Opportunities and barriers for implementation of Power-to-X (P2X) technologies in the West Sweden Chemicals and Materials Cluster´s process industries

Anna-Karin Jannasch (RISE), Hjalmar Pihl (RISE), Mattias Persson (RISE), Elin Svensson (CIT Industriell Energi AB), Simon Harvey (Chalmers) and Holger Wiertzema (Chalmers)

RISE Report 2020:

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Summary

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The interest for industrial electrification is currently increasing rapidly as it has been identified as one important strategy for achieving climate neutrality. This is for example illustrated by the initialization of several larger industrial cross-sectorial projects (e.g. HYBRIT, CemZero, co-operation Preem-Vattenfall) and supporting R&D-programs in Sweden and Europe during the past few years. Recently, the chemical industry in the Swedish region Västra Götaland has also shown an increasing interest for P2X, and the initiative *Klimatledande processindustri (KPI) (*in eng. *Climate smart industry),* coordinated by the West Sweden Chemicals and Materials Cluster, has identified P2X as a prioritized R&D area.

The purpose of this project was to identify opportunities and barriers for the introduction of P2X technologies in the process industries of the West Sweden Chemicals and Materials Cluster, with emphasis on the chemical and refinery industry in Västra Götaland and Södra´s pulp mill in Värö, Halland. The mapping was carried out for current conditions and markets (electricity, heat) as well as future scenarios, and the results provide a basis for a regional road map for industrial electrification in the region. Another aim of the project was to identify priority areas for continued development and innovation within the framework of the KPI initiative.

The analysis and the conclusions of the project are based on information collected from open literature and interviews with the participating industries and organizations.

The results of the project indicate clearly that the driving forces for industrial transformation and P2X within the West Sweden Chemicals and Materials Cluster are currently variable and different depending on the industrial sector. The refineries' interest in P2X and other transformative measures, e.g. biomass and CCUS, is primarily driven by the Swedish emissions reduction obligation, while the chemical industry expresses the shift to the circular economy as the main driver for P2X. Södra, as a forest industry and net producer of electricity, can contribute significantly to this transformation by supplying electricity and excess biomass at the same time as they have their own goal “Fossil-free transport in 2030”, in which increased electrification is one of the solutions. Neither the European Emissions Trading (EU-ETS) for CO2 nor the possibility of being an active player in an increasingly flexible electricity market provide significant incentives for electrification in West Sweden process industries.

There are many P2X technologies for producing different products, with widely different technology readiness levels (TRL) and suitability depending on the industrial sector. Within the cluster's oil refinery industry, there are concrete plans within the next few years for establishing P2H2 at demonstration scale. In the longer term, it is conceivable that the refinery industry will implement large-scale P2H2 concepts to satisfy a significant fraction of the hydrogen gas needs of their refinery operations (Preem), or even implement electro-fuel production, e.g. electro-methanol (Preem, St1). In addition, the SME company Liquid Wind is targeting for up to five regionally located electro-methanol plants. Borealis mainly expresses interest in various forms of P2heat, while Perstorp in the long run sees interesting opportunities in P2acids.

A number of barriers have been identified for the implementation of the different P2X technologies, such as low TRL levels, high costs, uncertainties linked to integration aspects and impact on existing processes and systems, access to carbon dioxide, water and electricity at one site if electro-fuel production, etc. Other barriers raised by the industries are the lack of long-term policy and funding. However, the most significant barrier that was pointed out for large scale P2X implementation concerns uncertainty regarding the availability of fossil-free or renewable electricity capacity at competitive prices in combination with long lead times for permitting processes and expansion of the electricity grid (up to 10-12 years).

The sum of the expressed power needs associated with a moderate electrification pathway (i.e. investments that are either likely to occur or that are at the planning stage) presented by the interviewed industries corresponds to a doubling of current power demand levels. A more speculative extensive electrification scenario beyond 2030 (i.e. assuming that *all* electrification concepts discussed during the interviews are implemented by 2045), the total power need becomes just over 10 times larger than today´s and would most likely require extensive grid reinforcements. But even with the moderate electrification plans, grid reinforcements could be needed, especially if they coincide with electrification of other sectors. This highlights the need for open and active communication between industries and power grid operators about future plans and possibilities.

Finally, a number of suggestions for further work in the field have been identified, including for example development and demonstration of different advanced P2X-technologies, inventories and implementations of heat pumps, the role of P2X in relation to other pathways (based on biomass, CCS, CCU) and how to design and integrate the P2X-technologies at the overall sites, where P2X is usually only one part of the solution.

Key words: *Industrial electrification, P2X, chemical and refinery industry, west Sweden, opportunities and barriers*

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Preface

This project was undertaken within the *Klimatledande processindustri* (*eng. Climate smart industry*) initiative as a first step to reach the goal of establishing a new R&D focus area in the field of industrial electrification within the next 10 years. The project´s results constitute an important contribution to Västra Götaland region's (VGR) electrification targets for both the industry and the road and shipping transportation sectors.

The project was undertaken by Anna-Karin Jannasch, Hjalmar Pihl, Mattias Persson (RISE), Simon Harvey, Holger Wiertzema (Chalmers) and Elin Svensson (CIT Industriell Energi AB) in co-operation with:

- Anders Carlson och Lars Pettersson (Borealis AB)
- Oleg Pajalic (Perstorp AB)
- Linda Werner and Johan Wennerholm (Preem AB)
- Johan Isaksson and Sven Hermansson (Södra skogsägarna ekonomiska förening)
- Claes Fredriksson, Thomas Stenhede (Liquid Wind AB)
- Anders Österlund and Rolf Edvinsson (Nouryon AB)
- Emil Andersson (Göteborg Energi Nät AB)
- Christian Janssen and Per-Arne Karlsson (ST1 Sverige AB)
- Eva Vittel (Vattenfall Eldistribution AB)

The project was financed by Vinnväxt Klimatledande processindustri, Västra Götaland Regionen (VGR) and the participating industries, which are all greatly acknowledged.

1 Introduction

1.1 Background

There is currently a strong interest for industrial electrification, often referred to under the collective concept name "Power-to-X" (P2X), which has been identified by several process industries as one important strategy for achieving climate-neutrality, both in Sweden [1] and in Europe [2]. Implementation of P2X on a commercial scale entails, however, major development needs for new technology, as well as knowledge building regarding electrification issues, the role of new technologies linked to electrification, connections between industrial systems and the electricity grid, and economic and climate aspects under prevailing conditions and possible future scenarios.

A number of European countries, e.g. the Netherlands, have initiated ambitious innovation programs (i.e. Voltachem) targeted at electrification of the chemical industry. In Sweden, the growing interest for industrial P2X is mainly illustrated by a number of larger cross-sectorial projects focused on electrification of the steel [3], cement [4] and refinery industries [5], supported by the Swedish Energy Agency. Recently, the chemical industry in Västra Götaland, i.e. the same region where the future electrification of the Swedish refinery industry may take place, has shown an increasing interest for P2X. Furthermore, the initiative *Vinnväxt Klimatledande processindustri,* hereafter referred to as the KPI initiative [6], coordinated by the West Sweden Chemicals and Materials Cluster, has also pointed out P2X as one of the prioritized R&D areas.

Despite the above mentioned P2X activities, there is still a lack of a comprehensive knowledge base of the opportunities and barriers for P2X technologies in the chemical and refinery industry in Västra Götaland, i.e. the central region for the KPI initiative. In the chemical and refinery industry, P2X can be applied for process heating (incl. direct heating as well as heat pumps and plasma combustion), for hydrogen production by electrolysis for use as feedstock, or as energy source for advanced electrochemical processes such as carbon reduction of carbon dioxide to ethylene. The different P2X technologies have been summarized by Voltachem in the form of a roadmap for 2050, which has also served as a valuable input and inspiration of approach for this specific study, Figure 1.

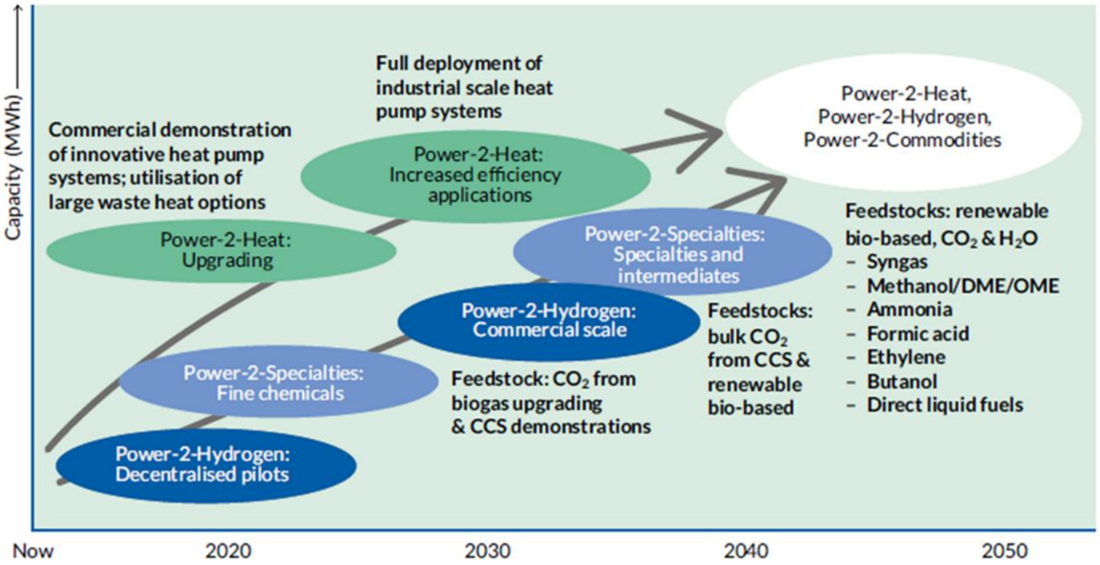


Figure 1. Electrification options for the chemical industry sorted in a roadmap for 2050 as proposed by the Dutch Innovation program Voltachem [7].

Furthermore, there is no overall regional assessment of the implications of various forms of electrification for the electricity demand and the development of the electricity grid in southwest Sweden. In this study, it should be noted that southwest Sweden includes Västra Götaland and Halland, given that other process industries in the West Sweden Chemicals and Materials cluster such as the pulp industry are also interested in the technology and see the potential of P2X. As in the chemical and refinery industry, P2X in the pulp industry can be used for process heating to replace fossil fuels or replace biofuels that can be sold on external markets. Unlike the significantly more fossil-based chemical and refinery industry, the pulp industry also has the opportunity to produce e.g. green methane or methanol for both internal and external use by implementing electrolysis on site and allowing produced hydrogen gas to react with existing point emissions of biogenic carbon dioxide [8].

1.2 Purpose and goals of project

The purpose of this project was to identify opportunities and barriers for the introduction of P2X technologies in the process industries of the West Sweden Chemicals and Materials cluster, with emphasis on the chemical and refinery industry in Västra Götaland and Södra´s pulp mill in Värö, Halland. The mapping was carried out for current conditions and markets (electricity, heat) as well as future scenarios. and the results provide a basis for a regional road map for industrial electrification in the region. Another aim of the project was to identify priority areas for continued development and innovation within the framework of the KPI initiative.

1.3 Organisation and procedure

The project was conducted in three main work packages:

1) **Compilation of potential P2X technologies of interest for the process industries in the West Sweden Chemicals and Materials cluster.** The

work was based on the project group´s previous work and experience in the P2X field, complemented by information found in the open literature.

2) **Identification of opportunities and barriers to the introduction of P2X technologies in the project´s participating process industries**. In this part, mapping of possible network restrictions in the electricity grid was also included. The information was mainly collected via interviews with the participating industries representing the majority of the chemical and refinery industry in Västra Götaland region, as well as the pulp industry in Halland and other stakeholders such as a technology supplier and an SME, see **Table 1** and **Figure 2**.

Table 1. List of interviewed organisations

Organisation
Borealis AB
Göteborg Energi Nät AB
Liquid Wind AB
Nouryon AB
Perstorp AB
Preem AB
Siemens AB
St1 Sverige AB
Södra skogsägarna ekonomiska förening
Vattenfall Eldistribution AB

Figure 2. Overview of the participating industries´ locations in Västra Götaland and Halland, Sweden.

A complete list of the interview/discussion questions is provided in Appendix A1. An overview of the interview questions is provided below:

Driving forces – development routes

- Role of P2X - overall and more specifically for one or several P2X technologies

Barriers and some general questions related to large-scale P2X implementation

- Access to electricity (energy and power) - today and in the future
- P2X technologies – technologies of most interest for industry, technology´s reliability, TRL, integration in existing processes, etc
- Legislation, environmental permitting processes
- Size, scale-up vs. time
- Flexibility from the industry´s viewpoint and core business

3) **Identification of the need for continued R&D to enable the introduction of P2X in the West Sweden Chemicals and Materials cluster´s process industries**.

2 Results

2.1 Electricity supply

2.1.1 Structure of the Swedish electricity grid

The Swedish electricity grid is subdivided into three network levels: the national grid (Swedish: stamnät), regional grids (regionnät) and local grids (lokalnät), **Figure 3**.

The national grid consists of large powerlines and substations that are operated at a voltage level of 220 kV or higher. The purpose of this “electricity highway system” is to transport large amounts of electrical energy over long distances. Some large electricity producers feed power directly to the national grid. It is owned and operated by state-owned Svenska Kraftnät, who also has the main responsibility for ensuring that the short-run overall balance between injections and withdrawals of power is maintained.

Figure 3. The Swedish national grid and its neighbours [9]

The regional grids transport electric energy at somewhat lower voltage levels (typically between 20 kV and 130 kV), connecting the national grid to local grids. Some electricity producers as well as some large industrial consumers are also connected directly to the regional grids. Most of the regional grids in Sweden are owned by Eon Energidistribution, Ellevio, and Vattenfall Eldistribution.

Finally, the local grids distribute electricity from regional grids to consumers. They are typically operated at voltage levels between 0.4 kV and 20 kV but may also include higher voltage levels. There is therefore no sharp limit between local and regional grids in terms of voltage. The local grids are owned by more than 150 different grid companies, which vary considerably in size as well as ownership structure.

Since the largest electricity producers are connected to the national grid while most consumers are connected to local grids, power tends to flow from the national grid, via regional grids, to local grids. However, due to the increase of smaller-scale renewable generation connected to local and regional grids, some of these flow patterns may occasionally be reversed.

The electricity market in Sweden is based on an unbundled approach, meaning that the grid companies do not sell electricity to end-users. Instead, end-users are free to choose electricity supplier in a competitive market, and the grid companies are required to provide access to the grid on a non-discriminatory basis. These grid companies are treated as regulated monopolies, with revenues monitored and capped by the Swedish Energy Markets Inspectorate (Energimarknadsinspektionen).

2.1.2 Grid capacity limitations

Any electric grid always has an upper limit for the amount of electricity that can be safely transmitted and distributed. At the national grid level, Svenska Kraftnät has some ability to control power flows to avoid overloading, for example by requesting electricity producers in certain locations to temporarily decrease production. Furthermore, the hourly wholesale electricity market is designed to take some national grid capacity limitations into account, creating price differences between different parts of Sweden.

However, at the regional and local grid levels, the grid operator typically has less (if any) possibility to directly control power flows in real time. Therefore, the grid infrastructure needs to be dimensioned such that any foreseeable flows can be accommodated. When the power flows in a certain area gets close to the capacity limit of the grid (even if only during a few hours per year), the grid owner may need to reinforce the grid or build new lines before additional consumers can be allowed to connect.

The amount of time needed for a grid expansion or reinforcement can be significant, especially at the regional and national grid levels. In some cases, it can take more than 10 years to build a new power line, much of which is due to permitting and legal processes [10]. At the local grid level, reinforcements typically take less time, but the local grid owner may still be constrained by limitations at the regional and national levels, preventing the local grid from increasing its connection capacity to the regional grid. Several urban areas in Sweden, such as Stockholm and Malmö, are currently affected by such capacity limitations, making it difficult to connect new large consumers within short timeframes.

2.1.3 Grid connection of the interviewed industrial sites

Because of their large size, many of the industrial sites considered in this report are directly connected to the regional grid. The refineries in Gothenburg are an exception, since they are connected to the Gothenburg local grid, owned by Göteborg Energi Nät AB (GENAB). However, GENAB operates their grid at voltage levels that are relatively high for a local grid.

The parts of the regional grid in West Sweden that supply power to the industrial sites considered in this report are owned by Vattenfall Eldistribution AB. Ellevio AB also owns some regional grid infrastructure in West Sweden but this infrastructure is not of significance for the sites of interest for this report. The Gothenburg local grid is primarily connected to Vattenfall Eldistribution regional grid, but also has a connection point to Ellevio's grid.

Therefore, a necessary condition for enabling large-scale electrification of the industries considered in this report, is that the Vattenfall regional grid in western Sweden has sufficient capacity to accommodate the increased power demand. Vattenfall Eldistribution does not publicly share information about exactly how much capacity is available at specific locations. However, they note [interview with Eva Vitell, Vattenfall Eldistribution AB, December 2019] that the national and regional grids in West Sweden and the Gothenburg region are less capacity-constrained, compared to Stockholm and Malmö. Nevertheless, this does not mean that the grid is without limitations – large industrial electrification projects may still be affected by capacity constraints.

2.1.4 Current electricity consumption and production at interviewed sites

To provide a frame of reference for the power consumption amounts that electrification projects may lead to, and to get a sense of what might count as a "large" increase in power consumption, this section describes the current electricity consumption and production at the industrial sites considered in this report.

A summary of the electricity consumption and production at the industrial sites considered in this study is given in **Table 2**.

Table 2. Electricity consumption (incl. purchased electricity plus eventual self-generated electricity) and production at the industrial sites considered in this work (Source: Industries´ environmental reports, 2018).

Industrial site	Electricity consumption 2018 (GWh)	Electricity production 2018 (GWh)
Borealis Cracker	445	103
Borealis Polyethylene (PE)	483	
Nouryon Stenungssund	103	
Nouryon Bohus	71	
Perstorp Stenungssund	83	
Preem Göteborg	177	
Preem Lysekil	522	
St1 Göteborg	144	
Södra Värö	606	856
TOTAL	**2634**	**959**

Since these industries to a large extent rely on continuous production processes, electricity consumption at all of the sites is relatively stable over time and does not vary significantly between night and day or between weekdays and weekends. The peak power load values for these sites are therefore relatively close to the average power loads.

This means that it is possible to (approximately) translate values for yearly total electricity consumption (MWh) into typical power load values (MW), and vice versa. Yearly total electricity consumption values are publicly available in environmental reports, and indicative power load values (typical as well as peak) have been estimated and verified in interviews with the participating industries.

In addition to electricity consumption, some of the sites also generate electricity. Most notably, the power production at the Södra pulp mill in Värö is sufficiently large to make the site a net electricity producer. However, since on-site electricity production may not always be fully available, the grid connection nevertheless needs to be able to supply sufficient power to meet the full on-site demand. Therefore, sites with on-site production need to contract for grid capacity that is only rarely fully utilized.

The industrial sites considered in this report collectively consume around 2.6 TWh and produce approximately 1 TWh of electricity annually. This corresponds to a typical total power load of around 300-350 MW, and 100-150 MW of power generation.

As a comparison, the city of Gothenburg consumes about 4.5 TWh per year, with peak loads of around 800-900 MW [11]. The Västra Götaland Region consumes about 19 TWh per year, of which about 6 TWh is consumed by industrial users (out of which the interviewed process industries constitutes approximately 33 %) [12].

The sites can be roughly categorized into two categories based on typical gross electricity power load:

- High loads (50 MW or more): Södra pulp mill in Värö, Preem refinery in Lysekil, Borealis cracker in Stenungsund, and Borealis polyethylene in Stenungsund.
- Medium loads (10-25 MW): Preem refinery in Gothenburg and St1 refinery in Gothenburg, Perstorp in Stenungsund, Nouryon in Stenungsund, and Nouryon in Bohus.

As previously mentioned, the largest electricity producer is Södra in Värö, with a typical power output of around 120 MW. Some electricity is also generated at the Borealis cracker in Stenungsund (10-12 MW).

2.1.5 Power supply reliability requirements

Power supply reliability requirements are high at all interviewed industrial sites, in the sense that even a short power interruption or temporary power quality issues may necessitate a production shutdown. In some cases, a shutdown and restart can take much longer than the duration of the power interruption, leading to high costs and significant loss of revenue.

Because of the risk of power supply interruptions or power quality issues, all interviewed sites report having UPS (uninterruptible power supply) and/or back-up generators available on site. However, these systems are primarily intended to enable controlled and safe shutdowns. The type of back-up generation that would be required to keep production processes operating are in general considered to be too expensive.

2.2 Potential electrification technologies

As briefly mentioned in the introduction of this report, there exists a wide variety of industrial electrification, or P2X, technologies. These may be grouped and categorized in different ways, for example, depending on product (heat, hydrogen, chemicals, fuels, etc), or the process used (electrolysis, heat pump, membrane separation, etc). Some options are generally applicable in various industrial sectors, while others are more specific to certain types of plants. For a list of technological options applicable in the chemical, petrochemical, refinery, and pulp and paper sectors, see Appendix A2. Note that the maturities (technology readiness levels – TRLs) of technological options vary from very early development stages (low TRL levels) to commercial (high TRL levels).

The chemical industry is heterogenous, and opportunities differ depending on site-specific conditions and production at each plant. However, many electrification technologies rely on water electrolysis, to produce for example hydrogen, syngas, ethylene or ammonia, which may then be used as input material for further processing into other chemicals.

For the petrochemical industry, a wide range of options exist (at widely ranging maturity levels). These include, but are not limited to, electric steam cracking and other electrified cracker options, processes relying on power-to-hydrogen (water electrolysis), and increased electricity use related to chemical or thermochemical recycling or increased reprocessing of by-products.

Power-to-hydrogen is also an important option for the refinery industry, where hydrogen may be used for biofuel production, electro-fuels production (in combination with carbon capture), as well as hydrocracking.

For the pulp and paper industry, opportunities related to the production of pulp include electrification of drying processes and of the lime kilns. By producing hydrogen through water electrolysis and capturing biogenic CO2 from their flue gases, pulp and paper mills could also become producers of green electro-fuels.

In all sectors, electrification of heating and steam generation to replace combustion of fuels, could be interesting options depending on the heat and steam balances of the plant. These options are generally mature and include e.g. electric boilers and heat pumps.

2.3 Drivers for industrial electrification

The drivers for industrial electrification are expressed differently by the participating companies. Depending on the industrial sector, more general drivers related to reduction of greenhouse gas emissions or transition to a circular economy are manifested through different policy instruments or market mechanisms such as EU ETS, the emissions reduction obligation scheme for motor fuels, or demand for sustainable products.

For example, for Borealis, transition to a circular economy (gradual transition to recycled plastics as feedstock) is a strong driver for electrification. Electrification is seen as a clear necessity in combination with recycled plastic feedstock, biomass feedstock and/or carbon capture with storage or utilization (CCS/CCU) to reach ambitious climate targets. Also for Perstorp, electrification is connected to the introduction of sustainable (recycled or biobased) feedstock and needs to be developed in parallel.

Södra aims to achieve fossil-free production by 2020, and fossil-free transportation of feedstock and products by 2030 (‘A fossil-free Södra’). Electrification is mainly seen to have a potential for transportation, including electrification of, for example, fork-lift trucks. Projects related to electrification of production processes are primarily seen as necessary to build up in-house knowledge necessary to prepare for future investments beyond 10 years.

Both Preem and St1 have goals to reach net zero emissions by 2045 for their entire value chains. Being producers of transportation fuels, they are affected by the emissions reduction obligation scheme, which is a strong policy instrument that drives the development towards increased use of bio-based feedstock as well as electrification. For Preem, this is mentioned as a very important driver for the development towards electrification. Their interest in electrification is strongly connected to their feasibility study for production of hydrogen through water electrolysis in the Gothenburg refinery. St1 agrees that the emissions reduction obligation scheme is a clear and strong policy instrument that provides some stability for investment decisions. However, they rather emphasize the goal as such (of reducing the carbon footprint of their products) and that electrification is a requirement for reaching this goal. St1 also has strong interests in building and operating wind power plants, which goes hand in hand with their interest in electrification.

Liquid Wind primarily see their e-methanol as an alternative to fossil transportation fuels and describe this electrofuel as an indirect electrification of the transport sector, particularly the shipping sector. Their concept is described in section 2.4.7. Thereby, reduction of greenhouse gas emissions (in the transport sector) is an important driver. Liquid Wind also mentions the flexibility towards electricity price variations, and the potential of electrofuels for energy storage as an opportunity. However, no other company considers flexibility towards power markets as an important driver or opportunity for electrification, which is largely explained by the very high, continuous capacity utilization rates of the production processes.

2.4 Electrification technologies and plans for up-scaling at the interviewed industrial sites

In this section, the different electrification technologies of interest and corresponding plans and scenarios for up-scaling at the interviewed sites are presented.

2.4.1 Preem

Preem has the goal to become the world´s first climate neutral petroleum and biomass based motor fuel company, with net zero emissions with respect to the whole value chain by 2045. The company plans for net zero emissions from their refineries 2040 at the latest. For reaching these goals, Preem is currently engaged in several large projects for investigating production of renewable fuels, including HVO-production, extraction and liquification of lignin and pyrolysis of solid biomass for up-grading at the refinery, as well of production of Electrofuels in connection with Carbon Capture Storage (CCS). If implemented on a large scale, these measures are expected to significantly increase Preem´s energy demand, particularly the demand for fossil-free/renewable electricity and hydrogen.

At the time of writing this report, Preem, in co-operation with Vattenfall, is about to finalize a feasibility study of establishing a production plant for fossil free/renewable hydrogen at their refinery plant in Göteborg [5]. The plant is planned to be based on electrolysis for a hydrogen production volume of 3800 Nm3/h corresponding to an electrical power demand of 18-20 MWe. The goal is to have the electrolysis process in operation by 2024. Compared to the use of the equivalent amount of hydrogen gas produced via traditional natural gas reforming, this would correspond to an annual reduction of climate emissions of 25 ktons CO2.

The electrolysis process is planned to operate continuously, without any downstream hydrogen buffer storage.

Both alkaline (AEL) and polymer membrane electrolysis (PEM) have been considered in the study, but so far, no decision of electrolysis technology choice has been taken.

Other technoeconomic critical tasks that have been in focus in the feasibility study are integration of the electrolysis process in the refinery, including the grid capacity, supply of electricity and ionized water, the use of electrolysis by-products (oxygen and low-grade heat) and necessary hydrogen compression.

Today, there are no concrete plans for upscaling the electrolysis capacity of 18-20 MWe. Even though this electrolysis capacity is relatively large (one of the world´s largest electrolysis installations at the preliminary planning stage) and challenging from many perspectives, it is important to note this electrolysis capacity is relatively small in comparison to what would be needed for covering the total hydrogen demand at this and other refineries of similar size (5-15%). As for the future, with an expected high proportion of biobased feedstock, up to 3-4 times more hydrogen would be needed.

As regards Preem´s plans for other new carbon mitigation technologies, e.g. CCS, no specific data were provided during the interview. Preem underlined however that a large-scale CCS-plant (currently under investigation for possible implementation at the Lysekil site for 2025 at the earliest) would imply an additional requirement of electricity. A recent investigation conducted by Chalmers [13] indicates that a significant increase of low pressure steam consumption to provide heat to a CCS capture process would decrease the potential for steam turbine shaft power production, which indirectly affects the future need to purchase electricity.

Figure 4 presents an overview of the electrification opportunities for Preem discussed during the interview and illustrates how these opportunities relate to the 2050 roadmap proposed by the Dutch Innovation program Voltachem (ECN).

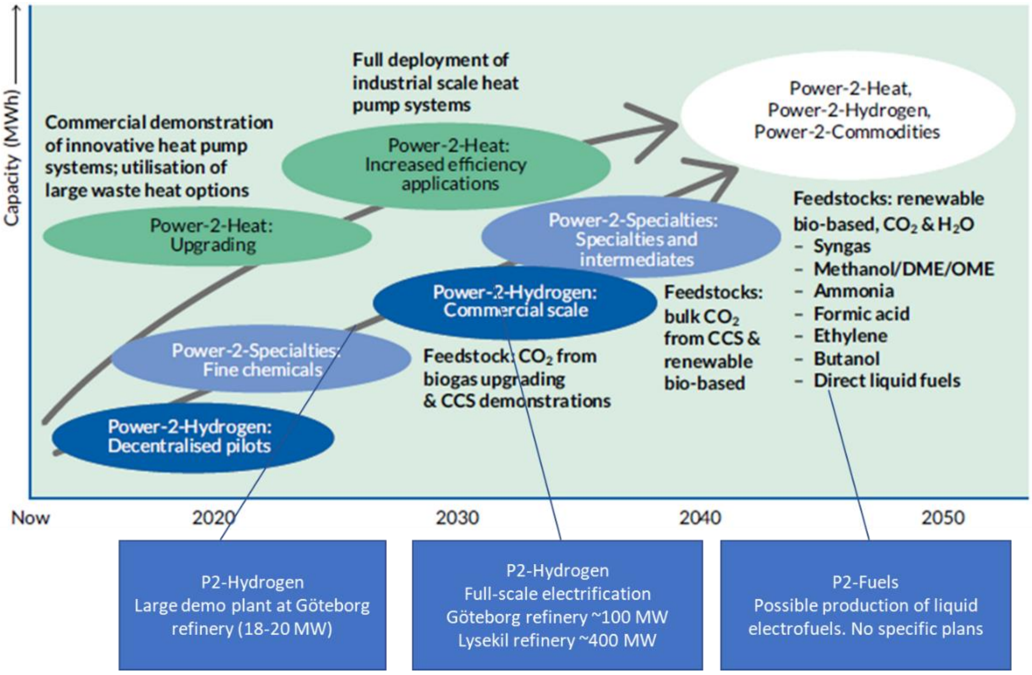


Figure 4 Electrification opportunities for Preem in relation to the 2050 roadmap proposed by the Dutch Innovation program Voltachem/ECN. *Note*: The power load numbers indicated in the figure are based on the authors' speculative interpretation of electrification options discussed during the interview. The numbers indicated are based upon current H2 production levels

2.4.2 St1

St1's goal is in line with the national target of net zero emissions of greenhouse gases until 2045. While much of St1's business development activities are in Finland, they also have some development connected to the refinery in Göteborg. The refinery emits about 0.6 million tonnes of CO2 per year. However, since the final use of St1's products stands for 13 out of 15 million tonnes/per year of CO2,eq as evaluated along the entire value chain, St1 focuses mainly on how they can reduce the CO2 emission footprint of their products. Because of this, one of their ambitions is to transform the refinery in Göteborg to production of biofuels and synthetic fuels (electrofuels). Due to limited availability of raw material for production of biofuel, there will also be a market demand for electrofuels produced by P2X/CCU technology. Electrification is regarded as a necessity and requirement for enabling such a transition.

Some of the short-term plans at the refinery will involve an increase in electricity demand (despite not involving actual electrification but rather new and increased production). These include a new hydrogen production plant, and one Green Processing Unit (GPU). The hydrogen production plant will be based on conventional steam reforming of natural gas and is built to meet the increased demand of hydrogen from production of biofuels. It will be started up during 2020 and increase the electricity demand by 1-2 MW (1.5-2 MVA). For the GPU, an investment decision has been made, and plant construction has begun. It is planned to be taken in operation in 2022. The GPU is a stand-alone biorefinery for production of 200 000 tonnes per year of renewable fuels such as HVO-diesel and biojet. The plant will be flexible for different feedstocks, but tall oil is one of the intended raw materials. The GPU will increase the electricity demand of the refinery site by a few MW (3-4 MVA).

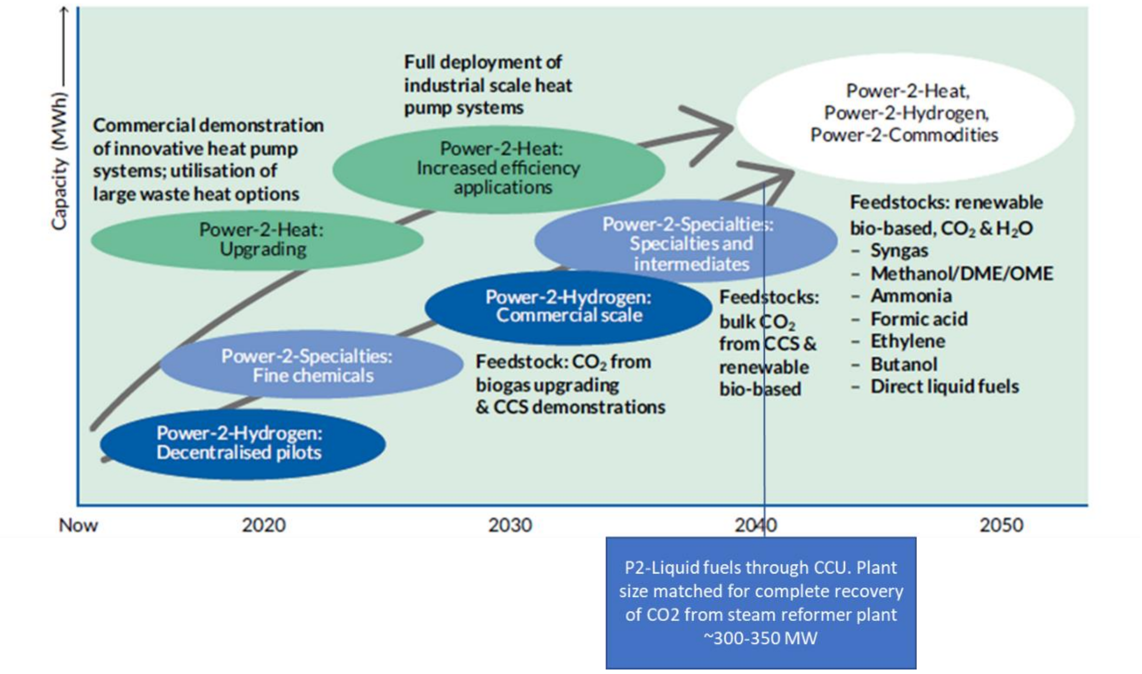
Regarding electrification, St1 has strong interests in P2X for production of synthetic fuels (electrofuels). If P2X will be implemented at the refinery in Göteborg, the production of synthetic fuels will probably be based on hydrogen from electrolysis and CO2 from existing stacks as well as from new stacks at the GPU (i.e. biogenic CO2). In collaboration with Lappeenranta University and VTT, St1 is currently working on a project to establish and evaluate a pilot plant for P2X and synthetic fuels production in Finnish Joutseno (part of Lappeenranta city). An extensive feasibility study is ongoing. The pilot plant in Finland is planned to start production in 2023 with a capacity of 27 000 tonnes/year. One of the objectives of the project is to learn as much as possible about the technology for electrification. Focus is, amongst other things, to reduce costs. The project includes looking at selection of electrolyzer technology, and to evaluate the synthesis of different fuels, with methanol as one of the main candidates. The feasibility study also includes some part about how P2X can be used for balancing power demand on the electricity grid, and what requirements that would imply for potential hydrogen storage.

A first P2X including additional hydrogen production capacity in Göteborg could be implemented at the earliest after 2025. In a longer time perspective, it is estimated that the current electricity demand at the refinery in Göteborg could increase by (very roughly) 20-25 times if the refinery would start producing synthetic fuels (liquid or gas) through P2X in very large scale. This estimate assumes that all CO2 form the steam reformer plant is captured and hydrogen is produced through electrolysis in corresponding amounts.

Together with implementation of P2X processes at the Göteborg refinery (probably towards 2030), St1 also investigated building wind power plants at the refinery site. This was estimated to provide 65 GWh of electricity per year with expected start up 2025-2027 (due to the long permit process). The plans have though been put on hold following a negative response from the Military. The area is a so callad "Militärt skyddsområde" (Military Protection Area). St1 is of the understanding the Government will request the Military to review its permitting in general and maybe that could help the case longer term.

Except for the new process and technologies mentioned above, St1 also mentioned opportunities related to replacing the fossil crude oil with different biocrudes. These opportunities are something that St1 is looking at on a more long-term perspective.

Figure 5 presents an overview of the electrification opportunities for ST1 discussed during the interview and illustrates how these opportunities relate to the 2050 roadmap proposed by the Dutch Innovation program Voltachem (ECN).



P2-Liquid fuels through CCU. Plant size matched for complete recovery of CO2 from steam reformer plant ~300-350 MW

Figure 5 Electrification opportunities for ST1 in relation to the 2050 roadmap proposed by the Dutch Innovation program Voltachem/ECN. *Note*: The power load numbers indicated in the figure are based on the authors' speculative interpretation of electrification options discussed during the interview.

2.4.3 Borealis

Borealis has ambitious plans to transform their Stenungsund operations in alignment with Swedish long-term climate targets and significant pressure to adopt their production to the requirements of a circular economy. To reach these targets, the company considers that a broad mix of transformative changes will be required, including electrification, feedstock switching to biomass and recycled plastic materials, as well as carbon capture and storage (CCS) or re-use (CCU). Their cracker furnaces are major energy users as well as major emitters of CO_2.

A first option that is being investigated involves integrating an electrically heated catalytic structure directly into steam-methane–reforming (SMR) reactors, in alignment with the technology developed by the Technical University of Denmark and Haldor Topsoe. This step could potentially be implemented in the 2027 main turn-around. The increased power demand is estimated at 150 MW. The concept could be further developed to include CO_2 capture and use (CCU). However, implementation of this concept would create a deficit of residual fuel gas, which would require partial electrification of some of the site boilers to maintain steam balances. This second phase could be implemented no earlier than during the 2033 turn-around. The estimated increased power demand is 150-200 MW.

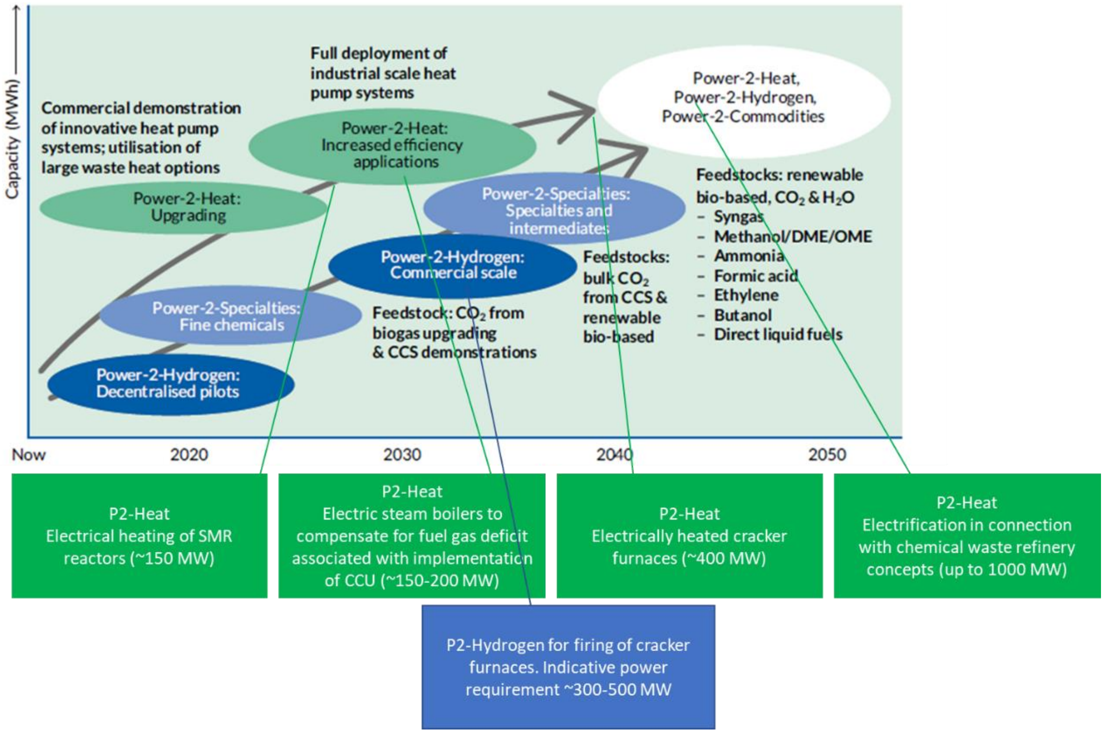
Another possible long-term (for implementation 2033 or later) development option for the cracker furnaces is to switch to electricity as the direct energy source. Borealis is currently engaged in a large European consortium ("Cracker of the future") investigating this technology in collaboration with BASF, BP, LyondellBasell, SABIC and Total). The estimated power demand is 50 MW per furnace. One drawback for this option is lack of space for the large transformer required for each furnace. Another major challenge is finding materials that can withstand the high temperature levels (1000 °C) involved. One advantage is the even temperature profiles that can be achieved.

A final option is to fire hydrogen produced through electrolysis as cracker fuel. This option has been investigated in collaboration with Vattenfall. Full implementation for all cracker furnaces would increase the site power demand by 300-500 MW.

In the future, the site may convert to chemical recycling of plastic waste through thermal gasification. Electricity-based heating in combination with electrification of the downstream product separation could result in electricity demands of around 1000 MW.

Borealis has also investigated more conventional electrification options, including electric boilers and electric drive compressors to run the site's cryogenic refrigeration system. They are also interested in high-temperature heat pumps. Borealis is currently collaborating with Qpinch at its Antwerp (Belgium) facility. The Qpinch technology provides a heat lift for industrial waste heat by raising the temperature of waste heat by means of a chemical process. In contrast to conventional heat pumps, this closed-loop process minimises operational costs as well as electricity use. One challenge for such projects is to avoid creating an excess of steam. Thus, advanced heat pumping and converting steam driven compressors will only be attractive if implemented concurrently for new demands for steam.

Figure 6 presents an overview of the electrification opportunities for Borealis discussed during the interview and illustrates how these opportunities relate to the 2050 roadmap proposed by the Dutch Innovation program Voltachem (ECN).



P2-Heat
Electrical heating of SMR reactors (~150 MW)

P2-Heat
Electric steam boilers to compensate for fuel gas deficit associated with implementation of CCU (~150-200 MW)

P2-Heat
Electrically heated cracker furnaces (~400 MW)

P2-Heat
Electrification in connection with chemical waste refinery concepts (up to 1000 MW)

P2-Hydrogen for firing of cracker furnaces. Indicative power requirement ~300-500 MW

Figure 6 Electrification opportunities for Borealis in relation to the 2050 roadmap proposed by the Dutch Innovation program Voltachem/ECN. *Note*: The power load numbers indicated in the figure are based on the authors' speculative interpretation of electrification options discussed during the interview.

2.4.4 Perstorp

Perstorp´s has a stated ambition to become "Finite Material Neutral". This objective is to be reached mainly through replacing fossil raw materials by biobased and recycled materials. At present, Perstorp has no concrete plans for implementation of industrial electrification. However, they foresee electrification as a development that is likely to constitute a valuable complement to the increased use of biomass and recycled material feedstocks.

For Perstorp today, industrial electrification primarily involves process units such as evaporation, pumping, heat pumps and in chemical processes via different types of hybrid reactors, membrane technologies and electrosynthesis. For heat pumps specifically, Perstorp expressed an interest for a new systematic inventory of implementation opportunities. The company has no current publicly announced expansion plans. The typical capacity growth rate is around 5 % and new investments are usually made from time to time rather than continuously.

Perstorp´s focus is downstream processing, and not to produce their own feedstock. There is a clear interest to buy climate-neutral feedstocks such as electro-methanol or electro-acids, but they have no interest themselves today to install and run an electrolysis plant to produce hydrogen and other feedstocks. However, in an effort to build up their own knowledge and contribute to technology development, Perstorp is currently participating in different R&D-projects with possible relevance for their site in Stenungsund:

- Valeric acid production from sugar feedstock through electrocatalysis (TRL estimated to 4-5). Perstorp is currently participating in the PERFORM (PowER platFORM) project in which a European consortium led by TNO (The Netherlands) is working to develop and build an electrochemical pilot reactor for direct conversion of biobased feedstocks to targeted products
- Organic electrolysis for oxidation

In addition, Perstorp expressed an interest for Proponic acid, which could be produced with different electrolysis methods and from CO2 as raw material.

Finally, another project of interest to mention in this report is Perstorp´s feasibility study "Project Air" [14]. This project is aimed to investigate the technoeconomic possibilities to produce methanol from recycled hydrogen from the chemical cluster in Stenungsund, captured carbon dioxide and hydrogen and carbon dioxide from Perstorp´s Oxo-process. Alternatively, and/or as a complement to the recycled hydrogen, renewable hydrogen from electrolysis could potentially also be of interest in this case. If successful, methanol produced in this way could expand the company's "Pro-Environment Solutions" portfolio.

Figure 7 presents an overview of the electrification opportunities for Perstorp discussed during the interview and illustrates how these opportunities relate to the 2050 roadmap proposed by the Dutch Innovation program Voltachem (ECN).

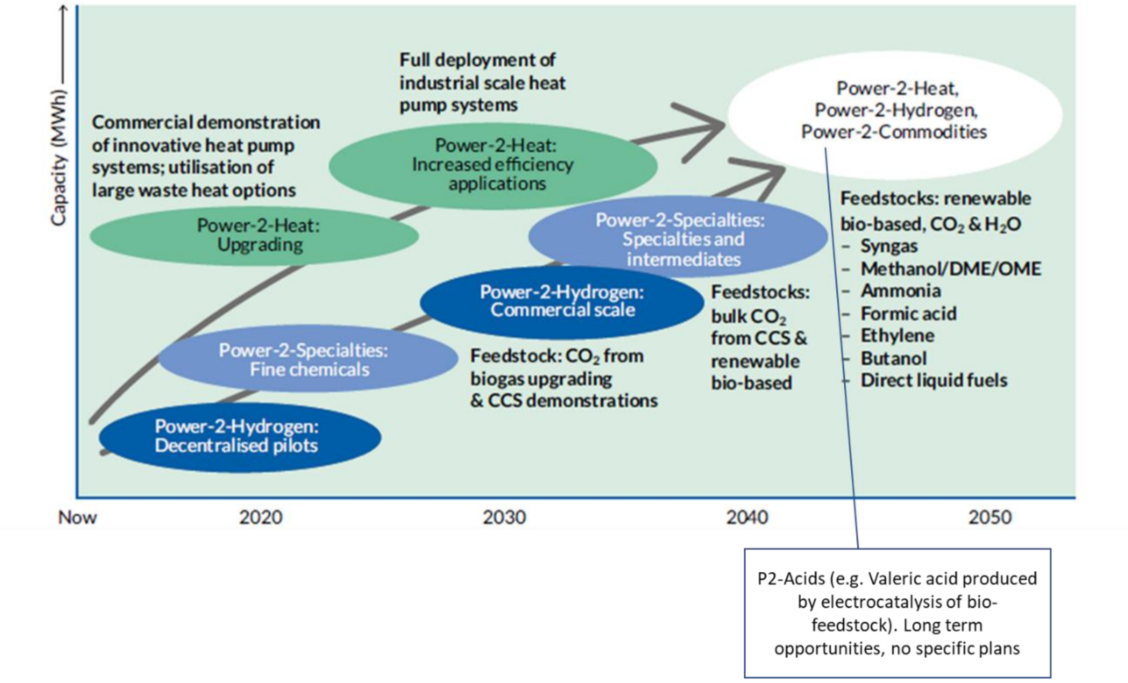


Figure 7 Electrification opportunities for Perstorp in relation to the 2050 roadmap proposed by the Dutch Innovation program Voltachem/ECN.

2.4.5 Nouryon

Nouryon owns and operates production plants in Stenungsund and Bohus. The Bohus plant's main product is hydrogen peroxide, and the plant uses approx. 70 GWh of electricity per year. The Stenungsund site produces ethylene oxide, glycol and amine derivatives and various surfactants, with an annual electricity usage of approx. 100 GWh. The main production processes run at constant load, and the electric power load is thus relatively constant.

Nouryon has no plans for implementation of new P2Chemicals or P2Hydrogen processes. Both sites have installed advanced MVR (Mechnical Vapour Recompression) heat pumps which compress low-grade excess steam up to utility level pressures. The company has of now not identified any further opportunities for P2Heat projects at their sites.

Nouryon have R&D activities related to electrochemistry in Sweden as well as activities in The Netherlands and Germany.

The company interviewees stressed that the Nordic countries are an attractive location for the company's electricity-based production processes, given that average CO_2 emissions associated with electricity generation are very low. The company is more concerned about how to replace natural gas as feedstock as requirements for deep decarbonization of their processes increase in the future. One option which they perceive as been attractive is to switch to synthetic bio-methane.

2.4.6 Södra

Södra has initiated the project ”A Fossil-Free Södra”, through which the company aims to achieve fossil-free production processes in 2020 and transports in 2030. The pulp production processes are already close to fossil-free, with various kinds of biofuels providing most of the energy needed.

Regarding specific plans for electrification at the Värö site in the near future, Södra is replacing diesel-powered on-site transportation, such as forklift trucks, with electric battery-powered alternatives. This is estimated to increase power load by approximately 1-2 MW during battery charging. Additionally, charging stations for electric vehicles are being installed with an estimated peak power load of around 1 MW. Finally, a new production facility for cross-laminated timber will require 1-2 MW within about 2 years. However, this is a new production process and not electrification of an existing process.

Therefore, the electrification efforts that currently are planned at the Värö site are expected to require only a modest increase in power load, compared to the existing electricity consumption and production.

In a longer-term perspective, other electrification possibilities exist for the pulp production process that could have larger impacts on electricity consumption. One such possibility is to produce electro-fuels from pulp using CO2 captured from the pulp production process, se Ch. 2.2 and reference [8]. Given that Södra has significant on-site electricity production, electro-fuel production plants could be constructed without the need to increase the size of Södra’s existing grid connections (assuming the electrolyzer can be stopped whenever the on-site electricity production is unavailable). An additional benefit of the Södra location is that the CO2 source is biogenic.

Other long-term possibilities include options for extracting additional by-products such as lignin for other uses than as on-site fuel. This would reduce the potential to generate electricity. Furthermore, such by-products can be utilized as feedstock for production of higher-value biofuels and biochemicals via hydrogenation, which would require large amounts of hydrogen.

2.4.7 Liquid Wind

Liquid Wind aims to develop and build sites that convert CO2 and hydrogen to methanol, where the hydrogen is produced using electrolysis with electricity from wind power. The envisioned size of each plant is around 50 MWe, located in connection to CO2-emitting industrial sites.

The ambition is to build 6 such sites in Sweden beyond 2030. Five sites (approximately 50 MW per plant) have been identified as potentially interesting within the West Sweden region. For the first site, alkaline electrolysis (AEL) has been retained as a suitable technology due to its technological maturity, but polymer membrane electrolysis (PEM) is also considered as a possible future option, as is a hybrid of the two.

Figure 8 presents an overview of the electrification opportunities for LiquidWind discussed during the interview and illustrates how these opportunities relate to the 2050 roadmap proposed by the Dutch Innovation program Voltachem (ECN).

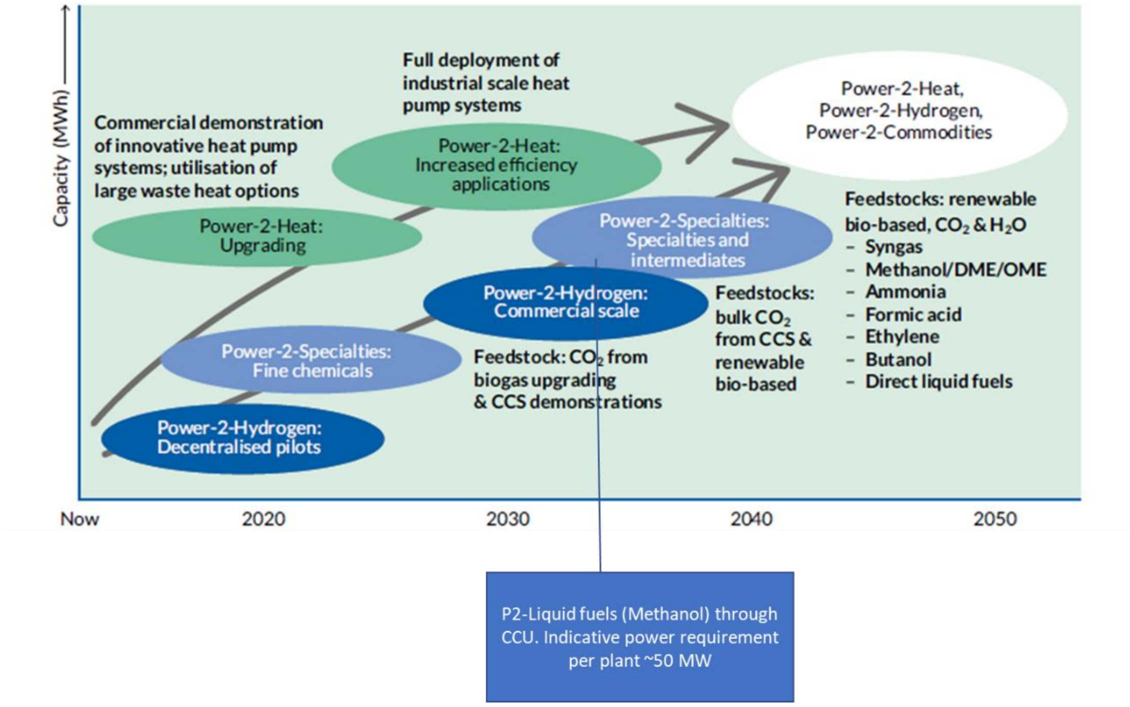


Figure 8. Electrification opportunities for Liquid Wind in relation to the 2050 roadmap proposed by the Dutch Innovation program Voltachem/ECN

2.4.8 Summary of possible power load developments

In this section, the different electrification development ideas presented in sections 2.4.1-2.4.7 are summarized. Figure 9 shows two possible development pathways. The *moderate electrification* pathway shown in the figure shows the total current electric power capacity for the interviewed plants, and how this power requirement could evolve if some of the more mature electrification options discussed during the interviews are implemented (i.e. investments that are either likely to occur or that are at the planning stage). The *extensive electrification* pathway is purely speculative and illustrates how the total power load for the respective industrial plants *could* evolve, assuming that *all* electrification concepts discussed during the interviews are implemented by 2045. We are very much aware that this pathway is unlikely to occur, but we nevertheless consider that it is of interest for the project to quantify the maximum possible power requirement for industry under an extreme electrification scenario.

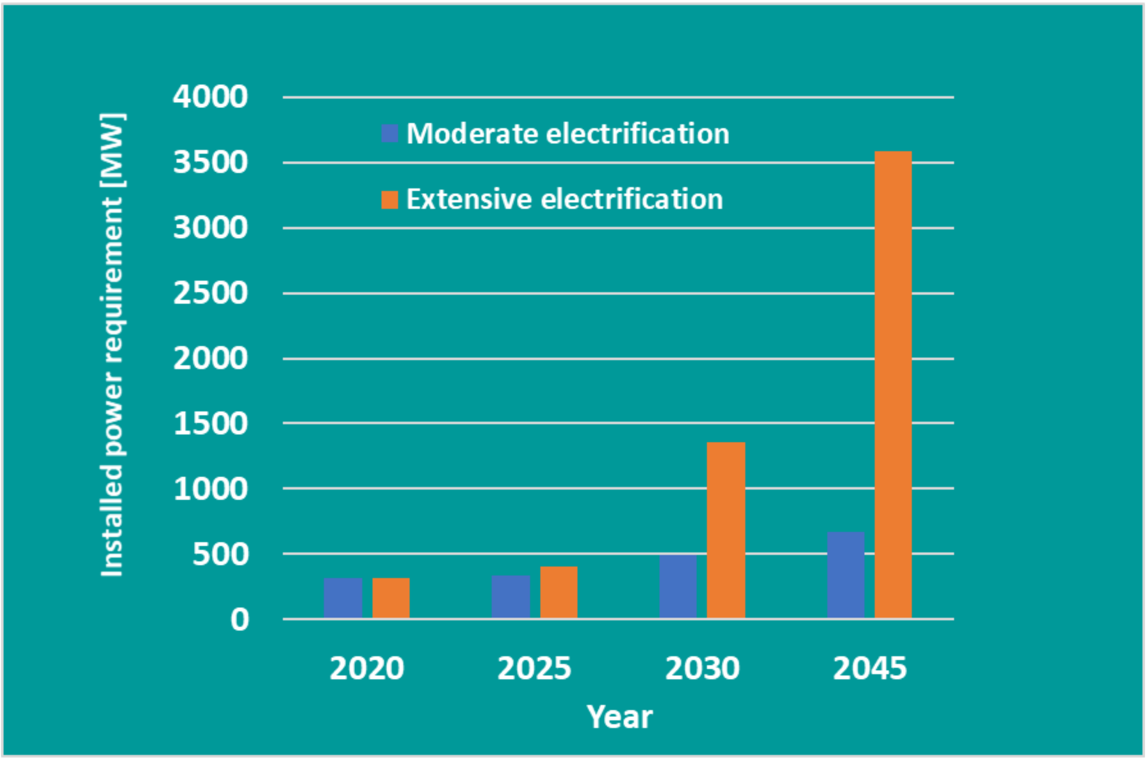


Figure 9 Overview of power requirement development pathways for the plants interviewed in the study. *Note*: The *extensive electrification* pathway is purely speculative

The figure shows clearly that the extensive electrification scenario implies an extremely high power requirement increase beyond 2030. Enabling such an increase obviously constitutes a major challenge for distribution, regional and transmission grid owners. Even the total load increase presented for the moderate electrification pathway could present major challenges for increasing grid capacity. A discussion regarding grid capacity increase and expected associated lead times is presented in Section 2.5.

2.5 The electric grid development – Issues and limitations

This section is based on interviews with the grid companies Vattenfall Eldistribution AB (Vattenfall) and Göteborg Energi Nät AB (GENAB). The questions are based around the main industrial plants and their locations for the distribution system operator (DSO) in the case of GENAB. The questions to Vattenfall were mainly related to their role as regional grid operator, supplying power from the national grid (see Chapter 2.1.1). The base for the questions is available in Appendix A1. This subsection aims to start from the load centers and move upwards, to higher voltage levels.

In Gothenburg, there is a relatively high capacity for increased connection in the distribution system close to the ST1 and Preem refineries. Hence, the planned expansion of 20 MW can most likely be accommodated relatively easily. However, the closest feed-in point from the regional grid is lacking in capacity for further expansions in the area. This is anticipated to be solved by an ongoing expansion of the Trollhättan-Stenkullen connection at the national grid level. Once that expansion is finalized, 2-3 years are estimated to enable further expansions of around 20 MW in the area close to ST1 and Preem's Gothenburg refinery. To conclude, the electric grid capacity currently does not seem to constitute a major barrier for small to moderate industrial electrification projects in the Gothenburg region. It should be noted that this conclusion can however change quickly, depending on developments in other sectors.

Moving away from the industrial sites towards a more generic Gothenburg capacity view, GENAB underlined concerns related to future operation of Göteborg Energi's Rya combined heat and power (CHP) plant. The plant has a nominal output of 261 MWe and 294 MWheat and is currently fired by natural gas. Göteborg Energi has recently adopted a target of fully fossil-free heat production within its district heating network, implying that all heat should either be produced from renewable sources or excess heat should be captured from industrial processes. Shut down of the Rya CHP plant would lead to a major loss of power generation capacity in the Göteborg area. Ongoing tests are being conducted by Siemens to investigate the feasibility of converting the plant to operation with alternative fossil-free fuels. Power generation from Rya CHP plant is not currently taken into consideration in the contracted capacity from the regional grid beyond 2025. Hence, if the plant were to be converted so as to enable continued operation after 2025, there would be a clear positive impact on the available capacity in the Gothenburg grid. Future local wind power capacity additions are considered as improbable, instead an expansion of both rooftop and centralized PV of several 10's of MWs is expected. The PV production patterns, however, correlate poorly with high electric load demand which is highly dependent on outdoor temperature.

Regarding the regional capacity, the region surrounding Gothenburg is close to maximal capacity for increased power consumption. Given the substantial total power demand increase associated with the extensive electrification scenario presented in this report, extensive grid reinforcement would most likely be required and the necessary lead times for such expansions at the various levels of power distribution should be communicated to regional energy system planners. Roughly 10 years is reasonable for the transmission grid, 3-7 years for the regional grid and 2-3 years for the local distribution grid. Of course, these numbers are subject to local variations, however the industry needs to have a good collaboration with their distribution grid operator. The opportunities for grid capacity increases at a given connection point can change year by year, and prior to a financial investment decision by industry it can be difficult to get distribution grid operators to commit to grid reinforcing activities to facilitate that investment. This behavior can cause a risk for a catch 22.

2.6 Barriers to industrial electrification

Technology. New technology must be demonstrated before it can be considered for large-scale implementation. Many electrification technologies have not yet reached technology maturity. Pilot plants and up-scaling are needed to enable technological breakthroughs and reduce costs to reasonable levels. For electrochemical routes, improved, proprietary technology is a requirement for maintaining a competitive edge. At the same time, there is a risk that these technologies are outfavoured if alternative catalytic or chemical routes are discovered. Furthermore, there are uncertainties about several of the electrification technologies, and how their implementation would actually affect the operation of the process plants, especially as many electrification opportunities would significantly impact the core production processes. This implies a major productivity risk considering that, currently, the demand for continuously high process availability and reliability is very high.

Integration aspects. Electrification may have large impacts on the overall energy balances of a process plant. There are many complex questions when evaluating, for example, the greenhouse gas emission reductions associated with electrification, which are related to system boundaries, value chains, export/domestic markets and allocation of renewable/fossil-free hydrogen, electricity and biomass. It is also not obvious how to best design and integrate the overall energy system, where electrification (for industrial process plants as considered in this project) often is only part of the required transition together with biobased raw-material and fuel, CCS and CCU, and material recycling. It is important to consider how steam balances in the steam utility systems are affected, to avoid sub-optimization. Since electrification may be considered for different parts of the process, and have effects on the overall process system, it is difficult to pinpoint specific units regarding general concerns about electrification. In Stenungsund, this is further complicated due to existing and potential future integration between the individual companies. Local conditions, such as limited space availability, may also be important barriers to specific electrification options. For P2X technologies for electrofuels production, it is for example important that there is availability of CO2, water, and renewable electricity and grid capacity in the same location.

Grid capacity and electricity supply. Sufficient grid capacity as well as electricity supply are obviously prerequisites for electrification. Ensuring sufficient, renewable/fossil-free capacity at competitive prices is regarded as important by most of the interviewees. This requires political decisions and large investments in electricity production as well as the power grid. Some of the interviewed companies consider building their own wind power plants to be able to guarantee 100 % fossil-free electricity, but such investments compete for investment budgets with the electrification projects themselves. Allocation principles (as also mentioned above) are also important to ensure the possibility to count the renewable electricity, for example, in the emissions reduction obligation scheme.

Water and environment. Problems were mentioned related to access to the large amounts of high quality water required for water electrolysis. There might also be environmental or safety issues with some of the new technologies (e.g. mediators in electrochemical processes, or electrochemical products being pollutants or carcinogens).

Long lead times. long lead times for power distribution capacity additions are a challenge, especially for high voltage transmission lines. Environmental permit applications usually require extensive processes over several years. Procedures related to compliance with the Seveso Directive for control of major-accident hazards are also time-consuming. Since electrification involves new processes, knowledge is lacking and must be built up within regulatory and permitting authorities, etc. An important challenge is that everything must keep in pace (permit applications, new process construction in industry, capacity additions in the electricity grid, call-off for electricity purchase…)

Political incentives. It is clear that the EU ETS has not been a large driver for substantial emission reductions (so far). Costs for CO2 emissions have a marginal impact on direct production costs. It was expressed that a major barrier to the climate transition in general is that there is not yet a cap on fossil fuels that is successively and rapidly decreased. The need to create a market also for “negative emissions” was also mentioned. There are (and have been) a number of policies in place for reducing emissions from transportation fuels. However, some of the interviewees expressed a preference for production-directed support, to make it possible to build new plants for renewable fuels production in Sweden, instead of increased import from other countries. Financing of the required infrastructure is seen as a barrier. However, other companies claim that they do not want to see a direct production support even if some kind of support for start-up of new technology could be motivated. Political risk was also brought up as a barrier in some interviews, with regards to the importance of clear, long-term policy instruments. More specifically, the case of being able to count electrofuels within the emissions reduction obligation scheme was mentioned as an example.

Other barriers. Other barriers include the risk that the public debate is rarely based on a complete set of facts, which makes it more difficult to reach public acceptance for new processes. Many interviewees talk about the need for collaboration, to share costs for technology development and demonstration, and costs for renewable electricity production, to reduce risks, avoid making the same mistakes, and to increase the knowledge about the expected overall increase in electricity demand. In some of the companies that are part of global company groups, research and development activities related to process electrification are mainly carried out in other countries. Large-scale electrification projects at their Swedish sites are not considered until the technology has been proven elsewhere. For Södra, with more or less fossil-free production, one barrier to electrification is the lack of concrete drivers for electrification in the production processes.

3 Conclusions

The driving forces for industrial transformation and specifically for industrial electrification/P2X within the West Sweden Chemicals and Materials cluster are currently variable and different depending on the industrial sector. The general driving force for the transformation of the region's chemical and refinery industry is the national goals of "Climate-neutral process industry 2045" and "Net emissions for the entire value chain 2045" in combination with an increasing demand for climate-neutral raw materials and products. More specifically, refineries' interest in P2X and other transformative measures (i.e. biomass instead of fossil raw materials, CCS and CCU) is primarily driven by the Swedish emissions reduction obligation, while the chemical industry expresses the shift to the circular economy (incl. renewable and recycled raw materials, CCS, CCU, integrated regional heating systems) as the main driver for P2X. Södra, as a forest industry and net producer of electricity, can contribute with valuable raw material (electricity and biomass) to this industrial transformation at the same time as they have their own goal “Fossil-free transport in 2030”, in which increased electrification is one of the solutions. Furthermore, from the interviews conducted within this study, it is clear that neither the European Emissions Trading (EU-ETS) for CO2 nor the possibility of being an active player in increasingly flexible electricity market provide significant incentives for electrification in West Sweden process industries.

Today, there is a large number of P2X technologies for different products, of different maturity and suitability depending on the industrial sector. Within the cluster's refinery industry, there are concrete plans within the next few years for establishing P2Hydrogen in demo scale. In the longer term, it is conceivable that the refinery industry will implement large-scale P2H2 concepts to satisfy a significant fraction of the hydrogen gas needs of their refinery operations (Preem), or even implement electro-fuel production, e.g. electro-methanol (Preem, St1). In addition, the SME company Liquid Wind is targeting for up to five regionally located electro-methanol plants. Borealis mainly expresses interest in various forms of P2heat (i.e. electrical heating of steam reformer reactors, electrical heated cracking, electrification in connection with chemical waste refinery concept, etc), while Perstorp in the long run sees opportunities in P2acids (e.g. valeric acid).

A number of barriers have been identified for the implementation of the different P2X technologies, such as low TRL levels, high costs, uncertainties linked to integration aspects and impact on existing processes and systems, access to carbon dioxide, water and electricity at one site if electro-fuel production, etc. Other barriers raised by the industries are the lack of long-term policy and funding. However, the most significant barrier that was pointed out for large scale P2X implementation concerns uncertainty in the availability of fossil-free / renewable electricity capacity at competitive prices in combination with long lead times for permitting processes and expansion of the electricity grid (up to 10-12 years).

In this study, the sum of the expressed power needs with the moderate electrification pathway presented by the interviewed industries corresponds to a doubling of current power demand levels. If the extensive (more speculative) electrification scenarios beyond 2030 are included, the total power need becomes just over 10 times larger than today´s and would most likely require extensive grid reinforcements. But even with the moderate electrification plans, grid reinforcements could be needed, especially if they coincide with electrification of other sectors. This highlights the need for open and active communication between industries and power grid operators about future plans and possibilities.

4 Knowledge gaps – suggestions for further work

Many electrification technologies are still at low technology readiness levels, e.g. P2acids, P2ethylene and electro-cracking (Appendix A2), and further technology development is needed. Interviewees mention the importance of finding the technological breakthroughs that reduce risks and costs to reasonable levels. For this, pilot and demonstration projects are needed.

There is also a clear need for conducting inventory studies for opportunities for implementing industrial heat pumps.

The role of electrification in relation to other pathways based on e.g. biomass, CCS and CCU, is still unclear even for companies that have set clear targets for reaching net-zero emissions. It is not obvious how to design and integrate the overall sites, where electrification is typically only part of the solution and needs to be combined with increased use of biomass or recycled feedstock and carbon capture and storage or re-use.

It is important to evaluate how steam balances and heat flows at a process site are affected by electrification of individual process units to be able to assess the consequences of electrification on fuel use, excess heat, and on- and off-site emissions. This is not obvious for the complex integrated systems of industrial process plants.

Another question raised, as also highlighted in the “Conclusions” section, is how to ensure that the electricity required for the transition will be available – at a competitive price – and that it will be renewable/fossil-free. If there is not sufficient electricity available, where can it be used in the smartest way? Realistic scenarios for up-scaling in all sectors are required.

For electrofuel production, it is important that biogenic CO2 is available at the same location as electricity (and water). However, the CO2 volumes required for electrofuel production are typically significantly smaller than the levels required to enable cost-efficient carbon capture. Consequently, there is a need to look at technologies for effectively capturing smaller volumes of CO2 (and maybe from lower concentration flows).

The need for collaborative projects is stressed by several interviewees, for example, to enable collaborative action along entire value chains for electrofuel production in the Nordic countries.

Lastly, another point brought up in the interviews is the value of electrification projects for enhancing in-house competence levels. This could pave the way for future investments in industrial companies that currently do not have any concrete electrification plans.

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Appendix

Appendix A1. Questions to participating process industries and power companies.

In the following, a list of the questions asked to the participating industries and power companies is given.

Questions to participating process industries:

Electricity supply – Current state:

1. Current electricity consumption per year (MWh)?
2. Which process(es) are the biggest consumers?
3. How does the load vary over time (season, weekday, time of day)?
4. How large is the peak power load (MW)?

Present grid connection:

1. Voltage level?
2. Multiple access points?
3. Regional or local area networks?

Reliability requirements:

1. Are back-ups/UPS available?

Grid connection contract:

1. How much power is contracted for?
2. Costs?

Relationships with network companies:

1. How is the relationship/dialogue?
2. On-going dialogue about future plans?

Electricity supply - Future investments:

1. Which investments are most likely?
2. How do they affect the electricity consumption?

Internal electricity network:

1. Any problems with the internal on-site grid, with respect to the capacity and/or the power quality?

General questions on P2X :

1. Driving forces/road maps – development routes, what role may electrification play (overall and more specifically for one or several P2X technologies)?
2. Barriers to large-scale implementation, provided that there is a willingness to pay for the new product(s)?

For the P2X-technology(ies) of interest, what about the:

3. Reliability?
4. TRL?
5. Legislation? Environmental permit application processes?
6. Integration in existing process (with respect to heat balance, other raw materials)?
7. Available size and up-scaling over time?
8. Pay-back time?
9. Flexibility from the industry´s viewpoint and core business?

Questions to power companies

Description of current situation:

1. How much power is contracted for from overlying electricity network?
2. Total load for the area (MWh)/peak power (MW)?
3. Future investments / reinforcements / production facilities (2025, 2030, 2035, 2040)?
4. Increase contracted power from overlying networks (problems/challenges, current communication about future investments)?

Process industry specific (for a given site):

1. Max power at connection point, and why? Bottlenecks?
2. What type of problems appear above the existing “max power at connection point”? Transmission restrictions? Connection reliability? Voltage problems?
3. Communication with the industry: is knowledge shared about future plans/loads/scenarios?

Flexibility:

1. Possibilities of buying power reduction to reduce investment costs?
2. Do you have a sense of how flexible the customer might be?

Appendix A2.

Table A2. Potential electrification technologies in the chemical, petrochemical, refinery and pulp and paper sectors.

Industry	Technology	Description	TRL*	Sources
Chemical	Power-to-Methane (electrolysis and Sabatier reaction)	Hydrogen from water electrolysis is combined with CO2 in a Sabatier reaction	Medium	
	Power-to-Syngas via RWGS	Reverse water gas shift reaction coupled with water electrolysis	Medium-High	
	Power-to-Syngas via low-temperature electrolysis	Coupling carbon monoxide production from low-temperature electrolysis of CO2 with hydrogen production from water electrolysis	Low	
	Power-to-Syngas via high-temperature co-electrolysis	Co-electrolysis of water and CO2 to produce syngas directly; takes places at high temperatures with solid oxide electrolysis cells	Low	
	Power-to-Ethylene	Single-step electrochemical reduction of CO2 with a Cu-based catalyst	Low	Siemens (2018)
	Methanol-to-olefins with renewable methanol	Hydrogen from water electrolysis is combined with CO2 in a methanol synthesis reaction to produce methanol. Methanol is then converted to olefins.	High	
	Water electrolysis for hydrogen and oxygen production	Hydrogen and oxygen for alcohol and acid synthesis from water electrolysis	High (for alkaline electrolysis)	
	Electro-hydrogen	Hydrogen from water electrolysis for EDA process in which ethylene amines are produced	High	DECHEMA (2017)
	Electro-ammonia	On-site ammonia production with hydrogen from water electrolysis	High	Material Economics (2019) DECHEMA (2017)
	Electrification of cooling, heating, compression, and steam	Example technologies: heat pumps, electric steam generation to replace fuel gas boilers	High	
Petrochemical	Electrification of steam crackers (as standalone option)	Electricity as heat source in steam cracker (currently, heat is generated from by-products) or natural gas	Low (for high-temp furnaces)	Material Economics (2019) Cracker of the future (2019)

	Electrification of cooling, heating, compression, and steam	Example technologies: heat pumps, electric steam generation	High	Material Economics (2019)
	Electrification of hydrogen production for plastics production		High	Material Economics (2019)
	Reprocessing of by-products (e.g. methanol to olefins)	Re-processing of by-products from the cracking process into chemicals to avoid fuel emissions	High (for MTO)	Material Economics (2019)
	Synthetic chemistry, new chemicals from CO2 (CCU)		Medium-High	Material Economics (2019)
	Electrification of polymerisation and other foreground processes		?	Material Economics (2019)
	Chemical recycling via gasification route	Hydrogen from water electrolysis to convert raw syngas to sweet syngas (removing sulphur compounds) plus Methanol-to-Olefins process. Methanol as new platform chemical. Main electricity demand from electrolysis	? (high for electrolysis and MTO)	Material Economics (2019)
	Chemical recycling via pyrolysis and steam cracking	Electric steam cracking of the pyrolysis oil from pyrolysis with methane as platform chemical; then MTO process. Methanol as new platform chemical. Main electricity demand from electric steam cracking	Low (for electric steam cracking)	Material Economics (2019)
	Thermochemical recycling with different degrees of implementation	The core idea is to introduce a plastic cracker into existing infrastructure. Electricity may come in for electric heating and/or water electrolysis	? (high for electric heating and water electrolysis)	Thunman et al. (2019)
	Bio-based plastics production	Water electrolysis to produce hydrogen for catalytic methanation plus MTO process	High (for electrolysis and MTO)	Material Economics (2019)
	Roto Dynamic Reactor	Cracking with strong kinetic energy by using a high-speed spinning rotor instead of thermal cracking	Low	Johannesdahl (2018)

	Membranes for olefin separation	Application of membranes in different hybrid distillation configurations (upstream, downstream) for ethylene/ethane and butandiene/C4 separation	Low	Motelica et al. (2012)
Refinery	Power-to-hydrogen for biofuel production		High	Grahn and Jannasch (2018)
	Power-to-hydrogen with CCU for electro-fuels production		Medium-High	CIEP (2018) Concawe (2019)
	Power-to-hydrogen for hydrocracking processes		High	
	Electrification of cooling, heating, compression, and steam	Mechanical vapour recompression, electric steam generation, switchable drives	High	CIEP (2018) Concawe (2019)
	Gas separation membranes	For hydrogen upgrading and recovery, as well as off-gas upgrading	High	
	Power-to-hydrogen for electro-fuel/chemical production	Production of hydrocarbons from industrial carbon dioxide and P-to-hydrogen, which can be refined to fossil-free petrol, diesel and chemicals	High	Bioeconomy+ (2018)
Pulp and paper	Electrification of heating and steam	Heat pumps, electric boilers, MVR to evaporation	High	Beyond Zero Emissions (2018)
	Electric drying (infrared)		High	Beyond Zero Emissions (2018)
	Plasma arc furnaces for lime calcination		Low	Beyond Zero Emissions (2018) Lundqvist R, (2008)
	Power-to-hydrogen with CCU for electro-fuels production		Low	Jannasch et al (2019)
	Electrolysis of sodium sulphate	To decrease the volume of make-up chemicals. In addition to production of acid and caustic there is production of oxygen and hydrogen, potentially also of carbon dioxide	?	Jannasch et al (2019) Öhman et al (2014)

[*] TRL (Technology Readiness Level) refers to the maturity of a technology and is generally measured on a scale from 1-9 (https://enspire.science/trl-scale-horizon-2020-erc-explained/). Here, indications are given as Low-Medium-High, where Low ≈ TRL 1-4, Medium ≈ TRL 5-7, and High ≈ TRL 8-9.

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