THE POTENTIAL OF HYDROGEN IN A SWEDISH CONTEXT

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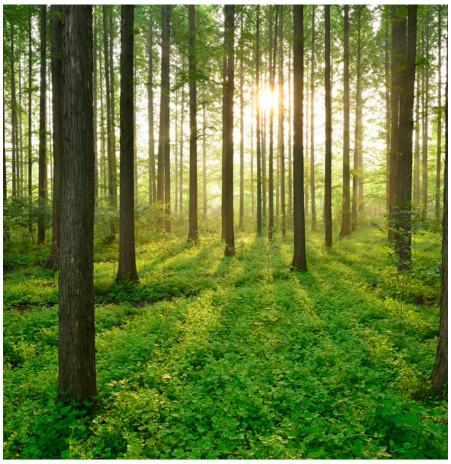

VÄTGASENS ROLL I ENERGI- OCH KLIMATOMSTÄLLNINGEN

Energiforsk

The Potential of Hydrogen in a Swedish Context

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Foreword

Hydrogen is expected to be an important piece of the energy transition puzzle. Hydrogen can be used in many applications and areas, such as feedstock in industry processes and in iron and steel production as well as a fuel in transportation and as energy storage. What is the potential for hydrogen and electrofuels in Sweden? This report aims to explores the answer to this question.

This analysis includes a compilation of literature, reports, roadmaps, interview response and a scenario analysis. It shows an overview over the production potential and demand scenarios for Swedish hydrogen and electrofuels.

The project has been carried out by a joint team from IVL Swedish Environmental Research Institute, Rise, DNV and Sweco consisting of project leaders Anton Fagerström and Mirjam Särnbratt, and team members Annika Carlsson, Maja Frost, Per Harrie, Julia Hansson, Maria Hernández Leal, Anders Hjort, Rebecca Lindman, Olga Lysenko, Marika Olsson, Benjamin Storm, Besawit Tsegai, Erik Östling and Elin Lindblad. The study has been conducted within the Energiforsk programme *The Role of Hydrogen in the Energy and Climate Transition* and has been financed by the foundation SIVL and Energiforsk.

A warm thanks to the reference group which has consisted of representatives from Energigas Sverige, Fu-Gen Energi, Jönköping Energi, Mälarenergi, Siemens Energy, Skellefteå Kraft and Svea Vind Offshore.

The programme is financed by nearly 40 companies and organisations. The programme goal is to facilitate the integration of hydrogen and to increase knowledge of hydrogen technology, market conditions and the potential for various applications from a systems perspective. It also aims to support business development and growth in the hydrogen area as well as bring together the ongoing hydrogen research in different parts of the country under the same umbrella.

Sara Hugestam,
Energiforsk

Summary

The aim of this report is to explore the potential for hydrogen and electrofuels in a Swedish context. The analysis includes a compilation of literature, reports, roadmaps, interviews and a scenario analysis.

Renewable hydrogen could be produced from biomass, bio-methane or electricity and water. The current cost of renewable hydrogen production is typically higher than its fossil counterpart regardless of production pathway, but the last few years have started to indicate that some production cases may be competitive to fossil hydrogen, due to the price increase of natural gas and favorable cost reductions of renewable power production. The costs of both electricity and electrolyzers are foreseen to decrease in the future, but the absolute cost reduction is unclear due to uncertainties in the electricity price development and component price development, where the downward trend has stagnated, and inflation and interest rates have increased significantly in the same time period. However, the production costs of renewable hydrogen in Sweden seem competitive or advantageous compared to production costs in other European countries.

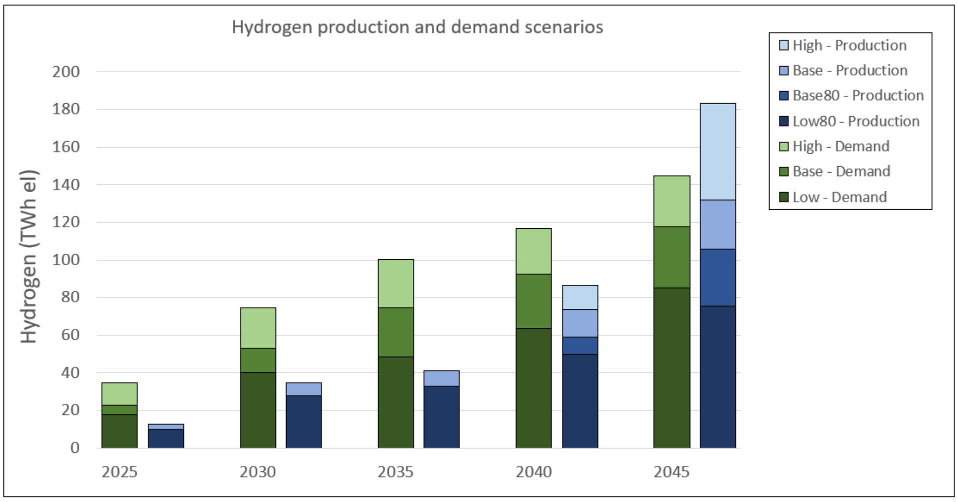
Both the production cost and environmental impact of hydrogen strongly depend on the feedstock and energy supplied to the production process. Sweden benefits from a low-carbon electricity mix that complies with conditions laid out in the recent EU delegated act (2023/1087) within the Renewable Energy Directive (2001/2018), targeting renewable fuels of non-biological origin. Hence, the electricity production benefits hydrogen production in Sweden compared to many other countries. Moreover, Sweden has plentiful resources in terms of biomass, other bio-resources, freshwater and electricity, albeit that all of these feedstocks are subject to competition for use in other sectors. The potential for producing hydrogen and electrofuels with a small carbon footprint in Sweden is therefore high. There are, however, uncertainties in how the climate impact of hydrogen slip should be considered and prevented.

There are some challenges to scaling the hydrogen technology in Sweden, and one is the lack of transmission infrastructure. Compared to many European nations there are almost no natural gas pipelines that could be retrofitted for hydrogen utilization. This also results in a lower societal acceptance for gas. Although there are plans for a Northern hydrogen pipeline, there is no national pipeline and therefore other transmission options must be resorted to, combined with reducing the need for transmission with nearby or on-site production. Another challenge is related to the power transmission capacity which is insufficient. Even though there are good conditions for power production, the electricity grid also has to develop to meet the increased hydrogen demand. A third problem compared to some other countries are fewer possibilities for underground large-scale storage, where e.g., salt caverns could be utilized. However, HYBRIT is now proving hydrogen storage in a lined rock cavern in Svartöberget for their steel production.

Hydrogen is a means to low-carbon chemicals, steel, energy and mobility. Out of these applications, steel reduction and chemical production with renewable hydrogen are already considered key technologies to decarbonization in the

respective industrial sectors in Sweden. Yet, the demand from the chemical industry is not as clearly defined in terms of how much fossil-free hydrogen will be needed in the transition. Meanwhile, electrofuels, which could fit into existing infrastructure and replace their fossil counterparts, likely will also have a role to fill in hard-to-abate sectors and applications. The targets within EU are set for several sectors. However, the market segments in which hydrogen and electrofuels will prevail will depend on the development of technology, investments and regulations.

The scenario analysis considers both announced plans for hydrogen and electrofuel productions and roadmaps as well as other studies for the future demand. The resulting six scenarios suggest that Sweden's hydrogen demand could reach 45-100 TWh (electricity demand) by 2035 and exceed the production in the short-term, while the situation might be reversed by 2045, but uncertainties in this analysis exist.



Production potential and demand scenarios for hydrogen. The production and demand of hydrogen for production of electrofuels are included in the presented scenarios.

Keywords

Eng: Hydrogen, electrofuels, scenario analysis, production and usage potential, market study

Swe: Vätgas, elektrobränslen, scenarioanalys, produktionspotential och användningspotential, marknadsstudie

Sammanfattning

Syftet med denna rapport är att undersöka potentialen för vätgas och elektrobränslen i Sverige. Analysen omfattar en sammanställning av litteratur, rapporter, färdplaner, intervjuer och en scenarioanalys.

Förnybar vätgas kan produceras på många sätt och av många sorters insatsvara, exempelvis biomassa, biometan eller av elektricitet och vatten. Än så länge är kostnaden för att tillverka förnybar vätgas högre än kostnaden för fossil vätgas men vissa prognoser och beräkningar av kostnaden visar på fall där likvärdiga kostnader kan uppnås. Även om kostnaden för elektrolysörer förutspås minska i framtiden är det osäkert till vilken grad och exakt när. Prisminskningen har de senaste åren planat ut på grund av dyrare komponenter och ett osäkert marknadsläge i övrigt. Jämfört med andra länder i Europa finns det dock flera faktorer som tyder på att Sverige skulle kunna producera vätgas till ett konkurrenskraftigt pris, som generellt låga elpriser och låg klimatpåverkan hos svensk elmix, vilket kan bidra till att Sverige gynnas av de nya kraven som ställs i EU:s definitioner av förnybara icke-biologiska bränslen.

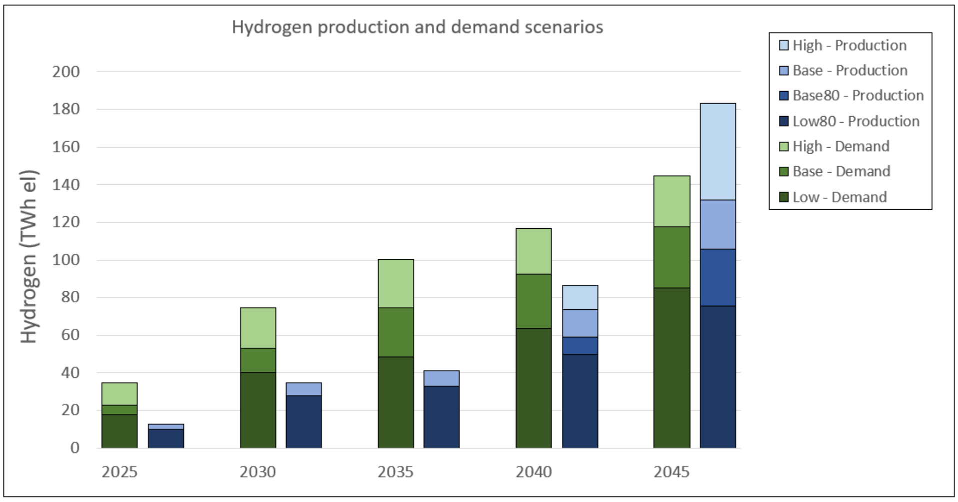
Både produktionskostnaden och miljöpåverkan hos vätgasen beror på vilka råvaror den tillverkas av och på den energi som tillförs produktionsprocessen, där Sverige både har tillgång till fossilfri el och förnybara bioresurser. Potentialen för att tillverka vätgas och elektrobränslen med låg klimatpåverkan är därför hög. Det är dock osäkert hur klimatpåverkan från det som kallas för *hydrogen slip*, eller vätgasslip (små läckage av vätgas som uppstår längs hela värdekedjan), ska beaktas och eventuellt förebyggas.

Utmaningar som står i vägen för en storskalig utbyggnad och användning av vätgas i Sverige utgörs bland annat av att det saknas infrastruktur för att transportera och distribuera vätgas i stor skala. Exempelvis saknar Sverige ett nationellt transmissionsnät för vätgas, vilket annars skulle kunna vara både kostnadseffektivt och energieffektivt. Jämfört med flera andra länder saknas det ett naturgasnät som skulle kunna anpassas för vätgas istället. Detta skapar också en låg social acceptans för gasanvändning. En annan utmaning är bristen på överföringskapacitet i elnätet. Även om det finns bra förutsättningar för elproduktion så måste elnätet utvecklas för att möta den ökade efterfrågan. Ett tredje hinder är relativt få tillgängliga underjordiska lagringsmöjligheter för vätgas. I flertalet länder finns saltgruvor som kan användas för storskalig lagring av vätgas. Däremot bygger Hybrit för närvarande en LRC (Lined Rock Cavern) i Svartöberget som kommer användas som storskaligt lager till stålproduktionen.

Vätgasen är en möjlig väg till att minska klimatpåverkan från Kemikalie-, stål-, energi- och transportsektorn. Bland dessa tillämpningar är stålproduktion och kemikaliesyntes redan utpekade som nyckeltekniker för att minska koldioxidutsläppen från dessa industrier i Sverige. Efterfrågan, sett till mängd vätgas, är dock inte helt klarlagd för kemisk industri, där effektiviseringar och industriell symbios skulle kunna bidra både till en ökning och minskning av vätgasbehovet jämfört med idag. Det är även troligt att elektrobränslen kommer att ha en roll att spela i tillämpningar där direkt elektrifiering eller direktanvändning

av vätgas inte är möjlig eller lämplig. Det är fortfarande osäkert inom vilka marknadssegment som vätgas och elektrobränslen kommer att bli som störst och den omogna marknaden kommer att förändras i takt med teknikutveckling, nyckelinvesteringar, policy och regelverk.

Scenarioanalysen sammanställde och analyserade planer för vätgasproduktion kombinerat med färdplaner och andra framtidsstudier. De resulterande sex scenarierna tyder på att efterfrågan på vätgas skulle kunna vara större än tillgången under de närmaste tio åren (i spannet motsvarande ett elbehov om 45-100 TWh år 2035), men att situationen kan vara omvänd till år 2045, även om det finns flera osäkerhetsfaktorer som påverkar resultaten.



Scenarier för produktion och användning av vätgas utifrån produktionsplaner, färdplaner och andra rapporter och styrmedel.

Den övergripande slutsatsen i rapporten är att Sverige har många resurser och förutsättningar jämfört med andra länder som gör att det vore fördelaktigt att se vätgas och elektrobränslen som en viktig del av omställningen. Huruvida denna potential förverkligas eller inte beror istället på andra aspekter, som politiska och samhälleliga prioriteringar.

List of content

1 Introduction

The view on the potential of using hydrogen as an energy vector and as a feedstock has consolidated and hydrogen is now considered one of the key technologies in the climate transition [1]. As of 2023, 41 governments have assumed a national strategy for hydrogen development [1]. In the European Union, a strategy for hydrogen was announced in 2020 and it notes that the number of announced projects globally nearly tripled in just a quarter of a year between 2019 and 2020 [2]. This pace has not decelerated: the International Energy Agency's forecast of installed capacity of hydrogen production projects has doubled from the release of the "Hydrogen Review 2022" to the "Hydrogen Review 2023" [1].

In Sweden, an industry-partnered initiative named "Fossil Free Sweden" [3] released a hydrogen roadmap in 2020 based on demand and strategies emerging from stakeholder dialogue [4]. One year later, the Swedish Energy Agency proposed a strategy for hydrogen and electrofuel development in Sweden [5]. Both roadmaps provide scenarios for what the future role of hydrogen in Sweden could look like. However, it is not yet clear what role Sweden could have in the future hydrogen landscape and how it could be used in an optimal way. Therefore, the aim of this project is to provide an overview of the potential for hydrogen and electrofuels in a Swedish context. The report seeks to answer the following research questions:

- What pathways could be utilized to produce renewable hydrogen and electrofuels? What are their associated costs and environmental impact?
- How much hydrogen and electrofuels could potentially be produced from available biogenic resources and renewable energy?
- What is the potential uptake of hydrogen and electrofuels in different sectors?
- What are the current plans for production of hydrogen and electrofuels and what amounts could realization of these plans result in?
- What are conditions that make hydrogen and electrofuel production in Sweden advantageous and what are the risks and drawbacks?
- Under what conditions is it advantageous to use bio-based raw materials and products directly, and when might it be justified to further refine them into hydrogen?
- What is the relationship between potential hydrogen and electrofuel production and potential demand for these in Sweden for various scenarios (e.g., set goals and different assumptions for electricity and biofuel production, etc.)?
- Could Sweden be expected to become a net importer or net exporter of hydrogen or other further refined products, and what factors have the largest impact on this?

2 Method

Multiple methods have been combined in this project to explore the potential of hydrogen in a Swedish context. These included a literature review of scientific papers and reviews, project reports, and EU documents and reports. This review served as the foundation for analyzing the technical aspects of hydrogen production, its theoretical production potential, associated costs, and the environmental implications of both hydrogen and electrofuels. Additionally, interviews were conducted with stakeholders active in the Swedish hydrogen network to learn their perspectives on hydrogen's potential within Sweden and gain insights into the current landscape and barriers. The actors were selected according to their role in the hydrogen and electrofuel value chain and according to their current or planned hydrogen and electrofuel solutions projects. Furthermore, the scenario analysis, described further in chapter 6, incorporated data from literature, existing roadmaps, and previous forecasts to project potential production and demand trends for hydrogen in Sweden in the upcoming decades.

3 Hydrogen production, distribution and use

Hydrogen could be produced through a plethora of processes and chemical reactions but always entail energy losses in the conversion. The benchmark efficiency of available generation technology ranges between 55 and 70%. Research is ongoing for how the use of noble materials could be reduced and how process efficiency could be optimized.

The current cost of renewable hydrogen production is higher than its fossil counterpart in all cases, although the last two years have started to indicate that some production cases may be competitive to fossil hydrogen, due to the price increase of natural gas. The costs of both electricity and electrolyzers are foreseen to decrease in future, but the absolute cost reduction is unclear due to uncertainties in the electricity price development and component price development, where the downward trend has stagnated in 2022. For biogenic hydrogen, the lower ends of the presented cost ranges suggest that bio-hydrogen might be cost-competitive to fossil hydrogen already in the short term. However, there are few examples of commercial production of biogenic hydrogen and therefore large uncertainties regarding the actual selling price. The last years' inflation has also led to higher capital costs and challenges in finding a viable business case.

The climate impact of renewable hydrogen is generally lower than that of fossil hydrogen and could be further improved in the future if the energy supplied to the production process is renewable as well. However, it is especially important in the case of grid-connected electrolysis that the emission factor of the electricity mix is low to ensure the reduction of greenhouse gas emissions. Another large uncertainty receiving attention in the later years is hydrogen leakage along the value chain and the resulting climate impact on a shorter time horizon, that causes a threat when unaccounted for to the effectiveness of hydrogen as a climate transition tool.

According to estimations made based on hydrogen roadmaps and a state public enquiry to establish for the national biogas potential, the maximum theoretical production potential in Sweden amounts to about 46 TWh in 2030, comprised of production of hydrogen from biomass and organic waste (about 20 TWh) and fossil-free electricity (26 TWh of hydrogen).

Large-scale storage of hydrogen poses a challenge in a Swedish context, due to the limited access to underground large-scale storage. For small-scale storage, the technological solutions are many. Another challenge to scaling hydrogen technology in Sweden is the lack of distribution infrastructure. Although there are plans for a Northern hydrogen pipeline, a national gas grid does not exist today and other distribution options must therefore be resorted to, combined with reducing the need for distribution with nearby or on-site production.

Hydrogen is a candidate for low-carbon chemicals, steel, energy and propulsion. Out of these applications, steel reduction and chemical production with renewable hydrogen are already considered key technologies to decarbonization in the chemistry and steel industry sectors in Sweden.

3.1 PRODUCTION ROUTES FOR RENEWABLE HYDROGEN

A significant amount of hydrogen is used in Sweden today: about 6 TWh per year. Out of these 6 TWh of hydrogen, or 180 000 tons, 3% is produced via electrolysis, the rest is either produced by direct use of fossil fuels (67%) or as waste streams in industrial processes (30%) [6]. The following sections will describe some production routes for renewable hydrogen from using existing and emerging technologies, to provide an understanding of their benefits and drawbacks and relate them to the analyses of later sections in this report. The different production pathways that will be presented are selected based on their technological readiness level (TRL) and whether their properties seem advantageous for certain applications.

3.1.1 Water electrolysis

Hydrogen can be obtained by the electrolysis of water. This is done in an electrolyzer cell, which consists of an electrolyte and two electrodes that are supplied by electric power. An electrochemical reaction forming hydrogen and oxygen according to Eq. 1 will take place at the cathode and anode.

$$H_2O_{(l)} \leftrightarrow H_{2(g)} + \frac{1}{2}O_{2(g)} \qquad Eq.\ 1$$

The standard enthalpy of the reaction is +286 kJ/mol. This means that the production of hydrogen by electrolysis requires a significant supply of energy [7].

There are different technologies achieving the reaction above, classified according to their applied electrolyte: polymer electrolyte membrane (water) electrolysis (PEMWE), alkaline water electrolysis (AWE), solid oxide electrolyzer cells (SOEC) and anion exchange membrane electrolysis (AEMWE). PEMWE and AWE are technologically developed processes, while SOEL and AEMWE are still emerging technologies with limited technological maturity [7], [8].

The principle of AWE is as follows. The electrodes are immersed in a liquid electrolyte separated by a diaphragm. The electrolyte is usually a 25–30% aqueous kalium hydroxide (alkaline) solution. It is circulated for the removal of product gas bubbles and heat either by pumps or by natural circulation due to temperature gradients and buoyancy of the gas bubbles. The electrolyte is stored in two separated drums for each product gas (oxygen and hydrogen) which serve also as gas-liquid-separator. AWE technology is divided on atmospheric and pressurized systems [9]. Pressurized systems require less compression if compare with other technologies and better suited to respond to changes in power demand from renewable energy sources. This gives the advantages of pressurized alkaline to still compete with other technologies such as PEMWE when combined with renewables [10].

In PEMWE technology a proton exchange membrane separates the two half-cells, and the electrodes are usually directly mounted on the membrane forming the membrane electrode assembly. The- corrosive acidic regime provided by the proton exchange membrane requires the use of noble metal catalysts like iridium for the anode and platinum for the cathode. PEMWE is characterized by very low cross-permeability, which gives higher purity hydrogen than AWE, typically over

99.99% hydrogen after drying. The PEM electrolysis features a compact modular design due to the solid electrolyte and high current density operation compared to AWE. [9] The operating pressure ranges between 30 and 80 bar_g [8], [11].

SOEC is increasingly drawing interest due to advancements in solid oxide fuel cells and the impetus behind carbon-neutral energy scenarios. Operating within the temperature range of 700–900 °C and atmospheric pressure, SOEC boasts higher efficiency compared to AWE or PEMWE. However, this high-temperature operation presents a significant challenge concerning material stability. The enhanced efficiency arises from improved kinetics and thermodynamics, enabling the utilization of internal heat at higher temperatures, as well as steam reforming [9].

The AEMWE (Anion Exchange Membrane Water Electrolysis) technology comprises multiple cells connected in a series in a bipolar arrangement. It involves a membrane electrode assembly utilizing a polymeric AEM (Anion Exchange Membrane) and specifically engineered cost-effective electrodes. The anodic half-cell contains a diluted KOH (Potassium Hydroxide) alkaline electrolyte solution, while the cathodic half-cell operates without liquid, generating hydrogen from water permeating the membrane originating from the anodic half-cell. Oxygen is produced on the anodic side and is carried out of the stack through the circulating electrolyte. The hydrogen is generated under pressure, typically at 35 bar gauge (bar_g), and is already highly dehydrated and pure, approximately 99.9%. [12]

One potential advantage of the AEMWE compared to the PEMWE is that the operating environment is less corrosive and therefore steel bipolar plates could be used instead of titanium plates. Furthermore, it also believed that the tolerance for impurities in the water is higher in the AEMWE case, which allows exploitation of other water sources for the electrolysis, electrolyzers can tolerate a lower degree of water purity, which reduces the input water system's complexity and allows filtered rain and tap water. Moreover, the AEMWE technology presents several potential advantages over AWE (Alkaline Water Electrolysis) technology. It operates within a significantly diluted alkaline milieu, rendering it safer for manipulation. This technology utilizes cost-efficient materials similar to those employed in AEL while achieving better efficiency in producing pure hydrogen. Additionally, AEM technology demonstrates full scalability and is well-suited for integration with variable renewable energy sources. [12]

Rated efficiency and energy consumption of electrolysis technology are in the range of 63–71%$_{LHV}$ and 4.2–4.8 kWh/Nm^3 for AWE, 60–68%$_{LHV}$ and 4.4–5.0 kWh/Nm^3 for PEMWE [7]. Anion exchange membrane electrolysis (AEMWE) is an emerging technology and research is ongoing for how to improve energy efficiency, membrane and catalyst stability, ease of handling, and cost reduction [8]. Therefore, it is considered mature enough yet to be included in the continued analysis of this report.

The main technical characteristics of some of the most relevant electrolyzer technologies are summarized in Table 1.

Table 1. Technical characteristics of existing electrolyzer technologies based on [8], [11].

	AWE	PEMWE	SOEC
Electrical efficiency (%, LHV)	63-70 (today) 65-71 (2030) 70-80 (long term)	60-68 (today) 63-68 (2030) 67-74 (long term)	74-81 (today) 77-84 (2030) 77-90 (long term)
Energy consumption (kWh/Nm3)	4.2–4.8	4.4–5.0	4.5-7.5
Operating pressure (bar)	1–30	30–80	1
Operating temperature (°C)	60–80	50–80	650-1 000
Load range (%, relative to nominal load)[1]	**10–110**	**0–160**	**20–100**

Producing hydrogen through water electrolysis is developing rapidly due to several benefits. One example is that it produces hydrogen with high purity. This will vary slightly depending on the manufacturer and the electrolyzer model. Alkaline electrolyzers produce hydrogen at around 99.98% purity, PEM electrolyzers produce hydrogen >99.999% purity [13], and Anion Exchange Membrane electrolyzers produce hydrogen at 99.9% purity [14]. This does not include the purification and drying step. As a result, hydrogen from water electrolysis is an attractive production route when the hydrogen is aimed for application where high purity is important, such as fuel cell vehicles. The process also produces pure oxygen as a by-product, which can be used in other applications for example the medical industry.

Another advantage for water electrolysis is the potential of achieving low emissions, an increasingly important driver for decarbonising different sectors. This is dependent on the source of electricity, as a direct connection to renewables result in very low total emissions, but a grid connected electrolyzer can reach emissions as high as 30 kg CO_2e/kg H_2 depending on the carbon intensity of the

[1] Nominal load = the load for which the production process is optimized

specific grid mix [15]. The Hydrogen Council published a report in January 2021 on well-to-gate emissions, which showed that electrolytic hydrogen produced by only renewables could reach total well-to-gate emissions between 0.3 kg CO_2e/kg H_2 (hydro power at 5,000 hours per annum with PEM electrolyzer) and 1.0 kg CO_2e/kg H_2 (solar energy 1,500 hours per annum with PEM electrolyzer) by 2030 [16]. The environmental impact of hydrogen production will be discussed in more detail in section 3.3.

3.1.2 Gasification of biomass and waste

Gasification is a mature technology that has been used conventionally with coal as feedstock. Nevertheless, biomass can be co-fed or individually gasified with the same technology. The technology used for gasification is usually a fluidized bed reactor, operating at temperatures between 800-950°C in comparison with 950-1100°C needed for coal gasification. The biomass should also be dried prior to enter the fluidized bed to reduce the moisture content to 5-10% [17]. The process consists in thermally converting hydrocarbons into carbon monoxide, hydrogen, and carbon dioxide in the presence of a controlled amount of oxygen and steam. Other unwanted species are also formed during the process and are separated downstream [17]. To increase the amount of hydrogen, the gases produced in the gasifier go through another step where the water-gas shift reaction takes place. Here, the carbon monoxide reacts with steam to produce hydrogen and carbon dioxide. The latter can be separated with a pressure swing adsorption unit (PSA) [18].

As gasification is a mature technology, it benefits from extensive industry knowledge. It opens the opportunity to convert waste products to a compound of higher value compared to today's incineration process. Furthermore, it has the potential to produce carbon neutral hydrogen, which is a strong driver for meeting net zero in 2050 [15].

However, when looking at waste specifically, there could be challenges related to homogenising feedstock (for example ensuring plastic of unified size and composition or obtaining woodchips of similar size). It could also potentially face challenges of introducing innovative technologies into a mature process. It requires careful consideration of location to ensure sufficient feedstock availability resulting in a risk of varying hydrogen content, a risk that is further increased with possible feedstock impurities [19]. The process does produce carbon gases that are either released into the air or captured, where the latter is preferred for reducing emissions. A char is formed in the gasification vessel as a by-product, which is directly repurposed to be burnt to heat the ceramic beads to 1000°C. The high-temperature beads are used to convert the waste feedstock into a hydrogen/methane/carbon monoxide/carbon dioxide mixture [20]. The overall process efficiency is about 35-50% [21].

3.1.3 Reforming of biogas

Biogas is produced by the anaerobic fermentation of organic material such as agricultural waste, municipal solid waste and landfill [22]. Raw biogas mainly consists of methane (60-70%) and carbon dioxide (30-40%) and small amount of hydrogen sulfide [23]. To produce hydrogen, the biogas requires a cleaning step. Carbon dioxide is removed by technologies like amine absorption, membrane permeation or pressure swing adsorption. Hydrogen sulfide is removed by passing the gas through a catalytic zinc oxide bed. Pure methane can then be converted to hydrogen by a catalytic reforming reaction. The process is optimally done by reacting methane with steam at a molar ratio of water/methane equals to 3 (excess of water) at a temperature of around 720°C and atmospheric pressure [23]. It can also be performed at higher temperatures and pressure, for example at 30 bar and 900°C. [23]. Carbon monoxide and dioxide are formed as by-products in this process. This mixture of gases is called syngas. The syngas goes through a water gas shift reaction where hydrogen concentration is increased. Finally, hydrogen is separated by a pressure swing adsorption unit.

As reforming of biogas replaces natural gas as a feedstock in the reforming process to produce hydrogen, it benefits from the advantages of using a known technology while reducing emissions. The process is dependent on available agricultural waste and residues, but this also creates a value to these waste streams and increases circular economy. There are still emissions involved, with carbon monoxide and dioxide as by-products, but the hydrogen produced has lower emission. It has the benefit of using a traditional production process (methane reforming) but would require carbon capture to achieve hydrogen with lower carbon footprint. There is a number of different methane reforming processes: steam reforming, tri-reforming, dual reforming and dry reforming; however, steam reforming is the most mature and commercialized. It is however an energy-intensive method. There are certain advantages with the three latter processes when using biogas as fuel due to its high quantity of carbon dioxide as this can be used as an oxidant [24]. Dry reforming uses carbon dioxide in the reforming process converting it into syngas and can therefore lower carbon emissions. Its main challenges are energy requirements at similar levels to steam reforming, high risk of coke formation and the syngas being of low quality [25], [26].

Partial oxidation offers simplicity, cost savings, a possible smaller size than conventional reforming units, fast start-up and a dynamic operation. However, it has challenges such as relatively low production yield of hydrogen and risks forming soot [27].

Tri-reforming is a complex process as it combines steam reforming, dry reforming and partial oxidation. The advantage of this is that it is versatile due to the quality of the synthesis gas being easily changed by altering the composition of the feed. This means it can be used for several possible applications [28].

3.1.4 Pyrolysis of Methane

Methane pyrolysis is the decomposition of methane into hydrogen and solid carbon, which distinguishes it from for instance steam methane reforming where carbon is released in gas form as carbon dioxide or carbon monoxide. While the overall reaction of methane pyrolysis is the decomposition of one methane molecule into one carbon atom and two hydrogen molecules, as in $CH_{4(g)} \rightarrow C_{(s)} + 2H_{2(g)}$ *Eq. 2*, the reaction involves several intermediate reaction mechanisms depending on the reaction conditions [26]. The reaction is endothermic and is thus favored by high temperatures.

$$CH_{4(g)} \rightarrow C_{(s)} + 2H_{2(g)} \qquad Eq.\ 2$$

Three different methane pyrolysis technology configurations are commonly referred to today: plasma, molten metal and thermal gas reactor systems. Plasma systems use energy to turn the gas into an ionized state (plasma state), in which the methane is decomposed. Most plasma systems do not use a catalyst [29], and the fast start up of the system means that it can likely be combined with fluctuating renewable energy sources such as wind power [30]. In molten metal reactor systems, methane is injected into the bottom of a reactor containing liquid metal, and after being decomposed in the reactor, hydrogen gas and carbon black exits at the top of the reactor. The liquid metal allows for efficient heat transfer but, depending on the choice of metal, it can also increase yield by acting as a catalyst [31]. Thermal gas reactor systems are more conventional, involving the injection of methane into a reactor such as a fixed-bed or fluidized-bed reactor, in which the gas is decomposed with or without a catalyst. In general, a non-catalytic reaction requires higher temperatures whereas the use of catalysts allows for a lower temperature as well as higher hydrogen yield [32]. Catalysts can be both metal (iron, nickle or cobolt) and carbon (e.g., activated carbon or carbon blacks), with latter being favorable in industrialization thanks to factors such as lower price, less sensitivity to impurities and higher quality of the carbon biproduct [32].

Depending on the reactor configuration and the type of catalyst use, different forms of processing is required for the product. However, most of the processing required is for the carbon by-product, to separate it and possibly also regenerate deactivated catalysts. For the hydrogen gas a membrane filtration is often sufficient to separate it from residual methane [32].

One of the benefits of pyrolysis of methane is that it produces carbon in solid form rather than gas form, removing the need for CCS. The carbon can then be used in other applications. This could create an additional revenue, although it is unknown how the market would accommodate this product produced at large scale. Environmental remediation and soil amendments are two potential markets. Several carbon products can be derived from the solid carbon such as carbon fibres and carbon black with different markets available. Carbon black is used in rubber and metallurgical industries, where its selling price will depend on its quality, and the global demand is expected to grow in the future [32].

There are however some barriers to consider for scaling up pyrolysis technology. It requires high process temperature, and the produced hydrogen may require additional purifying step depending on the final use demands and the process. Other barriers are its low TRL (TRL 3-8, depending on technology [33]), limited feedstock if biogas is used, or that it could still be fossil-based hydrogen if natural gas is used as feedstock.

3.2 HYDROGEN PRODUCTION COSTS

Conventionally, hydrogen has been mostly produced from fossil resources, namely coal and natural gas by gasification and catalytic steam-methane-reforming processes respectively. The cost of hydrogen produced by these means is approximately 2-3 EUR/kg [34]. Another study showed that traditional fossil-based hydrogen through Steam Methane Reforming (SMR) costs in the range of 0.8-2.7 USD/kg H_2 [15]. However, the unprecedented natural gas prices of 2022 led to levelized cost of hydrogen of 5.7 EUR/kg and a marginal production cost of 5.5 EUR/kg [35]. Meanwhile, the last years' inflation and increasing capital costs impose a risk on hydrogen projects' bankability, where a 3-percentage point increase in interest rate could make the costs of a project increase by 30% [36]. Therefore, it is not easy to predict what the future cost landscape will look like, especially on a longer time-horizon, although the current outlook may not seem optimistic in the short term.

The figure below summarizes the span of costs provided by the literature reviewed in this section. It is important to note that different sources have different underlying assumptions that are explained further in the coming sections and that numbers are not directly comparable to each other. Instead, the figure underlines the uncertainties and different results that could be obtained when the LCOH of hydrogen is estimated.

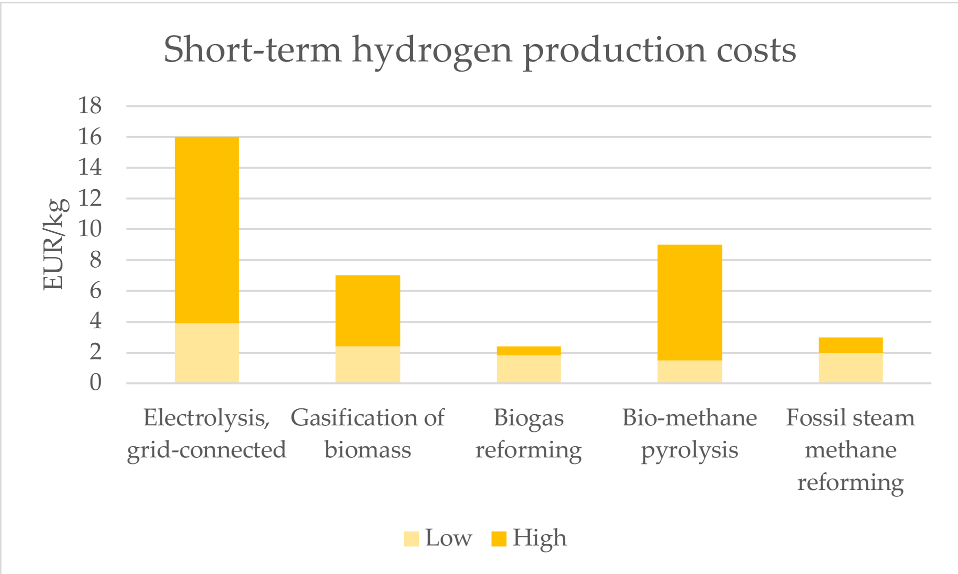


Figure 1. Summary of the wide range of cost estimations provided in the reviewed literature. The numbers are explained in more detail in the below sections.

The following segments will compile estimations on the costs of the different renewable hydrogen production routes.

3.2.1 Water electrolysis

There is currently a wide range of costs for electrolyzers both depending on chemistry and supplier. While average costs have been foreseen to decrease for all technologies are 25% by 2030 and 50% by 2050 [10], the likelihood of this development is discussed in the light of the recent equipment price increase [36].

For the most mature technologies, PEMEL and AEL, costs are believed to decline from the early 2030s [10]. SOE and AEM technologies are still in the development phase, and it is difficult to estimate their future cost upon full commercialization. SOE is likely to be applied in industrial areas with waste heat available and in combination with other conversion processes such as ammonia or syngas. AEM could be significantly less costly if the technology is successfully developed in the future. Its application is likely to be the same as AEM and PEMEL, but material costs may be lower [10].

The electrolysis CAPEX is one of the main factors affecting the cost of the hydrogen produced through this route. Furthermore, the low-temperature electrolysis (AEL, PEMEL) hydrogen cost is highly dependent on the electricity price. Cost estimations made by DNV GL in 2022 suggest that hydrogen currently cost \$5–\$6/kg-H_2, or approximately the same amount in EUR/kg H_2, if electricity price is in the range \$0.05–\$0.07/kWh [15]. The lower price of electricity can be obtained as a result from developing wind and solar resources in the range \$0.02–\$0.03/kWh, and the current development in electrolyzer technologies suggests a hydrogen cost less than \$2/kg. [15], [37].

According to the Clean Hydrogen Monitor 2023 [35] a report published by Hydrogen Europe, the estimated levelized cost of hydrogen (LCOH) production in Europe currently (as of end of 2022) ranges between 3.9 and 16.4 EUR_{2022}/kg H_2 for grid-connected hydrogen production. This is an increase from the end of 2021, when LCOH for grid-connected hydrogen ranged between 3 and 8 EUR_{2021}/kg H_2. In the status update accounting for the situation in late 2022 [35], the lowest LCOH was estimated for Sweden at 3.9 EUR_{2022}/kg H_2, while it was higher in the other Nordic countries, from 4.0 EUR/kg in Finland to 8.9 EUR/kg in Norway. The difference between the European countries could in part be explained by the difference in electricity prices between bidding zones (for example, the average electricity price for non-household customers was 0.11-0.13 €/kWh in Sweden in 2022 while it was 0.15-0.18 €/kWh in Norway [38], [39]), but also differences in grid fees and taxation. The particularly low LCOH of grid-connected electrolysis in Sweden could also be explained by the low use of natural gas in electricity generation, making the Swedish electricity mix more resilient to natural gas price fluctuations [35]. In the report released the previous year [34], the lowest LCOH was instead found in Finland, while Sweden is placed in the middle of the range with an estimated LCOH of 5.3 EUR_{2021}/kg H_2. The Clean Hydrogen Monitor also calculates the LCOH of hydrogen produced by direct connection of an electrolyzer to the cheapest renewable power generation of each country, either onshore wind, offshore wind or solar PV. In the latest report [35], Swedish hydrogen from offshore wind was estimated at an LCOH of 6.1 EUR_{2022}/kg H_2, which is a drastic increase from the previous year's estimation of 3.9 EUR_{2021}/kg H_2 [34]. The main reason for this difference, according to the report, is the inflation, resulting in higher interest rates and weighted average cost of capital, or *WACC*. However, the LCOH results are affected by the assumption made for the size of the electrolyzer (100 MW_e in this case) and the capacity ratio between the installed renewable energy and the electrolyzer [35] and the results do therefore not apply to all cases.

A challenge for electrolysis-based hydrogen are the low efficiencies associated with the electrolyzer technologies, as mentioned earlier in the technical description of the processes. Therefore, if the efficiency is improved through further development of the technology over time, the electrolysis costs can be expected to drop.

3.2.2 Gasification of biomass

The cost of hydrogen produced from gasification of biomass and waste depends on the quality and cost of feedstock used in the process. In comparison, the cost for coal gasification is 2.2-4.1 USD/kg H_2 or 3.7-5.2 USD/kg H_2 when a CCS unit is used[15]. For biomass gasification, an indicative value is around 2.7 EUR/kg (or 79 EUR/MWh) [40]. For waste gasification, a waste-to-hydrogen start-up (Ways2H2) claim they comfortably produce hydrogen at $5 per kg H_2 today and estimate that they could potentially reach $3 per kg of H_2 in 5 years [20]. Another compilation of the cost of biomass gasification was done in [41], where a cost range of 0.05-0.176 EUR_{2020}/kWh was presented, corresponding to about 2.4-7 EUR_{2022}/kg H_2 and 2.6-8 USD_{2022}/kg H_2. In [42], biomass gasification costs based on CAPEX and OPEX (in $/kg H_2) were compiled and presented and the interval of 1.21-3.5 $/kg H_2 was presented, which is equivalent to about the same amount in EUR_{2022}. These different indications show that the current renewable processes are similar in value to coal gasification with CCS and that the pathway could become cost competitive with coal gasification, depending on the case. However, given the few existing examples it is difficult to tell when the cost of biomass gasification could become competitive with the fossil and mature equivalent outside of techno-economic analyses.

3.2.3 Reforming of biogas

This process is often used for natural gas and as a reference fossil-based steam methane reforming results in a levelized cost of hydrogen of 0.8-2.7 USD/kg H_2 or 1.8-4.1 USD/kg H_2 if a CCS unit is used (values for 2022) [15]. One of the reasons for the cost of the technique is that catalysts are needed in several steps such as in hydrogen sulfide removal and the reforming step. For biogas reforming similarly as for the gasification process the cost of hydrogen will in part depend on the cost of feedstock. In [42], the cost of biomethane reforming is suggested as 1.83-2.35 USD_{2020}/kg, which is approximately the same amount in EUR_{2022}/kg.

3.2.4 Methane pyrolysis

Although there is currently a wide range of costs suggested for methane pyrolysis, the costs savings for emissions is one of its advantages compared to other fossil-based hydrogen. The solid carbon is generally associated with lower storage costs (if it is stored rather than used) compared to installing CCS. Among the studies reporting on costs for hydrogen production using fossil methane pyrolysis, the range of costs in most studies spans from approximately 1.5 to 9.0 EUR/kg H_2 [29], [30], [43], [44], [45]. The large range can be explained by several factors. Firstly, most studies are assuming natural gas (not biomethane) as the source of methane, having minor implications for the quality of the gas, but possibly larger implications for the assumed feedstock price, where the use of biomethane as a feedstock is likely to come with higher costs. Furthermore, different assumptions regarding scale, choice of technology configuration, feedstock price, electricity price, selling price for the carbon by-products and carbon tax have large impact on the selling price for hydrogen [30], [43], [44], [45]. Also, since methane pyrolysis still has a lower technology readiness level, with only a few companies claiming to have commercially available technologies, most costs referenced are based on capital estimations, not on actual plant costs, implying uncertainties in the numbers for fully commercial and industrialized plants. One review, [42], of techno-economic costs for pyrolysis of biomethane (theoretical values) suggests that the cost would be somewhere in the range of 1.2-2.6 USD_{2020}/kg H2, which corresponds to about the same amount in EUR_{2022}. In summary, the moderate TRL creates several degrees of uncertainty, leading to a widespread estimation of what the real cost of producing hydrogen through methane pyrolysis could be.

3.3 ENVIRONMENTAL IMPACT OF PRODUCTION

Hydrogen is usually classified by color depending on the production technology used and the feedstock. However, there has been a recent shift towards defining hydrogen in terms of carbon intensity, which is expressed in terms of CO_2 equivalents (CO_2e) per unit of hydrogen produced, rather than colour, allowing technologies, production routes and resulting emission levels to be compared on equal terms [10].

An emerging topic of discussion concerning the environmental impact of hydrogen, regardless of how it is produced, is the global warming potential of fugitive hydrogen (H_2) emissions. The losses may occur in leaks anywhere along the value chain or through venting, purging or incomplete combustion [46]. In [47], it is suggested that the hydrogen losses along the entire value chain could range between 0.1-7%. The mechanism behind the indirect climate impact of hydrogen is that the fugitive hydrogen interferes with tropospheric methane sinks through interactions with ozone, indirectly retaining methane in the troposphere and thereby increasing the radiative forcing [46], [47]. The exact value for the global warming potential of hydrogen is however uncertain, partly because there are few studies on the topic thus far, but also because the hydrogen molecule is short-lived, and the impacts are thus more difficult to capture compared to carbon dioxide which has a longer lifetime in the atmosphere [47]. According to [48], the global warming potential of hydrogen could be more than 3 times higher on a 20-year horizon compared to one of 100 years, corresponding to 33 and 11 CO_2e respectively. The study also found that the climate impact of hydrogen produced through steam methane reforming with CCS could have a larger climate impact than fossil fuels, when a high hydrogen leakage of 10% is assumed, while renewably produced hydrogen could still reduce the climate impact compared to fossil fuels and neatly halve the emissions. If instead a low hydrogen leakage is assumed, renewable hydrogen could be produced with barely any greenhouse gas emissions. The authors of [48] further called for more research on the atmospheric chemistry-climate interactions and to give attention this impact in order to secure systems with low leakage of hydrogen and the desired climate mitigation impacts of using hydrogen as an energy carrier. Just like the issue of methane slip and the subsequent climate impact is increasingly discussed, hydrogen leakage will likely need more focus to avoid any adverse effect of using hydrogen in the near term.

Apart from the molecule itself, the environmental impact of hydrogen production is strongly dependent on the environmental impact of the feedstock and energy inputs. Naturally, hydrogen of fossil origin will lead to emissions of fossil carbon dioxide, about 9 kg CO_2 per kg of hydrogen in the steam reforming of (fossil) methane case [49]. To contribute to the target of limiting climate change to 1.5 °C, hydrogen must be produced with a significantly smaller carbon footprint.

An overview of the climate impact associated with the different production pathways is presented in Figure 2, as a result of the information compiled in the following sections. The direct emissions denote the emissions resulting directly from the chemical reaction producing the hydrogen and the indirect emissions relate to the climate impact associated with the energy input and feedstock supplied upstream in the process. The numbers are further explained in the coming subchapters of this section.

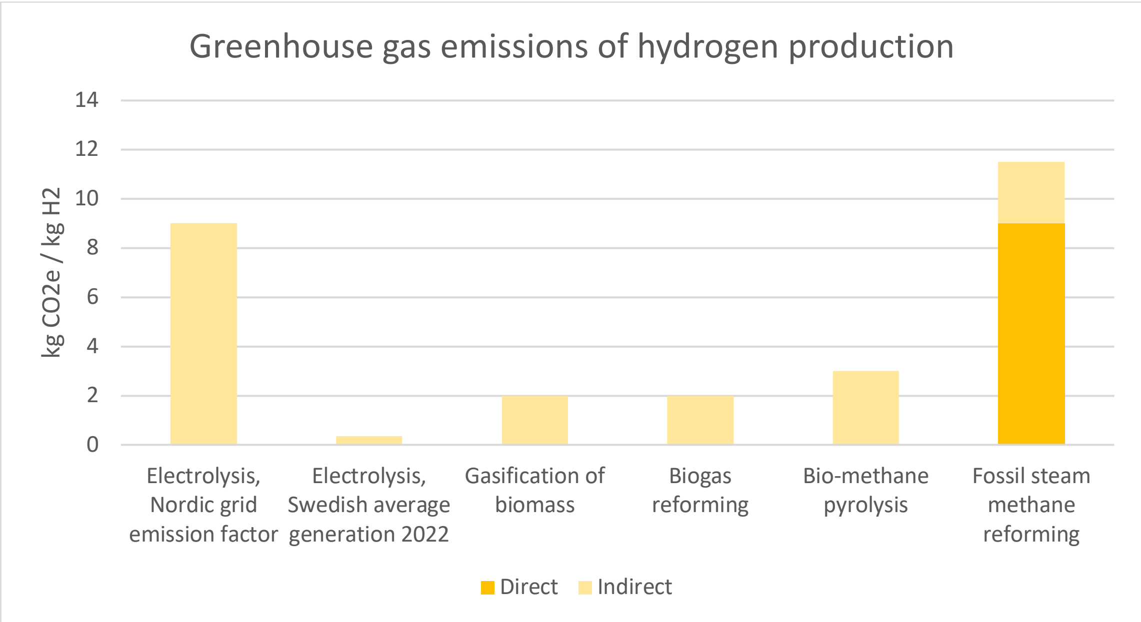


Figure 2 - Climate impact of renewable hydrogen production, expressed in kg CO_2e/kg H_2 and benchmarked against fossil steam methane reforming.

3.3.1 Water electrolysis

Electrolysis is an energy intensive technology with a lower energy efficiency compared to other existing hydrogen production technologies. Therefore, electricity with a low carbon footprint is a prerequisite to a low environmental impact [6]. In fact, an electricity supply consisting of a large share of fossil fuels will result in hydrogen with a higher carbon footprint than the fossil benchmark of 9 kg CO_2e/kg H_2.

In a Swedish and Nordic context, the emission factor of the electricity grid is generally quite low compared to the rest of Europe, although the EU27 average greenhouse gas emissions per kWh was historically low in 2023 at 208 g CO_2

equivalent per kWh [50]. In a report evaluating the climate impact of Swedish electricity and district heating and cooling [51], an average emission factor for Nordic electricity mix of 90 g CO2e/kWh was recommended to account for all direct and indirect effects of the current electricity production. If instead only the Swedish system is considered, the Swedish National Board of Housing, Building and Planning database suggested an emission factor of 37 g CO_2e/kWh [52] based on average values from 2015-2017 and accounting for imports and exports. However, recent statistics on Swedish electricity generation published by the European Energy Agency [53], suggest a number as low as 7 g CO_2/kWh, then resulting in a hydrogen carbon footprint of 0.35 CO_2 / kg H_2 if an electrolyzer efficiency of 65% is assumed. Using the suggested Nordic emission factor instead a carbon footprint of 4.6 kg CO_2 / kg H_2. It could be expected that the increasing penetration of wind power in the electricity mix will lead to an even lower climate impact in the coming years. A direct coupling of hydrogen production to renewable electricity generation would nearly minimize the carbon footprint, with the remaining greenhouse gas emission resulting from the building of the power plant and sourcing of materials. The Hydrogen Council [54] highlighted in their LCA overview of hydrogen production pathways how the improved use of recycled materials when building renewable power plants would further decrease the indirect emissions of renewable hydrogen production. When coupled directly to wind power, the climate impact of hydrogen production could become as low as 0.31 kg CO_2e/ kg H_2 in 2030 and 0.24 kg CO_2e/ kg H_2 in 2050 [54].

Hydrogen production through water electrolysis requires significant amounts of water: at least 9 kg of water per kg hydrogen, assuming perfect stoichiometric conditions. The water supply challenge will vary in magnitude depending on the resources available in a specific region, existing industry's water demand, permitting requirements for maximum allowable daily water extraction and the size of the electrolyzer plant. The water availability in the Nordics is generally considered good compared to the rest of Europe and other global regions, based on the AWARE (Available Water Remaining) methodology [8][55]. However, the access to water is a highly localized aspect where the watershed in one area may be very small in one area compared to another and therefore the viability of producing hydrogen in a specific place must be determined on a case-by-case basis [6]. Reports on expected future water levels in Sweden predict climate change's impact will result in warmer winters with more rain, but also with warmer and drier summers, especially in Southern Sweden. The expected future Swedish summers carries the increased risk of water shortage in some areas, which is already evident in some summers in the recent years [56].

The recent adoption of delegated acts to the Renewable Energy Directive has shed new light on what electrolysis-based hydrogen is considered renewable in the eyes of EU [57]. Apart from the more obvious case of connecting an electrolyzer directly to a wind park, other allowed pathways are producing hydrogen with grid electricity where the average grid greenhouse gas emissions are less than 18 g CO_2/MJ, i.e., less than 65 g CO_2/kWh, and producing hydrogen in bidding areas where the renewable energy penetration is more than 90% [57]. These conditions are met by bidding areas SE1 and SE2 [58] and possibly also SE3 and SE4, hence they are viable for production of hydrogen via grid-connected electrolysis, which could potentially become an advantage for Swedish production of hydrogen. This is also supported by the emission factor recommended for Sweden (4.1 g CO_2e/MJ) in the Renewable Energy Directive methodology for calculating greenhouse gas emissions of renewable fuels [59].

3.3.2 Gasification of biomass and waste

The impact of producing hydrogen by biomass or waste gasification can be expressed by indirect and direct GHG emissions. The use of a carbon capture unit makes it possible to achieve negative direct emission. The indirect emissions are about 1-3 kg CO_2e/kg H_2 [15] for biomass gasification while it has not been assessed for waste gasification. Indirect emissions include the feedstock supply-chain emissions as well as the energy generation supply-chain emissions The traditional route of coal gasification emits in comparison 18-20 kg CO_2e/kg H_2 [15] of direct emissions and 1.7 kg CO_2e/kg H_2 [15] of indirect emissions. These emissions are also reduced when using a carbon capture unit; 0.5-4 kg CO_2e/kg H_2 for indirect emissions and 0.5-7 kg CO_2e/kg H_2 for indirect emissions.

As mentioned above, the use of a carbon capture unit and a possible storage or utilization of the carbon dioxide reduces the direct impact of the production process. The energy needed for the process has a smaller impact.

Despite the relatively low carbon footprint, biogenic hydrogen is not included in the definition of renewable hydrogen, set by the delegated acts to the Renewable Energy Directive[2]. This implies a risk of biogenic hydrogen (regardless of whether it is produced via gasification or reforming or pyrolysis) not being considered renewable in a European context.

3.3.3 Reforming of biogas

The impact of producing hydrogen by biogas reforming is very similar to biomass gasification. The direct emissions can be negative if CO_2 is captured, and the indirect emissions are about 1-3 kg CO_2e/kg H_2 [15]. On the other hand, the reforming of natural gas (fossil-based methane) can have an impact of 9-11 kg CO_2e/kg H_2 of direct emissions without carbon capture and 0.5-4 when using carbon capture. Meanwhile, the indirect emissions of natural gas reforming are 0.5-4 kg CO_2e/kg H_2 without CCS and 0.5-7 kg CO_2e/kg H_2 with carbon capture [15]. In 2021, 47% of hydrogen in the world was produced from the reforming of natural gas [60].

As mentioned above, the use of a carbon capture unit and a possible storage or utilization of the carbon dioxide reduces the direct impact of the production process. The energy needed for the process has a smaller impact.

As a benchmark, fossil hydrogen can have direct emissions in the range of 9-11 kg CO_2e/kg H_2 and indirect emissions between 0.5-4 kg CO_2e/kg H_2 [15]. Replacing the natural gas with biogas has the potential to minimize the direct emissions and, moreover, lead to indirect emissions as low as 1-3 kg CO_2e/kg H_2. However, this

[2] Snart publicerad IVL-rapport om **vätgasbussar i Luleå lokaltrafik** (2024). Gustavsson-Binder, T. & Hjort, A.

depends on how much methane leakage is avoided during operation and storage. As mentioned in Section 3.1.3, the biogas goes through a cleaning step before it is used to produce hydrogen and methane leakage is expected in this upgrading step. This can be in the range of 0.04%-5% of the biogas produced. Methane emissions can also occur from the digestate when stored, in the range of 0.65% to 10% of the biogas produced [61].

3.3.4 Pyrolysis of biogenic methane

Several studies look at the environmental impact of methane pyrolysis, with most of them focusing on the GHG emissions [31], [62], [63], [64]. Investigating different methane pyrolysis technologies – including thermal, plasma and molten metals – but all assuming fossil gas as feedstock, the results range from 1.9 to 6 kg CO2e/kg H_2. The value chain fugitive emissions of the methane supply constitute a major source of emissions, as does the electricity production in the cases where electricity is used to supply the process heat [63], [64]. Another study shows that indirect emissions of hydrogen produced by pyrolysis (0.5-5 kgCO_2e/kg H_2 [15]) depend largely on the source of electricity, where, if renewable energy is used, it has the potential to achieve significantly lower emissions. Meanwhile, the formation of solid carbon in the pyrolysis process implies an easier carbon sequestration process and that negative emissions could be achieved also in this case.

There are several measures that can be taken to decrease the environmental impact of hydrogen produced using methane pyrolysis. Some are general measures such as increasing the energy efficiency and yield of the process and choosing a fuel for process heat with the lowest possible emissions. This is particularly clear for the cases where electricity is used, and where electricity from renewable energy can give a considerably lower environmental impact [63]. Considering that the numbers reported for GHG emissions of hydrogen produced from methane pyrolysis all assume natural gas as the methane supply, the most obvious way to decrease the environmental impact is to use biogas/biomethane as feedstock instead. In contrast to natural gas, biogas or methane generally have much lower GHG emissions, which could even be negative if the biogas is produced from manure [65]. Considering that methane is often the main source of emissions, biomethane pyrolysis could even yield hydrogen with negative emissions, depending on what the carbon biproduct is used for and how this is accounted for. The use of the carbon product and whether it is allocated a share of the emissions or not also has a general impact on the emissions from the hydrogen production by methane pyrolysis.

3.4 SUMMARY OF PRODUCTION ROUTES

In this section of the report, the different production routes are compared to aid the reader in comparing significant data. The best solution of hydrogen production route in the future will depend on a number of factors including cost, sector coupling and emissions. An overview comparing the different production routes discussed in this report in Chapter 3.1 are summarized in Table 2.

Table 2. General comparison of different hydrogen production routes.

Production Route	Cost of H2 produced (€/kgH2)	Energy efficiency	Emissions (kg CO_2/kg H_2)	By-products
Water electrolysis (PEMWE) **Water electrolysis (AWE)**	2020: 5-6 [15] 2022: 3.9-16.4 [35] (Sweden: 3.9) 2030: 3.1-6.5 €/kg [137]	56-60% (PEMWE today) 63-68% (PEMWE 2030) 63-70% (AWE today) 65-71 (AWE 2030) [66]	Direct emissions: None [15] Indirect emissions (Electricity): 0-30 [15], 0.4 when using Swedish emission factor from 2022. [53]	Oxygen Heat
Gasification of biomass and waste	3-5 (estimate from start-up companies)	35-50% [21]	Direct emissions: Zero, negative with CCS Indirect emissions: 1-3 [15]	Tar formation [19], Carbon monoxide and dioxide [20]
Reforming of biogas (SMR)	Without CCS: 0.8-2.7 With CCS: 1.8-4.1	Without CCS: 66-76% With CCS: 69-79%	Direct emissions: Zero, negative with CCS Indirect emissions: 1-3 [15]	Carbon monoxide and dioxide
Pyrolysis of methane	1.5 to 9	58%	Direct emissions: Zero, negative with CCS	Solid carbon

	Indirect emissions: 0.5-5 [15]

3.5 THEORETICAL PRODUCTION POTENTIAL AND ONGOING PROJECTS FOR HYDROGEN PRODUCTION

In this section the theoretical production potential of hydrogen based on the predicted capacity from different sources such as electrolysis, and biomass conversion through (reforming, pyrolysis and gasification) is estimated. The *theoretical potential* for feedstock is usually defined as the amount that is the result of physical processes [67], but is in this context instead defined as the maximum hydrogen production that could be obtained from existing feedstock. The fossil routes or sources are excluded from this segment as most new planes focus on renewable resources.

3.5.1 Electrolysis roadmaps and estimates

For electrolysis, the current production of hydrogen is about 5000 tons per year, or 180 GWh. As for future production potential for hydrogen produced through electrolysis, either plans for fossil-free hydrogen or electricity could be considered. Two significant roadmaps for the future development of hydrogen in Sweden have been published so far. Firstly, there is the roadmap published in 2021 by Fossil Free Sweden [68], which is an initiative started by the Swedish government in 2015 to promotes collaboration between organizations, industries and public administrations in the transition towards net zero GHG emissions in 2045 [12][69]. In this roadmap, there is a target on installed electrolyzer capacity of 3 GW_{el} by 2030 and 8 GW_{el} by 2045 [68]. The resulting amount of H_2 is 15 TWh in 2030 and 41 TWh in 2045, assuming a capacity factor of 0.9 and an electrolyzer efficiency of 65%. A lower capacity factor of 0.5 instead yields 8.5 TWh in 2030 and 23 TWh in 2045.

A second roadmap was drafted by the Swedish Energy Agency [70] in 2021 and made available to the public later the same year. The targets set in this strategic document are more ambitious, aiming for 5 GW_{el} and 15 GW_{el} of installed electrolyzer capacity, resulting in a span of 14-26 TWh of H_2 in 2030 and 43-78 TWh in 2045 using the same assumptions for the capacity factor and electrolyzer efficiency. This also falls within the range of the Swedish Energy Agency (SEA) definition that 1 GW_{el} (electricity) is the capacity required to produce 5 TWh (0.15 Mton) H2 over 8,400 hours at 65% electrolyzer efficiency which would correspond to very high utilization.

Combining these two roadmaps and their respective targets for installed capacity, the range for the amount of hydrogen produced in 2030 is **8-26 TWh** (depending on the capacity factor assumed) and **23-78 TWh** in 2045. The targets set by the two roadmaps could be compared with scenarios and prognoses made by the Swedish Energy Agency and by Svenska Kraftnät, the Swedish TSO, for the future electricity system. Both Svenska Kraftnät and the Swedish Energy Agency foresee the increased demand for electricity from industry and transport and includes those sectors' development in their scenarios.

In the short term, the Swedish Energy Agency expects domestic wind power production to increase from 33 TWh in 2023 to 50 TWh by 2025 [71]. The longer perspective is provided by a scenario analysis published in 2023 [72]. In said report, production of electricity from wind and solar power in 2045 amounts to 125-174 TWh (depending on degree of electrification in industry and transport), with net exports up to 25 TWh in 2045.

The Svenska Kraftnät scenarios suggest a range for the amount of wind production between 82 and 211 TWh in 2045, depending on the scenario while the corresponding use of electricity in the scenarios ranges between 174 and 286 TWh. A surplus occurs in the four scenarios, 2-21 TWh [73].

The Swedish Wind Energy Association (SWEA), a Swedish industry organization, published their own roadmap with a target on *at least* 120 TWh of electricity produced by wind power by 2040 [74].

When combining the roadmaps for hydrogen production and the estimates and scenarios for renewable electricity, the targets for hydrogen production (8-26 TWh 2030 and 23-78 TWh in 2045) could be seen to fall within the ranges presented for renewable electricity production. Whether the amount of electricity would be available for hydrogen production is however unclear. This depends on the demand for renewable electricity from other sectors, which is believed to increase with the future from widespread electrification. Another limiting factor is the capacity of the electricity networks

3.5.2 Theoretical potential for hydrogen from Biomass

Gasification of biomass and waste

The production potential of hydrogen from biomass depends on the availability of feedstock. In Sweden, a comprehensive mapping of available biogenic feedstock was made to quantify the Swedish biogas potential in a state public enquiry (Biogasmarknadsutredningen SOU 2019:63) [75]. In this national survey, the availability of biomass and waste in Sweden that could be converted to biogas through gasification was quantified to the range of 30.1–37 TWh. Using the same feedstock to instead produce hydrogen would result in approximately 13-16 TWh of hydrogen, assuming a mean energy efficiency of 40% for the conversion process. Although this is merely the theoretical production potential, this estimate provides a maximum value for how much hydrogen could be produced from these resources.

Reformation of biogas

In Sweden the amount of biogas produced has been increasing from 1384 GWh in 2010 to 2161 GWh in 2020 [76]. The percentage of biogas upgrading, the removal of CO2 and other impurities from the methane, has also been increasing from 44% in 2010 till 65% in 2020 [76]. This upgraded biogas could be used for biogas reforming and subsequent production of hydrogen. The energy efficiency of the process can be estimated as 52% based on [77] who investigated the process from raw biogas to pure hydrogen with a reforming reactor, 2 water gas shift reactors and a pressure swing absorption unit for hydrogen purification. Biogasmarknadsutredningen [75] has shown a potential of 30-37 TWh of produced biogas in Sweden by 2030. Using these values and assuming a process efficiency of 70%, the amount of hydrogen that could potentially be produced in Sweden from biogas reforming is around 21-26 TWh. This assumes that all biomass and waste is used for biogas production and then hydrogen production, which is unfeasible but will be adjusted for below in calculations of theoretical max hydrogen production. Further policy instruments, premiums to promote biogas production from anaerobic digestion and other renewable gases could further elevate the upper range of estimated H2 capacity. [78]

Pyrolysis of methane

The Swedish production potential of hydrogen from biomethane pyrolysis can be estimated by combining the amount of methane assumed available with the methane-to-hydrogen yield from the process.

The methane-to-hydrogen yield of the methane pyrolysis found in literature ranges from at least 30-71%$_{LHV}$ with differences seen between different technologies, scales, operating conditions and energy source for process heat [7], [30], [43], [44].

The methane availability depends on what feedstocks are considered and the level of utilization of these. In this case, it is assumed that only biogas, not natural gas, is used as a feedstock, restricting the potential to looking at renewable hydrogen production. The production potential is then considered for two cases: a present scenario where all the biogas produced in Sweden during 2020 ([79]) is used for hydrogen production; and a future scenario assuming the use of all the biogas in the 2030 technical practical biogas potential of "the biogas market investigation" (Sw: *Biogasmarknadsutredningen*) (30.1–37 TWh) [75]). While these are overestimations of the production potential of hydrogen from methane pyrolysis (other uses of biogas are unlikely to be completely outcompeted), they can still serve as an indication of a higher production potential.

Assuming a methane-to-hydrogen yield of 50% (LHV) and a methane availability of 30.1–37 TWh TWh biogas in 2030, gives a theoretical production potential of 15-18 TWh hydrogen per year from methane pyrolysis.

3.5.3 Combined production potential

To estimate the maximum theoretical potential of Hydrogen production, two cases are considered a high case and a low case. All calculations are done for the estimate in 2030.

High case:

- For Biogenic hydrogen, a third of the high estimate is assumed to go to each hydrogen production route, meaning it is assumed that all biomass/waste is used for hydrogen in some way.
    - Gasification yields 5.2 TWh H_2

  - Reformation yields 8.7 TWh H_2
  - Pyrolysis yields 6 TWh H_2
- Electrolysis the highest estimate from the SEA is used, 26 TWh H_2

Low case:

- For biogenic H_2 a fifth of the low estimate is assumed to go to each hydrogen production route, meaning it is assumed that 40% of all biomass/waste for other purposes than hydrogen.
  - Gasification yields 0.2 TWh H_2
  - Reformation yields 0.3 TWh H_2
  - Pyrolysis yields 0.2 TWh H_2
- Electrolysis the lowest estimate from the roadmap proposed by Fossil Free Sweden is used, 8.5 TWh H_2

Total theoretical hydrogen production was then calculated as,

$$Total = TWh_{H2-electrolysis} + TWh_{H2-ref.biogas} + TWh_{H2-gasification} + TWh_{H2-pyrolysis}$$

The underlying assumption is the strategy goals set for 2030 as not all production routes had specific goals further in the future.

To thereafter convert the energy value into megaton (Mton) the lower heating value (LHV) for hydrogen was used (33.33 MWh/ton of H_2).

$$Mton_{H2} = \frac{TWh_{H2}}{LHV_{H2}}$$

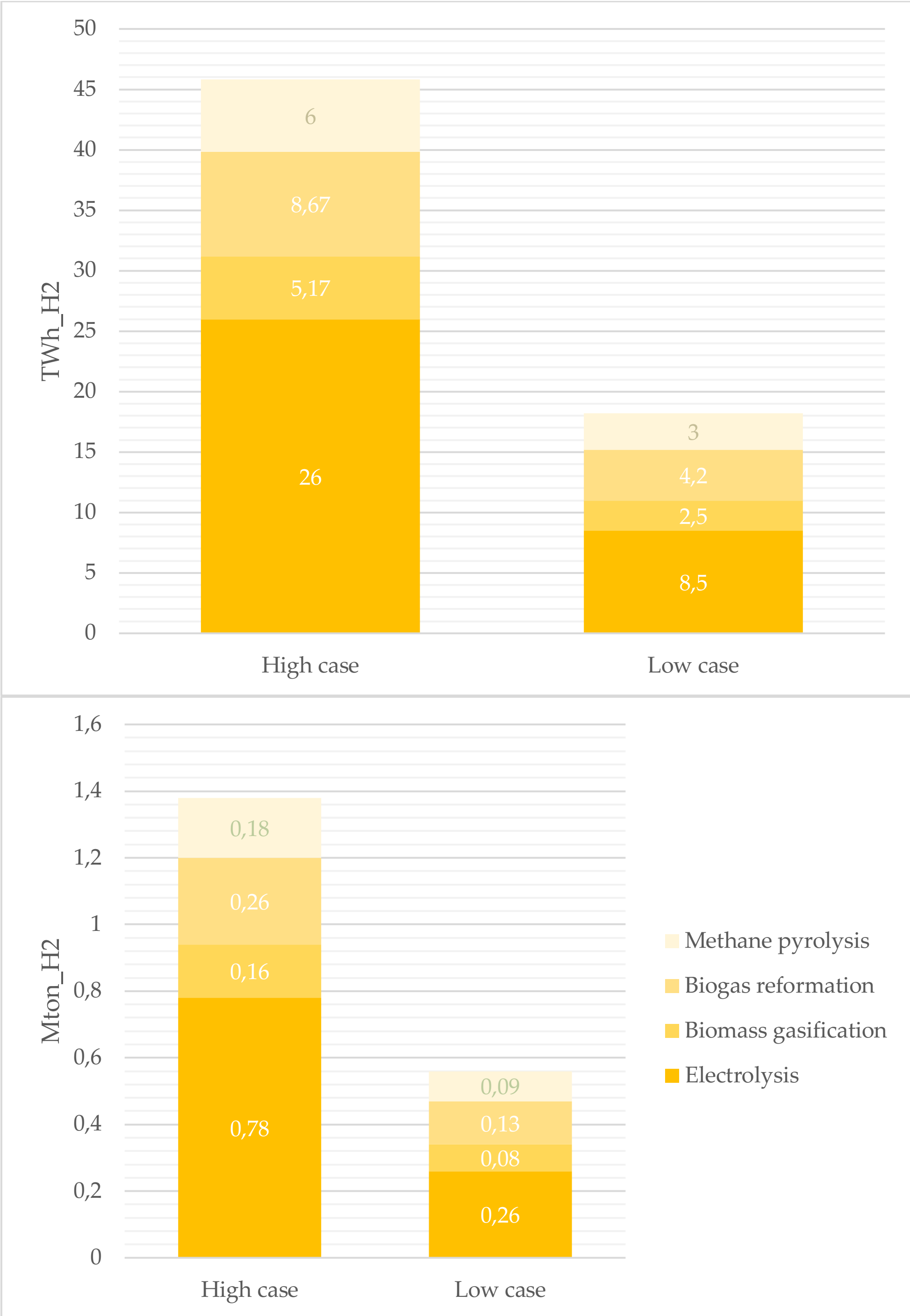


Figure 3 – Theoretical hydrogen production estimates in TWh of energy content (left) and Mton (right) of hydrogen.

The resulting theoretical production estimates are shown in figure 3. The totals are around 46 TWh (1.38 Mton) and 18 TWh (0.55 Mton) hydrogen for the high case and low case respectively.

Planned hydrogen production in Sweden

A graphical representation of announced Hydrogen production in Sweden from the major players over the years until 2030 across different projects is shown in Figure 4. Figure 4 compiles the proposed annual hydrogen production capacity from projects that have been announced publicly, e.g., through press releases, news articles or applications to the so-called *Climate Leap* ("Klimatklivet" in Swedish), if the start of operations take place according to stated time plans. The overall picture offered here is one of a hydrogen economy dominated by a small number of very large projects, namely the plans of LKAB/HYBRIT and H2 Green Steel for hydrogen and low-carbon steel production, Fertiberia's plans for production of green hydrogen to Ammonia in Boden and the plans of Wpd and Lhyfe to establish large scale hydrogen production in connection to a planned offshore wind farm in Söderhamn.

Some points to consider are that these are only "announced plans", i.e,. actualization can be questioned, both regarding timelines and whether projects will be implemented at all. For example, according to the IEA Hydrogen projects database that was released in October 2022, the Lhyfe-Wpd project is said to be in conceptual phase, production based on dedicated offshore wind. The announced size is 600MW and is expected to produce 104 kton H_2/year. This information is used in the figures below, to show Wpd-Lhyfe to start production from 120 kton H_2 in the years 2025 and 2026 [80]. From the same IEA database, the status of H_2 Green Steel is under construction and will be online for full scale commercial production from 2030 with 800 MW and 139 kton H_2/year. The HYBRIT project, which is a joint initiative of LKAB, SSAB and Vattenfall is planned for commercial production of steel from 2026 resulting in a Hydrogen requirement of 86 kton of H_2/year under 500 MW capacity.

In 2030 the total amount of hydrogen production is shown (in Figure 4) as 0.9 MTon of H_2 (~30 TWh) from all the known major hydrogen producers and the average production of hydrogen between the years 2025 to 2030 is 0.67 MTon of hydrogen (~22 TWh). This value is higher than the 0.55 Mton of H_2 (~18 TWh) in the low case and lower than the 1.38 Mton of hydrogen (~46 TWh) that is the high case in the theoretical estimation of hydrogen production above. Meaning that the announced production data gathered from key players in the hydrogen industry is in the range of theoretical values. However, many of the announced project focus on electrolysis while the theoretical production potential is a sum of many different production techniques. If the announced projects are instead compared with purely the theoretical hydrogen production from electrolysis the announced plans of 0.90 Mton, are higher than the high theoretical case of 0.78 Mton (~25 TWh). Hence, if all of the planned projects are built on time, it is likely that at least the electrolysis production will exceed the two roadmaps published in 2021 by the Swedish Energy Agency [70] and Fossil Free Sweden [68].

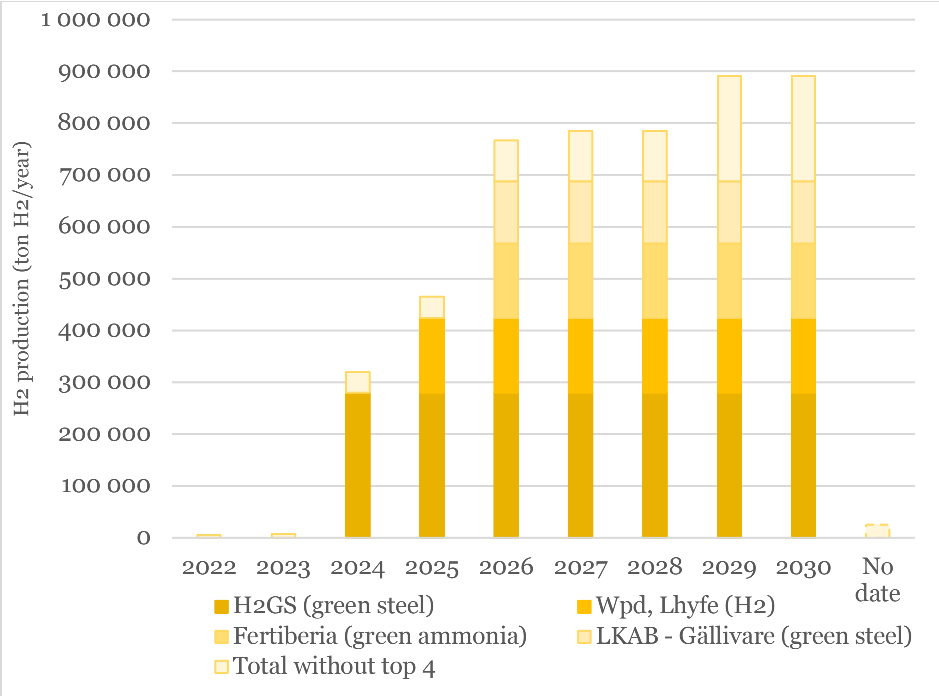


Figure 4. Announced plans for hydrogen production Hydrogen production (ton H_2/ year) announced across major projects until 2030.

3.6 STORAGE AND DISTRIBUTION OF HYDROGEN

How hydrogen is stored and transported depends on the state of aggregation the hydrogen is in and what volumes are offered and demanded. Added to this is the fact that hydrogen can be stored chemically or adsorbed, which are also stored and transported in their own way depending on the properties. Note that chemical storage is also covered under electrofuels and is described more thoroughly there, while here its assumed that chemical storage can also deal with hydrogen from sources other than hydrogen produced through electrolysis of water.

Storing hydrogen can be done both before, during and after transport, such as a terminal at a port (before) or terminal on land (intermediate storage) or at the end user (after). Hydrogen is in principle transported in a mobile storage, which means that in some cases the mobile storage can in theory also be left in place at the end customer and exchanged for an empty storage at the same site.

Distribution of hydrogen also includes supplying the end customer with the hydrogen, which is, for example, a filling station for vehicles or a reception facility for an industry. Note that filling stations and reception facilities is not described in this chapter.

The density of hydrogen (kg/m3) is one of several properties of interest where liquid hydrogen (LH_2) has approximately 10-15 times higher density than that of compressed hydrogen (CH_2) depending on the pressure and that chemical storage solutions could have approximately two times higher density than LH_2 [81].

3.6.1 Storage

Stationary storage of hydrogen is described in this chapter. Stationary storage can serve the purpose of pre-storage, intermediate storage and storage before final use.

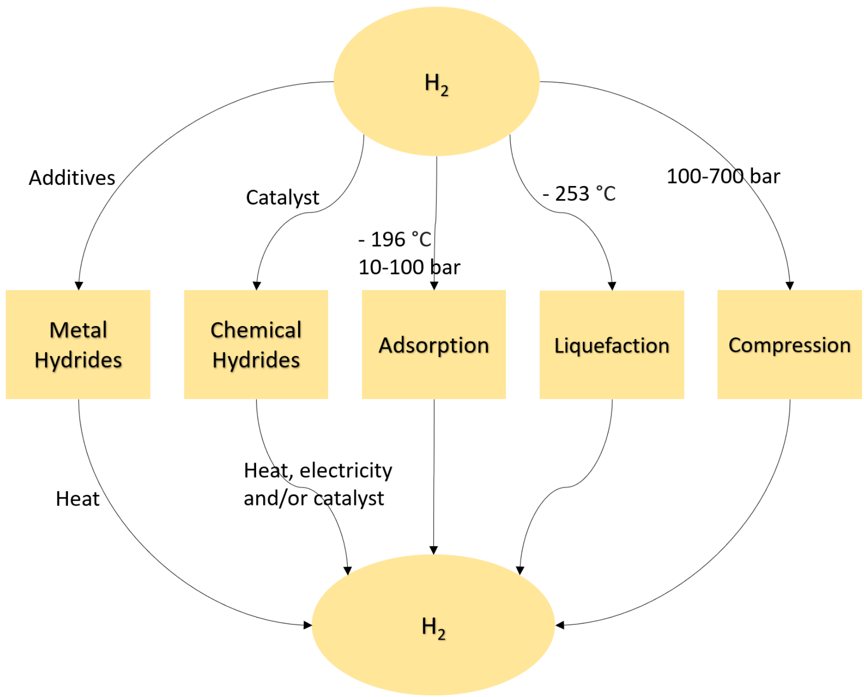


Figure 5 - Overview of stationary hydrogen storage technologies. Adapted from [81] **under a CC BY 4.0 license.**

Compressed storage

Compressed hydrogen (CH_2) can be stored in compressed form in steel cylinders, carbon fiber-cylinders, in gas pipelines and large underground storage such as lined rock caverns. Due to reasons of material properties and operating costs, large amounts of gaseous hydrogen are usually not stored at pressures exceeding 100 bar in aboveground vessels and 200 bar in underground storages [81].

Small-scale amounts of gaseous hydrogen can however be stored in higher pressure for distribution purposes in for example swap bodies or as storage in FCVs vehicles when using carbon fiber tanks. Carbon fiber tanks is not considered viable for large stationary applications due to the need for advanced vessel materials, e.g., carbon fiber according to [81].

Liquid storage

Hydrogen can be liquefied (LH_2) by cooling it to a temperature below the boiling point of hydrogen, which is dependent on the pressure. At atmospheric pressure, the temperature must be lowered to -253 °C; at higher pressure, the temperature may be higher. Cryo-compressed hydrogen (CCH_2) is an example of when the temperature is higher than -253 °C.

After the hydrogen has been liquefied, it is essential that it can be stored so that evaporation is minimized. The evaporation of LH_2 constitutes not only a loss of the energy spent liquefying the hydrogen but also, eventually, a loss of hydrogen as the evaporated gas must be vented due to the pressure build-up inside the storage vessel. This loss of stored hydrogen over time is known as boil-off and it could be liquified again instead of vented [81]. However, as mentioned in the section on climate impact of hydrogen production, concern has been voiced regarding adverse climate effects of venting hydrogen, due to the short-term high climate impact of hydrogen molecules' interactions with other atmospheric molecules, mainly ozone and methane.

Underground hydrogen storage

Here the hydrogen is stored in gaseous form under a pressure that depends on the conditions of the specific storage facility. In principle, there are rock caverns, salt deposits, salt domes and depleted gas and oil fields that can be used for storing hydrogen in gaseous form underground.

The technology for storing gas in a lined rock cavern (LRC) is according to HYBRIT [82] well proven and has been used in southern Sweden for about 20 years for storing natural gas. Now the technology is taking a step forward by the development for storage of hydrogen gas, and the storage facility will also be used more dynamically, being filled and emptied at pace with the hydrogen production. The HYBRIT rock cavern is in Svartöberget and a full-scale hydrogen gas storage facility measuring 100,000 to 120,000 cubic metres may be required, in which case it will be able to store up to 100 GWh of electricity converted to hydrogen gas, which is sufficient to supply a full-sized sponge iron factory for three to four days.

It is estimated that Europe has the technical potential to store 84.8 PWh of hydrogen in bedded salt deposits and salt domes [83]. Most of these salt caverns are concentrated in northern Europe at offshore and onshore locations. Germany accounts for the largest share, followed by the Netherlands, the United Kingdom, Norway, Denmark and Poland. Other potential sites are in Romania, France, Spain and Portugal [83]. However, there are no such fields according to the study in Sweden [81].

Hydrogen storage in depleted oil and gas reservoirs is proposed as a strategy to increase flexibility for future supply and seasonal outtake. It has for example been investigated whether depleted gas and oil fields outside Norway can be used [84]. However, there are no such depleted oil and gas reservoirs in Sweden. Therefore, it can be concluded that Sweden does not have as advantageous a position as countries with access to these types of geological storage, but that solutions like LRCs might still allow for large-scale storage of hydrogen in Sweden to some extent.

Hydrogen terminals

Hydrogen terminal could be a facility for managing the import and/or export of mainly LH_2 or chemical stored hydrogen in various forms. It comprises equipment for loading and unloading of hydrogen cargo to/from ocean going tankers for transfer across the site, liquefaction re-gasification, processing, storage, pumping, compression, metering etcetera. Terminals for LH_2 and Liquid Organic Hydrogen Carriers (LOHC) already exist in, for example, Japan [85].

The same aspects as for LNG terminals could be true for LH_2 terminals but there are probably other aspects to consider, such as safety aspects and whether sufficient land is available. In principle, all Swedish harbours may establish an LNG terminal of the smaller size. Establishment of a medium-sized LNG terminal, based on the size of the fairways and available land area, is possible in a relatively large number of harbours in Sweden. Establishment of large LNG terminals can be done in a very limited number of harbours in Sweden. The ships calling at such a terminal is so large that only very few ports can handle them.

Terminals for chemical stored hydrogen are already in place in, for example, Gävle Harbour, Nynäshamn Harbour and Gothenburg Harbour where for example LNG, jet fuel and methanol are handled [86], [87], [88], [89].

Adsorption storage

In contrast to the storage of compressed gaseous or liquid hydrogen, there is relatively little experience with the application of adsorbent based hydrogen storage; most developed adsorption-based storage vessels have yet only been on the laboratory scale. Many adsorbents have been suggested for hydrogen storage according to [81]. For example:

- Porous carbon-based materials
- Metal-organic frameworks (MOFs)
- Porous polymeric materials
- Zeolites

Chemical storage

Chemical storage is the storage of hydrogen in the form of metal hydrides, liquid organic carriers (LOHC), or molecules such as ammonia, formic acid, methanol, jet fuels etcetera. Molecules such as ammonia, formic acid, methanol, jet fuels et cetera are already used in Sweden and use conventional storage technologies described further in later chapters on electrofuels.

Metal hydrides are known as a potential efficient, low-risk option for high-density hydrogen storage since the late 1970s. Materials suitable for hydrogen storage in solid-state must meet specific requirements to be used for the development of hydrogen-based technologies, in particular storage. Applications of hydrides could be divided in two main groups: stationary and mobile ones. There are different requirements and therefore some hydrides are better suited to one or the other [90]

LOHC are liquid or low-melting organic compounds that can be reversibly hydrogenated (to add hydrogen) and dehydrogenated (to remove hydrogen) in the presence of a suitable catalytic system and heat. The benefits of using LOHCs could be their potential of being cheap, safe, and easily manageable relative other options. LOHCs could present advantages as they provide a high gravimetric and volumetric hydrogen storage, LOHCs could also be stored long-term without hydrogen losses, and transported overseas under ambient conditions. Moreover, LOHC could also be compatible with existing transport and refuelling infrastructure. However, more similar assessments are needed before any firm conclusion about the potential for LOHC versus other hydrogen-based energy carriers (as marine fuel and for transport) can be drawn. The actual potential is also affected by the development of other hydrogen-based alternatives. [91]

3.6.2 Distribution and transmission

Hydrogen can be transported by different means, the most common being truck, train, and shipping transport in gaseous or liquid state on the one hand, and pipeline transport on the other hand.

Hydrogen can also be transported in a chemical storage form and be distributed by road, railroad and shipping. It is also possible to use pipelines and hydrogen in a liquid chemical storage form, but that distribution form is not described in this chapter, because it is assumed that the techniques employed in this case are similar to distribution of other liquids chemicals such as jet fuel.

However, transportation as LOHC and metal hydrides has not taken place in Sweden but could be possible in the future, the same for adsorbed hydrogen.

Gas pipelines

One option for the transportation of hydrogen is via a gas grid. Gas pipelines offer a convenient method to transport large quantities of gas at low running costs. Another advantage of this form of distribution is that it could be easier to market/sell the gas to costumers within range from the grid. The addressable market is generally larger, and the gas will not be limited to a local market in the same way as it would be if it relied on the storage and transport of compressed gas in cylinders where the cost is higher for transportation of similar volumes; neither does it require the same type of storage as this is partly secured by the grid.

The grid could be comprised of a transmission grid operated at relative high pressure, and distribution pipelines, normally operated at a low pressure and both are usually located underground. Local gas grids are grids that are not connected to the larger transmission and distribution grids. This alternative is suitable in areas without a hydrogen gas grid infrastructure.

There are significant differences in the injection of hydrogen into the transmission grid as compared to the distribution grid. Distribution grids can often not accept more hydrogen than what is consumed within the grid at each time. Therefore, injection quantities are normally limited to the lowest consumption during the year (summer holiday). On the other hand, the operating pressure in distribution grids is usually low, so no additional compression is sometimes needed after the production of hydrogen depending on the operation pressure. In contrast, the transmission grid has a virtually unlimited capacity, so injection into it is an interesting option for larger plants. The drawback is the grid's higher operating pressure making an additional compression step necessary. Local gas grid usually has capacity pressure limitations and the conditions depends on the specific site.

Transmission and distribution grids do not exist in Sweden but are planned in for example in the north of Sweden [92]. Local grids already exist in Sweden, for example in Sandviken, where a filling station is supplied with hydrogen from an electrolyzer located nearby at Linde's facilities [93]. However, the lack of regional or national infrastructure for hydrogen transmission and distribution is a potential barrier to hydrogen uptake in Sweden.

Road Transport

Hydrogen is usually transported in tanks in compressed or liquid form. The efficiency of the transport depends on the choice of cylinders and whether the gas is compressed or liquefied as this determines the quantity of gas that can be transported per transport.

Compressed hydrogen can be transported in steel-tube or composite material tubes at a pressure of usually 200-350 bar. In terms of the amount of gas that can be transported on swap bodies or transport module, it is the overall weight of the truck including the load that is the limiting factor. A transport module consists of several connected cylinders and can, according to e.g., UMOE Advanced Composites [94] have a capacity of 220 kg to 1000 kg hydrogen/module. Each module holds just a little bit less during transportation because the cylinders are usually not completely filled or emptied and each road transport could carry several transport modules depending on the legislative weight limits for road transports. Trucks carrying gas cylinders made from low weight composite materials have higher capacity compared to steel tube containers. The main challenge with compressed hydrogen transport modules is the logistics, so the demand is met at any time with a minimum of unnecessary transports. This is especially difficult in cases where the consumption suddenly and unpredictably increases.

Liquid hydrogen is usually transported with semi-trailers that have storage tank mounted on a trailer and towed by a truck. The hydrogen can also be transported with a trailer on which the tank is mounted. The distribution tanks where liquid hydrogen is stored are well insulated and act as a large thermos. The tanks usually consist of an inner container of stainless steel which resists pressure from the inside, i.e., the pressure of the LH_2 being transported, as well as an outer vessel designed to withstand external pressure. In between there is insulating material and a vacuum is maintained in the space to prevent heat transfer and consequent evaporation of hydrogen [95].

As large quantities of energy can be transported in liquid form, this method is more competitive over long distances compared to hydrogen in compressed form. A standard LH_2 trailer can carry a larger mass of hydrogen compared to a standard trailer for compressed hydrogen. At the same time, cryogenic vessels are not as heavy as vessels for compressed hydrogen [95].

Railroad Transport

Today neither compressed nor liquified hydrogen is usually transported by rail in Sweden, which is why train carriages for this purpose are still under development.

For rail transport to become relevant, a minimum critical volume of deliveries is probably required, as rail is best suited for large volumes. Ideally, deliveries should be able to fill entire trains and be tied to regular circulation between sender and recipient. Deliveries by train can amount to large volumes per train (a full train can consist of several carriages), which can be compared with truck transports which can deliver much lower volumes.

In the case of rail transport, large delivery volumes mean a high degree of utilization of the trains and lower terminal costs, but at the same time, the requirements for depot size are increasing both at the supplier and at the receiver. If more frequent deliveries are chosen with fewer wagons and lower storage volume, the utilization rate decreases, and terminal costs become higher. The railway logistics should thus be designed considering sea logistics and the depot size of the recipients so that the entire transport chain is optimized.

Hydrogen could however be transported by railway when stored in a chemical absorbent or adsorbent.

Shipping

Compressed or liquid hydrogen is usually not transported by ship to and from Sweden today and vessels for hydrogen transport are still being developed. Hydrogen could be transported on conventional vessels today if the hydrogen is stored in a chemical form. This still requires a port terminal at the port, however.

3.7 APPLICATIONS FOR HYDROGEN

Hydrogen can be used as a chemical feedstock, as a reduction agent and as a fuel for propulsion or heat and power. These different purposes lead to a vast array of possible applications, where some are already well-developed today. As previously mentioned, the Swedish hydrogen is mainly used in the chemical industry (including petrochemicals) but the emerging applications include hydrogen as in fuel-cell vehicles or in internal combustion engines, as a vector for heat and power through storage and then conversion of hydrogen, as a reduction agent for of iron ore reduction and as a green feedstock to renewable bio- and electrofuels.

One note for the use of hydrogen in different applications is that it will result in the overlap of several sectors, where there has previously been a clear distinction between the resources needed in the transport, energy and industry sector. In the future they, will all equally compete for both available hydrogen and cheap electrification.

3.7.1 Transportation

The use of hydrogen in the transport sector extends to a range of powertrain designs/sizes and many different application areas. Depending on the type of transport considered the maturity of the technology is vastly different, as well as the type of propulsion used. The most common type of propulsion is today based on a fuel cell/battery electric hybrid driveline. There are also smaller commercial lines and proof of concepts for hydrogen piston internal combustion engines and for the larger applications such as ships and airplanes much investigation now goes into hydrogen turbine propulsion. Other than the type of propulsion used there is a distinction with the state of hydrogen storage. For smaller transport applications such as cars, buses and distribution trucks the state-of-the-art today is hydrogen stored as compressed gas. For larger transport applications such as ferries and initial aerospace demonstrators the choice has instead been liquid hydrogen. There are also investigations into an in-between option for hydrogen storage in transport applications called cryo-compressed hydrogen [96]. The transport sectors use of hydrogen can be split into different sections: On-road, Off-road, Maritime, Rail, and Aerospace. The view of the use of hydrogen and fuel cells for propulsion is sometimes optimistic and sometimes more pessimistic. There is constant ongoing debate due to power-hydrogen-propulsion having a low overall efficiency compared to battery electric vehicles (BEVs) [97]. BEVs are where renewable electricity can charge the battery in the application directly and the be used in an electric engine. The same type of electric engine is used for fuel cell electric vehicles. Using the electricity directly omits the losses during hydrogen production. Still, when comparing transport alternatives there are more limitations than overall efficiency of the power systems. Some of the main things to consider is the usage climate, local restrictions and the operating cycles of the application. To give some examples, the best solution for a zero-emission powertrain will be an exercise in optimizing:

- Climate effects: What is the average surrounding temperature?
- Operational cycle: How many full shutdowns per year? How long refuelling time can be allowed? Required reliability? How many and frequent fast accelerations/decelerations? Range requirements?
- Local restrictions: Zero-emission zones? Infrastructure? Special safety regulations?
- Space or weight limitations on the application?
- Cost and efficiency

Different types of hydrogen-based propulsion

As mentioned above there are several acknowledged techniques for using hydrogen to propel transport applications:

- Fuel cells (various chemistries) with an electric engine
- Hydrogen piston engines (A type of internal combustion engine)
- Hydrogen turbines (A type of internal combustion engine)

The powertrain design is different for these different types of engines, and also dependent on the application they are used in. Most hydrogen applications today use fuel cells, but also hydrogen piston engines have been in commercially sold applications on a small scale.

Fuel cell powertrains – Consist of an electric engine that drive the wheels or propellers. The Electric engine is supplied with DC power from a battery and fuel cell through a power electronics and control system. Depending on the design the battery is either charged by the fuel cell or by external charging from the grid. The fuel cell is in turn feed with hydrogen from a storage tank and air from the surroundings through a compression system. Inside the fuel cell the electricity for propulsion is produced by electrochemical reactions of oxygen and hydrogen, the reactions also produce water. In various fuel cells other fuels can also be used, depending on the fuel cell design. For all fuel cells heat is a by-product and depending on the application and surrounding climate sometimes result in more complex cooling-systems. On the overall the fuel cell systems have an efficiency around 50% at mean operation and up to 60% at peak efficiency [98].

Hydrogen piston engine powertrains – Here the engine can be described as a modified version of a diesel/gasoline engine. The concept is also referred to as a heat engine where the combustion of hydrogen with air is intermittent (burst wise). The heat from combustion then moves pistons and generate rotational energy for the wheels/propellers. Again, the hydrogen is supplied from a storage tank. The efficiency for these engines is around 40%. Furthermore, they have a downside of not being considered zero-emission as they still produce NOx emissions during the combustion process.

Hydrogen turbine engine powertrains – Hydrogen turbine engines a type of gas turbine used as engines have the same operational principal regardless of the fuel. Contrary to the internal combustion engine with pistons these use a continuous combustion process. Here the heat produced drive a propeller that make the applications move or can generate electrical energy. This technique is common in both ships and airplanes with conventional fuels. For hydrogen there are ongoing test and demo installations.

On-road transport

In this report the on-road transport will refer to all sizes of passenger cars, trucks and buses, and the potential per vehicle type will be briefly discussed. Passenger cars is the first application where fuel cells are used in the on-road sector. In Sweden there have been very little interest for these vehicles, related to the limited amount of refueling possibilities. Now there are many planned refueling stations, approx. 67, that have received financing and will be constructed before 2030 refueling stations planned locations [99]. Some of the cities where new refueling stations are planned are: Uddevalla, Göteborg (2), Helsingborg, Malmö, Trelleborg, Växjö, Karlshamn, Oskarshamn, Linköping, Örebro, Stockholm (2), Borlänge, Östersund, Sundsvall, Luleå, Kiruna, Skellefteå, Jönköping and Älghult. With this it should be possible to travel across Sweden in a hydrogen car based on their range of 650-750 km in-between refuelings. All of the planned stations are for refueling with gaseous hydrogen and as of yet there are no plans for liquid refueling stations. The size of the stations has not been fully set yet, but based on the stations built in the rest of Europe they can be expected to have a storage of approx. 1000-2000 kg hydrogen. This is in-line with the stations specified by the Swedish Energy Agency where they demand a daily capacity of 1500 kg [100]. There are some station designs that may have a larger storage in order to meet this goal, but many initially plan to focus on more frequent refilling of the HRS storage. For refilling the storage there are different approaches depending on the location, most common alternatives are trailer swapping or on-site production through electrolysis. In order to agree with the EUs hydrogen agenda in the alternative fuel infrastructure regulation (AFIR), Sweden would need to have deployed approx. 85 functional refuelling stations by 2030. This will also promote an increase in the number of vehicles [99].

For the on-road vehicles there are brands that already today commercially sell cars, trucks (both light- and heavy-duty), and buses (primarily for public transport). Meaning the vehicle technology is proven, however the number of vehicles in the world is still quite low. There are, at the last available count from IEA [101], over 42 000 passenger cars, around 6000 buses and 5000 trucks in the world today. In Sweden we have a few cars owned by for example Sandvik, Mariestad kommun and Kinto, together with a handful of other early adopters. There are also some trucks in initial investigations and two buses running in Sandviken. In the on-road sector, much of the current development is focused on the heavier vehicles or for specialized applications where long charging or downtime is not possible. It is difficult to predict the future demand from the road sector as few users have announced concrete plans in Sweden. It should also be noted that for trucks the hydrogen demand is approx. 70 kg per refueling, cars 6kg, and buses 40 kg for the various applications. This means that most refuelling stations built in Sweden can fuel around 15-30 trucks, 25-50 city buses or 170-300 passenger cars before the storage needs to be replenished.

Off-road transport and machinery

This sector of transport refers to construction, forestry, agriculture, mining and smaller vehicles for industrial sites such as forklifts. Here there are today a very large difference in vehicle maturity within the sector. For example, forklifts propelled by fuel cells have been in use for multiple years in the US. The forklifts have been especially useful in cold storage and where they want to limit refueling time [102]. For larger/heavier machines the development is just now starting. In Sweden there is no clear reason for not utilizing this type of machinery, both the small and the large. So far, there have been some demo-projects such as the heavy forklift by Kalmar[103], and most recently a dumper by Volvo construction equipment [104]. The hydrogen demand per vehicle will vary greatly in this sector and current development is still very much in the early stages.

Railway transport

In 2022 the first full train fleet of hydrogen trains were announced in Germany, these are smaller passenger trains. They have been demonstrated in Germany since 2018 and one of the trains were also demonstrated in Östersund during the summer 2021[105]. There is an interest for these trains mainly on the non-electrified rail lines in the world. In Sweden one example is Inlandsbanan where it could be cheaper to run zero-emission hydrogen fuel cell trains rather than electrifying the whole stretch of rail or parts of it [106]. In Sweden most of the rail lines are electrified so the need is not as large as in other parts of Europe. However, there was a large EU project application regarding novel railways and train sets sent in, where Sweden took part and the project has now been decided. It should lead to new developments and demonstrators for the heavier rail traffic as well as smaller applications. Here hydrogen was integrated as a central part. For the currently established hydrogen trains the demand is appox. 94 kg per cart or 188 kg per full train and refuelling. The train model available today has a range of between 600 to 800 km on one refuelling [107].

Maritime

There have been international projects with ferries based on fuel cell propulsion for several years most have been developed on paper, but at least two are in operation [108][109][73]. Many of them initially for shorter distances. In Sweden there is a market with the archipelago short-distance ferries on both the west and east coast. The demo-projects ongoing primarily focus on technology using liquid hydrogen storage on-board and fuel cells [108]. This to get the range needed without compromising on capabilities. In Sweden there is also currently an ongoing project with Gotlandsbolaget for a larger passenger ferry driven by hydrogen [110]. Here the final driveline is not yet decided, but indications are that they aim for on-board gaseous storage. Looking at larger shipping vessels the feasibility of using hydrogen is still debated. Different solutions are competing, e.g., liquid hydrogen, methanol, or ammonia.

Aerospace

The aerospace industry is currently developing in the hydrogen arena on a more global scale where two of the main front runners are the companies Airbus and Zeroavia. Airbus have announced a plan for hydrogen fuelled airplanes run both using fuel cells (electric flight) and using jet-turbines. Zeroavia tested their first hydrogen propelled flight in January 2023 [111]. Here all designs are focused on the use of Liquid hydrogen as on-board storage. The potential for the use of hydrogen fuelled flights in Sweden would most likely increase if there was local production of liquid hydrogen, the closest plant today is located in Germany. There are also Swedish projects focused on the use of hydrogen at or around airports such as H2Jet (development of gas turbines) or "Fossilfritt flyg i norra Sverige – en genomförbarhetsstudie"[112]. The demand for the aerospace industry is still very unclear, as the industry has not yet established the primary route forward, but in a report by McKinsey the estimated global hydrogen demand could be 10-40 million tons (330-1320 TWh) by 2040 and 40-150 million tons (1320-4950 TWh) by 2050. In translation for Sweden this means that this will still be a smaller hydrogen need. The report also highlights that for shortrange flights hydrogen may be more cost efficient than other fossil free solutions. For the hydrogen fuel cell powered solutions mostly smaller commuter planes of 19-80 passengers and up to 1000 km range are mentioned. For longer range and lager airplanes hydrogen turbines are mainly considered. Still LH2 tanks take more space than conventional fuel tanks and this affect the viable range applications when compared to other sustainable airplane fuels [113].

3.7.2 Steel Industry

The increasing interest for use of hydrogen in the steel and iron industry is primarily based on drivers for an end product with a lower carbon footprint. The three main divers for that change were identified in a report by McKinsey&Co

[114] as customer requirements/demand, sharper CO2 regulations and increasing sustainability demands from investors as well as society. The same study presented hydrogen as a solution for the steel and iron industry in Europe. Hydrogen is competing with CCU alternatives, IEA estimates 2% of world production of steel to use H2 by 2030 [115] [116]. This is quite low compared to another report that estimates between 6% and 16% of steel to be produced using hydrogen for the same year [117]. A few percent may seem a slow start over the next years, but it will be a significant step in lowering CO2 emissions from the steel industry. If global production is converted the iron and steel sector should be able to reduce their emissions by at least 70%, as there are still some different elements in the production chain where hydrogen cannot be implemented as a solution.

The technological uses of hydrogen in the steel industry

The main technology that could be replaced by hydrogen is the blast furnaces, where alternatives have been verified on the demo scale are. Traditionally reduced iron has mainly been produced in blast furnaces using carbon and this is a very carbon dioxide intensive process. There are also some direct reduction shaft furnaces that use natural gas. For the blast furnaces it is possible to already in current configurations to start blending in up to 20% hydrogen to lower the emissions. For complete conversion to hydrogen the blast furnaces need to be replaced. In direct reduction shaft furnaces using natural gas there is also the possibility of blending in hydrogen and here to a slightly larger degree [118].

Other some of the hydrogen technologies presented now are:

- Hydrogen reactors producing steel and water (for example Primetals)
- Direct reduction furnaces designed for hydrogen (replacing either natural gas or coal)
- Hydrogen plasma smelting reduction (replacing coal)
- Hydrogen burners (replacing natural gas)
- Hydrogen for heating and forming steel

The function of hydrogen in the different technologies above varies. For the technologies 1-3 hydrogen is used as a reducing agent. Triggering the two following two reactions[119]:

$Fe_2O_3 + 3\ H_2 \rightarrow 2\ Fe + 3\ H_2O$ *Eq. 3*

$FeO + H_2 \rightarrow Fe + H_2O$ *Eq. 4*

Which results in iron and only water as by-product. The difference between the technologies lies in the pre-treatment of the iron-ore and the reactor design. Direct reduction furnaces designed for hydrogen are a development of the shaft furnaces that have been used with natural gas [120], [121]. These operate at high temperatures (800-900 °C) and utilize iron ore that has previously been formed into pellets. Hydrogen reactors producing steel (e.g., Primetal's technology) have a fluidized bed reactor design that is not fully revealed. This process allows for the use iron ore fines and can hence remove a pre-processing step [121], [122]. Hydrogen plasma smelting reduction the last of the technologies where hydrogen is used as a reducing agent uses a plasma furnace for the processing [123].

For the last two technologies in the list, 4. hydrogen burners and 5. hydrogen for heating. They both use hydrogen combustion in burners or ovens to heat the iron or steel for further processing [118].

3.7.3 Chemical industry

There are many different industries that already today use hydrogen in their processes such as petrochemical refineries, ammonia producers, methanol producers or in various chemistry feedstock options. Bio-refineries are also large future consumers of hydrogen as they are based on traditional refineries that today use approx. 4 Mt per year for oil refining.

Methane, methanol and ammonia

All of these three chemical industries use the same manufacturing processes based on hydrogen as when the substances are considered electrofuels. In this report, the description of how hydrogen is used as a raw material in the process is described in the segments below in this chapter.

Refineries

Traditional refineries based on crude oil are one of the industries that use a lot of hydrogen today, in Europe they use approx. 4 Mt (132 TWh) hydrogen per year for oil refining [124]. Hydrogen is used in several reaction steps commonly described as hydroprocessing (hydrodeoxygenation, hydrodesulfurization and hydrodenitrogenation) as well as for hydrocracking. The different processes can be shortly described as [125]:

- *Hydrodeoxygenation:* Catalytic reaction using hydrogen to reduce the amount of oxygen in the fuel.
- *Hydrodesulfurization:* Catalytic reaction using hydrogen to reduce the amount of sulfur in the fuel.
- *Hydrodenitrogenation:* Catalytic reaction using hydrogen to reduce the amount of nitrogen in the fuel.
- *Hydrocracking:* This is a process step that simultaneously crack longer chains and have them undergo hydrogenation.
- *Hydrogenation:* Reaction of hydrogen with double bonds in the olefins to result in a lighter fuel with higher H/C ratio.

Even if we are moving away from fossil oil refining some of the hydroprocessing and the hydrogenation is needed also in bio-refineries [125], [126]. One of the well-known outputs from a biorefinery that use hydrocracking and hydrogenation of vegetable oil is HVO (Hydrotreated Vegetable Oil). This is a type of green diesel but is classified differently from bio-diesel as the processing is different. One producer of HVO in Sweden is the Preem refinery on the west coast who are also looking at using green hydrogen for their future hydrogen production [127].

It should also be mentioned that most vegetable oils contain more oxygen and other undesirable atoms in the raw material than fossil sources. This means that the hydroprocessing will require more hydrogen in bio-refineries than in traditional refineries [126], [128]. How large the increase in demand will be is still unclear maybe it will balance out against other reduced demands in the same sector.

Other industries

There are several industries (such as manufacturing, textile, food and beverage industries) that could use hydrogen energy for steam/heating needs, in 2050 this could be a need of around 18 Mt H2 in Europe [124]. The aim of using hydrogen for steam or heating needs is related to partly or completely replacing natural gas in the processes today. This means that this need is uncertain as both heat and steam can be produced by other processes and the number represents a more uncertain value.

The manufacturing of metal powders is generally considered a part of the chemistry industry in Sweden and here we have several companies where they are considering or already using hydrogen in their processes. Two examples are Höganäs and Boliden, who are considering the implementation of their own electrolyzers to ensure a supply. Höganäs has a use of approx. 1500 Nm^3/h continuously during the year and they expect to need up to 2700 Nm^3/h in the future. For Boliden they have the potential to use up to 5000 Nm^3/h in the future [129].

3.7.4 Energy storage

Balancing the power demand can be seen on several different levels, either for more seasonal storage and compensation or for frequency regulation of the electricity grid. Depending on which of these cases is considered the technologies and limitations vary significantly as support for frequency response can have very short initiation times [130]. In combination there are discussions regarding on which system level various balancing applications will be most appropriate. Historically Sweden has a relatively centralized electricity production, and large production facilities such as the hydropower in the north and nuclear powerplants. Now production is moving to more distributed solutions with private citizens and also industrial sites starting to function as both producers and consumers of the grid electricity. Therefore, there might be a new need for how the grid balancing and redundancy infrastructure will look in the future. In Sweden there is no clear established initiatives for using hydrogen to balance the electricity grid hence it is difficult to predict a clear demand. On the European level there are estimates of around 12 TWh in 2030 and 301 TWh in 2040 hydrogen needed for the power sector [131]. The report also indicates that the largest need is in countries such as Germany, Poland, Italy and United Kingdom. For Sweden, the predicted need is also here stated as zero, indicating that the demand in this sector is very unclear or not considered applicable in our energy grid [131].

Balancing frequency response or short-term electricity demand peaks

For frequency response electrolysis is considered a valid contributor to flexibility, as has been discussed above. There are also some discussions on using fuel cells or gas turbines with hydrogen for balancing this type of spikes. This is mainly related to operation cycle of the facilities that aim to produce electricity from the hydrogen storage. It is uncertain whether novel technologies for the balancing of power demand should be distributed in the same way to be most efficient. Therefore, it is also important to discuss possibilities of distributed solutions for energy storage and balancing of the power demand on a more local level such as in connection to refuelling stations or other industrial sites already using hydrogen [132].

Hydrogen as seasonal storage

For smaller applications for grid balancing up to maybe 2-3 MW fuel cells are an alternative, but for larger scale such as balancing full power plants, then the gas turbines are the more viable alternative today. This even though there are some NOx contaminants from the turbines used. There are examples of powerplants for up to 50 MW generation with fuel cells, but they are space demanding. Regardless of technology used for the generation of electricity one of the limiting factors is the storage of hydrogen especially for longer storage from summer to winter large quantities are needed. For the frequency regulation considering it can be done both with electrolyzers and fuel cells/gas turbines, the storage sizes can probably be smaller [132]. A more in-depth study of different hydrogen storage alternatives corresponding to different applications will be performed in a different project and is beyond the scope of this report [133].

Back-up power/local distributed applications

In agriculture, back-up power and other remote/naturally distributed areas hydrogen is also much considered as it can be used in off-grid systems. Primarily in Japan, but also to some degree USA and Europe, the concept of fuel cells for combined heat and power applications have become popular. In Japan these types of stationary fuel cells now number above 300 000 units [134], [135]. They are either fed directly with hydrogen or from the different cities' natural gas grids. The methane is then converted into hydrogen before reaching the fuel cells in the units. The technology used in these applications are a combination of PEMFC and SOFC and are small in size, one unit per residential house or several per apartment complex. In Korea there are recent initiatives to start introducing larger 1.4 MW solutions aimed to be shared between up to 1600 households. They are used both for continuous supply and as back-up power. In Sweden there are few discussions regarding these types of initiatives and any future potential is unclear [136].

4 Electrofuels

There are several co-existing definitions of what an electrofuel is, however this report defines electrofuels as *fuels that combine hydrogen produced from electrolysis with carbon or nitrogen of renewable origin*. The electrofuels analyzed in this section of the report include electro-methane, electro-methanol, electro-Fischer-Tropsch fuels and electro-ammonia. The processes could be viewed as further refining of hydrogen into molecules adapted to their specific applications. However, more refining and processes also imply more energy losses.

Using data provided in literature reviews, the cost range for a number electrofuels is presented and it is noted that biofuels and bio-electrofuels (i.e., when electrolysis-based hydrogen is used to boost production of biofuels) seem to remain the less costly option in the nearest decade. Within electrofuels, the less complex fuels like electro-methane and electro-ammonia have a lower production cost compared to Fischer-Tropsch fuels that consist of longer hydrocarbon chains. It is difficult to foresee the potential long-term effects of the short-term component price and interest rate increase. The span of costs presented for electrofuels capture more and less optimistic outcomes. Regardless of the exact price endpoint in 2030, Sweden has a potentially advantageous position for electrofuel production, thanks to its access to low-carbon electricity and abundance of biogenic sources of carbon dioxide.

The climate impact of the selected electrofuels is also provided in a wide range due to both differences in process setup of the studied cases and methodological decisions. Despite the wide range, electrofuels seem to be able to lower the climate impact compared to their fossil counterparts. However, to produce electrofuels that have a low climate impact, fossil-free energy and biogenic carbon sources are required.

The distribution of electrofuels has the potential of using existing distribution chains already built for the fossil equivalents. However, a significant production of electrofuels in Sweden would likely require an expansion and fortification of the existing infrastructure to fully exploit the economies of scale.

The potential for using electrofuels in the Swedish transport sector is affected by the development towards growing focus on zero-emission (tailpipe) vehicles. This could potentially limit the uptake in road transportation. The potential of using electrofuels in on-road transportation is also deemed limited due to competition with biogenic methane (biogas) and other biofuels and electrified vehicles. However, in the maritime and aviation sector, the potential uptake is larger thanks to the longer ranges provided, although the impact of NO_x emissions is a risk receiving more focus as of lately.

In the subsequent chapter, these results will be presented in more detail.

4.1 PRODUCTION ROUTES FOR ELECTROFUELS

Electrofuels are a heterogenous group of fuels that could be used in numerous applications thanks to their wide range of properties. In some of these applications, a fossil equivalent to the electrofuel is used today, which implies that a smaller degree of adaptation is required to decarbonize that certain process. Other applications are completely new and require new supply chains to reach sufficient technological maturity. In this section, the electro-fuels that will be further evaluated are electro-methane, electro-methanol, Fischer-Tropsch fuels and ammonia [137], [138], [139], [140].

4.1.1 Electro-methane

Methanation is the name of processes where hydrogen and carbon-oxides (carbon monoxide or carbon dioxide) are converted to methane [141]. This can be done through either chemical methanation, where catalysts are used, or through biological methanation, utilizing microorganisms. However, to date, biological methanation is only of its commercial application, whereas chemical methanation has come a longer way [141], [142]. When carbon monoxide is used as carbon source, the process is referred to as *CO methanation* and follows the reaction in equation. 5., whereas the process where carbon dioxide is used is referred to as *CO_2 methanation* and follows the reaction in 6. This reaction is a linear combination of the CO methanation reaction and reverse water-gas shift reaction (7), where CO2 is first converted to CO. Both CO and CO_2 methanation are exothermic reactions and thus release heat corresponding to 2.3 and 1.8 kW heat respectively, for each 1 m^3 methane produced per hour.

$$CO + 3H_2 \rightarrow CH_4 + H_2O\ (g) \qquad Eq.\ 5$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O\ (g) \qquad Eq. 6$$

$$CO_2 + H_2 \rightarrow CO + H_2O\ (g) \qquad Eq.\ 7$$

Several methanation concepts have been developed over this time, including adiabatic fixed-bed, cooled fixed-bed, fluidized-bed and three-phase methanation, but today most commercial technologies apply some form of adiabatic fixed-bed reactor [141]. All technologies use a chemical catalyst to increase reaction rate, and while several catalysts are possible (e.g., Ru, Co, Fe and Mo), nickel (Ni) is often used in commercial applications because of its relatively high reactivity and favorable price [141]. The methanation reaction is favored by high pressures but limited by high temperatures, and due to the exothermal nature of the reaction, some form of cooling (normally gas recycling or intermediate cooling) is an important part of achieving an efficient process [141]. Operating temperature and pressure are normally in the range of 250-700˚C and 5-20 MPa respectively [143], [144]. The energy efficiency of the process is in the range of 70-83% [145].

Biological methanation is similar to chemical methanation in the overall reaction, but instead of a chemical catalyst, methanogenic archaea are used for catalyzing the reaction [146]. The process is often discussed in the context of anaerobic digestion (AD) or biogas upgrading, but it can also be applied in other feedstocks, such as syngas from gasification or pyrolysis of solid biomass that is not suitable for anaerobic digestion [147]. Two dimensions that are often used for biological methanation are whether the process is *direct* or *indirect* and if it is *in-situ* or *ex-situ*. Biological methanation where hydrogen is injected into the anaerobic digester of a biogas production plant can be referred to as direct methanation in-situ. It is direct in the sense that it utilizes raw biogas (mix of mainly CH_4/CO_2) and in-situ in the sense that is applied in the same reactor as the original AD. At the other end you find indirect methanation ex-situ, which is when the carbon dioxide stream separated from the raw biogas in an upgrading facility is used as a feedstock (together with hydrogen) in an external biological methanation reactor. In-between these you find direct methanation ex-situ, where the raw biogas stream is fed into an external biological methanation reactor. Further processing/refining

Depending on if chemical or biological methanation is used and what conversion rate of carbon-oxides is possible, different purification steps might be necessary. A drying step is always required to remove water and water vapor from the product gas, and in the cases where methane productivity is not high enough, separation of residual CO or CO_2 might also be necessary.

Methane is a molecule currently used (in its fossil version) for a wide range of applications, where it apart from being used as a fuel for transport, electricity generation and heating is also used as feedstock for the chemical industry to produce mainly fertilizers and methanol [148]. While it is possible for methane produced from chemical or biological methanation to be used to produce the same derivatives, it is likely that these are rather produced directly from the hydrogen source, as described in 3.1.3.

4.1.2 Electro-methanol

This process starts with CO_2 and H2 as raw materials. CO_2 is obtained by capture technologies such as Air Capture Units which separate the CO_2 directly from air or absorption columns and membranes which separate the CO_2 from the flue gases that come out of chimneys of industrial production plants. H2 comes from the electrolysis of water. H2 and CO_2 are fed in a reactor at a pressure of approx. 8 MPa and temperature of 210°C. The methanol synthesis reactor uses $Cu/ZnO/Al_2O_3$ as catalyst. The reaction that occurs in the reactor is shown equation 8. This is a highly exothermic reaction, having an enthalpy of -49.5 K/mol [149]. The CO_2 overall conversion efficiency is 97% [150], while the energy efficiency of the process is about 70-90% [145].

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \quad \text{Eq. 8}$$

Liquid methanol, water and unreacted gases leave the reactor at 30°C and same pressure. The unreacted gases are separated from the liquids in a flash vessel and recirculate to enter the reactor again. The methanol and water are depressurized to almost atmospheric pressure and heated up to 80 °C to enter a distillation column and be separated. The final methanol has a purity of 99%.

Methanol could be further refined to Olefins, a pathway abbreviated MTO, *methanol-to-olefins*. Methanol is converted to olefins such as ethylene and propylene, which are the main block to produce long chain of polymers. The reaction takes places in a reactor where zeolites play an important role as catalysts. Higher temperatures (above 523 K) favor the production of olefins while lower temperatures favor the production of dimethyl ether (DME) [151]. Currently there are 4 different technologies used commercially; (a) D-MTO/D-MTO-II, (b) S-MTO (which uses a more advanced catalyst than (a)), (c) MTO and (d) MTP. The first two technologies consist of a fluidized catalytic reactor where 100% of the methanol is converted to mainly ethylene and propylene at temperatures of 400-500°C and pressures between 0.1-0.3 MPa [152].

4.1.3 Fischer-Tropsch synthesis

The raw materials of this process, CO_2 and H_2, are obtained by carbon capture and electrolysis of water respectively, same as in the methanol synthesis. These components enter a reverse water gas shift (rWGS) reactor and are heated up to 900°C. The rWGS reaction is endothermic and produces syngas which is a mixture of H_2 and CO and a small amount CO_2. A catalyst is used to make the reaction shown in Eq. 9. The goal of this step is to produce CO from CO_2 to achieve a H_2:CO ratio of about 2 [153]. Palladium and Platinum based catalyst are selective for producing CO [154]. Water is a by-product which is separated from the reactor by condensation.

$$CO_2 + H_2 \leftrightarrow H_2O + CO \qquad Eq.\ 9$$

The syngas is then compressed and heated up to temperatures between 150-300°C before it enters the Fischer-Tropsch reactor. Currently used reactor types are fixed bed, slurry phase, fluidized bed and circulating fluidized bed. In this reactor H_2 and CO react with the help of a catalyst to form a mix of simple hydrocarbons of different chain length (FT-crude)[155]. Higher temperature favor shorter hydrocarbons like methane which can damage the catalyst. With lower temperatures the velocity of reaction is low. Pressure can be increased to increase the conversion but with a compromise of coke formation and special equipment [155]. The reaction that occurs in the reactor, shown in Eq. 10, is highly exothermic, with an enthalpy of -165 KJ/mol CO [156]. Cobalt and iron are industrially used as catalysts because of their performance and cost [153][157]. Unreacted CO, CO_2 and H_2 is recirculated to the FT-reactor. The conversion efficiency of CO to FT-crude is between 60 and 90% [158] and the energy efficiency of the process is in the range of 59-78% [145].

$$(2n+1)\,H_2 + n\,CO \leftrightarrow C_nH_{(2n+2)} + n\,H_2O \qquad Eq.\ 10$$

The different hydrocarbons produced in the FT-reactor are separated by distillation and absorption columns in a similar way as in the petrochemical industry [155]. In a first step, light hydrocarbons like ethene, propene and butene are separated and can be sold in the market. Other low molecular weight hydrocarbons are hydrogenated and fractionated. Finally, high molecular weight hydrocarbons (wax fraction) are converted to speciality wax products by hydrogenation, hydro-isomerization or controlled oxidation. Wax can also be converted to naphthalene, diesel and fuel jet by hydrocracking [155].

4.1.4 Haber-Bosch synthesis

The current ammonia process plants use grey hydrogen and the plant design for e-ammonia will be slightly different as the initial streams will contain different substances and have a lower temperature. The process as described below is based on literature statements, but it is uncertain how many of these plants are in operation today over 95% use grey hydrogen [159], [160], [161], [162]. It should be mentioned that there are other ways to produce e-ammonia than Haber-Bosch under development and they may be more efficient in the future [161].

For e-ammonia, a plant consists of reactant production, ammonia synthesis and ammonia condensation and extraction. The reactants are hydrogen produced through electrolysis and nitrogen extracted from air through pressure swing adsorption. The two reactant gases are mixed and fed into a compression unit and thereafter a Haber-Bosch reactor. The modern Haber-Bosch reactor is a multi-storey continuous flow reactor.

The main energy cost in the process is from hydrogen production through electrolysis, this corresponds to approx. 85% of the total energy demand. However, if we focus on the Haber-Bosch part of the process, the reactor operates at high temperature (400-500 °C) and the reactant streams are heated prior to entering the reactor. For traditional plants, the hydrogen stream from SMR is already at high temperature and residual heat can also be used to heat the nitrogen stream. For e-ammonia the initial streams will be colder and the same heat integration across the process is not possible. This implies that the heating is done by electricity or if there is other residual heat available. Furthermore, the process takes place at high pressure (100-450 bar). Due to the high activation energy of the ammonia formation reaction both high temperature and pressure are needed in combination with a catalyst (often iron-based)[159], [163]. The reaction is defined below.

$3\ H_2 + N_2 \rightarrow 2NH_3\ Eq.\ 11$

Even with the high temperature, pressure and catalyst the reactor efficiency is low and on a single pass only 15% conversion is achieved. To improve the overall performance the gas is recycled through the reactor several times. This can improve the conversion up to around 97% on the plant level. It can also be expressed in the terms of energy need to produce the ammonia and this is approx. 8.3 MWh/ton including H2 production and 1.3 MWh/ton including only the Nitrogen extraction and Haber-Bosch process [163]. The ammonia is then condensed out of the recirculating gas stream at near room temperature and after this no further processing is needed. The process energy efficiency is in the range of 61-79% [145].

4.2 ELECTROFUEL PRODUCTION COSTS

In a review [138], publications from 2016 to 2020 addressing fuel production costs were analyzed. From this array of publications, the authors of [138] presented electrofuel production cost estimates for the year 2030, using data from a previous review by the same authors [145]. A number of factors, such as the electricity price, the price of CO_2 capture, cost of feedstock and other investment costs were found to have a high impact on the electrofuel production cost.

Table 3 below presents some of the assumptions that provided the basis for the base case, the optimistic case and the high case.

Table 3 - Key assumptions in the three cost cases in [138].

Assumption	Base case	Optimistic case	High-cost case
Electricity price (€$_{2019}$/MWh)	50	50	75
Biomass feedstock price (€$_{2019}$/MWh)	25	25	35
Price of CO_2 capture (€$_{2019}$/ton)	60	25	120

The higher cost case also considered higher capital costs, component costs and engineering costs compared to the other two cases.

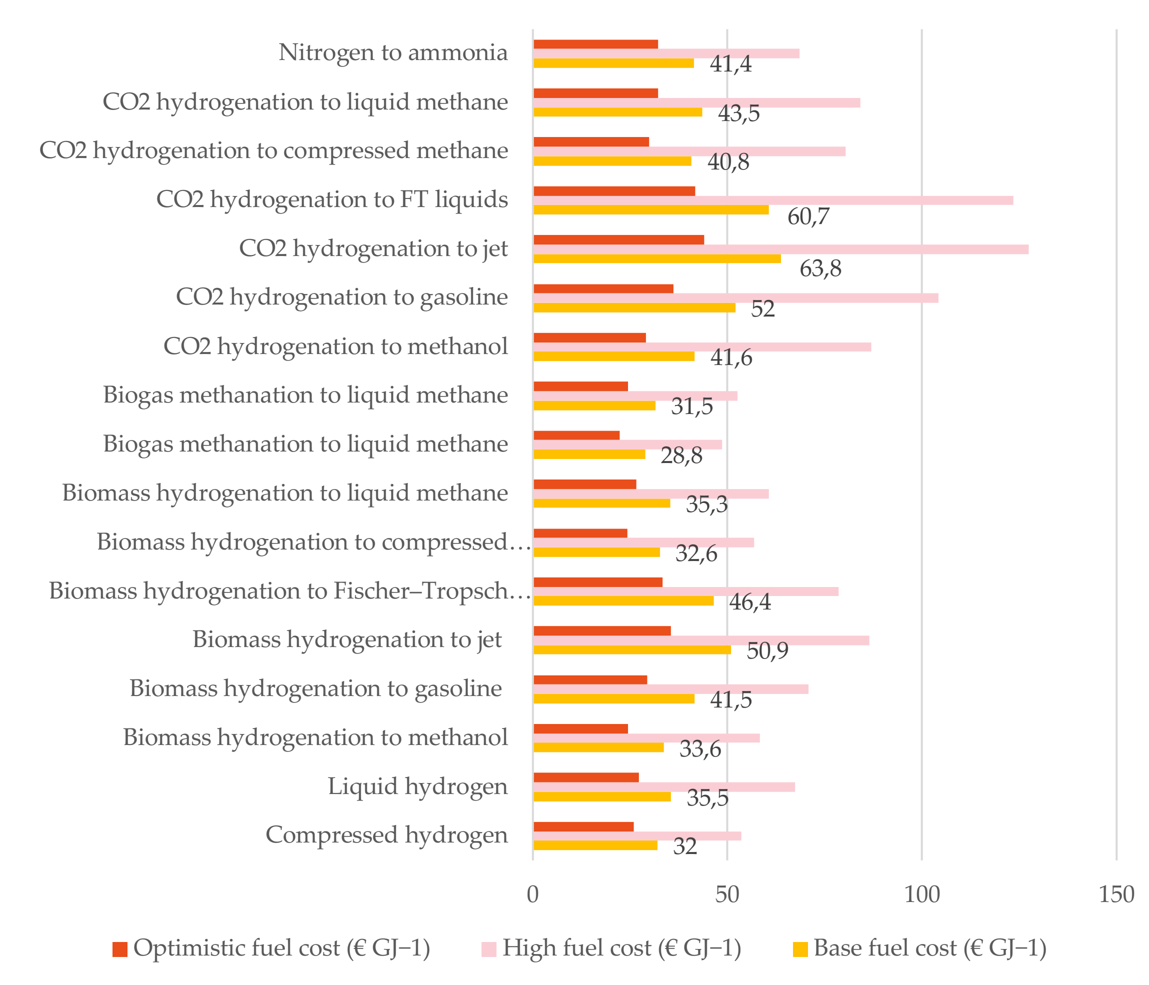


Figure 6. Cost cases for 2030 presented in [138] **for electrolytic hydrogen, bio-e-fuels, and e-fuels using base values. The data labels are added to the base-case fuel cost of each of the fuel.**

As discussed in the section on costs for hydrogen production, the high inflation and stagnating downward trend of component prices might lead to a high-cost case becoming more likely. However, the long-term cost development is difficult to predict, where the economic landscape and global supply chains may be strengthened or worsened compared to today.

4.3 ENVIRONMENTAL IMPACT OF ELECTROFUELS

Environmental impact of novel technologies is always case dependent, where results often depend on specified system boundaries and source of feedstock. Grahn et al. [145] highlighted the differences between studies in methodological approach in a recent review and showed how the extent to which system boundaries can vary in terms of both analysis methodology and technology. One important division when discussing environmental impact is between carbon-based electrofuels and e-ammonia, as they have separate feedstocks after the hydrogen production. The environmental impact of the hydrogen production is described in earlier parts of this report and therefore studies covering well-to-wheel and well-to-tank for the full e-fuel value-chain will be discussed in this section. A well-to-wheel perspective considers the production of hydrogen and carbon or nitrogen and all subsequent process steps ending with the use of the electrofuel in a process or as a transportation fuel. In a well-to-tank perspective, the environmental impact associated with the use of the electrofuel is not considered.

A summary of the compiled information on climate impact is presented below in Figure 7 and highlights the wide range of results for each electrofuel. This will be discussed in more detail in the following sections.

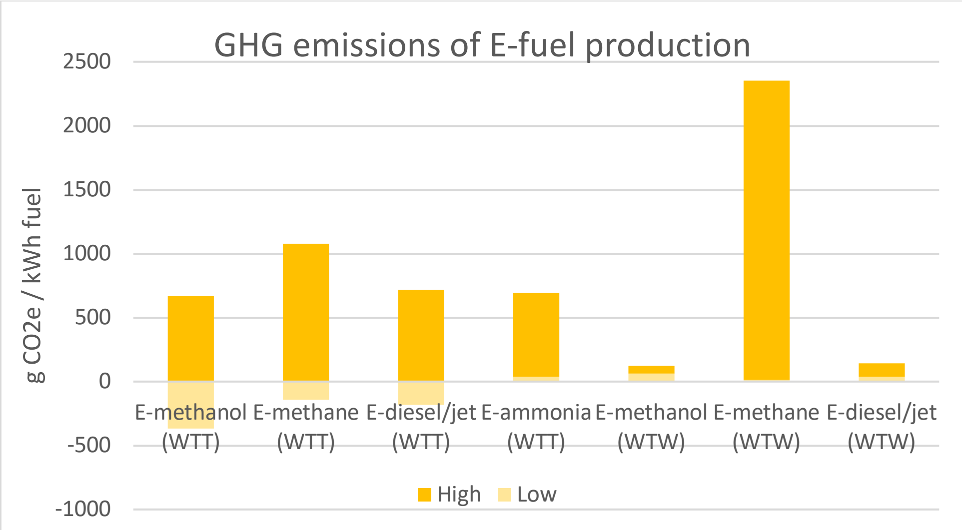


Figure 7. Climate impact (in g CO_2e/kWh) of electrofuels. Compiled results from review articles, arranged according to system boundaries. Climate impact assessments assuming a well-to-tank (WTT) perspective are represented in the first four bars, while a well-to-wheel (WTW) perspective is assumed in the last three bars.

Apart from the specific impacts associated with each electrofuel and process, the environmental impact of electrolysis-produced hydrogen is also of consequence to electrofuels. For this reason, the water consumption of hydrogen production could be an environmental risk depending on local conditions. Moreover, the emerging focus on the impact of hydrogen molecule leakage impacts environmental feasibility of electrofuels. However, as this has been discussed in section 3.3.1, the following sections will instead target the environmental impact from the electrofuels as a whole.

4.3.1 Carbon-based electrofuels

In carbon-based electrofuels, the source of carbon has a strong effect on the climate impact is the carbon source. The end use of the electrofuel is also of importance for the climate impact. For example, if a biocarbon source is used as feedstock, this will have different environmental impact compared to if the electrofuel is used in combustion, releasing biogenic carbon dioxide. This leads to methodological difficulties in accurately reflecting the environmental impact of an electrofuel.

In Table 4 some different numbers for environmental impact are shown, different technology, methodology and feedstock routes have been used, but an overall range of values can be seen.

Table 4 - ***Some reported values of CO2-emissions based for carbon-based electrofuels.***

	E-fuel	Environmental impact [g CO_2 /MJ fuel]	Reference
Well-to-tank	e-methanol	-102-174	[164]
	e-methanol	19-185	[165]
	e-methane	-40-300	[164]
	e-methane	4-110	[166]
	e-diesel/jet	-50-80	[164]
	e-diesel/jet	7-200	[166]
Well-to-wheel	e-methanol	~17	[164]
	e-methane	3-650	[164]
	e-diesel/jet	11-28	[164]

The widespread ranges point to the fact that there are different methodological assumptions that could be made that also have a strong impact in the results, for example, whether any climate impact is assigned to excess electricity or waste streams of carbon, as pointed out in [145]. Meanwhile, the lower ends also represent what could be achieved when more optimal process conditions and low-carbon energy sources and renewable carbon sources could be obtained. Many of the lower values in the table above represent the following improvements:

- Cleaner renewable carbon source such as direct air capture or capture at renewable energy plants
- Cleaner electricity mix
- More energy efficient process
- Lower emissions during use of fuel
- Access to clean water

As pointed out in [145], this highlights the need for a fully renewable energy system in order to produce electrofuels (in this case carbon-based electrofuels) with a low climate impact. However, Grahn et al. [145] note that the negative values are caused by the methodological choice of analysing the climate impact cradle-to-gate without consideration of the combustion. As mentioned previously, the negative emissions become more attainable when the electrofuel is used a chemical feedstock rather than a fuel, which could be the case for, e.g., electro-methanol.

4.3.2 Electro-ammonia

Greenhouse gas emissions of electro-ammonia are calculated in a similar manner as for the carbon-based electrofuels. Again, the values reported in literature are widespread, with as low as 10 g CO_2 /MJ NH_3 presented in the review by Grahn et al. [145] or intervals from 19-183 g CO_2/MJ NH_3 as shown by Campion et al. [165].

Both analyses are on the basis well-to-tank or cradle-to-gate. In the study by Campion et al. it is shown that the main difference between a high or low amount of CO_2 emissions is the electricity mix considered. This is related to the production being energy intensive. For the higher values an electricity mix from the grid in northern Chile is considered, while the lowest consider electricity from renewable resources in Denmark. This shows that the main way to reduce emissions is by using renewable electricity resources and to produce the production plants in an environmentally friendly way.

Not considered in these sources is the impact during use, where CO_2 emissions are not present, but NOx emissions will be as well as other potential environmentally harmful substances. This is also mentioned by Grahn et al. [145], they state that there are few environmental impact assessments for e-NH_3 that consider the usage phase. The legislation on NOx is still not fully developed especially as a fuel. Still, with today's combustions engines EU exceeds the NOx limits [167] and hence NOx emissions for e-NH_3 may be interesting for future studies to consider.

4.4 THEORETICAL ELECTROFUEL PRODUCTION POTENTIAL

4.4.1 Theoretical production potential

Based on the definition of electrofuels as fuels produced from electricity, the theoretical max production can be calculated by using the value for the hydrogen production from electrolysis in combination with reaction formulas and conversion rates. There are two levels of theoretical max for hydrogen from electrolysis 8.5 TWh per year (Low estimate) and 26 TWh per year (high estimate) and for these calculations the higher estimate will be used. For the carbon-based e-fuels, the availability of biogenic CO_2 may also pose a limitation. In a previous study [168] it was shown that as long as the carbon source is from existing industries and their waste streams it should in the next couple of years exceed the hydrogen produced by electrolysis. The plans for the fully circular source, direct air capture, are today very vague and difficult to quantify. Therefore, in this study estimates of production capacity will focus on the maximum hydrogen production from electrolysis. Further assumption made are that:

- Available electricity is non-limiting
- Nitrogen for ammonia production is abundant and non-limiting
- Reaction yields are representative
- Highest case 50% of the theoretical max of H2 from electrolysis (26 TWh/year) is used for a single e-fuel
- Lower maximum case 15% of the theoretical max of H2 from electrolysis (26 TWh/year) is used for a single e-fuel
- Hydrogen from other sources than electrolysis are excluded based on the definition of electrofuels
- For FT-fuels the most common chemical structure is between 9-16 carbons, as a mean value 12-carbon structures will be used.

- Additional hydrogen demand for upgrading FT-fuels in hydroprocessing is not included.

The method for calculation used for hydrogen feedstock as limiting is:

$$Moles\ of\ hydrogen: n_{H2} = \frac{m_{H2}}{M_{H2}}$$

Where n_H2 are the number of moles, m_H2 is the mass and M_H2 is the molar mass of hydrogen.

$$Moles\ of\ electrofuel\ produced\ n_{e-fuel} = n_{H2} * SR * \%conv$$

Where SR is the stochiometric ratio of hydrogen relative the produced e-fuel and %conv is the conversion ratio of the reaction. From this the mass e-fuel theoretically possible to produce can be obtained by:

$$Mass\ e - fuel\ produced\ m_{e-fuel} = n_{e-fuel} * M_{e-fuel}$$

All cases are calculated for the projection of production in 2030. The results are presented in Figure 8 and show the high and low theoretical production cases as both energy and amount. The highest case is improbable as most of the projects for hydrogen produced by electrolysis announced are aimed at use in other sectors than electro fuel production. Even the low case is most likely a high estimate as, if all these e-fuels are produced, it would correspond to 60% of the total hydrogen production by electrolysis in Sweden in 2030. This indicates an already well discussed issue in the overall energy transition to mitigate climate change, that there will at least initially be many sectors competing for the same resources.

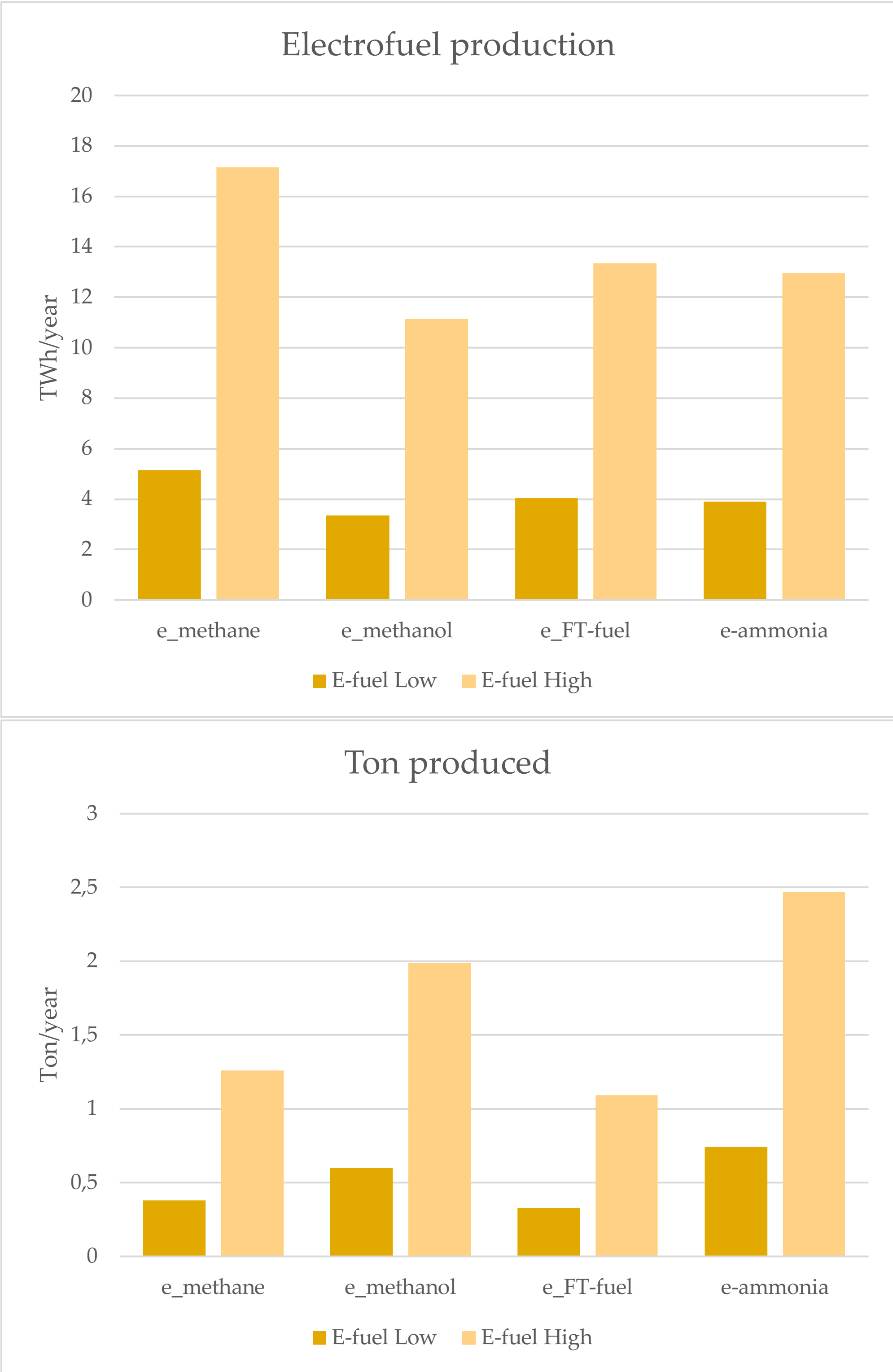


Figure 8 - Maximum theoretical production of e-fuels in Sweden for two cases when limited by the theoretical maximum production of Hydrogen in 2030 (26 TWh per year). Low case 15 % and High case 50% of theoretical max. electrolysis hydrogen is converted to one type of e-fuel, plotted as Mass of e-fuel in Mton (rigth) and Energy content in TWh based on lower heating value (left).

The above theoretical production potential will be compared to the planned initiatives in the next segment. The same methodology can be used for CO2 sources as limiting, however at the stage of this report it is difficult to estimate what the maximum production would be in a close time frame.

4.5 DISTRIBUTION OF ELECTROFUELS

4.5.1 Existing distribution chains

The electrofuels discussed in this report are chemically identical or close to chemically identical to their fossil counterparts. Hence, the mode of transport for their distribution, in principle and at large, can employ the same infrastructure and follow the same routes as the conventional, fossil, alternatives already utilize. In fact, the ability to tap into already existing distributional patterns is one of the benefits of electrofuels compared to other renewable alternatives for the same purpose [138].

In many cases, the introduction of electrofuels into different modes of transport is likely to be gradual, and as an increasing level of blend-in of renewable electrofuels in conventional fossil fuels (Clean Vehicles Directive [169]). This may require additional facilities for blending and mixing the different fuels, but in many cases, this is something that is already done when various parts of existing fuels are blended to achieve the desired properties, at a refinery. However, additional blending facilities may be needed.

As Sweden does not have any oil or gas fields of its own, all the raw material for conventional fossil fuel production is currently being imported. The major refinery capacity is located on the west coast of Sweden and the distributional pathways is hence also aligned with this being the main entry for fossil fuels into the Swedish market. Electrofuels may very well be produced somewhere else in Sweden then be refined on the west coast and this creates the need for additional distributional capacity from the production site.

For electrofuel production facilities economy of scale applies to a large extent and this means that the amount produced will be rather large [170]. The amounts will probably not be easily swallowed by the already existing distributional capacity and additional capacity will therefore most likely be needed to be constructed. Access to locations where distributional capacity is already large, like ports or high-capacity railroad is therefore one of the steering parameters when the localization of electrofuel production facilities is being determined.

For the electrofuels specifically discussed in this report, e-Methane, e-Methanol, Aliphatic compounds from Fisher-Tropsch synthesis (FT-fuels), and Ammonia from Haber-Bosch synthesis, the same distribution solutions as for their fossil counterparts thus apply.

Electro-methane

Methane can either be distributed in a gas-grid system, where it is likely to be mixed with both fossil natural gas and biomethane from digestion or gasification or compressed and transported in tubes of various sizes by road, rail, or sea. E-Methane can also be liquified into an equivalent to LNG, likely to be denoted by e-LNG or e-LBG, depending on the origin of the carbon in the electro-methane. In liquid form, methane can be distributed in cooled tanks of various sizes on road, rail, or sea. Distribution systems for e-methane include existing infrastructure for methane, such as natural gas pipelines, LNG terminals and existing refuel and industrial infrastructure. Furthermore, bunkering of electro-methane is the same as for methane.

Electro-methanol

Electro-Methanol is in a liquid state at ambient conditions and as such does not require either liquification of compression to be transported in conventional tanks by road, rail, or sea.

Electro-ammonia

The ammonia distribution system consists of sea and land transportation routes to and from large storage terminals and/or smaller storage systems at retailer or end-user locations. Ammonia is typically transported in liquid state and therefore needs to be compressed, cooled, or both. Stress corrosion cracking, which can occur under distribution and operating conditions, is a primary concern when storing and handling ammonia.

Fischer-Tropsch fuels

Fischer-Tropsch fuels are in a liquid state at ambient conditions and as such does not require neither liquefaction nor compression to be transported in conventional tanks by road, rail, or sea. The application in which FT-fuels are of certain interest is within aviation and air-transport [171]. Hence, a comparison with bio-jet fuels is relevant.

The current bio-jet-fuel is imported to Sweden and the port of Gävle by ship. In the port of Gävle the certified bio-jet fuel is blended with fossil jet fuels and the quality is checked. From the port the jet fuel is transported by truck to for example Landvetter airport, Åre Airport, Umeå Airport, Malmö Airport and by rail and pipeline to Arlanda (and further by truck to Bromma airport). The bio-jet fuel is used at airports owned by Swedavia and other airports for example Karlstad. [170]

4.6 APPLICATIONS FOR ELECTROFUELS

For electrofuels, the main application areas currently discussed are within the transport sector. The electrofuels could also be used as chemical feedstock and be further synthesized into other useful molecules such as polymers, however this is rarely described in the same reports, probably because the chemical industry refers to it more as just ammonia, methanol, methane and so on. The application of the different electrofuels will therefore be divided in the two segments: transport and industry. One general observation of the use for electrofuels in Sweden and the transport sector is that in the government's official investigation from 2021 [172] only Fischer-Tropsch diesel and sustainable aviation fuels (SAF) are mentioned initially. Methane and methanol are mainly specified as a step on the way to the heavier e-fuels and not as fuels in themselves [172].

Another important aspect for the transport sector is the trends in the EU-directives that are expected to also affect Sweden. One example is the Clean Vehicles Directive [169], which regulates the emission requirements for new vehicles bought through public procurement. The directive is focused only on-road transport, and primarily affects the public sector. Here the requirements include a certain percentage of new vehicles/transports purchased that should be low emission (<50g CO_2/km) and a certain percentage should be zero-emission. The percentages per year for Sweden are listed in Table 5.

Table 5 - *The emission requirements according to the Clean Vehicle Directive for Sweden* [169]. *Note that the zero-emission goals are under the total goal of low-emission vehicles.*

Required per year	Light-duty vehicles	Heavy-duty vehicles	Buses
2021-2026 (Low emission + Zero-emission)	38.5%	10%	45%
2026-2030 (Low emission + Zero-emission)	38.5 %	15%	65%
2021-2026 (Zero-emission)	--	--	22.5%
2026-2030 (Zero-emission)	38.5%		32.5%

The requirements are based on tail-pipe emissions and today only batteries and fuel cells fall in the zero-emission category. This means that electrofuels will under current regulation be somewhat limited for uptake in the on-road sector for certain applications, especially for example for city buses. In addition to the limits on carbon dioxide there are also limits of NOx emissions for light-duty vehicles.

4.6.1 Electro-methane

An easy starting point regarding methane is to first acknowledge that it is the same as the main constituent in natural gas or biogas and is thus suitable in applications where methane is already used today. Some of these applications are as transportation fuel, as heating fuel in industry and in other energy sector applications.

Electro-methane as a transport fuel

A possible application, as mentioned before, is electro-methane replacing natural gas. This means that the technology readiness level is high for electro-methane used as a fuel. The propulsion systems for methane are based on internal combustion engines or turbines either developed for or converted to methane combustion. Further, refuelling infrastructure for LNG (liquefied natural gas), natural gas and biogas already exists today and has been tested and standardized for years. The transport applications that use natural gas or biogas vary from small passenger vehicles to larger shipping vessels and space travel. There is however less mention of it for commercial flights.

For on-road transport, Sweden already today has a city bus fleet and to a smaller degree trucks and passenger cars that run on biogas and the same applications can probably be used with e-methane in the future. However, for city buses the future use of all fuels with carbon dioxide tail pipe emissions will be limited by the Clean Vehicles directive on EU level as described above [150][169]. Hence, vehicles driven by biogas are not considered zero-emission and e-methane vehicles will most likely fall in the same category. This legal framework does not yet affect the private procurements processes and are limited to on-road applications, but directives may change in the future. The extent of usage of e-methane in the transport sector can therefore be said to partly depend on future legislations. In the maritime sector, the regulations linked to alternative fuel options are to a large extent still under development but are not yet as strict. There are some LNG ships (approx. 251 [173]) in use around the world that should be ready to use e-methane as a substitute. In Swedish shipping, about 180 GWh of LNG was used domestically and 255 GWh of LNG for international shipping [174] (Swedish Energy Agency, 2021; as presented in Holmgren et al., 2021). The potential for replacing LNG with liquid methane gas for Swedish shipping is further discussed in Jivén et al., [175]. The international council of clean transport also presented that for maritime applications to have uptake of renewable bio-methane or e-methane compared to natural gas in Europe 2030 there is a need for policy incentives due to the cost difference [176].

Electro-methane for industrial applications

Methane today is used in many industrial sectors primarily in chemical industries and the energy sector. It should be noted that one main use for methane in chemical industries have been to reform it to hydrogen, which most likely no longer will be a revenue for e-methane because of the redundancy. In the chemical and steel industries the usage will probably focus on development of more complex chemical compounds or as used today for heating and power generation. Examples of chemicals where the preparation today uses methane as a raw material are some plastics such as polyethylene via methanol, or fertilizers. However, most of these processes can also be based on methanol or directly through Fischer-Tropsch and may not be as relevant for e-methane as when the main source is natural gas.

There is also a very established use in the heating and the power sector in many parts of the world, where methane is used in burners or gas turbines. These technologies could be implemented in Sweden as well, for example using a blend of methane and hydrogen in gas turbines for energy balance on a larger scale. In Europe, where the gas network is more extensive, there are already now tests of injecting hydrogen in the areas where natural gas is already used for the residential sector. This sector will probably never be 100% hydrogen and here e-methane can continue to be used as a balance to reduce emissions [177].

4.6.2 Electro-methanol

Like methane, methanol is a compound that has been in use for a longer time. Here it has not been as frequently used for transport, but instead as industrial feedstock. There are some safety issues related to methanol, even if they are not as severe as for some other fuels. Considering methanol for any applications where untrained personnel has to handle it, the main issues would probably be skin contamination and adsorption. Still there are known cures to methanol poisoning and an established handling system in many industries.

E-methanol is not commonly used as a transport fuel today, but there have been extensive trials where existing combustion engines have been converted to or designed for methanol usage [178], [179]. There are also fuel cells that use methanol directly, however they have quite low power density per volume and weight and are not today used in transport applications. Much talk about methanol as a fuel today is related to the maritime sector where it is considered more difficult to solve the energy needs by hydrogen or batteries. This is related to large shipping vessels rather than smaller ferries as hydrogen and batteries here would result in a to large payload loss. For maritime applications there are in general two types of propulsion systems considered, either the more conventional 2-stoke combustion engine alternatives or using a reformer and PEM-fuel cell system. Which driveline will become dominant is still uncertain and with continued developments there is a large uncertainty in the maritime sector. There are also discussions of combined systems where a fuel cell system is used for auxiliary power and a combustion engine for propulsion [179], [180]. Furthermore, there is also competition between different fuels in the marine sector, and companies are placing focus on the several available alternatives. Today, main discussions revolve around liquid hydrogen, Liquid methane, methanol, or ammonia [181].

E-methanol for industry applications

In industries, the use of methanol as feedstock is well established and it is used as a raw material for many of our valuable chemicals today:

- Formaldehyde
- Eten/propene and other olefines as precursors for polymers
- Acetic acid
- Silicone
- Methyl methacrylate

These chemicals are in turn used to produce a wide range of materials needed, such as paints, lubricants, protection equipment, components in vehicles, and many more. In Sweden there are industries in place for production of several of these materials. A continued wide need for methanol as a raw material in industry is expected [179], [182]. Methanol is also the starting point for many of the Fischer-Tropsch e-fuels and if they gain momentum, so will the applications for methanol.

4.6.3 Fischer-Tropsch fuels

Fischer-Tropsch fuels are closer to traditional fuels than the remainder of the e-fuels and hence have very established value chains and applications today. Included here are e-gasoline, e-diesel, e-jet fuel and similar.

Fischer-Tropsch fuels for transport

The main aspect for use of these e-fuels is going to be related to the overall cost and efficiency loss in manufacturing. For lighter applications such as on-road applications the efficiency from power-to-wheel is often considered too low for hydrogen [97] and for these fuels the efficiency is significantly lower. The many energy losses in the production chain will most likely lead to a long-term use primarily in specific segments where other e-fuels with more efficient production pathways are not an alternative. Today there is a high focus on the aerospace industry, where sustainable airplane fuels (SAFs) such as e-jet fuel will be a requirement for traveling longer distances. Some SAFs can also be produced from bio-refineries, among e-fuels the main type considered is e-kerosene. It has also been shown that the on-board propulsion turbines and storage used today is compatible with e-kerosene [183]. The main advantage for synthetic SAF compared to other alternatives considered today is that changing the fuel will not change the range or operation of the airplanes. Contrary the downside is that there will still be significant NOx emissions. On the overall the emission reduction using e-kerosene is estimated to between -30-60% compared to today. The higher value is calculated based on CO2 capture from air where the emissions are made [113]. There is ongoing investigation on theses fuels in Sweden by Vattenfall, SAS, Shell and LanzaTech. The initial plan here is to use nuclear power and CCS from local industries and the overall reduction potential has then not been calculated [184]. From the technological perspective e-kerosene has no limitations similar as for many other e-fuels, and initially it is expected to have a strong up-take. In the long-term past 2050 much of the use will probably be based on future legislation, policy and development of competing technologies.

There is talk of a smaller usage segment for maritime and heavy-duty trucks, but these applications have alternative fuels and discussion often vary. Initially, during a transition period, the use of Fischer-Tropsch fuels may be more extensive as it is similar and can be used in current applications. However, for the long-term cost and efficiency as well as the technological maturity of competing propulsion technologies will change the usage.

Fischer-Tropsch fuels for industry applications

These types of fuels will likely be relevant for industrial use, since the hydrocarbon chains used in industry today is often used for heating. There are many other ways to heat processes and as the precursor is already methanol or similar going backwards would mean very low efficiency.

4.6.4 Ammonia

One of the main upsides of ammonia usage is that the value-chain is well established and that it has been distributed and used for a long time. The main downside is its high toxicity and the serious health risks involved in handling the substance. Today there is no known cure once over exposure has occurred, and this means that serious mitigation is needed during handling. So far most concentrated ammonia is handled either in industrial or agricultural contexts, where it is limited exposure possibilities for the general public. This may change when looking at it as transport fuel or in a wider context.

Ammonia for transport

For the transport sector ammonia is seen both as a possible fuel and a hydrogen carrier for long distance distribution. Focusing on its use as a fuel for propulsion most discussions are focusing on the maritime sector. The propulsion systems for the maritime sector today use ammonia in converted internal combustion engines. This means that while there are no CO2 emissions there will still be NOx formed [185]. NOx is a substance with limited emission in cities, this may not be as harsh in the maritime sector. As for use of ammonia as a fuel in other transport segments very little is mentioned today. This can be because the technology is not yet fully developed, and applicability is uncertain.

Ammonia for industry applications

The main industry that uses ammonia today is the agricultural sector (approx. 80%) where it has been used both to manufacture fertilizers and to directly fertilize fields. Further ammonia is used in the textile industry as a softener and as a precursor for nitrogen rich chemical compounds [186]. There are ongoing tests to use ammonia in turbines in the energy sector for power generation, however these are at an early-stage development [187].

As a hydrogen carrier ammonia is frequently mentioned, that is because it has an established import/export value chain and mature storage technology. What is uncertain are the losses and limitations when regaining the hydrogen. Again, much development is needed to establish the feasibility and predict the actual potential for use of ammonia in this capacity.

5 Potential for use of hydrogen and electrofuels

This chapter describes the current markets of fuels (fossil fuels, biofuels and electricity) in the transport sector, steel and chemical industry in Sweden, to provide the theoretical ceiling of how much hydrogen and electrofuels could be used. These sectors were chosen based on their high fuel consumption and potential application for hydrogen and electrofuels. Out of the selected sectors, the transport sector is dominating the energy consumption, followed by the steel sector which mainly consumes fossil fuels. The market descriptions are followed by future demand of hydrogen and electrofuels in each sector. Future demand of these fuels is estimated to increase in all sectors, but to various degrees and in different segments of the sector. The final section of the chapter discusses barriers for usage of hydrogen and electrofuels based on interview results. One example of a main barrier that was discussed was the lack of regulations (e.g., political instruments and standardization) which creates uncertainties for actors working with hydrogen.

5.1 END-USE OF ENERGY IN SWEDEN

The market size of fuels and energy carriers will be described in this section for all the fuels available and used in the Swedish market for both energy production and raw material. This includes fossil fuels such as diesel and natural gas as well as biofuels such as ethanol and biogas. Use of electricity as energy source will also be included since this is a source that is replacing some sources of liquid fuels. The sectors included in this analysis are transport, steel and chemical industry which are the ones that have the highest consumption of fuels and electricity as well as the sectors where hydrogen and e-fuels have applications. The fuel and electricity demand in the different Swedish sectors during 2020 is summarized in Table 6.

Table 6*: Fuel and electricity demand of different sectors in Sweden (2020).*

Sector	Fossil fuel [TWh]	Biofuels [TWh]	Electricity [TWh]	Total energy use [TWh]	REF
Transport (domestic)	59	20	3.2	79	Energimyndigheten 2023
Transport (international)	32.9	0	0	33	Energimyndigheten 2023

Iron and steel	13.1	0	7	20	Energimyndigheten 2023
Non-metallic minerals	2.5	0.2	0.9	2.5	
Chemical	2.3	0.4	4.7	7.4	Energimyndigheten 2023 SCB 2021[188]
Petrochemical	1.9	-	1	2.9	Data from 2017 (update!)

The transport sector (domestic) has the highest consumption of fossil fuels and biofuels. The steel industry has the second largest consumption of fossil fuels and no biofuels consumption as of today. As complementary information, the use of fossil fuels such as natural gas, petroleum products, coal and coke in other industrial sectors in Sweden 2020 is summarized in Table 7.

Table 7*: Fossil based fuel usage of minor consumer sectors in Sweden 2020. Source:* [78].

	Pulp and paper [TWh]	Mechanical Eng. [TWh]	Mining [TWh]	Food beverages tobacco [TWh]	Non-metallic minerals [TWh]	Wood products [TWh]	Small industries [TWh]	Total [TWh]
2020	**2.1**	**0.6**	**2.3**	**1.3**	**2.5**	**0.3**	**0.5**	**9.6**

5.1.1 Transport sector

The transport sector has the highest energy demand, consuming 82 TWh of fossil fuels, biofuels and electricity within Sweden and 33 TWh on international shipping and flights [78]. Within the transport sector, each transport type has some specific type of fuel that are more predominantly used. This is shown in Table 8 for Sweden 2020. Electricity use is also shown. From this data, it can be seen that road transport has the biggest consumption of fuels. Petrol and diesel are the most consumed fuels followed by biofuels. Among the transport segments, biofuels are mainly used in road transport. Electricity is only used in road and in a minor scale in rail.

Table 8*: Fuel and electricity usage in TWh for different transport types in Sweden 2020* [78].

	Road	Shipping (dom.)	Shipping (int.)	Aviation (dom.)	Aviation (int.)	Rail	Total fuel /el usage
Gasoline	21.6	0.0014	-	-	-	-	21.60
Diesel	35.7	0.29	-	-	.	0.17	36.16
Light fuel oil	-	0.32	8.1	-	-	-	8.42
Heavy fuel oil	-	0.76	20.65	-	-	-	21.41
Aviation fuel	-	-	-	0.72	3.99	-	4.71
Natural gas	0.11	0.33	0.16	-	-	-	0.60
Biofuels	19	0.17	-	-	-	0.006	19.17
Total by transport type	76.41	1.88	28.91	0.72	3.99	0.176	
Electricity	0.82	-	-	-	-	2.42	3.14

For a better overview of the fuel and electricity consumption in the different transport types see Figure 9.

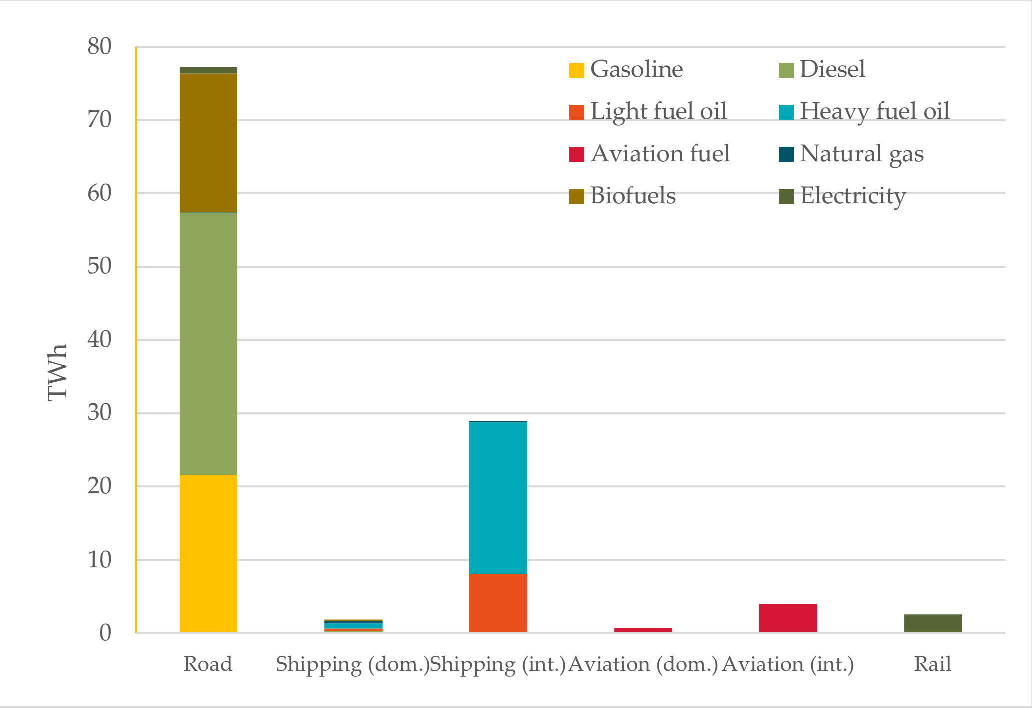


Figure 9: Fuel and electricity usage for different transport types in Sweden 2020. Statistics from the Swedish Energy Agency [78].

Historically, the consumption of gasoline has decreased by 60% over the last 20 years, from about 50 TWh to 20 TWh while the use of diesel and biofuels has increased during the same period. Biofuels like bioethanol, biodiesel, biogas, HVO and FAME have been replacing diesel, natural gas and gasoline. Electricity used in electric cars has increased very slowly throughout the years.

5.1.2 Steel industry

The steel sector is the second largest consumer of energy with a total of 13 TWh of fossil fuels [78]. In Table 9 the use of fuel and electricity in 2020 can be seen. In this industry, the highest consumption is for coal and coke gas. Coal is used as reduction agent in one of the manufacturing processes and in blast furnaces as a fuel. Oil and gas are used for heating treatments. Electricity is used to run auxiliary equipment and for heating [189].

Table 9*: Fuel and electricity usage in the iron and steel sector in Sweden 2020 in TWh* [78].

Coal and coke gas [TWh]	Oil [TWh]	Gas [TWh]	Total fuel usage [TWh]	Electricity [TWh]
10	0.5	2.5	21	7

While the electricity demand from industry has been stable during the last 50 years, this is believed to change soon, due to the emerging arc electric furnace technology that is deemed promising as means to decarbonization. These new furnaces will replace the blast furnaces that run with coal [190]. Coal used for reduction of iron will potentially also be replaced by hydrogen, which would produce water instead of CO_2 in the reduction process. This transformation is very attractive for the reduction of emissions in this sector. The coke gas and the have historically been replaced by natural gas and eventually this natural gas can be replaced by biogas [191].

5.1.3 Chemical industry

Different definitions and delimitations exist for what sub-sectors should be included in the chemical industry exists. In this report, the basic chemistry sector, petrochemical sector and plastic manufacturing sector are all included in this category in order to capture as much of the potential hydrogen demand as possible.

The fossil energy consumption in the chemical industry in Sweden (e.g., petroleum products) was approximately 2.3 TWh in 2020, a slight increase by 0.3 TWh from 2019 [188]. The different fossil fuel types used for energy in the chemical industry are listed in Table 10 showing that natural gas dominates the energy consumption.

Table 10*: Energy consumption in the chemical industry for the years 2019 and 2020, by energy source.*

Year	Total	Coal	Coke	Sulfite lyes, black liquor, tall oil and peat	LPG	Fuel oil no. 1	Fuel oil no. 2-6	Natural gas
2019	**2.0**	…	0.0	0.3	0.3	0.1	0.1	1.2
2020	**2.3**	…	…	…	0.2	0.1	0.2	1.5

5.2 DEMAND FOR HYDROGEN AND ELECTROFUELS

This section begins with a short outlook on international hydrogen demand, followed by the current and future demand of e-fuels and hydrogen focusing on transport, steel, and process industry in Sweden.

Globally, the hydrogen demand across all sectors is expected to have grown substantially from the 115 Mt/year in 2021 (~3800 TWh), to about 500 to 800 Mt/year by 2050 (14000 to 22000 TWh) as a result of increasing demand in both existing and new applications [192]. In European reports, the future demand for hydrogen is expected to approach 30 Mt or 990 TWh by year 2030 [124]. The European Union implemented a hydrogen strategy in 2020 with objectives to install at least 6 GW of renewable hydrogen electrolyzers by 2024 and producing 1 million tons of renewable hydrogen[193]. By 2030, the goal is have installed 40 GW of renewable hydrogen electrolyzers and up to 10 million tons produced renewable hydrogen. Hydrogen is defined as a key priority to achieve Europe´s clean energy transition and the European Green Deal.

In Sweden, the annual consumption of hydrogen is approximately 6 TWh, whereof about 72% is used in refineries and 27% within the chemical industry [194]. The remaining 1% is used for metallurgical processes and to fuel transport [140]. A small amount (3%) of this is produced via electrolysis and shifting to a complete production of hydrogen via electrolysis would with today’s numbers demand 9 TWh electricity [194]. The biggest source of hydrogen production nowadays is by reforming natural gas (67%) and the next biggest source is by-streams in industrial processes (30%) [194].

According to the report that laid the base for Sweden’s proposed hydrogen strategy in 2021, the full Swedish system’s hydrogen demand will be around 21 TWh in 2030 and closer to 90 TWh in 2045 [195]. This corresponds to approx. 2.5 and 10 GW continuous production, and the usage is focused mainly on industrial initiatives already planned in 2021. There are more and more initiatives occurring and the full demand of hydrogen might change, especially for the estimate of 2045. In a report by Energiforsk in 2021, the lowest and highest demand for hydrogen was calculated for different user scenarios [196]. For major usage, the case 24 TWh and 68 TWh was estimated respectively for 2030 and 2045. Another report made by the Royal Swedish Academy of Engineering Sciences (IVA), estimated a hydrogen demand of 20-25 TWh by 2030, resulting in an increased electricity demand of 30-40 TWh it the hydrogen would be produced via electrolysis [197].

5.2.1 Transport

The transport sector is a vital part of our society but stands for a significant share of GHG emissions. In Sweden, the transport sector stands for a third of the total emissions and the goal is to reduce emissions with 70% by 2030, compared to emissions levels at 2010 ([198]). Which type of decarbonization measure that is appropriate for different transport segments varies. Hydrogen can be a solution, especially to segments that are difficult to electrify such as heavy and long distant transport like aviation, maritime and heavy road transport [199],[200]. How significant the role of hydrogen will be depending on various factors such as infrastructure, technology, characteristics, readiness, and competitiveness [200], [201]., [201].

The use of hydrogen in the Swedish transport sector is low, the exact number in 2023 is uncertain, and in written reports for Sweden the overall demand from the transport sector is rarely quantified and often considered a minor part of the hydrogen economy (e.g. [202]). [202]). Statistics from 2020 showed that 0.2% of all hydrogen used in Sweden went to refuelling stations, corresponding to approx. 360 tons or 12.5 GWh. (Fossilfritt sveriges färdplan). The current use is most likely higher today as the number of hydrogen refuelling stations have increased. However, there are next to no hydrogen vehicles in use today, apart from the few examples found in Gothenburg, Mariestad and Sandviken. The filling stations in operation as of 2023 are located in Gothenburg, Mariestad, Stockholm outside Arlanda, Sandviken, Umeå and Älghult [203].

On the European level, the transport sector has an estimated demand of approximately 21 TWh and 140 TWh for 2030 and 2040 respectively [200]. Hydrogen is projected to fuel 55% of trucks, 25% of buses, and 10% of airplanes in 2050. 12% of total energy demand from the transport sector will be for direct hydrogen in 2050. The report [200] also shows a breakdown per country and for Sweden the estimated demand is 1 TWh and 6.5 TWh for 2030 and 2045 respectively (including road, aviation, and shipping) [200][165][167]172][174],[65]

The future demand of e-fuels in the transport sector is ambiguous. On European level, e-fuels might a have a small role in the short-term perspective (2030) and long-term forecasts are highly variable [204].It will mainly be an option for maritime, aviation and long distant heavy road transport [204], [201].

Road Transport

Electrification is a popular measure within the transport sector due to its development in technology, expanding charging infrastructure and lower costs

[200]. Electrification is especially applicable to light vehicles. For heavy vehicles, fuels with high energy density and fast refueling times such as hydrogen, is desirable [140] [205],[200]. In 2022, there were five active hydrogen refueling stations in Sweden and another 40 stations had been approved to receive financial governmental support for establishment [206]. These approved refueling stations shall be active in 2025 and maintain a capacity of 1 500 – 2 000 kg/day depending on which type of financial support that will be given. This translates to about 0.75 TWh in 2025.

Regarding e-fuels in the road transport sector, a study forecasting the demand in the Nordic countries estimated that the share of e-fuels of the total transport fuel demand would increase from 0.2% in 2025 to 9% in 2045 [205]. Regarding e-fuels in the road transport sector, a study forecasting the demand in the Nordic countries estimated that the share of e-fuel of the total transport fuel demand would increase from 0.2% in 2025 to 9% in 2045 [205]. In the low scenario, the e-fuel demand share reaches 4% in 2045 but 19% in the high scenario. The e-fuels included in that study were e-methanol, e-DME, e-methane and FT-liquids.

Aviation

Aviation is a suitable transport segment for hydrogen and e-fuels as it is challenging to use other measures such as electricity which has a relative low energy density [140], [201]., [201]. The European Commission initiated the ReFuelEU Aviation Initiative included in the Fit for 55 with aim to reduce GHG emissions [207]. In the current draft regulation, there is an obligation for all fuel suppliers at the EU airports to include and gradually increase a certain share of sustainable aviation fuels of which a specific part must be synthetic fuels (including e-fuels and hydrogen) in the aviation fuel [208]. This share of synthetic fuels would be 0.7% in 2030 and increase to 28% in 2050. This can be compared with forecasts showing that the EU demand share of hydrogen technology per aviation technology will be 0% until 2040 and then increase to 1%, and further 10% in 2050 [200]. The share of synthetic kerosene is projected to start at 2% in 2025 and end at 40% by 2050.

There are currently no known studies of the future demand of hydrogen or e-fuels for aviation in Sweden, however DNV projected the demand for the EU and Norway respectively. For Norway, the share of hydrogen as direct aviation fuel would be zero by 2040 but increases to about 6% in 2050, equal to 1 MtH2/year. These values may be applicable for Sweden considering the countries many similarities.

Shipping

Among the different non-fossil-based shipping fuels, HVO is the most common in Sweden. Electrification also exists but mainly for smaller ships. Hydrogen is an appropriate decarbonization option for shipping, especially heavy and long-haul shipping, due to its high energy density [140] [201], [204]. However, hydrogen has challenges such as need to store large volumes of hydrogen on the vehicle, high costs, and lack of infrastructure, technological and policy readiness as well as production scale [209] Despite these challenges, there are a few ships and ferries in

Sweden using hydrogen and there are possibilities that hydrogen usage will increase, also in hybrid solutions e.g., combining hydrogen and batteries [210]. Another report from DNV estimated that hydrogen and ammonia will be commercialized maritime fuels in a few years [211]. One practical example is Gotland Horizon with is a project to build a hydrogen fueled passenger ferry between Gotland and the Swedish mainland with aim to be in traffic by 2030 [212], [213].

In 2023, the EU agreed on regulation on the use of renewable and low-carbon fuels in maritime transport (2023/1805) which was based on the FuelEU Maritime proposal within the Fit 55 package with aim to reduce GHG emissions from maritime fuel [181]. The regulation sets rules and obligations to limit GHG intensity on energy used by ships accessing ports of an EU Member State and to use zero emission technology or on-shore power supply [182]. Before the regulation was final, IVL [176] estimated the use of hydrogen in Sweden based on the proposals in FuelEU Maritime. The result showed that out of the total energy use in shipping, the share of hydrogen will be zero in 2030 and 4.8% in 2050. For e-fuels, the estimation was also zero in 2030 and 23 % in 2050. E-ammonia and e-methanol are especially promising e-fuels for the shipping sector due to e.g., relatively low production cost and investment risk for infrastructure [169]. Although extent of the future usage is uncertain as there are challenges such as safety issues with ammonia and carbon sourcing for methane [169].176].

5.2.2 Steel industry

The steel market is one of the industries with the most concrete plans forward for the use of hydrogen and here Sweden is considered one of the world leading countries. The goal is for the Swedish steel production industry to be fossil-free by year 2045 [214]. Converting to hydrogen-based reduction of ore would require an additional 15 TWh in energy demand per year [190]. In addition to this, the steel industry has ambition to grow in the future. For example, LKAB's plans for iron refinery in Sweden would increase the electricity demand for the Swedish iron and steel industry by an additional 35 TWh, compared to today's electricity consumption of about 4 TWh [190].

Table 11. Translated steel production energy demand based on current production and energy demand-steel production ratio in the Swedish steel industry (red = calculated values). Assumption: the Swedish steel production is equivalent to world and Europe production methods, in terms of energy consumption

Year	Location	Annual production [Mt]	Energy demand for fossil free production [TWh]
2020	Sweden	4.7**	20*
2022	EU & UK & Other Europe	197.5	840.4
2022	World	1 796.7	7645.5
2023	EU & UK & Other Europe	196.7	837.0
2023	World	1 814.7	7722.1

* [167]
** [214]

E-fuel demand in this sector was excluded due to lack of information about this matter and the assumption that e-fuels will not be applied on a noteworthy scale within this sector.

5.2.3 Chemical industry

Hydrogen and e-fuels are forecasted to be used in different chemical industries. In a recent report, the current hydrogen demand of industries on the Swedish West Coast was estimated to 6.4 TWh per year [215]. The assumptions included operating time to be 8400 h/year and an electrolysis capacity of 65%. This value includes the use in bio-refineries, production of specialty chemicals and in bio-technology companies. The included companies cover about 90% of Sweden´s total hydrogen demand. The main use for these industries is hydrogen as a raw material. The future use in this cluster can either increase or decrease in the future, with the highest estimate at 14 TWh. A similar study for the Sothern region in Sweden, Scania, with estimated hydrogen demand to 15–25 tons H_2/day in 2025 and 25–35 tons of H_2/day in 2030 [216].

The chemical industry in Sweden specifically, uses approximately 27% of Sweden's annual consumption in 2020 of hydrogen (6 TWh) which equals 1.6 TWh [REF]. On a European level, based on a review study, the estimated total hydrogen demand expected in chemical industries by 2050 will be around 7-8 million tons (231–264 TWh) [124]. This refers to feedstock for European industries with a focus on ammonia and methanol production, a smaller part of the need is expected to come from the cement and pulp and paper industry. There are also some industries in Sweden that use/can use hydrogen to produce metallic powders and in reductions of other metals not included in the steel industry. Examples of these are Höganäs and Boliden [102][129]. Whether these types of industries are included in the overall chemical industry for Europe is uncertain. For feedstock use of hydrogen, mostly ammonia and methanol are mentioned which are the two large hydrogen consumers. The total amount of hydrogen needed for the chemical industry difficult to define.

Regarding demand for e-fuels within chemical industries, we primarily focus on e-methanol due to the limited extent of available information on future demand for different e-fuels. The consumption in Sweden is only registered statistically if it is classified as a fuel, leaving private actors to evaluate the total methanol consumption. The biomethanol company VärmlandsMetanol conducted a market study with information from Swedish methanol consumers Perstorp, Casco, Adesso etc. and concluded a total Swedish consumption of 300 000 tons of methanol per year in 2021 [217]. The total CO2-emissions from this consumption were estimated to 400 000 tons. To produce the same amount of methanol with hydrogen, it would approximately require 5 400 tons of hydrogen and 0.3 TWh of electricity per year. The total methanol consumption can be compared to Project Air by Perstorp, Uniper and Fortum which will produce 200 000 tons of sustainable methanol [218]. This amount will cover the total methanol consumption from Perstorp in Europe each year.

Globally, the overall consumption of hydrogen within the chemical sector is 46 MtH2/year, whereof the majority of the consumption goes to the production of ammonia and methanol demanding 31 MtH2/year and 12 MtH2/year respectively.

5.3 BARRIERS FOR HYDROGEN AND ELECTROFUEL UPTAKE

To gain insight into what obstacles the production and usage of hydrogen might give rise to, interviews were conducted with a broad range of actors that are connected to production and utilization of hydrogen and e-fuels in Sweden and Europe. The following section is a summary of their thoughts and experiences within the area.

A major barrier for the use of hydrogen is the lack of political instruments and regulations made for a hydrogen network. At the present time the instruments and regulations that are being used are not made, or meant for, hydrogen. The lack of standardization and clarification result in uncertainties when the actors are deciding upon investments. Clarifications needed are for example how hydrogen from the electrical grid is classified; what financial support that is available, and what taxes that the actors would be subjected to.

Furthermore, an opinion among actors in Sweden is that the permitting system and processes related to large-scale hydrogen and e-fuel production and usage are labor and time intensive as well as unpredictable. The time and more so, the predictability of the permitting system, are important factors that affect the actors' decisions regarding investments in hydrogen and e-fuel projects. A connection to acceptance and safety has been made in regard to the slow permitting system. To make the permitting process faster, acceptance from society plays a key role. It is therefore important to be able to prove that usage and production of hydrogen is safe to gain acceptance.

The lack of support system and uncertainty/unpredictability does, according to several actors, extend to EU-level as well. Combined with the high investment cost related to green hydrogen production, these are the main hinders reported regarding the usage and production of hydrogen. With the current energy crisis in mind, it will also be important to prove to that projects related to hydrogen production via electrolysis will not cause problems for the rest of society.

Other limiting factors for large scale production and utilization of hydrogen are the production capacity of electrolyzers and the hydrogen production dependency on the electricity spot prices [219]. To meet an increasing hydrogen demand, suppliers need to increase their production capacity of electrolyzers significantly. However, to be able to produce hydrogen from electrolyzers in a financially viable way it is important to be able to follow the electricity price fluctuations and produce hydrogen in line when the prices are acceptably low and avoid production when prices are too high [219]. To be able to utilize renewable, weather-based sources, such as solar and wind-power a buffer in the form of hydrogen storage will be of key importance.

An obstacle for use of hydrogen in road transport is the 2.5 times higher electricity consumption per kilometer compared to battery electric vehicles [194]. One contrasting advantage with hydrogen fuel cell vehicles is that battery-driven vehicles have a lower load capacity following the high battery weight – this is however likely to change in the future when technology development allows for smaller batteries. A stronger argument for hydrogen is that it takes more time charging a battery than filling up with hydrogen and this could save time, and with that money, for the transport companies. However, this future scenario is dependent on the implementation of a reliable hydrogen infrastructure which requires financial support from national states or the EU [194].

6 Scenario analysis

Scenarios of the future production potential and potential demand of hydrogen and electrofuels in Sweden for the period 2023-2045 have been developed based on the results from the previous chapters. The scenarios were developed to explore Sweden's potential role in the hydrogen landscape in the future, and whether it is likely that Sweden could become meet its demand with domestic production of hydrogen and maybe even become a net exporter. In the following sections the assumptions and the basis for the development of the production and demand scenarios are described and the results of the scenarios are presented and compared to each other. The results provide a wide span for the possible development and the dynamics between supply and demand. The results of the scenario analysis imply that the demand of hydrogen will likely be greater than the production potential up until about 2035. In 2045, the situation could be opposite, although there are many points of uncertainty for the analysis.

6.1 PRODUCTION POTENTIAL OF HYDROGEN AND ELECTROFUELS

The following section describes how the scenarios for the production potential of hydrogen and electrofuels were defined and developed. The parameters and assumptions that were used, as well as the results of the scenarios are presented and analysed.

6.1.1 Development of scenarios for production

The scenarios of the production potential are based on a mapping of hydrogen and electrofuels production plans in Sweden performed by IVL and Profu that is presented in Appendix – Hydrogen and electrofuel production plans. The data includes the amount of hydrogen produced and whether it is produced for production of electrofuels or not. Furthermore, the compilation of plans is divided of hydrogen for on-site purpose or off-site use. The mapped plans range from the year 2025 until 2035. The assumptions used throughout the scenario analysis are presented in Table 12.

Table 12. ***Assumptions used to develop the scenarios for the production potential and demand of hydrogen and electrofuels.***

Parameter	Value	Unit
Operating hours	8000	hrs/year
Electrolyzer efficiency	64	%
LHV (Lower heating value) of hydrogen	33.33	kWh/kg

The collected data was recalculated to the amount of electricity needed to produce the hydrogen in an electrolyzer, using the assumptions Table 12. The high capacity factor (8000 full-load hours = ~90%) reflects a continuous production strategy, with down-time resulting only from maintenance or avoidance of the highest electricity price peaks. Although there might be many different operation strategies for hydrogen production in the future, with a lower or higher degree of optimization in relation to the electricity price, the 8000 hours assumption was made to showcase the maximum for the production scenarios and that different operational strategies were not considered in-depth in the development of the scenarios. The corresponding installed capacity of the production scenarios are discussed in section 6.4.1.

The production potential scenarios were developed by extrapolation from the known production plans. The yearly increase was calculated from 2025 to 2035 for the mapped production plans and was thereafter used to extrapolate from 2035 to 2045. This will hereafter be called the base production case (Base prod). A sensitivity analysis was made of the base production case where 70% and 130% of the yearly increase was used to extrapolate from 2035 to 2045. The two cases are called the high production case (High prod) and the low production case (Low prod).

Furthermore, a scenario was developed where 80% of all plans from 2025 until 2035 were realized, as in reality there are often a certain share of plans that are not realized for various reasons. The same yearly increase as in the base production case was assumed. This scenario was named Base80. To capture the uncertainty related to the yearly increase, a sensitivity analysis was then carried out for the Base80 scenario in the same way it was done for the base production case. The two resulting cases are named Low80 and High80. The assumptions made to develop the different production scenarios are presented in Table 13.

Table 13. ***Assumptions made for development of the hydrogen production potential scenarios.***

Production scenario	Yearly increase (2025-2035)	Yearly increase (2035-2045)	Number of total plans (2023-2035)
Base prod	12.4%	12.4%	100%
High prod	12.4%	16.1%	100%
Low prod	12.4%	8.7%	100%
Base80	12.4%	12.4%	80%
High80	12.4%	16.1%	80%
Low80	12.4%	8.7%	80%

The resulting scenarios are visualized in Figur 10.

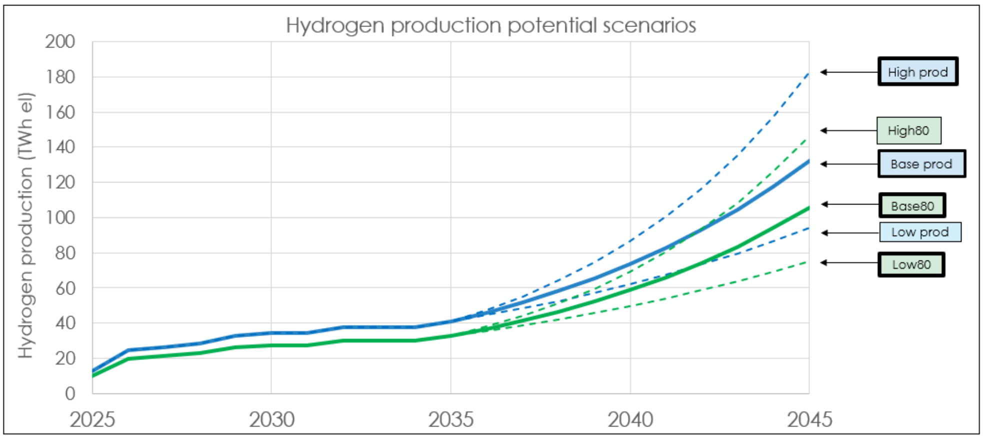


Figure 10. Visualization of the six scenarios for hydrogen production potential. The blue solid line represents the base case (Base prod) and the green solid line represent the Base80 scenario, while the dashed lines are the sensitivity analysis for the yearly increase of these two scenarios. The scenario cases whose names are marked with a bold square were selected for further study.

The blue solid line represents the base case (Base prod) and the green solid line the Base80 scenario. The dashed lines present the sensitivity analysis made of the yearly increase of the two scenarios. From the six developed scenarios, four (including High prod, Base prod, Base80 and Low80) were selected for further study and comparison with the demand scenarios. This selection was done to indicate the potential broad outcome i.e., including the highest and lowest scenario as well as the base scenario (Base prod) and the Base80 scenario, while the remaining 2 scenarios (Low prod and High80) were excluded. The reason for the exclusion was that the Low prod scenario is similar to the Base80 scenario and the High80 scenario is similar to the Base prod. The Low prod and High80 scenario would therefore not provide further information and were hence excluded from further analysis.

6.1.2 Context of the hydrogen production scenarios

The results from the SWOT-analysis in Chapter 1.5 and the information from the interviews in Chapter 3.3 were used to put the different production scenarios into a context. The scenarios are defined by how the barriers to an increased hydrogen production are addressed and overcome.

From the SWOT-analysis and the interviews with key hydrogen actors throughout the value chain in Sweden, it is conveyed that the main barriers for production of hydrogen are the lack of (clear) political instruments and regulations for hydrogen, in Sweden and the EU. An example of this is the variety of hydrogen definitions depending on markets/regulations/application (for example renewable and low-carbon hydrogen versus color-coded into green, blue, grey etc.) which leads to uncertainties and confusion which can impact investment decisions from actors.

Furthermore, it is mentioned that the Swedish permitting systems and processes for large-scale production of hydrogen is time intensive and unpredictable (which may partly be connected to the low acceptance and safety concerns from society regarding the management of hydrogen). Thus, there is a slow process to build out renewable energy sources in Sweden required for green hydrogen production. As a final note on the key challenges, a global limiting factor for increased hydrogen production is the lack of large-scale electrolyzer manufacturing.

Scenario 1 (High prod)

The *High prod* scenario (in which all mapped plans are realized followed by a higher continued introduction) represents a case where the renewable energy in Sweden is expanded, along with both new and clarified political instruments and regulation. In this scenario, Sweden also has introduced faster and more reliable permitting systems in addition to developed processes for large-scale production. The High prod scenario assumes that hydrogen storage and distribution technologies are developed and installed, resulting in increased safety and high societal acceptance. This combination of assumptions results in increased willingness for key actors to invest in the hydrogen value chain (including production, storage, and distribution). Thus, large-scale production of electrolyzers is facilitated.

Scenario 2 (Base prod)

The *Base prod* scenario (in which all mapped plans are realized followed by a continued expansion of hydrogen at the same pace) represents a case where political instruments and regulations promoting hydrogen are gradually adapted. The development of hydrogen technologies results in increased safety and higher societal acceptance. The permitting systems are thus improved, being both more reliable and time efficient. Furthermore, more renewable energy sources are gradually built out in Sweden, which facilitates the usage and production of electrolyzers.

Scenario 3 (Base80)

The *Base80* scenario (in which 80% of the plans from 2025 – 2035 are realized and with the same yearly increase as in the Base prod scenario) represents a case similar to the *Base prod* scenario. However, the development of the political instruments and the hydrogen infrastructure is somewhat slower than in the Base prod scenario. Thus, the hydrogen market develops somewhat slower.

Scenario 4 (Low80)

The *Low80* scenario (in which 80% of the plans from 2025 – 2035 are realized but with a slower yearly increase from 2030-2045 is slower than in the Base prod and Base80 scenario) represents a case where the mentioned barriers are not addressed. The time intensive permitting systems and lack of clear hydrogen regulations for production, storage, and distribution results in less investment decisions in hydrogen being taken. Furthermore, the slow development of renewable energy sources results in a lower potential to produce green hydrogen. The lower production potential and decreased interest in hydrogen production results in a slower development of the hydrogen infrastructure.

6.1.3 Scenario analysis – Production

The four selected hydrogen production scenarios are presented in Figure 11.

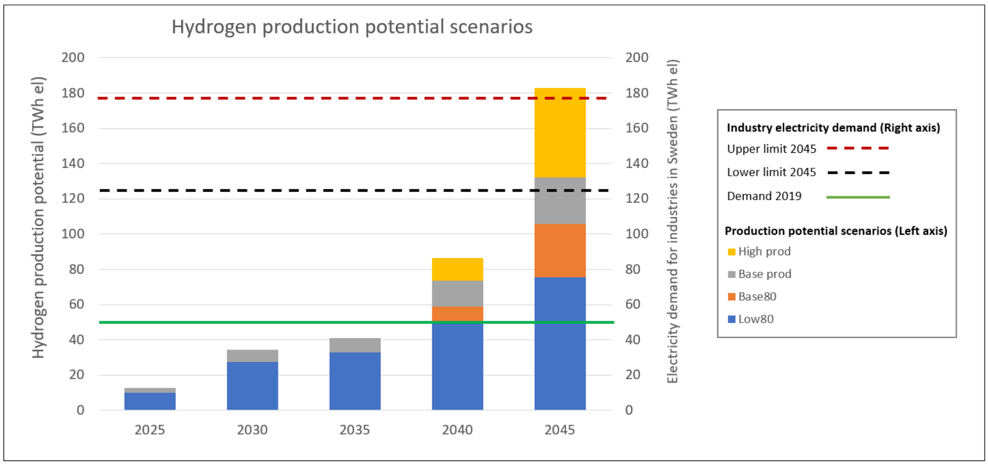


Figure 11. Hydrogen production potential scenarios from 2025 to 2045. The green dashed line indicates the industry electricity demand 2019 in Sweden of 50 TWh. The red and black dashed lines indicate the upper and lower estimated electricity demand from industries in 2045 from an investigation done by Profu and Energiforsk [220]. The lower estimated electricity demand is 122 TWh and upper range is 177 TWh.

The four scenarios are compared to the values of an investigation for the electricity need from Swedish industries including the chemical industry, the iron and steel industry, pulp and paper industry as well as new other industries in 2045 done by Profu and Energiforsk [220]. The current electricity demand for industry (2019) was calculated to be about 50 TWh and predicted to reach between 122 TWh and 177 TWh the year of 2045. The total electricity demand for Sweden was predicted to be within the range of 240 TWh to 310 TWh.

As can be seen in Figure 11, the current electricity demand of the Swedish industry is mainly related to other sources than hydrogen production. However, according to the developed scenarios, most of the industries electricity demand will be related to production of hydrogen by year 2045. Under the assumption that most of the electricity demand will be related to hydrogen production, the High prod scenario is well aligned with the predicted upper limit from Profu's and Energiforsk´s report, while the Base prod case is well aligned with the lower limit. The purpose of the plans for production of hydrogen can be divided into hydrogen produced for off-site use and hydrogen produced for use on-site. The on-site production can be divided into on-site production for electrofuels and on-site production for other purposes. Figure 12 shows the share of hydrogen produced for different purposes from 2025–2035. This division was only analyzed for the Base prod scenario and no extrapolation was done for 2035–2045. This is because the methods used for extrapolation of the total production plans for 2035–2045 would lead to too uncertain results if applied to the division between different usages of hydrogen.

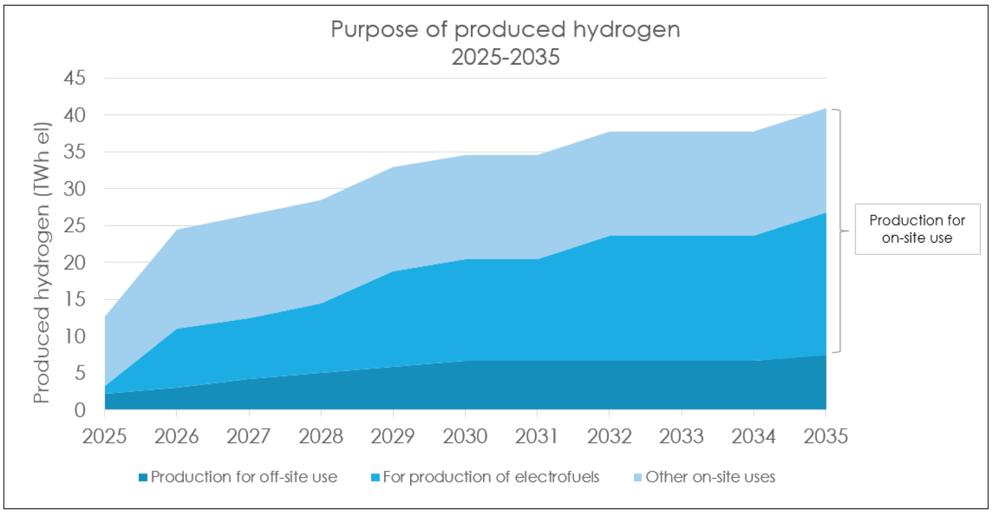


Figure 12. The amount of hydrogen that is produced for off-site use and on-site use. The hydrogen produced on-site is divided into hydrogen produced for electrofuel production, and hydrogen produced for other on-site uses.

As can be seen, the majority of the plans until 2035 are aimed for production of hydrogen for on-site use with an increasing amount of hydrogen used for production of electrofuels. In

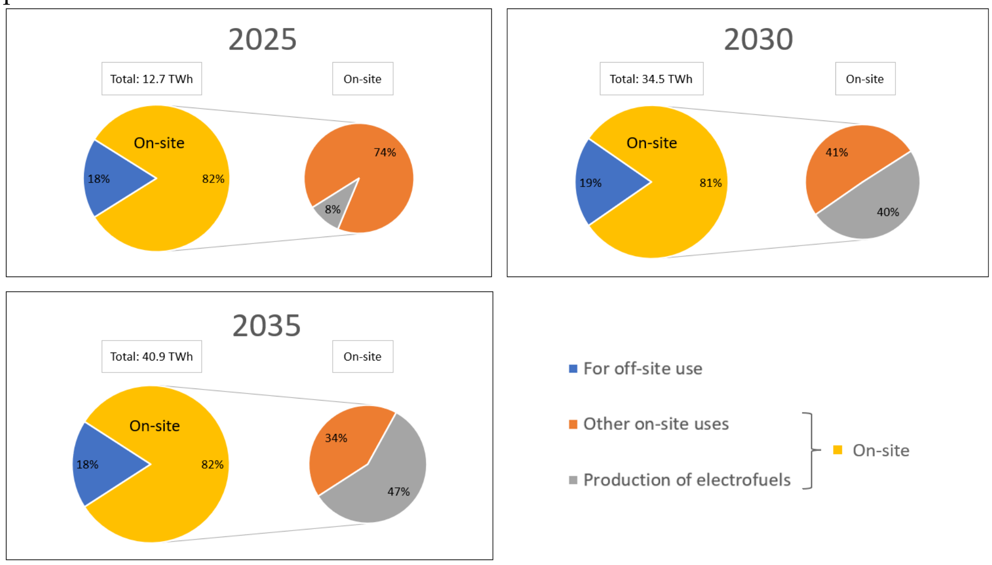


Figure 13, the share of hydrogen for different purposes are presented more in detail for the year 2025, 2030 and 2035.

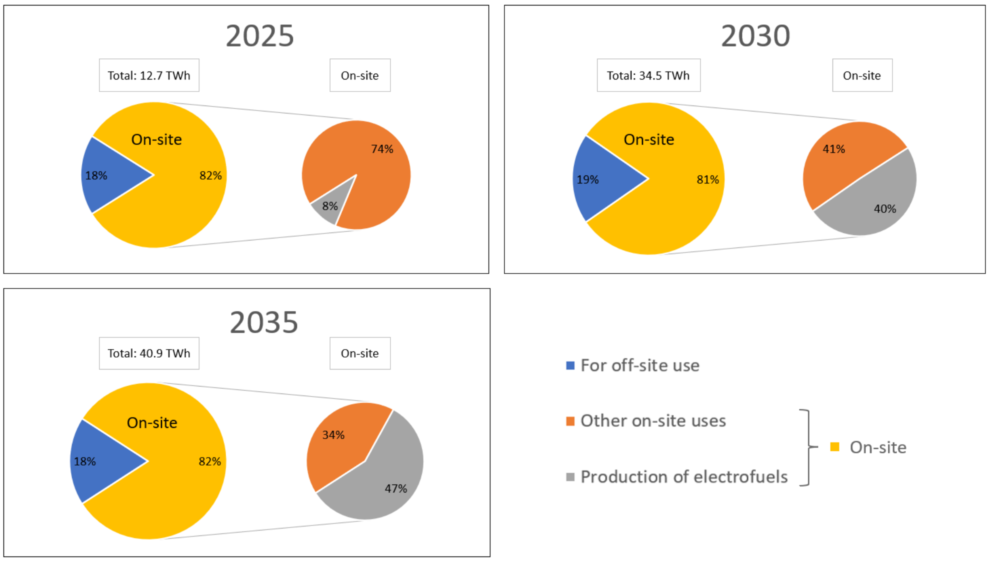


Figure 13. Percentage of produced hydrogen for on-site use (production of electrofuels and other uses) and for off-site use for the years 2025, 2030 and 2035. The large pie-chart shows the division of on-site production (yellow) and production for off-site use, while the small pie-chart shows the division of on-site production for the production of electrofuels and for other purposes.

From 2025 and onward, there is an increased total production of hydrogen. The share of hydrogen produced on-site for the purpose of producing electrofuels increases from 2025 until 2035 and in 2030, the hydrogen produced for on-site use for production of electrofuels is equal to the hydrogen produced on-site for other uses. By 2035 the production of electrofuels is the major reason for on-site production of hydrogen. The production of hydrogen for off-site use increases from 2025 until 2035. However, the share of hydrogen produced for off-site use stays at about 20% of the total hydrogen production.

6.2 POTENTIAL DEMAND OF HYDROGEN AND ELECTROFUELS

The following section describes how the scenarios were developed for the potential future demand of hydrogen and e-fuels in Sweden for 2025-2045. The results of the scenarios of the future demand are presented and discussed.

6.2.1 Development of hydrogen demand scenarios

The demand scenarios were developed in steps. The first step was to develop a base case, a low- and a high case scenario for each investigated sector (transport, steel industry and chemical industry). The transport sector was further divided into road transport, aviation, and shipping. Each sector was also divided into hydrogen demand, and demand for hydrogen for e-fuels. The low-, base- and high case scenario for each individual sector were thereafter combined into low, base, and high scenarios for the total potential hydrogen demand in Sweden. How the different cases were developed for each sector is described below.

In the developed scenarios, the hydrogen used for production of electrofuels that later will be used on-site is expressed as a hydrogen demand rather than an electrofuel demand. Therefore, the developed scenarios might not accurately express the total future demand of electrofuels. The electrofuel demand expressed in the developed scenarios is instead representing the possible demand of electrofuels that are produced for off-site use.

Transport sector

The transport sector was divided into three sub-categories: road transport, aviation, and shipping.

Road transport

The scenarios developed for road transport were based on the material presented inn Table 14 (which are also described in Chapter 3). For the scenarios regarding electrofuels, the projected energy demand from transport in Sweden [221] was multiplied with the projected share of eletrofuels that are forecasted to be present in the Nordic [222]. This Nordic forecast had a base, low and high scenario which was also used in this analysis. For the hydrogen demand scenarios, the capacity of hydrogen charging stations granted with governmental financial support [223] was the basis for the base scenario. About 40 charging stations with a capacity of 1500-2000 H2/day are planned to be active by 2025 [223]. From 2025, a linear extrapolation until 2045 was applied. A sensitivity analysis was then carried out where the yearly increase was changed to 70% and 130% of the base case. The results of the sensitivity analysis were used as the low and high case scenario for road transport. The yearly increase for each case is presented in Table 15.

Table 14. ***Material used to develop the road transport scenarios.***

Source	Description	Data usage	Data management
Swedish Energy Agency, 2023 [221]	The Swedish Energy Agency has published various future scenarios for Sweden's energy system with a focus on electrification until 2050.	Values for future transport energy demand (p.100, 105 and 110).	The Swedish transport energy demand (minus the use for aviation, train and shipping) was multiplied with the predicted percentage share of electrofuels from Nordic Energy Research (2022).
Nordic Energy Research, 2020[222]	Analysis of the Nordic region's future use of electrofuels within road transportation.	Future share of electrofuels of total road transport (p. 31)	
Swedish Energy Agency, 2023 [223]	Description of status and review of assignments, regulations, government support, financial support, and requirements regarding programs for hydrogen infrastructure.	The number of hydrogen charging stations granted from the governmental financial support called Klimatklivet and Regional electrification pilots (p.17)	The number of hydrogen charging stations: - 13 stations funded by the Regional electrification pilots with capacity of at least 1 500 kg H2/day - 27 stations funded by the Klimatklivet with capacity of at least 2 000 kg H2/day Each station has to be active for minimum 5 years. The capacity and life span are conditions to get funding.

Table 15. ***Yearly increase for road transport for low, high, and base case.***

Case	Yearly increase	Unit
Base	0.36	TWh/year
High	0.47	TWh/year
Low	0.25	TWh/hear

Aviation

Scenarios for aviation were based on the material presented in Table 16 (also described in Chapter 3). The base case scenario for hydrogen was built on values for projected future aviation energy demand in Sweden and forecasted share of hydrogen and e-fuels in Norway based on modelled results from DNV's Energy Transition Outlook. Values for Norway were considered appropriate to apply on Sweden due to the countries' similar context. The high scenario case for hydrogen and e-fuels was based on the EU goals set in the ReFuel Aviation Initative for including synthetic fuels in aviation. The low scenario was formed like the sensitivity analysis for the steel sector where the yearly increase was changed to 70% compared to the base scenario.

Table 16. ***Material used to develop the scenarios for aviation.***

Source	Description	Data usage	Data management
Swedish Energy Agency, 2023 [221]	The Swedish Energy Agency has published various future scenarios for Sweden's energy system with a focus on electrification until 2050.	Values for future use of aviation energy demand (p.100, 105 and 110)	High scenario: The value for future aviation fuel in Sweden was multiplied with the EU goal of share of synthetic fuels in aviation fuel.
ReFuelEU Aviation Initiative, 2021	ReFuelEU Aviation Initiative is included in the Fit for 55 package from the European Commission with aim to reduce GHG emissions.	The goals for including synthetic fuels (incl. hydrogen and e-fuels) in aviation fuel.	
DNV, 2023 [224]	Fuel demand forecasts using the Energy Transition Outlook data 2023.	Data for aviation hydrogen fuel and e-fuels for Norway (data for Sweden did not exist). The data is derived from the ETO dataset.	Base scenario: The value for future aviation fuel in Sweden was multiplied with the projected use of hydrogen and e-fuels for aviation in Norway (DNV, 2022)

Shipping

The scenarios for shipping were based on scenarios developed by IVL in 2022 [225]. The high scenario is based on scenario 5 in the mentioned work and the low scenario assumes that there will be no inclusion of hydrogen and e-fuels in the shipping sector. The base case scenario for shipping is an average of the high and low scenario.

Steel industry

The scenarios in the steel industry were mainly based on a press release from LKAB [226] and the plans of H2 Green Steel since these two stands for a significant part of the Swedish steel industry's hydrogen demand. They both plan to cover their demand by producing hydrogen. In LKAB's press release, they state that their electricity demand for hydrogen production is predicted to be 20 TWh 2030, 50 TWh 2040 and 70 TWh 2050. The production of H2 Green Steel is assumed to start 2025 and reach full capacity of about 14 TWh_{el} 2030.

Based on this information, the base case was developed where the hydrogen demand for the steel industry would be according to LKAB's press release, with a linear development between each year. In addition, the plans of H2 Green Steel were included with a linear development between 2025 – 2030. The high scenario was developed based on the same values; however, it was assumed that the development of LKAB's plans would be faster. In the same way, the low scenario was developed by assuming a slower development than stated by LKAB. The values used to develop the scenario from LKAB's data are presented in Table 17.

Table 17. ***Assumptions made about the development of LKAB's hydrogen demand. The year when the demand (20, 50 and 70 TWh) is reached are presented for each case.***

	Base case	High case	Low case
20 TWh	2030	2025	2035
50 TWh	2045	2040	2045
70 TWh	2050	2045	2055

The values were combined with the plans of H2 Green Steel and the demand of 2025 as well as the yearly increase from 2025 – 2045. The yearly increase is presented in Table 17. . It is assumed that no electrofuels will be used within the steel sector.

Table 18. ***Assumptions made for the hydrogen demand in the Swedish steel industry. The demand 2025 as well as the yearly increase for each scenario is presented.***

	Demand 2025 (TWh_{el})	Increase (TWh_{el}/year)			
		2025 - 2030	2030 - 2035	2035 - 2040	2040-2045
Base case	10	4.79	3	3	2
High case	20	5.79	3	2	2
Low case	9.45	4.12	1.33	3	3

Although the scenarios are developed based on the plans of LKAB and H2 Green Steel, the aim is that they should represent a range that also could encompass the plans of other actors within the steel sector with a lesser contribution to the overall demand.

Chemical Industry

The demand for hydrogen in the chemical sector was developed based on the values from [227]. According to the report, the national demand of hydrogen in

Sweden is about 7.3 TWh [[227]. Furthermore, it is stated that the demand on Swedish West Coast stands for 90% of the total hydrogen demand in the chemical sector in Sweden. The scenarios for the chemical industry were based on the assumption that all hydrogen would be produced via electrolysis. Based on these assumptions the electricity demand required to cover the current demand of hydrogen would therefore be 10.9 TWh_{el}.

In the mentioned work [227] it was predicted that the demand on the Swedish West Coast would either increase to 14 TWh or decrease to 4.9 TWh by 2045. Based on this information and previously explained assumption, the electricity demand required if the entire chemical sectors hydrogen demand would be covered was calculated to 23.2 TWh_{el} and 8.1 TWh_{el} for the high and the low case respectively. The base case was taken as an average of the two values. A linear increase/decrease from 2025 to 2045 was assumed.

The demand for hydrogen for electrofuels in the chemical industry was calculated using the assumption that all electrofuels in the chemical industry is e-methanol and that the annual percental increase of methanol is equivalent to what is expected for Europe. Based on the values from and the estimation that the methanol demand in Sweden in industry was 300 000 tons/year in 2021 [217], the total amount of methanol was calculated from 2025 – 2045. The base, high and low case was developed by assuming 50%, 80% and 20% of the methanol demand in the industry would be e-methanol.

It is important to mention that part of the chemical industries hydrogen demand could be for production of electrofuels to be used on-site. These values would, in the developed scenarios, be expressed as a hydrogen demand, rather than an electrofuel demand.

6.2.2 Context of hydrogen demand scenarios

The description for the high-, base-, and low hydrogen demand scenarios are presented in the following section.

Scenario 1 (High demand)

The high demand scenario represents a case where the development within the steel industry is fast. In the chemical sector there is an increased demand for hydrogen due to development of new value chains for production of fuels and products from processes such as hydrodeoxygenation for upgrading of bio-oils and an increased introduction of CCUS solutions. The road transport sector sees an increased energy demand with a relatively high share of hydrogen and e-fuels. This is a result of development of hydrogen and fuel cell vehicles, leading to a lowered production cost of the vehicles. Furthermore, the development of hydrogen infrastructure and fuel stations as well as development of renewable electricity production contributes to the development of hydrogen for road transport. In the maritime sector, there is an introduction of hydrogen and e-fuels from 2035 as a result of the fit-for-55 policy package and related legislation in the EU.

Scenario 2 (Base demand)

The base demand scenario represents a case where the development within the steel industry is slower than in the high demand scenario. The development in the chemical sector is also somewhat slower than in the high demand case. Within road transport, the development of hydrogen infrastructure and fuel stations are to some extent inhibited by the lack of clear regulations and reliable permitting systems and processes. There is an introduction of hydrogen and e-fuels in the maritime sector, however the share is lower than in the high demand case.

Scenario 3 (Low demand)

The low demand scenario represents a case where the development within the steel industry is slower than in the previous scenarios. The development within the chemical sector results in a reduced hydrogen demand due to reduced production volumes and a transition to more refined raw material [227]. Furthermore, the strong development of electric vehicles and continued use of biofuels results in a very low share of hydrogen (or electrofuels) within the road transport sub-sector. Within the maritime sector, no hydrogen or electrofuels are introduced into the fuel mix before 2045.

6.2.3 Scenario analysis – Demand

The hydrogen demand scenarios are presented in Figure 14. The presented scenarios include the demand for hydrogen as well as the demand for hydrogen for production of electrofuels. According to the scenario analysis the demand could fall between 17.5 – 34.7 TWh_{el} 2025 and increase to 48.5 – 100.3 TWh_{el} 2035 and 81.8 – 144.5 TWh_{el} 2045.

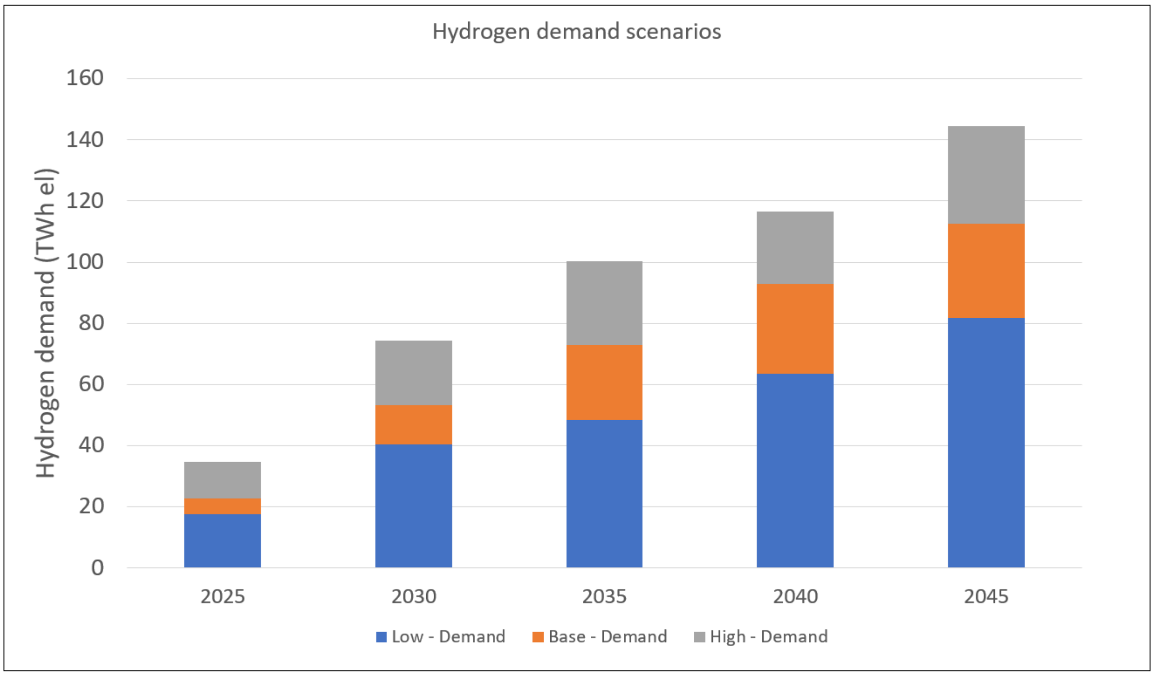


Figure 14. Scenarios for potential hydrogen demand in Sweden for 2025 to 2045.

Figure 14 shows a range of the total demand of hydrogen for 2025 – 2045. The demand in percentage for each sector for the three scenarios for 2030 and 2045 are presented in Figure 15.

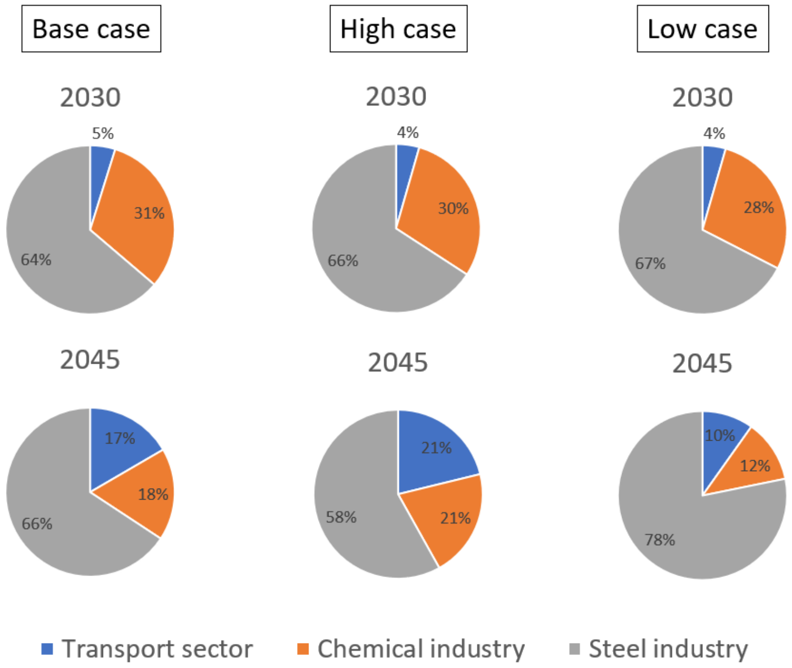


Figure 15. Demand of hydrogen for each sector the year 2030 and 2045 for the base, high and low scenario.

The division for the different cases is similar 2030. The majority (64% – 67%) of the demand 2030 is due to the steel industry. However, a substantial part of the demand can be related to the chemical industry (28% – 31%). The demand of hydrogen in the transport sector constitutes 4% - 5% of the total demand 2030. The year 2045 the share related to the steel industry constitutes between 58% – 78% of the hydrogen demand. The transport sector is between 10% – 21% and the chemical industry is between 12 – 21%.

The overall results shows that the steel industries will keep being the major consumer of hydrogen, and the demand from the steel sector will keep increasing up until 2045. The demand of hydrogen within the transport sector will mainly increase after 2030 up until 2045 while the demand of the chemical industry might either decrease or increase from 2030 until 2045. The division between hydrogen demand for electrofuels and for other purposes for the three cases are presented in Figure 16.

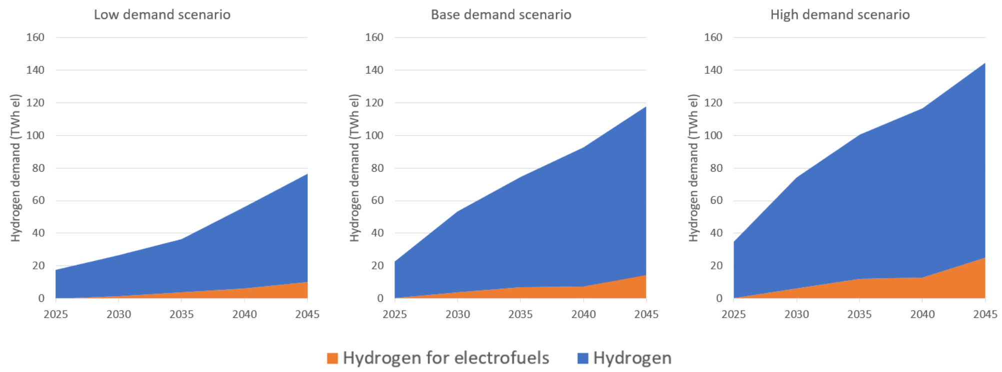


Figure 16. Share of total hydrogen demand that is needed for e-fuel production for each case.

The demand for electrofuel production has a slower increase in the low case scenario and reaches about 10.2 TWh_{el} 2045. For the base case and high case, there is a larger increase in hydrogen demand for electrofuels from 2025 to 2030. In the base case the hydrogen demand for electrofuel production is about 14.6 TWh_{el} 2045 and in the high case the demand is about 25 TWh_{el} 2045.A comparison of the potential hydrogen demand in the scenarios in this project and the hydrogen demand scenario presented by the Swedish Energy Agency [221] is presented in Figure 17.

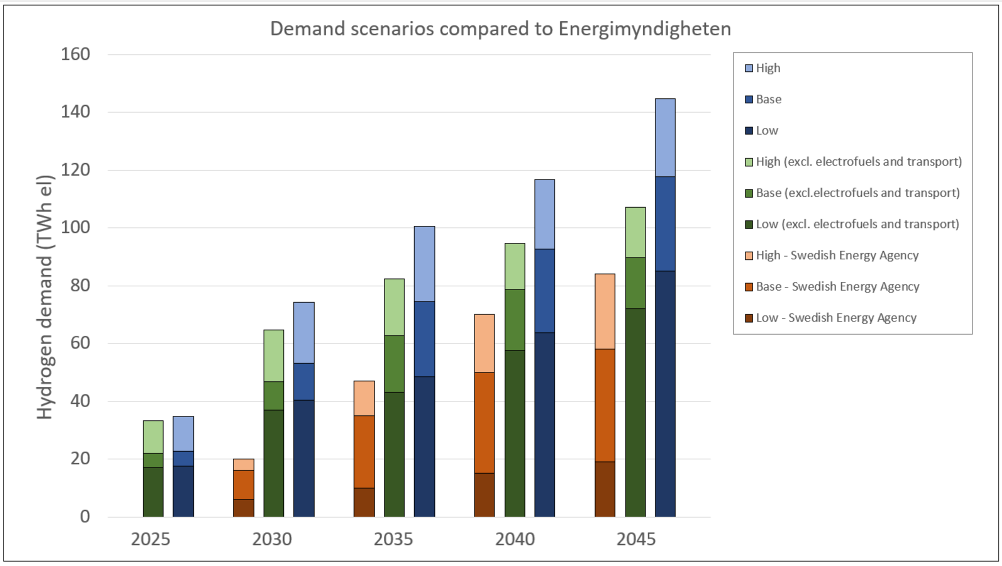


Figure 17. Demand scenarios in this study (blue) compared to scenarios developed by the Swedish Energy Agency (red). The scenario marked in green represent the scenarios in this study but excluding the demand for electrofuels and hydrogen for transport which is not assessed in the scenarios by the Swedish Energy Agency.

In the work done by the Swedish Energy Agency, the use of electrofuels and hydrogen within the transport sector were not assessed. Thus, the result of the Swedish Energy Agency´s scenario analysis was compared with both i) the scenarios from this work and ii) the scenarios from this work excluding the estimated demand for electrofuels and hydrogen in the transport sector.

Comparing the results to the Swedish Energy Agency, the possible demand for 2025 is higher in this work. According to the work done by the Swedish Energy Agency, the demand for hydrogen will reach a critical phase by 2030. In this work it is assumed that projects related to hydrogen that are planned to be finished around 2030 gradually will increase from 2025 reach their full capacity by 2030.

From the year 2030 to 2040 the Swedish Energy Agency's results shows a faster increase of hydrogen demand compared to the scenarios depicted in this work and by the year 2040, the high scenario by the Swedish Energy Agency is similar to the high case scenario in this work when demand of electrofuels and hydrogen for transport are excluded. However, the low case scenario presented by the Swedish Energy Agency is much lower than the low case scenario in this report. The demand scenarios developed in this report shows a higher and narrower range than the scenarios developed by the Swedish Energy Agency.

The year 2045, the hydrogen demand presented in this report exceeds the demand presented by the Swedish Energy Agency. The high case scenarios are similar if the transport sector is excluded, while if the transport sector is included there is a 60 TWh_{el} difference between the results. The low case scenario made in this report is similar to the base scenario from the Swedish Energy Agency if the transport sector is excluded, and similar to the high scenario if the transport sector is included.

In conclusion, the potential demand for hydrogen estimated in this work is higher than that of the Swedish Energy Agency. The main reason for the large difference is related to the use of hydrogen within the steel industry. The use of hydrogen in the steel industry is mainly connected to a few large actors. In this work it is assumed that there will be an increased hydrogen demand in accordance with the plans and goals revealed by these large actors. In the work done by the Swedish Energy Agency, the low demand scenario is represented by that there is no increase in extraction of iron ore, and as a result less hydrogen is required from electrolyzers for direct reduction.

6.3 COMPARISON OF POTENTIAL HYDROGEN PRODUCTION AND DEMAND

The comparison of the production and demand scenarios are presented in Figure 18.

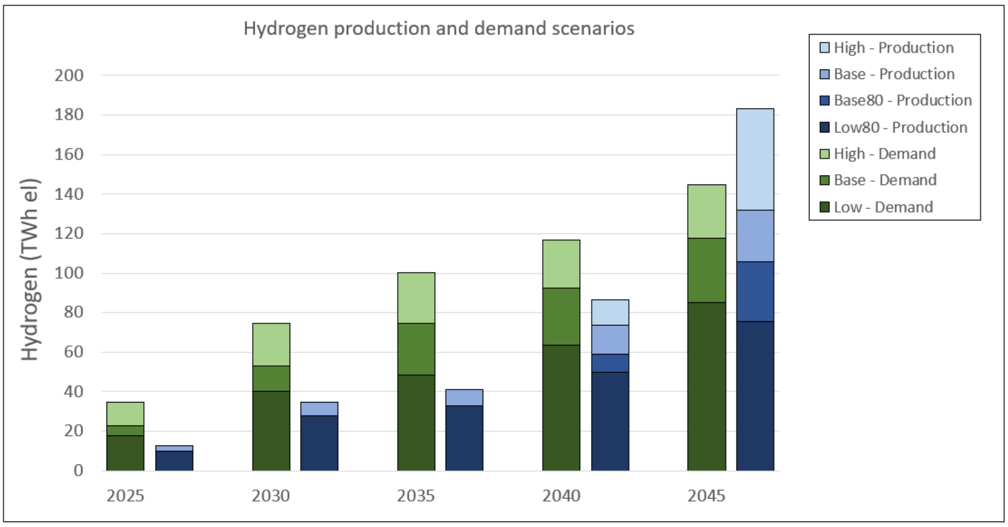


Figure 18. Production potential and demand scenarios for hydrogen. The production and demand of hydrogen for production of electrofuels are included in the presented scenarios.

The estimated potential hydrogen demand is greater than the production potential for base and high demand scenarios in 2025 – 2035. In 2030 and 2035 the demand for hydrogen could be met if the production of hydrogen reaches the upper end of the production potential. The production increases faster from 2035 to 2040 while in 2040–2045 the production potential might surpass the hydrogen demand.

6.4 SCENARIO ANALYSIS DISCUSSION

6.4.1 Production scenarios

The production scenarios are based on mapped available plans from 2025 to 2035 for producing hydrogen from electrolyzers in Sweden. From 2035 to 2045, the scenarios are based on the assumption that there will be a continuous yearly increase of hydrogen production that is varied among the scenarios to capture the uncertainty. The scenarios are not aimed to predict the future but rather to give a range of possible outcomes. The scenarios result in a hydrogen production potential that ranges from 75 to 183 TWh_{el} in 2045. Compared to the predicted electricity demand for industry (which is within the range 122–177 TWh), this is a broad range, but the future hydrogen production is also very uncertain. If this amount is produced in facilities operating 8000 hours per year (as initially assumed in Table 12) the corresponding installed capacity in 2045 ranges between 9 and 23 GW_{el}. The 8000 full-load hours reflect a conservative assumption of the installed effect, but if an assumption of 6000 h is made instead (equivalent to a capacity factor of roughly 70%), the installed effect would instead be 13-30 GW_{el}. Therefore, a span for the installed capacity of 9-30 GW_{el} would cover a wider range of operation strategies. The span is in the same range of order as the installed capacity of 15 GW in 2045 suggested in the strategy proposed by the Swedish Energy Agency [5]. However, regardless of whether the installed capacity would be closer to 9, 15 or 30 GW_{el}, there will likely be implications for the electricity system on a local, regional and national level resulting from the oncoming load from hydrogen production.

At present it is uncertain how much of the future production of hydrogen will be produced for off-site use and on-site use for electrofuel production or other purposes. Therefore, it has not been estimated for the period 2035 – 2045. However, the trend that can be seen from the current plans (up to 2035) is that there is an increased share of produced hydrogen allocated to the production of electrofuels, while only a minor increase in the production of hydrogen for off-site use. At present, the majority of the produced hydrogen is produced for on-site use. To facilitate production of hydrogen for off-site usage, the infrastructure for storage and distribution of hydrogen has to be developed [223].

6.4.2 Demand scenarios

The hydrogen demand scenarios were developed based on reports, industry data and other scenario analyses. The overall method was linear inter- and extrapolation from datapoints found through the literature search. A low-, base-and high case scenario were developed for each sector (transport, steel, and chemical sector) which was thereafter combined into one total low-, base- and high demand scenario.

The steel and metals industry stand for the largest part of the potential hydrogen demand. The scenarios assume that the steel industry will use hydrogen in all scenarios, but that the development will occur with different rates of increase. The development within the steel sector could both be dependent on the development of hydrogen infrastructure and on the development of the electricity grid capacity. Since the current electricity demand for the entire industry (including the chemical industry) is about 50 TWh_{el}, and the predicted demand for hydrogen in steel industry ranges from 64 to 84 TWh_{el} year 2045 depending on the developed scenarios, the rate of development in the steel and iron sector will be determined by the development of the electricity grid capacity in Sweden as well as the development of hydrogen infrastructure.

At present it is uncertain if the hydrogen development in the chemical industry in Sweden will increase or decrease. Since the chemical sector generates hydrogen as a byproduct and the processes and feedstock might change, it is difficult to predict the development in the chemical sector.

The hydrogen demand in the transport sector is dependent on development of vehicles and infrastructure for storage and distribution of hydrogen. It is likely that light road transport will use electricity rather than hydrogen while for heavy road transport hydrogen might be more attractive. In the shipping sub-sector, hydrogen or electrofuels as fuels might not be introduced until around 2035. The development after that is uncertain. Furthermore, it is uncertain if there will be a hydrogen and electrofuel demand on the levels assumed in the high demand scenario, which is based on the successful implementation of certain EU policies. However, hydrogen-based fuels are expected to be used in this sector as battery-electric options and biofuels have limitations particularly for certain segments. The development within the shipping sub-sector is dependent both on hydrogen infrastructure and development of carbon capture and storage technologies.

6.4.2.1 Production and demand combined

Based on the scenario analysis, there is a possibility that Sweden could be either a net importer or exporter of hydrogen. Until 2035, the demand for hydrogen is larger than the production potential. Depending on the development of the hydrogen infrastructure, the lower production of hydrogen could either result in import of hydrogen or that the lack of produced hydrogen slows down the development. With an increasing production potential from 2035 until 2040 the increasing hydrogen demand can more readily be met, which in turn could be an incentive to increased usage of hydrogen as well as development of hydrogen infrastructure. The tipping point might come between 2040 and 2045 where the production potential of hydrogen might surpass the demand and a developed infrastructure could lead to export of hydrogen.

It is important to mention that the demand and production scenarios were developed independently of each other. In reality, the demand and production are connected, and many large actors will produce hydrogen to meet their own demand. Since the scenarios are developed independently of each other, this is not reflected. However, the aim of the developed scenarios is not to predict the future demand and production of hydrogen, but rather to present a possible range of outcomes for the production and demand of hydrogen in Sweden up until 2045.

7 SWOT analysis for hydrogen and electrofuels

The aim of this chapter is to provide an overview of what strengths, weakness, opportunities and threats hydrogen and electrofuels have and face in Sweden, considering primarily the production, storage and distribution. The analysis and discussion are based on all previous sections of the report.

7.1 STRENGTHS, WEAKNESSES, OPPORTUNITIES AND THREATS FOR HYDROGEN

The SWOT analysis is based on the compiled information on the most or least promising cases for hydrogen, and from stakeholder interviews presented in more detail in chapter 5. As discussed previously mentioned in the report, the viability of hydrogen is case-dependent and strongly affected by local aspects Table 19 below presents a summary of the SWOT analysis for hydrogen in Sweden. [illegible]

Table 19. Summary of SWOT analysis for production, storage and distribution of hydrogen.

	Production	Storage/distribution
Policy	Threat	Weakness
Legislation	Weakness	Weakness
Permitting process	Threat	Threat
Active producers/users	Strength	Weakness
Technological readiness	Strength	Weakness and Strength
Supply chain	Threat	Strength
Environmental impact	Strength or Threat	Threat
Cost	Weakness	Threat
Resources	Weakness and Opportunity	Opportunity
Skills	Weakness	Strength
Sector coupling	Opportunity	Opportunity
Public perception	Threat	Threat
International influence	Weakness	Strength

Strength **Weakness** **Opportunity** **Threat**

Some threats are considered independent of which part of the value chain is considered. Such as:

- Environmental impact of hydrogen slip now being considered

Energiforsk

- Lack of clear legislation and standards regarding hydrogen installations
- Public perception of danger, affecting the social acceptance of hydrogen-based solutions

The overall the most frequently highlighted obstacles for the hydrogen value chain in Sweden were policy (based on the political environment), legislation, and permitting processes. Overarching strengths and opportunities were Sweden's renewable energy capacity, the large industry interest, and the possibility of interaction between sectors. A more detailed description on these aspects is provided in the belo Table 20.

Table 20. SWOT analysis of production, storage and distribution of hydrogen

	Strengths	Weaknesses	Opportunities	Threats
Production	Potential for extensive renewable electricity production The high amount of stakeholders interested in using H2 in northern Sweden Possibility to utilize fluctuations in electricity price Balance the electricity grid Sweden connected to Northern countries – opportunity to use excess electricity (depending on transition strategy of those countries	Local availability of pure water Lack of skills and know-how Sweden's visibility on the international arena Earlier electrolyzer degradation with varied demand Lack of legislation on how to handle/manage H2 It is easy to get locked into one type of technology	Swedish bidding areas may be exempt from additionality principles in the RFNBO definition Exploit electricity price fluctuations Experienced in usage of residual hydrogen from other industrial processes Utilize other products from hydrogen production for more circularity and better economics. Production from waste for further circularity Coupling to different sectors and actors, heating, food processing Collaboration with the electricity companies Wind energy build-out	Definition of biogenic H2 by the EU is unclear Decision makers consider H2 a plan B Lack of legislation for building production facilities Slow process to build out renewable energy sources in Sweden Competition with other fuels in some sectors

	Strengths	Weaknesses	Opportunities	Threats
Storage/ Distribution	Experience with LRC storage for methane. Concept could be replicated Good knowledge of storing gases in gas tubes and pipelines Good railway infrastructure	Low volumetric density More safety and requirements are needed on the storage of hydrogen compared to other fuels.		Lack of hydrogen infrastructure, Limited large-scale storage methods available (for example lack of salt caverns)

7.2 STRENGTHS, WEAKNESSES, OPPORTUNITIES AND THREATS FOR ELECTROFUELS

The below results are a qualitative compilation based on the data gathered in discussions (in the working and reference groups), during interviews, and based on the literature survey. Along the value chain of electrofuels from production to storage and distribution, there are many aspects to consider. The most critical for the implementation of e-fuels threated on a high-level not distinguishing between type are illustrated in Table 21 from the Swedish perspective. The more detailed information is described in Table 22.

Table 21. SWOT analysis for production, distribution and storage of electrofuels.

	Production	Storage/distribution
Policy	Threat	Strength
Legislation	Threat	Strength
Permitting process	Threat	??
Active producers/users	Opportunity	Strength
Technological readiness	Weakness	Weakness, Strength
Supply chain	Opportunity	Strength
Environmental impact	Strength or Threat	Weakness
Cost	Threat	Strength
Resources	Weakness	Weakness
Skills	Strength	Strength
Sector coupling	Opportunity	Opportunity
Public perception	Strength	Strength
International influence	Strength	Strength

Strength **Weakness** **Opportunity** **Threats**

Based on the most or least promising applications.

Table 22. The key aspects of the SWOT analysis.

	Strengths	**Weaknesses**	**Opportunities**	**Threats**
Production	Swedish and European actors active in Sweden Sweden has raw material and renewable energy There has been market for the substances previously Can support decarbonization of hard-to-abate sectors that cannot be electrified	Volatile electricity prices. Toxicity or ecotoxicity of some e-fuels Energy intensive production processes Lower overall efficiency from power to e-fuel European actors have different prerequisites may affect international trends CO2 capture technology	Increase in interest in fuels for aviation by policy means Market potential big: Fuel for shipping, aerospace Available CO2 from combustion plants, available N2 from air Several significant plans for production of e-fuels, energy crisis within the EU (REPowerEU) European actors have different prerequisites possible export	Lower prices for renewable electricity in other countries, Market potential is small: chemical industry Competing fuels (e.g., biofuels) Electricity market reforms and electricity availability Policy for source of CO2 Competition for resources between different types of electrofuels All electrofuels are not carbon neutral

	Strengths	Weaknesses	Opportunities	Threats
Storage/ Distribution	Electrofuels that are liquid fuels, can be handled similarly to diesel. More energy dense than pure H_2, does not require liquefaction, could exploit synergies with existing fuel infrastructure Could be stored for long durations Shipping actors with experience and interest. Most electrofuels are not new and there is experience on handling them.	Toxicity and ecotoxicity Some substances are very corrosive Gaseous fuels are still not strong in Sweden	Utilize existing infrastructure Lower cost build-out Established standards	Repurposing of current infrastructure for hydrogen Integration of different fuels safely on one site

8 Discussion and outlook

Judging from the abundance of renewable resources, it certainly seems possible that Sweden could become a producer of hydrogen and even a future exporter. The industrial initiatives and their strong commitment in reducing their climate impact also makes it clear that there is a demand for hydrogen in Sweden. Therefore, the role of hydrogen in the Swedish climate transitions could be distilled to one of prioritization of resources.

The holistic perspective on hydrogen production versus direct use of electricity and biofuels

On earth, gaseous hydrogen is not an abundant natural resource that can be harvested or tapped from large undisturbed reservoirs. Instead, hydrogen gas is formed in chemical processes where one raw material source is converted to H_2, often with the addition of external energy. In this report, two main routes are discussed: hydrogen production through i) Electrolysis of water, and ii) conversion of biomass. For both routes the energy content of the hydrogen gas exiting the process is less than the total energy supplied to the process. Hence, the conversion includes energy being lost to other species or in other forms and the efficiency is thus less than 100%. One may argue therefore that the production of hydrogen is thermodynamically unsound and should not be advocated. But despite the energy lost, there are many more than a few instances where hydrogen is preferred compared to electricity or biogenic feedstock. Nevertheless, it is not trivial to determine when conversion to hydrogen is justified as it depends on many factors and parameters. In this section, several of these will be addressed and exemplified, but the list will not be completely comprehensive as each individual hydrogen production situation is unique and cannot be generalized in all its aspects. There are three main aspects of hydrogen production that can influence the outcome whether it is sound or not to convert other resources to hydrogen: technological, market-related, and environmentally related.

Technological aspects include circumstances related to the production, distribution, and usage of hydrogen. As mentioned above, when hydrogen is produced, side-streams of material and energy are also produced as by-products. The possibility to utilize the by-products in a reasonably satisfactory way can greatly influence the overall economy of the hydrogen value chain and therefore, it can in many cases make sense to co-localize such production to where utilization of by-products is feasible and to apply economy of scale when doing so. On the other hand, a distributional approach to production sites localization may also have its benefits, especially concerning distribution and redundancy. This is since distribution of both biogenic feedstock and electricity, in general, is significantly easier than that of hydrogen. This means, that in many cases it makes more sense to produce the hydrogen closer to its intended final usage. Hydrogen can be used both as an energy source and as a raw material. As an energy source hydrogen has some special characteristics that are unmatched by both electricity and biogenic alternatives. Firstly, it burns very clean and at a high temperature, providing strong thermal effect to processes that may need this. Secondly, the by-product of clean hydrogen combustion is water and nothing else, removing several of the considerations regarding process emissions. In many cases discussed today, the hydrogen is supposed to be used as a raw material rather than a fuel, meaning that the actual hydrogen atoms will be incorporated into the final product (like in the cases of various electrofuels), or a by-product (like in fossil-free steel production). In these cases, utilization of electricity or biogenic feedstock in the actual process is not an option.

Market aspects regarding hydrogen depends to some extent on classic market characteristics of supply and demand. The higher the demand of hydrogen within a certain area or sector the higher investment cost can be justified for establishing relevant infrastructure for production and distribution. Another aspect of the hydrogen market is the competition over biogenic feedstock and electricity as both supplies have many other areas of usage than just hydrogen production. In Sweden a lot of the demand for increased electricity production is driven by the industrial need for direct or in-direct electrification (hydrogen utilization). The competition for biogenic feedstock is however increasing and many other sectors are looking to allocate material containing biogenic carbon for potentially more speciality high-value products than what hydrogen will likely be in the future, which must be a bulk commodity if the economic calculations will ever make sense.

Environmental aspects relate to the emissions associated with the life cycle of hydrogen. When hydrogen is produced through electrolysis, the main emitter is the production of the electricity used in the splitting of water to hydrogen and oxygen. If the electricity is produced from renewable sources the overall emissions can be very low, but never zero as the equipment needed in the value chain always have some associated emissions when they are produced and employed. The situation is rather different when it comes to hydrogen from biogenic feedstock as the conversion of hydrocarbons to hydrogen includes the removal of carbon in some stage. In such processes the output of hydrogen is maximized, meaning that the share of energy going to the product hydrogen is as high as possible. In turn, this means that the remaining energy in the carbon-rich material output needs to be minimized and thus, as oxidized as possible. In other words, carbon dioxide will be produced in at least one stage of the process. By selecting where this takes place certain benefits can be had. If hydrogen is used as a fuel in vehicles for example it has the benefits of zero tailpipe emissions. Additional benefits can be had if the energy content from hydrogen can be utilized through a fuel cell, which compared to combustion engines will result in lower NOx emissions as well as less noise compared to biofuels in an internal combustion engine. The justification of hydrogen from electricity is higher if electricity is abundant and risks being curtailed as an alternative, or if the use case requires hydrogen for its specific qualities, i.e., as a reduction reagent, feedstock or as a vehicle fuel with greater range than conventional electric vehicles.

9 Conclusions

The purpose of this project and report has been to analyze the potential for hydrogen and electrofuels in Sweden and explore what potential role could be played by these emerging energy carriers. The overarching conclusion of the report is that Sweden has numerous resources and advantages compared to other countries. Producing hydrogen and electrofuels for decarbonization of relevant sectors could therefore be an important strategy in the Swedish transition. The realization of this potential instead depends on other aspects like political and societal priorities.

Production potential

Hydrogen is a flexible energy carrier that could be produced from a multitude of feedstocks and production pathways, although the production of hydrogen is intrinsically linked to energy conversion losses. The theoretical production potential in Sweden amounts to about 46 TWh in 2030, comprised of production of hydrogen from biomass, organic waste and fossil-free electricity and without accounting for competition with other applications for available resources.

There is a window of opportunity in the newly adopted EU definition of *renewable fuels of non-biological origin*, where Swedish production of hydrogen is simplified and benefits from the exception from the additionality principle thanks to the low carbon emissions and high renewable energy penetration in the electricity system. This definition simultaneously creates a disadvantage for biogenic hydrogen, as it is not mentioned in the newly adopted definition. Regardless of definitions, the climate impact of renewable hydrogen is in most cases significantly lower than that of fossil hydrogen, but the processes would generate less greenhouse gas emissions if 100% renewable energy and feedstock would be supplied in all pathways. The potential for realizing a low climate impact of hydrogen production in Sweden is therefore high. There are, however, uncertainties regarding how the climate impact of hydrogen slip should be reflected and mitigated to avoid adverse climate effects in the short term. Furthermore, the abundance of concentrated CO_2 streams thanks to biofuel usage and production makes Sweden a suitable contributor to electrofuel production with a low climate impact, although developments in the CCS market and infrastructure may lead to competition between CO_2 utilization and capture pathways.

Potential for use of hydrogen and electrofuels

The analysis was focused on fuel consumption in the transport sector, steel and chemical industry in Sweden, in order to capture the potential of the largest off-takers. Out of the selected sectors, the transport sector is currently dominating the energy consumption with about 115 TWh in 2020, followed by the steel sector which mainly consumes fossil fuels. In the transport sector, the consumption of gasoline has been reduced over the last 20 years and the use of biofuels has increased. In the steel and chemistry sector, fossil fuels such as coal and natural gas are still the main energy carriers.

Future demand of hydrogen and electrofuels is estimated to increase in all sectors, but to various degrees and in different segments of the sector. For example, hydrogen as a fuel is more promising for heavy road vehicles and shipping rather than light vehicles within the transport sector, while electrofuels show stronger potential in long-distance transport modes like long-haul sea transport and aviation. The steel sector in Sweden has a clear goal to become fossil free and hydrogen will be one tool for reaching that goal. For other industries, hydrogen and electrofuels will be utilized but the demand is uncertain as various studies state that the demand may either decrease or increase. However, the demand from these *hard-to-abate* sectors is established in their decarbonization roadmaps. The potential for hydrogen as energy storage in the power sector is not clearly pronounced by industry actors but should not be disregarded.

The final section of chapter 5 discusses barriers for usage of hydrogen and electrofuels based on interview results. One main barrier was found to be the lack of regulations (e.g., policy instruments and standards), which creates uncertainties for actors working with hydrogen and hinders further usage. Another significant barrier is unpredictability in the permitting processes. These barriers, in combination with high investment costs, lack of infrastructure and technological challenges, make it difficult for actors to invest in this market without financial support.

In conclusion, there is a market for hydrogen and electrofuels in Sweden but the future scale and width (width in terms of application range of sectors and segments) are still uncertain and depend on the development of technology, investments and regulations.

Scenario analysis

The current work has identified potential barriers for the development of the production and usage of hydrogen in Sweden. However, further conclusions regarding the barriers and their effect on the hydrogen development is not addressed. Furthermore, it has been observed that the large majority of the planned projects for production of hydrogen will produce the hydrogen through electrolysis. The reason for electrolysis being the main route of hydrogen production has not been addressed in this project.

The scenarios for potential production and demand of hydrogen have been developed independent of each other and does therefore not reflect the fact that actors may produce hydrogen to meet their own demand. Instead of presenting the future development of the hydrogen production and demand, these results represent a possible range of outcomes from 2025 – 2045 for the production potential and demand. If the hydrogen demand is greater than the production potential, it does not necessarily indicate that there will be a need for import of hydrogen. It could instead indicate that there are barriers that slow down the development, but that there is potential for greater use of hydrogen if these barriers were to be overcome. The scenario analysis resulted in the following main outcomes:

- The demand of hydrogen will be greater than the production potential up until about 2035.

- After 2035, it is possible that the production will catch up to the demand and by 2040 potentially meeting the total demand of hydrogen.
- The tipping point is between 2040 and 2045 where in most scenarios, the potential production capacity exceeds the demand and Sweden could become a net exporter of hydrogen.
- The progress of hydrogen usage is dependent on the development of the hydrogen infrastructure as well as the regulations and policies governing production, storage, and distribution of hydrogen.
- Other factors that may play an important role for the development of hydrogen production and demand include the need for clearer definitions of renewable hydrogen, more reliable and explicit guidelines as well as faster permitting systems.
- Furthermore, development of technologies and societal acceptance are important for the potential progress of hydrogen usage.

The conclusion from the scenario analysis is that there is a future potential for hydrogen in Sweden. Depending on if barriers are overcome and how the hydrogen infrastructure and technology develops, Sweden has the potential of becoming a net exporter of hydrogen by 2045. However, if this potential is realized or not, and how it could be realized, is not explored in this report.

Future work

From the results and conclusions of this project, the following questions have arisen and could provide a basis for the next steps:

- How could the potential mapped and described in this work be realized?
  - And what is needed in policy incentives for its realization?
  - Does current policy promote demand increase to a larger extent than production increase and what are the potential drawbacks with such a system?
- What are the specific opportunities and obstacles for biogenic hydrogen?
  - How can the opportunities be realized?
  - How can the obstacles be overcome?
- What are the export benefits at different stages of the hydrogen value chain?
  - What will the export value of each refinement step be?
  - Will the additional investments for each step be worthwhile?
  - How large are the logistical issues related to export for products from each stage?
  - What are the benefits and drawbacks of de-coupling hydrogen production and usage?

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Appendix – Hydrogen and electrofuel production plans

Company	Capacity (GWh_{el})	Year	Project	Location	Description	Source
H2 Green Steel	9332	2024	H2 Green Steel	Boden		[228]
Fertiberia	4800	2026	Green Wolverine	Luleå - Boden		[229]
Wpd, Lhyfe	4800	2025 – 2030		Söderhamn		[230]
HYBRIT (Vattenfall, SSAB, LKAB)	4000	2026	HYBRIT Demo	Gällivare		[231]
ST1, Vattenfall	3573	2029				[232]
Borealis, Vattenfall	3200	2032		Stenungsund		[214]
Uniper	1200	2028	SkyFuelH2	Sollefteå		[233]
Liquid Wind	1040	2026	FlagshipTWO	Sundsvall		[234]
Liquid Wind	903	2026		Umeå		[235]
Gotland Tech Development	809	2030		Visbyfärjan		[REF]
Liquid Wind	520	2024		Örnsköldsvik		[236]
Preem, Vattenfall	2800	2025 – 2035		Lysekil		[237]
Rabbalshede Kraft	400	2024		Southern Sweden		[238]
Uniper, AAB, Luleå Hamn, Luleå Energi, ELS Shipping	401	2027	Botnialänken H2	Luleå		[239]

Plagazi AB, Köping municipality	400	2025	Green Hydrogen from Waste	Köping	[240]
SAS, Vattenfall, Shell	223	2027			[241]
Perstorp, Uniper, Fortum	200	2026	Project Air	Stenungssund	[242]
Ovako, Volvo Technology, Hitachi ABB, H2 Green Steel, Nel Hydrogen	160	2023		Hofors	[243]
RES	800	2025 – 2027		Ånge	[244]
Höganäs	104	2024 – 2030		Höganäs	[REF]
Svea Vind Offshore	67	2023		Gävle	[245]
Höganäs	48	2024		Höganäs	[246]
Trelleborgs kommun, Lhyfe	40	2022		Trelleborg	[247]
Karlstad Energi, Everfuel	160	2025 – 2035		Karlstad	[248]
Hybrit Development AB (LKAB, SSAB, Vattenfall)	36	2020 – 2024		Luleå	[249]
Stena Line, DFDS, Ørsted, Göteborgs hamn, Liquid Wind	32	2025		Göteborgs hamn	[250]
Strandmöllen	24	2023		Ljungby	[251]
Rabbalshede Kraft	8	2022		Southern Sweden	[252]
Uniper	5.6	1992		Oskarshamn	[253]
Dala Vind	4	2023		Malung	[254]

Gislaved Energi, PLS Energy Systems	4	2024		Gislaved Energipark	[255]
Siemens Energy	1.22	2022	Zero Emissions Hydrogen Turbine Center	Finspång	[256]
Väner Energi	0.13	2019		Mariestad	[257]
Lhyfe	40	2025		Härjedalens municipality	[258]

THE POTENTIAL OF HYDROGEN IN A SWEDISH CONTEXT

Hydrogen is expected to be an important piece of the energy transition puzzle. Hydrogen can be used in many applications and areas, such as feedstock in industry processes and in iron and steel production as well as a fuel in transportation and as energy storage. What is the potential for hydrogen and electrofuels in Sweden? This report aims to explores the answer to this question.

This analysis includes a compilation of literature, reports, roadmaps, interview response and a scenario analysis. It shows an overview over the production potential and demand scenarios for Swedish hydrogen and electrofuels.

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