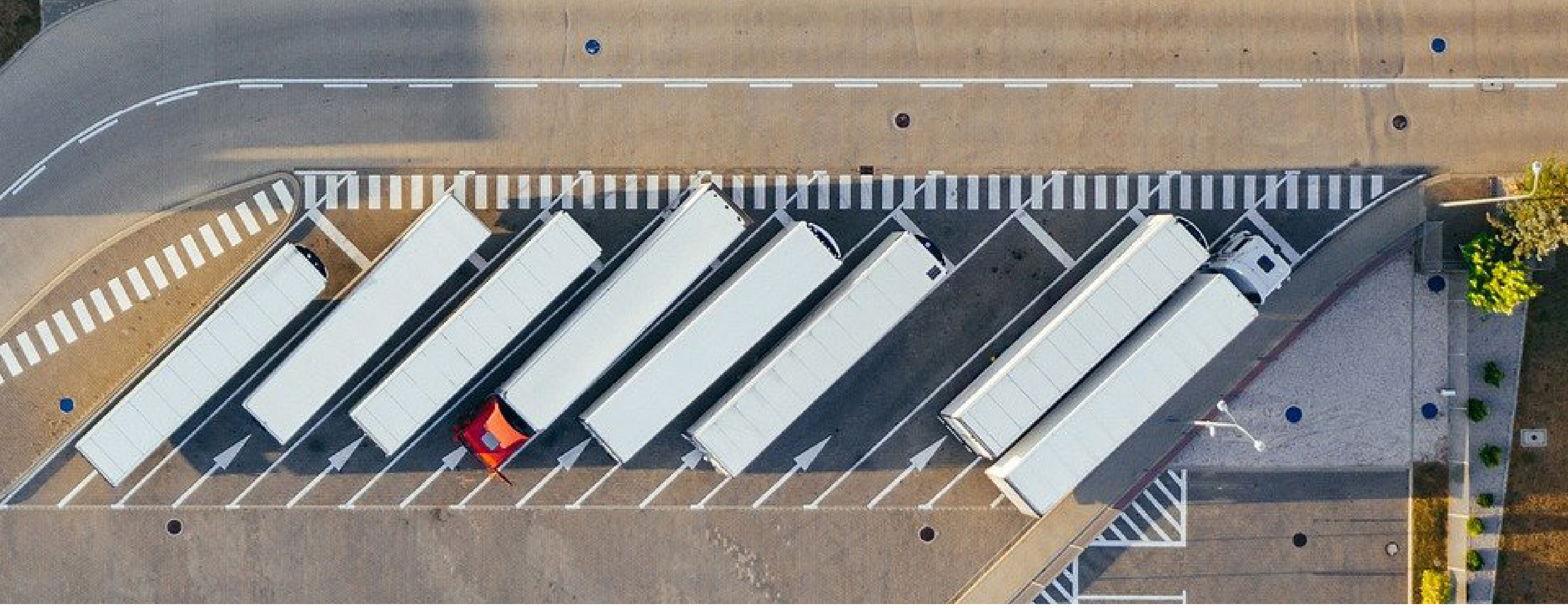

Photo: Marcin Jozwiak, Pixabay

Iceland

There is not a widespread industrial use of hydrogen in Iceland. Currently, hydrogen is only produced at two sites; on is the Svartsengi geothermal power plant and the other at Hellisheidi geothermal power plant. The latter is small (150 Nm^3/h capacity) and was specifically built for providing transport with H_2 in the H2ME-2 (FCH-JU funded project). It is oversized for the vehicles deployed today directly within that project, but the goal is to increase the demand with more vehicles and buses the coming years.

Industrial H_2 production and use

All the H_2 at Svartsengi geothermal power plant is produced by Carbon Recycling International[8] (CRI) for production of methanol. The capacity of the H_2 production is 1,500 Nm^3/h.

Information of the actual usage of H_2 by the CRI is not known. A few years ago, Icelandic New Energy and Skeljungur (operator of H_2 HRSs) sent a request if it would be possible to access H_2 from the production to utilize for transport purposes. CRI representatives gave a negative reply as the operation permit would have to be renewed if H_2 would be handled differently and compressed on site for on-site trucking and/or bottling. This would change the HAZOP and therefore not be a simple process. Whether this will change is unknown but there is a good dialogue between stakeholders in the "new" fuel market so if opportunities occur there could be extra H_2 available from CRI.

Potential new H_2 initiatives in Iceland

Power to X (PtX) pathways are becoming more interesting for both local and international companies in Iceland. No such projects have reached execution stage yet but already one project actually filed an environmental permit to operate a PtX (e-fuel production). The permit is also connected to the Hellisheidi geothermal power plant where CO_2 will be available for the e-fuel production. The estimated capacity of the H_2 production at the plant is 3,000-4,000 tonnes of H_2 per year.

8 https://www.carbonrecycling.is/

During the preparatory stages, the project owners have started a dialogue with stakeholders working with new fuels in Iceland to explore opportunities to provide some of this H_2 and/or the new e-fuel to local customers.

The current industry (CRI) in Iceland is a PtX pathway and it is gaining momentum. With gaining momentum it is highly likely that more of such PtX e-fuel industries will be established in the coming years. If designed to also deliver H_2 to the local market from the onset, this could be the large-scale/low-cost H_2-source during the initial phases of hydrogen becoming a real competitor to gasoline and diesel.


Photo: Samuel Scrimshaw, Unsplash

Norway

The main operative hydrogen producers in Norway can be listed as follow:

- ammonia production at Herøya (Yara)
- methanol production at Tjeldbergodden (Equinor)
- oil refineries at Mongstad (Equinor) and Slagentangen (ExxonMobil)

Since the related hydrogen production is based on fossil fuel reforming without CCS (grey hydrogen), a considerable potential for reduction in CO_2-emissions exists implementing CCS (blue hydrogen) or by means of electrolysis (green hydrogen when based on renewable energy). Yara is taking actions – see *Ammonia Production* below.

In addition, important new initiatives have come along recently:

- hydrogen production at CCB Energy Park, Kollsnes (ZEG Power)
- green hydrogen production for Hyundai trucks (Green H2 Norway)
- re-establishment of large-scale hydrogen production in Glomfjord (Glomfjord Hydrogen)
- liquid hydrogen production for commercial shipping (BKK *et. al.*)
- hydrogen production for ferries and cruise ships in Geiranger (Hellesylt Hydrogen Hub)
- hydrogen production in Berlevåg (VarangerKraft Hydrogen)
- hydrogen production in Meråker (Meraker Hydrogen)

Ammonia Production

Worldwide ammonia production accounts for over half of the world's hydrogen consumption. In Norway, ammonia is produced at Yara's factory at Herøya in Porsgrunn. The installed production capacity is about 500,000 tonnes of ammonia per year (requiring some 90,000 tonnes of hydrogen). Actual production, however, is close to 400,000 tonnes ammonia per year consuming about 70,000 tonnes of hydrogen produced by means of on-site reforming of natural gas (DNV GL, 2019).

To Yara, ammonia is not a product but an input factor in their fertilizer production. Consequently, since their hydrogen production is based on natural gas and thus sensitive to the natural gas market, Yara might turn away from in-house ammonia production simply due to economic reasons. Another possibility is that they can ship in ammonia from their plant in Trinidad and Tobago.

Running the ammonia plant at Herøya at full capacity would result in annual CO_2-emissions of approx. 895,000 tonnes per year (OED, 2016). As indicated above, normally production is somewhat lower and, thus, the annual CO_2-emissions are also lower. Yara has considered various options in order to reduce the CO_2-emissions from their hydrogen/ammonia production, including CCS and electrolysis based on renewable electricity. As a first step, in August 2019 Yara signed an agreement with Nel Hydrogen confirming their ambition of developing clean hydrogen which would allow Yara to realize low carbon footprint fertilizer production at their plant at Herøya (Yara, 2020). The initiative is supported by the Research Council of Norway, Innovation Norway and Enova through the PILOT-E programme, a funding scheme that aims to speed up the development and implementation of green energy technology. The initial capacity of the electrolyser will be 5 MW corresponding to 1% of the hydrogen production. It is expected to be installed in 2022.

Ammonia is a possible hydrogen carrier amongst other being evaluated in several maritime applications, e.g., the EU-project ShipFC (Prototech, 2020). In their synthesis report on the production and use of hydrogen in Norway, DNV GL indicated Yara had been looking into the possibility of using ammonia as a carbon-free fuel (DNV GL, 2019). Just a few months later, Yara was contracted to supply the green ammonia for the world's first ammonia-powered fuel cell onboard a vessel. The 2 MW ammonia fuel cell system will be installed in Viking Energy in late 2023 (Prototech, 2020).

Methanol Production

Worldwide methanol production accounts for about 10% of the global hydrogen consumption. Methanol is mainly used as an input factor of various chemicals products such as formaldehyde and acetic acid (Shell, 2017), but it might also be used as a fuel in internal combustion engines and fuel cells, directly or indirectly. The recent growth in methanol demand (the average annual growth rate since 2016 is 4.3%) is expected to continue in the coming years (IHS Markit, 2017). In line with this growth, hydrogen consumption for methanol production is expected to increase from around 6 Mt/year today to more than 8 Mt/year in 2025 (DNV GL, 2019).

Equinor and ConocoPhillips' methanol factory at Tjeldbergodden west of Trondheim is Europe's largest, with a production of about 900,000 tonnes methanol per year (about ¼ of the yearly European production) consuming about 112,500 tonnes of hydrogen per year produced on-site from natural gas without CCS (DNV GL, 2019).

In addition, from a mixed gas stream, about 15 tonnes of H_2 / day (5,500 tonnes of H_2 / year) are recycled for heating purposes. According to (DNV GL, 2019), it can be cost effective to purify this gas stream to extract high quality hydrogen compared to building a new hydrogen production plant based on electrolysis or reforming of natural gas. However, as the volumes are relatively low, again CCS is considered to be of little relevance without financial incentives. In a more environmentally benign approach, Equinor is said to consider conducting a technology study at Tjeldbergodden on the use of excess oxygen and some 10% of the natural gas stream for the methanol production to produce hydrogen with autothermal reforming (ATR) and CO_2 capture. This can give a production of approx. 30 tonnes of pure H_2 / day reducing the carbon emissions at the methanol plant by about 100,000 tonnes CO2e / year.

New hydrogen production initiatives

Hydrogen production at CCB Energy Park, Kollsnes

Established in 2008, ZEG Power is a Norwegian company delivering technology for efficient production of clean hydrogen from gas phase hydrocarbons, with integrated carbon capture. Examples of hydrocarbon gases are natural gas and biogas. Natural gas is currently the largest source of hydrogen, while hydrogen from biogas combined with carbon capture can achieve a negative carbon footprint. Another advantage of the ZEG (Zero Emission Gas) technology is the possibility of co-production of hydrogen and electricity (Blue Move, 2018). Depending on the size and shape, techno-economic studies shows the potential for an overall efficiency of 70-80% including CO_2 capture. In comparison, state-of-the-art gas-based power plants have an overall efficiency of about 60% dropping to 50% if including an amine plant for CO_2 capture.

In July 2020, ZEG Power entered into a partnership with Coast Center Base (CCB) to establish a plant for production of clean hydrogen from gas with integrated CO_2 capture (ZEG Power, 2020a). The first step is to establish a pilot plant at CCB Energy Park, next to the Northern Lights onshore CO_2-terminal at Kollsnes northwest of Bergen. The longer-term target is large scale hydrogen production, *Figure 1*. The plan is to be fully operational in 2022.

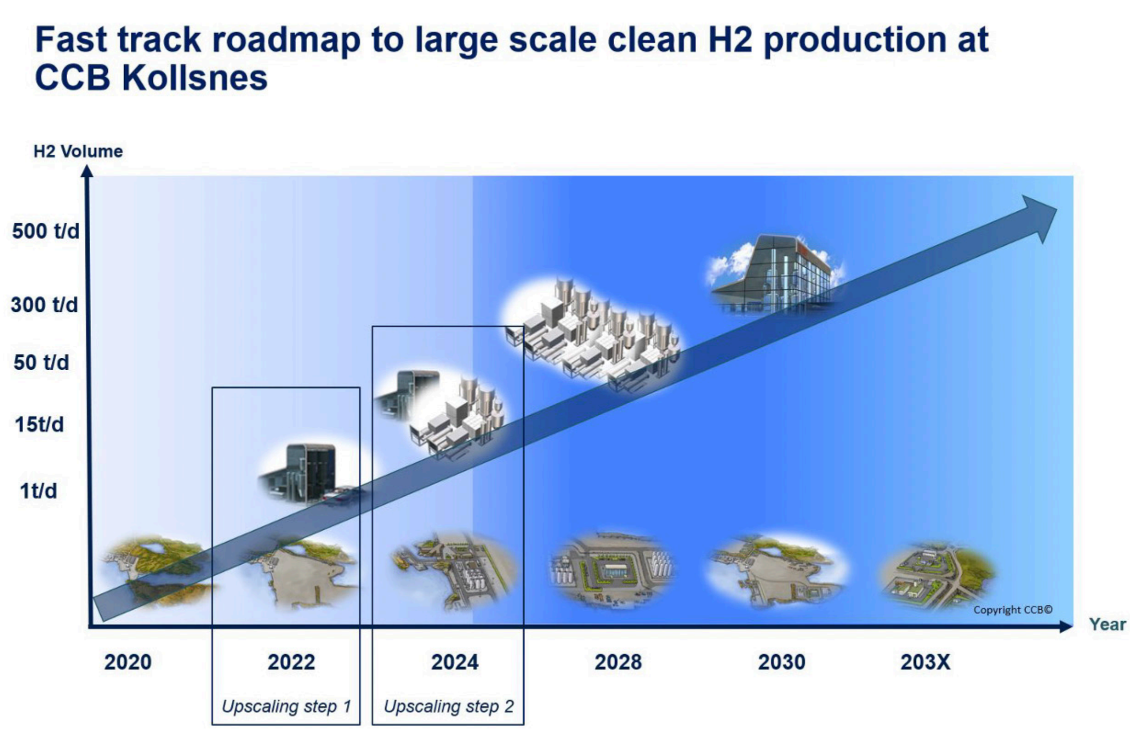

Figure 1. Fast track roadmap to large scale clean H_2-production at CCB Kollsnes (ZEG Power, 2020b).

Green hydrogen production for Hyundai trucks

In December 2019. Nel Fuel, H2 Energy, Greenstat and Akershus Energi Infrastruktur have formed Green H2 Norway, which will establish hydrogen production facilities to supply hydrogen to Hyundai trucks expected in Norway from 2020 (Nel, 2020). The company is equally owned by the four involved parties and will, in dialogue with other potential partners as well as national authorities, initiate the first project in 2020, which will include exploring sector coupling aspects of large-scale electrolysis-based hydrogen production. Green H2 Norway is intended to be the exclusive supplier of hydrogen for Hyundai trucks in Norway but, in addition, Green H2 Norway plan to serve a wider range of transport means such as busses, cars and coastal maritime applications such as ferries and speed boats (Akershus Energi, 2020).

Re-establishment of large-scale hydrogen production in Glomfjord

In Mai 2020, Glomfjord Hydrogen and Air Liquide signed a co-operation agreement with the intention to establish a complete value chain for the production and liquefaction of hydrogen in Glomfjord Industrial Park (Glomfjord Hydrogen, 2020a). The goal is to be able to offer zero-emission fuel for the new ferry services to be put into operation in Vestfjorden in 2024. In addition, the possibility for upscaled production so that liquid and compressed hydrogen can be offered to other consumers in maritime, land transport and industry is being looked into.

From 1949 until 1993, the world's largest hydrogen plant based on electrolysis was operated in Glomfjord. Now, Glomfjord Hydrogen, a joint venture between Nel Fuel, Greenstat and Meløy Energi, will re-establish electrolysis-based hydrogen production in Glomfjord taking advantage of local, low-cost renewable hydro power. Together with partners, Glomfjord Hydrogen will gradually expand the production capacity from 1,000 kg H_2/day to 10,000 kg H_2/day in parallel with the expected increasing market demand (Glomfjord Hydrogen, 2020b).

Liquid hydrogen production for commercial shipping

Late 2019, it was announced that a project led by BKK, Equinor and Air Liquide was granted financial support through the governmental PILOT-E funding scheme (PILOT-E, 2020). The project aims to make liquid hydrogen available for commercial shipping within the first quarter of 2024 and includes the entire value chain from production, storage and transportation to end user in the maritime sector. The other project partners are NCE Maritime Cleantech, NORCE, Norled, NorSea Group, Viking Cruises and Wilhelmsen.

The project is currently in the concept phase but already BKK Nett has made a request for a 30 MW grid capacity to Mongstad north of Bergen. The goal is to start hydrogen deliveries in the Bergen area in 2024. According to Greensight (Greensight, 2020), the requested 30 MW is only a start as the consortium aims at a capacity of 80 MW (corresponding to about 600 GWh/year) within a few years.

Mongstad/Bergen is regarded a well-suited location for the hydrogen production as the maritime activity in the region is substantial (Greensight, 2020). Another possible production site is Husnes in Kvinnherad municipality south of Bergen[9]. In the future, the goal is to transport liquid hydrogen in containers on ship to Trondheim, Stavanger, Oslo, as well as other destinations for further distribution to customers.

Today, liquid hydrogen is considered as one of the optimal zero-emission fuels for ships with high energy demands. It has already been selected for Norway's first hydrogen ferry, which will be in operation for Norled on the Hjelmeland connection starting in 2021 (see transport section below).

Hellesylt Hydrogen Hub

The Hellesylt Hydrogen Hub is another PILOT-E funded project on the development of a complete hydrogen value chain. The project aims to establish a hydrogen production facility at Hellesylt located in the Sunnmøre region of Møre og Romsdal county that can deliver hydrogen to ferries and cruise ships in the Geirangerfjord, as well as to other mobility applications. The ambition is to achieve zero-emission operations in the Geirangerfjord, one of two World Heritage Fjords in Norway, by producing green hydrogen locally (Gexcon, 2019).

Geiranger, a UNESCO World Heritage site, receives around 800,000 visitors a year – of which about 360,000 are cruise tourists. To tackle the local pollution, ships that are not zero-emission will be prohibited from entering the Geirangerfjord by 2026.

The project will start its activities in January 2020 and aims to deliver green hydrogen latest by 2023 at a minimum of 1 ton H_2 per day (Hexagon, 2019). The electrolysis-based hydrogen will be produced by renewable surplus hydropower at Hellesylt, powering hydrogen fuel cell ferries operating the route Hellesylt – Geiranger. This contribution could reduce the CO_2 emissions in the Geirangerfjord with 2,370 tonnes per year. In addition, hydrogen will be made available to other vessels, trucks, buses and vehicles in the region.

VarangerKraft Hydrogen

Raggovidda wind farm situated at the extreme North of Norway, the Varanger peninsula, started operation in 2014. The wind farm has a concession for 200 MW. Due to limited grid capacities in the region, however, only 45 MW of the installed load capacity has been realized (SINTEF, 2020). In order to harvest the additional stranded wind energy, the owner, Varanger Kraft, in January 2019 established VarangerKraft Hydrogen with the intention to start hydrogen production in Berlevåg by the start of 2020, using a prototype 2.5 MW PEM electrolyser with a capacity of just above 1 ton H_2 per day or about 390 tonnes per year. The hydrogen production is established as part of the Horizon 2020 project Haeolus (Haeolus,

[9] Earlier, in Hydrogen in Kvinnherad – A feasibility study (Greensight, 2019), Greensight found co-localisation with the Blåfalli power plant in Matre to be the best location for hydrogen production in Kvinnherad. This probably means that several options exist. Most important is the local engagement in Kvinnherad. In January 2019, the municipality, the local power producer (Sunnhordaland Kraftlag) and the gas producer Gasnor signed a collaboration agreement with the goal to achieve large-scale production of liquid hydrogen from renewable power (SINTEF, 2020).

2020). Based on the pilot plant experiences, the possibility of for upscaling and facilitating green hydrogen production in proximity to other wind farms in the region will be considered. This could open opportunities for hydrogen export.

Possible hydrogen production plant in Meråker

Meråker municipality got substantial excess hydro power. Today, due to grid-limitations in the region, losses are however significant. In addition, both E14 and the Meråker line between Trondheim and Östersund passes through Meråker. Furthermore, Trøndelag county council is planning for zero-emission speed boats and at the other side of the boarder, the owner of Inlandsbanan (passing through Östersund) is considering hydrogen as a fuel representing an estimated hydrogen consumption of 15 tonnes H_2/day (Greensight, 2020).

In a study, Greensight has shown the possibility of establishing a hydrogen value chain in Sweden and Norway based on competitive hydrogen production in Maråker provided an installed production capacity of minimum 4-5 tonnes H_2/day (~10 MW).

Meraker hydrogen AS was founded in June 2020.

Oil refinery

There are currently two oil refineries in Norway. The refinery at Mongstad north of Bergen is owned and operated by Equinor. The refinery at Slagentangen in Tønsberg is owned by ExxonMobil and operated by Esso Norge.

Mongstad

Mongstad does not have a hydrocracker. As a result, Mongstad does not have its own hydrogen plant. Instead, the need for hydrogen (for instance for the desulphurisation processes) is covered by the by-production of hydrogen in upgrading crude oil to gasoline. According to (DNV GL, 2019), this amounts to between 30,000 and 35,000 tonnes of hydrogen per year. About half of this is used in further treatment of petroleum products, and the remainder is used for firing as part of the fuel gas stream.

About half of the surplus hydrogen at Mongstad has a hydrogen concentration that allows cost-efficient extraction of the hydrogen for use in refinery processes or for other purposes outside the refinery. Therefore, should there be a market for it, as of today there is a commercial potential to produce approx. 20-25 tonnes of hydrogen per day for use outside the refinery. However, it should be noted that the need for hydrogen to refine additional volume of oil from the Johan Sverdrup field (from 2019) will help to reduce the amount of "excess hydrogen" and that in the long run it may be necessary to buy extra hydrogen or have a separate hydrogen plant at Mongstad.

A possible decision to produce hydrogen for use outside the Mongstad plants, or possibly design a hydrogen plant for such production, requires a secure market for this, and a robust business case with at least 10-15 years of perspective.

Slangentangen

The ExxonMobil refinery at Slagentangen in Tønsberg has a capacity of around 6 million tonnes of crude oil, and produces propane and butane, gasoline, kerosene, diesel and heating oil. The refinery also has a biodiesel blend plant and ethanol blend in gasoline. About 60% of the refinery's production of petroleum products is exported (DNV GL, 2019).

As at Mongstad, neither this refinery has a hydrocracker and the hydrogen produced comes from the refinery process itself. According to (DNV GL, 2019), this amounts to around 9,000 tonnes of H_2 / year, of which around 30-45% is used for firing. In the short term, there are no current plans that will change this balance. It is therefore potentially possible to extract hydrogen from this combustion gas for use outside the factory. However, this will require extra supply of natural gas (or other fuel) and will only be appropriate from a climate perspective if produced CO_2 is trapped and deposited in a suitable CO_2 storage facility (the current CO_2-emissions from the refinery amounts to approx. 360,000 tonnes per year). No such plans exist today. Nor is there any other industry near the refinery that are current users of large quantities of hydrogen.

In the longer term, it may be appropriate to produce more biofuels at Slagentangen, for instance from wood. This will require large amounts of hydrogen, and more than what is available from the refinery process itself. This means that a separate hydrogen production plant is required for a significant production of wood-based biofuel to be realised. As a result, ExxonMobil wants to look at opportunities to establish a hydrogen plant in or near the refinery, not necessarily owned by ExxonMobil, which can supply hydrogen for increased consumption at Slagentangen, and possibly also for sale to other consumers (DNV GL, 2019).

Petrochemical industry

The petrochemical industry in Norway constitutes the three companies: INEOS Bamble, INEOS Rafnes and INOVYN Norge situated on both sides of the Frierfjord just outside Porsgrunn. These convert natural gas into plastic raw materials. INEOS Rafnes cracks natural gas into ethylene and polyethylene. INOVYN produces chlorine and uses it to convert ethylene into vinyl chloride monomer (VCM; or chloroethene) and to make the plastic raw material polyvinyl chloride (PVC). Lye is a by-product of chlorine production. INEOS Bamle uses ethylene to make polyethylene (INEOS, 2020).

McKinsey & Company (McKinsey & Company, 2018) has analysed opportunities for decarbonisation of industrial sectors, including ethylene production. Here it is pointed out that the emissions, totalling to 0.2 GtCO2e worldwide, originate from combustion of fossil fuels for heating the pyrolysis furnace. They point to several possible measures to reduce these emissions. One of these measures is to replace the fuel in the pyrolysis furnace with biomass or hydrogen produced with a low carbon footprint.

INEOS Rafnes produces a fuel gas consisting of hydrogen and methane as part of the ethylene production. According to (DNV GL, 2019), the raw material used is of main importance for how much hydrogen is contained in the fuel gas. INEOS Rafnes uses approx. 80% ethane, which gives a high proportion of hydrogen. The fuel gas is used as heating in pyrolysis furnaces. Here different gas mixtures can work well, and heating with pure hydrogen is quite possible. If INEOS's ethylene plant (earlier owned and operated by Noretyl) were to be fired by means of pure hydrogen, it would require some 90,000 to 100,000 tonnes of hydrogen per year. The use of biomass was considered by Noretyl to be less relevant due to technical and energy considerations.

Except for the INOVYN's PVC-factory at Herøya, all the petrochemical plants are connected to the same fuel gas system. The fuel needs are covered by the fuel gas from INEOS Rafnes, some hydrogen produced from INOVYN's chlorine plant, and some ethane added. A tunnel underneath the Frierfjord allows VCM to be supplied directly to the PVC-factory at Herøya. Until recently, also by-product hydrogen from INOVYN's VCM-factory was fed through this tunnel supplying the oldest refuelling station in Norway with FC-grade hydrogen (Porsgrunn hydrogen refuelling station was opened in 2007 and was operated by Hyop AS – a predecessor of today's Hynion AS) (Blue Move, 2018).

Potential exploitation in industry

The need to limit climate emissions is the driving force behind the use of hydrogen as fuel or reducing agent in industry. This is achieved by replacing fossil fuel with hydrogen produced with a low carbon footprint. Hydrogen Council (Hydrogen Council, 2017) points to significant potential for such hydrogen use (globally 4 million tonnes in 2030, and over 100 million tonnes in 2050). This includes use in the cement industry, steel industry, refineries (for heating), and in the chemical and petrochemical industries.

Hydrogen is one of several possible measures to decarbonize the heat-intensive industry. Any decision to use hydrogen should typically be weighed against the cost, feasibility, and potential for emission reductions that can be achieved with alternative measures such as energy efficiency, biomass firing, and the use of CCS.

Cement production

In Norway, cement is manufactured in Brevik and Kjøpsvik by Norcem, which is owned by the HeidelbergCement Group. Norcem supplies cement to the Norwegian market as well as markets around the North Sea and the Baltic Sea. Norcem also exports cement and clinker to the international market.

The total production of Norcem is approx. 1 million tonnes of clinker, which is processed to approx. 1.3 million tonnes of cement (DNV GL, 2019). Energy consumption is approx. 0.9 MWh per tonne of cement, of which approx. 85% of this is thermal energy. Limestone calcination represents approx. 69% of CO_2 emissions. The rest of the CO_2 emission comes from the burning of fossil fuels for heating a rotary kiln (the cement kiln).

According to (DNV GL, 2019), Norcem has investigated the potential of applying hydrogen in their cement production. However, along with other measures such as electrification of the calcination furnace together with reduction in CO_2 emissions from both the calcination process and the cement kiln by means of

CCS, investments in hydrogen combustion was considered to have little overall cost-benefit effect regarding CO_2 emissions.

Internationally, in some cases, cement producers fire their furnaces with both coal, natural gas and other fuels without requiring significant changes in the design of the calcination furnace or cement kiln. This indicates that it might be possible to run on hydrogen without requiring extensive refurbishment of the furnace. However, this is a hypothesis that must be tested and verified through research and development (DNV GL, 2019).

Aluminium production

In Norway, aluminium is manufactured by Hydro at 5 locations (Husnes, Høyanger, Karmøy, Sunndal and Årdal). In addition, Alcoa produces aluminium at Lista and Mosjøen. Almost all energy consumption in Norwegian aluminium production is in the form of electricity produced from hydropower. Natural gas, however, is used as fuel in Alcoa's anode bakery in Mosjøen and in foundries in Mosjøen and Lista. LPG is used as fuel in Hydro's anode bakery and foundry in Årdal. The consumption of gas at these plants can potentially be replaced by hydrogen.

According to (DNV GL, 2019), Hydro has considered the use of non-grey hydrogen in their anode bakery and foundry in Årdal. Due to small volumes and lack of infrastructure, CCS will however be very expensive, thus only hydrogen production with electrolysis is considered relevant. A possible decision to proceed with this requires that the solution is competitive with the use of LPG, given oil price, electricity price, CO_2 price, and development at capital cost for electrolysis plants - the latter factor being the most important. Hydro also point out that as Norway has ample supply of clean and cheap electricity, Norway can play an important role in contributing to the rapid scaling of hydrogen production from electrolysis, and that this is necessary to achieve a sufficient reduction in the capital cost of electrolytic systems for use of hydrogen in their plants.

In Mosjøen, Alcoa states that electrifying the heating for the anode bakery will not be possible as this will not provide enough inductive heat (DNV GL, 2019). On the other hand, replacing the natural gas by hydrogen should be possible and could potentially be relevant if locally produced hydrogen from electrolysis can show cost competitiveness compared to natural gas. Also, for the foundries, it should be technically possible to replace natural gas with hydrogen but according to Alcoa this requires technical testing and that challenges related to logistics and commercial barriers can be overcome.

Melting plant

There are many smelters in Norway. These are operated by Elkem, Eramet, TiZir (wholly owned by Eramet), Finnfjord, Wacker Chemie, Washington Mills and Saint-Gobain Ceramic Materials. Common to these is that electricity is used to heat the raw materials in high temperature melting furnaces and that carbon is used to remove oxygen from these raw materials to produce metal or alloy. Some industries also use fossil fuels for processing heat. Here, reductions in greenhouse gas emissions can be achieved by replacing this fuel with hydrogen. In addition, it is sometimes possible to use hydrogen as an agent to reduce ore to metal. This is considered for the TiZir titanium dioxide smelter in Tyssedal (Greenstat, 2016).

Roadmaps for gas in the metal industry (SINTEF, 2017) indicate that increased use of gas such as hydrogen and biogas can make Norwegian metal production more environmentally friendly and competitive. Because carbon is only used to remove oxygen from ore and to make it transportable as gas, SINTEF argues that "carbon consumption, and thus CO_2 emissions, in the metal-producing industry is [...] essentially process-related and not product-related." In line with this, the report describes several possible gas applications linked with new technology, and assesses their environmental impact, technological maturity and degree of change. The uses that have the highest technology maturity, and could potentially be implemented in the medium term (before 2030) are:

- Pre-treatment and pre-reduction of manganese -> relevant to Eramet
- Pre-reduction of ilmenite with gas -> relevant to TiZir
- Direct Reduced Iron (DRI) -> an application with great potential worldwide but not relevant in Norway as iron ore steel is not produced in Norway today

Elkem and Eramet, together with Teknova, NCE Eyde, Hydro Vigeland's Brug and Saint Gobain Ceramic Materials, participated in a preliminary project on «Hydrogen technology in the process industry». The report from this study (NCE Eyde, 2017) suggests that the scope for using hydrogen in the process industry differs from that described in (SINTEF, 2017), as well as in "Roadmap for the Process Industry - Increased Value Creation with Zero Emissions in 2050" (Norwegian Industry) , 2016). The companies say that "basic thermodynamic conditions mean that hydrogen is not usable as a reducing agent in their industrial processes". On the other hand, they see opportunities to produce hydrogen or other value-creating products from the exhaust gases from their processes. It is also stated that hydrogen may be relevant for pre-reduction, but that this requires a fundamental change of production processes and require long-term research efforts. These views are reflected in the input we received from Elkem and Eramet, which are described below (DNV GL, 2019).

Elkem

Elkem is one of the world's leading suppliers of silicon-based materials, covering the entire value chain from quartz to specialized silicone products in addition to the production of ferrosilicon and carbon materials. According to (DNV GL, 2019), Elkem has considered opportunities to use hydrogen as a reducing agent but finds it not relevant to develop such a technology. This is because it is more expensive than coal and, according to Elkem, because "the furnaces have great buoyancy and any hydrogen supplied will disappear before it has reacted". Elkem's main strategy for reducing their CO_2 emissions is:

- Use of biocarbon/charcoal from low-cost renewable sources
- Melting furnace closure and carbon capture

By closing the furnace, a flue gas with around 60% concentration of CO will be formed. Thus, Elkem is considering the possibility of producing hydrogen from carbon monoxide (CO) based on the water-gas shift reaction. Elkem's preliminary analyses suggest this may incur costs comparable to existing hydrogen production technologies and will, as an added value, produce relatively high-concentration CO_2 that can be cost-effective to capture. If this technology is applied to all Elkem's smelters in Norway, it will be possible to produce around 150,000 tonnes of H_2 / year (DNV GL, 2019). It is emphasized, however, that this is not applicable in the near to medium term.

Eramet

The Eramet Group is the world's second largest producer of manganese ores and manganese alloys and the world's leading manufacturer of refined manganese alloys. Eramet Norway has processing plants in Sauda, Kvinesdal and Porsgrunn, which supply manganese alloys to the international steel industry. Almost 90% of the world's total manganese alloy production goes to steel production (Eramet Norway, 2020).

Manganese (Mn) is produced by reducing ore with manganese oxides (MnO_2, Mn_2O_3, and Mn_3O_4) with carbon to Mn metal and CO_2. The reduction of ore with manganese oxides occurs in several steps, where higher order oxides are first reduced to MnO and then by reduction in liquid phase to manganese.

In their synthesis report on the production and use of hydrogen in Norway, DNV GL highlights so-called pre-reduction[10] as one potential use of hydrogen in the production of manganese (DNV GL, 2019). In (NCE Eyde, 2017), it is claimed that the later reduction step will produce such large amounts of CO that it has no intention of using hydrogen in previous reduction steps. However, pre-reduction of manganese ore with CO is done by Kashima Works in Japan, which with this has an energy consumption that is 600 kWh / tonne lower than corresponding production without pre-reduction (SINTEF, 2017). Although the use of some gases for pre-reduction can result in reduced CO_2 emissions, SINTEF suggests that the main driver for the use of pre-reduction gas is flexibility in the energy source, the possibility of reduced energy consumption, and possible improvements in the existing process (SINTEF, 2017).

As Elkem will conclude with furnace closing, Eramet has a high content of CO (60-65%) in the exhaust gas, in addition to 5-10% H_2 and 10-20% CO_2 (NCE Eyde, 2017). Therefore, there is also a potential here to produce hydrogen in a highly concentrated form from the exhaust gas. Each of the production sites produces 17-20 thousand Nm^3 of exhaust gas per hour (DNV GL, 2019). This means that such a plant can potentially produce over 20 tonnes of H_2 / day. Today, Eramet sells the gas in Porsgrunn to Yara (replaces naphtha / ethane in heating gas) and uses the gas in Kvinesdal in a gas turbine (NCE Eyde, 2017). In Sauda, some of the gas is burned today for heating of critical refractory equipment for the production processes and heating of buildings and raw materials in the winter season (DNV GL, 2019). But Eramet is exploring other opportunities for value creation, including using parts of the gas for drying ore (NCE Eyde, 2017) and use in gas engines (DNV GL, 2019).

TiZir

TiZir Titanium & Iron in Tyssedal is a titanium dioxide smelter that produces titanium slag (TiO_2) for pigment and special grades of pig iron. TiZir has considered the

[10] Here: heating, drying and partial reduction to MnO takes place in a separate unit before the rest of the oxygen is removed with carbon and metal produced in a traditional melting furnace.

possibility of replacing coal-based pre-reduction in rotary kilns with a fluidized process with hydrogen as reducing agent (Norsk Industri, 2016).

The use of hydrogen as a reducing agent could reduce CO_2 emissions by 90% and energy consumption by 40% (Norsk Industri, 2016), as well as reduce the oven temperature, and the heating time of the ovens (NCE Eyde, 2017). With a full production line with pre-reduction with hydrogen and a further furnace, the goal is to more than triple the production, while reducing CO_2 emissions to 35% of the current level (Norsk Industri, 2016). For further planning and implementation of this, in October 2015 TiZir signed a letter of intent with Sunnhordland Kraftlag and Greenstat on a study for hydrogen production for the smelter (Greenstat, 2016). To meet the hydrogen requirement, an electrolysis plant of about 50 MW is needed feeding 30,000 kg of green hydrogen per day (almost 11,000 tonnes H_2/year) as reducing agent into the TiZir- pre-reduction process.

TiZir has made experiments in a small pilot plant. The results have been good and TiZir still believes that it is possible to achieve the goals of reducing CO_2 emissions and energy consumption with this technology (DNV GL, 2019).

The next step is to build a larger pilot plant. An expensive step, triggering major R&D investments. Furthermore, TiZir will not gain any profit from such an investment until a full-scale plant and production line is put into operation in step four. In between, in step three, a functional plant (as of today) must be replaced by an untested concept. No doubt, the current development step is a high-risk investment.

Asphalt production

Møre and Romsdal County Council (MRF) is conducting a feasibility study on the use of hydrogen in asphalt production. Here they want to map:

- Energy and power requirements
- Reduction of greenhouse gas emissions
- Industrial solution; burner, boiler, tanker, etc.
- Transport and bunkering solution
- Profitability assessment

The asphalt factories in Møre og Romsdal (Ålesund and Kristiansund) and Trøndelag (Trondheim and Ørlandet) currently use LNG or LPG as fuel. By replacing LNG and LPG with hydrogen in these factories, approx. 1,400 tonnes H_2/year will be needed (DNV GL, 2019). As the asphalt plants are located along the coast, it will potentially be appropriate to consider the use of surplus hydrogen from the methanol plant at Tjeldbergodden west of Trondheim for this purpose.

Exploiting surplus hydrogen from the methanol plant at Tjeldbergodden has been a motivating factor behind the feasibility study conducted by MRF. MRF also indicates they are working on a hypothesis that hydrogen can be used without major changes to the plant. Among other things, it is assumed that the same combustion chamber can be used.

Another alternative to hydrogen that could lead to large reductions in CO_2 emissions is wood pellets, amongst others being evaluated by Veidekke (tu.no, 2016). Veidekke, accounting for about 40% of the asphalt production in Norway, has approx. 30 asphalt factories in Norway (tu.no, 2016).

Potential exploitation in transport

The transport sector accounts for about a quarter of the net domestic energy consumption in Norway, and 31% of the national greenhouse gas emissions (Miljødirektoratet, 2018). This includes domestic energy consumption for road transport, coastal transport, air transport and rail transport. In 2016, total energy consumption and emissions in the transport sector amounted to 54.6 TWh and 16.5 million tonnes of CO2e, respectively.

The Government's report on "Climate strategy for 2030 - Norwegian restructuring in European cooperation" adopted requirements relevant to national ambitions for the use of hydrogen (Regjeringen, 2018). The resolution asks, among other things, on «requirements and regulations for emissions from cruise ships and other ship traffic in tourist fjords as well as other suitable means to ensure the phasing in of low and zero emission solutions in shipping until 2030, including introducing requirements for zero emissions from tourist ships and ferries in the World Heritage fjords as soon as possible, technically feasible, and no later than 2026." In addition, the Parliament requested a comprehensive strategy for research, technology development and the use of hydrogen as an energy carrier.

A significant phase-in of low- and zero-emission solutions has been set in the transport sector according to National Transport Plan (NTP) for 2018 - 2029 (Regjeringen, 2017) The Government will, inter alia:

- Establish the following target figures for zero emission vehicles in 2025:
  - New passenger cars and light vans shall be zero emission vehicles.
  - New city buses should be zero-emission vehicles or use biogas.
- By 2030, new heavier vans, 75% of new long-distance buses and 50% of new trucks will be zero-emission vehicles.
- By 2030, the distribution of goods in the largest urban centres will almost be zero emissions.
- Have an ambition that by 2030, 40% of all ships in short sea shipping will use biofuels or be low- and zero-emission vessels.

The road transport target assumes that "improvements in technological maturity in the vehicle segments" are realized, so that zero-emission vehicles become competitive with conventional solutions.

The Norwegian emission targets and Norwegian requirements for zero and low emissions for ferries, speedboats and inland transport, as mentioned above, are important drivers for both electrification with batteries and for the use of electric motors based on fuel cells and hydrogen in the transport sector. It is important to note that the goals in NTP do not provide binding guidelines. Therefore, there is considerable uncertainty as to how the goals will be implemented politically in the period up to 2030.

Maybe except for some marine and rail applications, overall system weight is of main importance for transportation applications. In the passenger car segment, the weight difference between a hydrogen/fuel cell system and a battery electric system might not be a showstopper, but since battery weight scales almost linearly with the energy storage capacity, this will not be the case in the larger vehicle/heavy-duty transport segments. Here, as the energy demand increases, the difference in volumetric and gravimetric energy density between hydrogen/fuel cell and battery electric systems will become evident in favour of the significant higher gravimetric density of the hydrogen/fuel cell alternative. In 2018, the Norwegian Hydrogen Forum (NHF) together with Greensight launched a vision of 1,000 FC trucks on Norwegian roads by 2023 (Greensight, 2018).

Summary of hydrogen need in 2020-2030 in Norway

In Norway, around 225,000 tonnes of hydrogen are produced today from industrial processes (DNV GL, 2019). Yara's ammonia production at Herøya and Equinor's methanol production at Tjeldbergodden account for most (182,000 tonnes) of this. Both these plants have their own gas reformer and produce all the hydrogen they need themselves. The rest of the hydrogen production in Norway is mainly a by-product of gasoline production at the oil refineries at Mongstad and Slagentangen. The oil refineries and the methanol plant collectively use about 25,000 tonnes of hydrogen, in a mixture with natural gas, for firing. More than half of this hydrogen can potentially be replaced by natural gas or another fuel but will then lead to increased CO_2 emissions at the plants unless carbon capture is implemented.

Only one industry player (TiZir) considers that the use of hydrogen in its industrial process is technically and economically interesting in the short to medium term, until 2030 (DNV GL, 2019). The need for hydrogen in the TiZir based hydrogen concept is around 11,000 tonnes of H_2 year to be produced by electrolysis.

Hydro and Yara have both made assessments on hydrogen production by means of electrolysis; Yara to possibly replace parts of today's hydrogen production from gas reform, and Hydro to replace LPG as fuel in the anode plant and foundry in Årdal. However, a potential transition to (electrolysis-based) hydrogen is a cost issue to both of them. According to DNV GL (DNV GL, 2019), it is considered unlikely that electrolysis-based hydrogen will be competitive with natural gas reforming or the use of LPG at these plants before 2030.

For other heat-intensive industries in Norway (cement, petrochemicals, and smelters), hydrogen is considered to be of little relevance as a fuel. One possible exception to this rule is asphalt production. Møre and Romsdal County Municipality is conducting a feasibility study for the use of hydrogen in asphalt production.

On the other hand, several industries (including Elkem and Eramet) see a potential for cost-effective production of hydrogen from the exhaust from the industrial plants. This is due to the high concentration of CO, which can be converted to hydrogen through the water-gas shift reaction, and for Eramet's case up to 10% hydrogen in the exhaust gas. Altogether, Elkem and Eramet have the opportunity to produce around 200,000 tonnes of hydrogen from their plants. Such production will also provide a cleaner CO_2 stream, which could thus be easier to capture (cleanse), with subsequent deposition in a CO_2 storage facility.

Quite a few new hydrogen production initiatives – mainly based on water electrolysis but also on gas phase hydrocarbons with integrated CO_2 capture – have surfaced recently:

- At Kollsnes, ZEG Power takes the first step to establish emission-free hydrogen production at CCB Energy Park based on their unique ZEG (Zero Emission Gas) technology taking gas phase hydrocarbons as their feedstock.
- Green H_2 Norway, a company recently formed by leading Norwegian hydrogen and infrastructure companies, will establish large-scale electrolysis-based hydrogen production facilities to supply hydrogen to Hyundai trucks – and other transport means – expected in Norway from 2020.
- From 1949 until 1993, the world's largest hydrogen plant based on electrolysis was operated in Glomfjord. Now, Glomfjord Hydrogen intends to re-establish electrolysis-based hydrogen production in Glomfjord taking advantage of local, low-cost renewable hydro power.
- Two projects granted PILOT-E funding in 2019 (one led by BKK, the other by Hellesylt Hydrogen Hub) are about to establish hydrogen production with focus on shipping and costal maritime applications.
- VarangerKraft Hydrogen was established in 2019 with the intention to start hydrogen production in Berlevåg by the start of 2020, using a prototype 2.5 MW PEM electrolyser with a capacity of just above 1 tonne H_2 per day, sourcing stranded wind energy at Raggovidda wind farm.
- Also, in the Trondheim area, at Meråker, the potential for hydrogen production from stranded renewable energy sources is investigated nicely coupled to various hydrogen transport means. In a study (Greensight, 2020), Greensight has shown the possibility of establishing a hydrogen value chain in Sweden and Norway based on competitive hydrogen production in Maråker provided an installed production capacity of minimum 4-5 tonnes H_2/day (~10 MW).

Most evident, the main new segment for utilisation of hydrogen in Norway is for transport means.

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Photo: Ali Kazim, Unsplash

Sweden

Iron industry

LKAB, SSAB and Vattenfall are together undertaking the project HYBRIT where they will produce iron from iron ore by using hydrogen instead of fossil coal as a means of chemical reduction. The aim is to transform the whole production of iron, and a pre-study has already been made resulting in that a pilot plant will be built. The project is supported by the Swedish Energy Agency, and a first plant is expected to be ready by 2035. To substitute the whole coal consumption of the Swedish iron industry, two nuclear reactors or 2,000 wind power plants of 3 MW each are needed. This makes up a large proportion of the energy production of Sweden and will imply a large demand for hydrogen in the future iron industry.

Höganäs is a producer of metal powders for a wide range of applications, such as manufacturing additives, construction, mining, energy and thermal management. They want to keep their volumes confidential, but they are included in *Table 2* below.

Polymer production

Borealis in Stenungsund is the only producer of polyethylene in Sweden. They can use four different materials for their cracking process: naphtha, ethane, propane and butane. The outcomes of the process are ethylene and propylene, which is used to produce High-density polyethylene (HDPE), Low-density polyethylene and Borstar products. Hydrogen is a by-product in their process, but utilized by themselves, and sold via pipeline to nearby clients. They explain that hydrogen is a product with high demand in the Stenungsund area, and they are satisfied with the amount of customers they have today. They were not willing to share their current volumes. Values reported in previous publications show 10,000 tonnes/year in 2007[11] and 1,800 tonnes/h in 2016[12] .

[11] http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=D117F1003C62EBC0DE079B139F82ADD0?doi=10.1.1.477.3069&rep=rep1&type=pdf

[12] http://www.diva-portal.se/smash/get/diva2:1201734/FULLTEXT01.pdf

Hydrogen as a by-product is most often used for heating of premises through burning. During the summer, when no heating is needed, the gas is simply released. At the same time, heating facilitates through burning excessive and unwanted hydrogen hinders the incentives for improving energy efficiency in buildings. If this gas instead is used to produce electricity in a stationary fuel cell with high efficiency, the value of the hydrogen becomes higher. This is already implemented today at several chloride producing industries around the world. The waste heat from this process, in the most common type of fuel cell, is circa 60-80 °C, which is enough to be used for heating of the premises. Some fuel cell technologies can produce up to 1,000 °C in heat. Then the remaining hydrogen can be delivered to a fuelling station, where hydrogen gas has a higher market value.

Inovyn in Stenungsund produces PVC and caustic soda. In this production process they also produce chlorine, in which hydrogen is a by-product. Part of the hydrogen is sold via pipeline to Borealis as a back-up for Borealis' clients, and part of it is used for energy production in their own plant (by burning it in their steam heater). According to their environmental expert, they are not interested in selling more of their hydrogen because they want to burn it - if they would not burn hydrogen, their CO_2-emissions would be higher. Their production capacity is 87 tonnes, for the year 2018, according to their Environmental report of 2019 (Miljörapport).

Chemical industry

The chemistry company Nouryon produces a variety of chemical substances. In their sodium chlorate process, at their plant outside Sundsvall (Stockviksverken), hydrogen is formed as a by-product, about 2,700 tonnes/year, corresponding to 89 GWh /year. Of this, 30% is used by the sister company Surface Chemistry for the production of detergents, 60% is used as energy supplement (for drying and steam production). A small quantity is sold to Linde and 10% is vented away due to difficulties in synchronizing use and production. The company also has a sodium chlorate production plant in Alby, 1 km outside Ånge, where about twice as much hydrogen is produced as in Sundsvall. The hydrogen gas is used here to produce hydrogen peroxide.

Kemira Kemi AB in Helsingborg use natural gas to extract hydrogen in order to produce hydrogen peroxide. They produce 3,500 tonnes/year.

Perstorp Oxo in Stenungsund manufactures bio fuel RME, rape seed methyl ester. Besides purchasing hydrogen from Borealis, they also produced 4,950 tonnes in 2016 (Sundqvist & Petersson 2017), for their own processes. They have however not a surplus of hydrogen, and it is not a by-product.

Petrol refineries

Preemraff in Lysekil transforms natural gas into hydrogen and utilize it for production of "greener diesel" where 50% of the diesel has renewable content[13]. The quantity is currently 20 tonnes/year, with the target 29 tonnes in 2020 and 270 tonnes in 2030. In Gothenburg, they produce the hydrogen via steam

13 https://www.preem.se/foretag/produkt-och-tjanster/Produktkatalog/

reforming of natural gas for the same purpose: to use it in their green diesel[14]. At the moment their capacity is 15,000 tonnes/year, although they have a permit for 1,200 tonnes/year because they want to increase their production[15]. They are now considering a 20 MW electrolyser that could deliver 3,200 tonnes/year, but in fact their need is 32,000 tonnes/year.

AB Nynäs Petroleum utilize hydrogen for producing naphthenic oils at their plant in Nynäshamn, and they produce this hydrogen from natural gas. The quantity still unknown.

Ammonia production

Yara is a fertilizer producer in Köping, and they need hydrogen in their Haber-Bosch process, to produce ammonia. However, all the ammonium they need for their production of fertilizer in Sweden is imported from their production plants in Norway, Germany and the Netherlands. This ammonium is made from natural gas. The company is investigating making hydrogen from renewable energy, but these processes are not planned to be implemented in Sweden. However, the company makes it clear that they are interested in purchasing hydrogen from other, Swedish producers.

Electrolysis production for commercial purposes

In Sweden, Linde and Air Liquide produce hydrogen for sale, via electrolysis. Linde has large scale production in Halmstad and Sandviken where hydrogen is transported in steel tubes on trailers to clients and distributors. The volume produced in Sandviken is 1,800 tonnes annually. In Sandviken, hydrogen is also distributed via pipe-line to the Sandvik Coromant plant, delivering cutting technologies. A small amount is also used for the hydrogen refuelling station in Sandviken. Linde has small scale production of hydrogen for pipeline-clients also in Borlänge, Fagersta, Halmstad and others, with a total production capacity of 690 tonnes annually. Air Liquide has an electrolyser in Surahammar, where they have one large pipeline-client and several smaller clients to which hydrogen is transported in steel tubes on trailers. The pipeline-client (Surahammars bruk, a steel producer) receives 90 tonnes/year, while other clients buy 23 tonnes/year. They have only one electrolyser which is used to its full capacity, and in case of down time they have no back-up.

In oil refineries, the cracking process produces hydrogen as a by-product. However, in Sweden this hydrogen is utilized in the refinery, and the refineries are currently short of hydrogen.

Oil refinery

Preemraff in Lysekil transforms natural gas into hydrogen, and utilize it for production of "greener diesel" where 50% of the diesel has renewable content[16].

[14] https://www.preem.se/om-preem/hallbarhet/preem-evolution-drivmedel/framtiden---var-viktigaste-marknad/framtidens-drivmedel/ (accessed 2020-05-08)

[15] https://www.preem.se/globalassets/om-preem/om-oss/vad-vi-gor/raffinaderier/preemraff-goteborg/170330_dom_hpu.pdf (accessed 2020-05-08)

[16] https://www.preem.se/foretag/produkt-och-tjanster/Produktkatalog/

Premraff oil refinery has sites in Gothenburg and Lysekil. They produce a diesel with 50% renewable contents, and for this, they need hydrogen[17] for their hydrogen cracker (vätecracker), as shown in *Figure 2*.

The hydrogen that comes as a by-product from the refinery is not enough for the quantities they want to produce of their renewable diesel, and they need to add more. In Lysekil, they produce hydrogen from natural gas and in Gothenburg from electrolysis[18]. In Lysekil the quantity is currently 20 tonnes/year, with the target to reach 29 tonnes in 2020 and 270 tonnes in 2030. In Gothenburg, their capacity is 14,600 tonnes/year, although they have a permit for 29,000 tonnes/year because they want to increase their production[19]. They are now considering a 20 MW electrolyser that could deliver 3,200 tonnes/year, but in fact their need is 32,000 tonnes/year. Thus, hydrogen is in high demand for their refining process, and can thus not be considered a by-product.

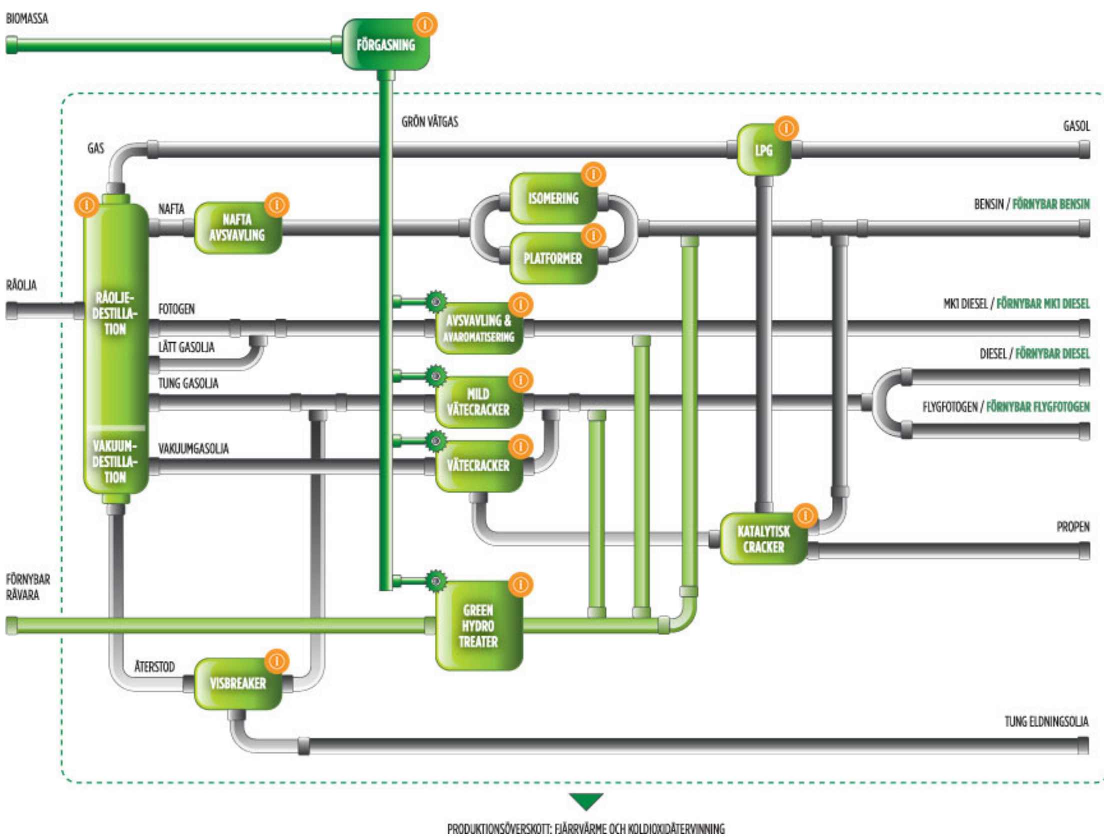

Figure 2. The refining process of Preemraff, where hydrogen is used to produce renewable fuels (Source: https://www.preem.se/om-preem/hallbarhet/preem-evolution-drivmedel/framtiden---var-viktigaste-marknad/framtidens-drivmedel/)

17 https://www.preem.se/om-preem/om-oss/vad-vi-gor/raff/preemraff-goteborg/pagaende-projekt/

18 https://www.preem.se/foretag/kund-hos-preem/hallbart-foretagande/har-ska-koldioxiden-fangas-in/

19 https://www.preem.se/globalassets/om-preem/om-oss/vad-vi-gor/raffinaderier/preemraff-goteborg/170330_dom_hpu.pdf (accessed 2020-05-08)

The Nynäs oil refineries are located in Nynäshamn and Gothenburg. These refineries do not work oil as a source of energy, as commonly refineries do – instead their specialization is NSP (naphthenic specialty products) mainly used by electrical, lubricant and chemical industries and bitumen. Bitumen is a viscous mixture of various hydrocarbons derived from the distillation of oil and forms the asphalt 'glue' or binder and influences the performance of the asphalt. These refineries need hydrogen gas for hydro treatment. The distillate is mixed with hydrogen gas at high pressure and temperature over a catalyst bed in the reactor. This 'treatment' removes sulfur and nitrogen, while also reducing aromatic content. Nynäs needs "a lot" of hydrogen and produce it from natural gas in a hydrogen gas facility (Nynäs annual report 2018:121). They have permission to store 16,000 tonnes/year. The production quantity is confidential.

Summary of the Swedish hydrogen market

The Swedish industries that have surplus hydrogen production are not looking for opportunities to sell. Companies were very unwilling to share their information because of market fears, and the authorities issuing the environmental permit sometimes referred to confidentiality, making it impossible to reach the volumes. Moreover, in the instances that the permit has been accessible it only reveals the storage volumes – not the production volumes. The companies that were willing to share their data expressed various situations indicating that hydrogen is in higher demand than there is availability:

- Lack of back-up for their hydrogen production
- Interest in buying more hydrogen
- Unwillingness to sell it because they prefer burning it to keep their CO-emissions down

The current hydrogen production is presented in *Table 2*. Some companies that do not produce it are also included for comparison to the other countries, where they do produce and also to highlight the connections between companies as well as to allow understanding how the market has changed (companies that previously produced hydrogen may have changed their processes and no longer have it as a bi-product for instance).

Table 2. Hydrogen production in Sweden

Company	Plant/site	Annual hydrogen production	Hydrogen production process	Use of hydrogen	Sources
INOVYN	Stenungsund	87 tonnes	CS	By-product from chlorine production. Burned for steam. Serves as backup for Borealis clients.	Environmental report
Nouryon	Sundsvall	2,700 tonnes		By-product from sodium chlorate.	Biofuel report
Nouryon	Alby	5,400 tonnes		Hydrogen peroxide production.	Biofuel report
Sandvik	Gimo	150 tonnes	Electrolysis	Steel processing.	Personal contact
Preemraff	Lysekil	65,000 tonnes	SR (natural gas)	Production of biofuel	Preem homepage
Preemraff	Göteborg	15,000 tonnes	SR (natural gas)	Production of biofuel	Preem homepage
Borealis	Stenungsund	1,800 tonnes	Ethylene, naphta	By-product from cracking. Utilized by themselves to produce ethylene and sold via pipe to nearby clients.	Personal contact and Sundqvist & Petersson 2017
Linde	Total for Borlänge, Fagersta, Halmstad and Sandviken	910 tonnes ***	Electrolysis	For sale (via pipes and in bottles)	Personal contact
Air Liquide	Surahammar	112 tonnes	Electrolysis	For sale	Personal contact
AB Nynäs Petroleum	Nynäshamn	16,000 tonnes*	SR (natural gas)	Naphthenic oils production.	Personal contact
Kemira Kemi AB	Helsingborg	3,500 tonnes	SR (natural gas)	Hydrogen peroxide production.	Personal contact
Höganäs	Höganäs	0,9-1,26 tonnes**	SR (natural gas)	Metal powder	
Perstorp Oxo	Stenungsund	4,950 tonnes	SR (natural gas)	Production of biofuel (rape seed methyl ester)	Sundqvist & Petersson 2017

CS = Chlorine sodium hydroxide electrolysis
SR = Steam reforming

* *This is the volume they have permission to store - the production volume is confidential.*
** *Confidential.*
*** *Production capacity, not actual production.*

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