Flexibility in emerging e-methanol production in Sweden

An assessment & case study of technical and economic flexibility potential

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Preface

This degree project for the degree of Master of Science in Engineering, Environmental Engineering has been conducted under the supervision of the Division of Environmental and Energy Systems Studies, Department of Technology and Society, Faculty of Engineering, at Lund University, in collaboration with Uniper/Sydkraft AB in Malmö.

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Abstract

As a part of the climate transition of hard-to-abate sectors such as shipping, aviation, and chemical industry, electrofuels may play a key part. In Sweden, e-methanol has gained interest, and several production facilities are currently planned or under construction. These will be very large electricity consumers, but because of the traditionally inflexible methanol synthesis they may not be able to adapt their consumption in accordance with renewable electricity availability and the needs of the electricity grid. This is not ideal, as the grid is already predicted to face large challenges due to increased electricity demand and more intermittent electricity production.

This thesis investigates the possibilities of emerging e-methanol production facilities to become more flexible in their electricity consumption as a way of lessening their burden on the electricity system and better correlate with renewable electricity availability. This is done primarily by examining the technical and economic aspects of flexible e-methanol production. Other integral factors such as EU policy and the future of the electricity system are also discussed.

The technical assessment was conducted mainly by gathering information from literature and industry, and concludes that the methanol synthesis itself is likely the limiting factor in overall flexibility of an e-methanol plant. The publicly available information on synthesis flexibility is however contradictive, which complicate conclusions. Some industry sources point in a very positive direction, but actual numbers to confirm this are not publicly available.

The economic analysis was performed by calculating production costs for plant configurations with varying degrees of flexibility. This was done for eight different assumption cases to examine the impacts of investment costs, electricity prices, and CO_2 source. The economic analysis also carries large uncertainties, but indicates that in most scenarios, plants likely could be designed with at least some flexibility capacity without increasing costs compared to constant operation configurations. Even a small amount of flexibility could however be very valuable from a grid standpoint. Under the most favorable investment cost assumptions, designs with very high degrees of flexibility were economically feasible, and as much as 12% of production costs could be saved compared to designs for constant operation. Signs from industry however point to these assumptions being very optimistic, at least for the near future. In addition to investment costs, electricity prices are also shown to have a very large impact on production costs and flexibility. Both investment costs and electricity prices are however very difficult to predict for the future.

As e-methanol is likely economically uncompetitive compared to fossil alternatives, policy is integral in enabling implementation. EU policies such as the Renewable Energy Directive, EU ETS, FuelEU Maritime and ReFuelEU Aviation have the potential to create important markets for e-methanol. They do however not differentiate between e-methanol and other comparable renewables, meaning it still has to compete against these. The EU's delegated acts on renewable fuels of non-biological origin provide a clear framework for e-fuel production, and the more stringent demands on correlation with renewable electricity production from 2030 will likely increase the importance of flexibility in the future.

A large scale-up of e-methanol prodution would have a significant impact on the electricity system. The transition of all current Swedish marine transport to e-methanol could mean more than 50 TWh of additional electricity demand per year. As such, scale-up of low-carbon electricity production and upgrades in the grid are likely prerequisites for widespread e-methanol production. Increased flexibility could help facilitate the integration of new plants into the grid.

Sammanfattning

Som en del i klimatomställningen av svåråtkomliga sektorer som sjöfart, flyg, och kemiindustri kan elektrobränslen komma att spela en viktig roll. I Sverige har e-metanol väckt intresse, och flera produktionsanläggninar är planerade eller under byggnation. Dessa kommer att vara stora elkonsumenter, men på grund av den traditionellt icke-flexibla metanolsyntesprocessen finns det frågetecken kring hur väl dessa anläggningar skulle kunna anpassa sin konsumtion efter elnätets behov och tillgången på förnybar el. Eftersom elnätet redan spås utsättas för stora prövningar på grund av ökande elefterfrågan och mer variabel elproduktion hade nya icke-flexibla storkunsumenter därmed inte varit optimalt.

Detta examensarbete undersöker möjligheterna för framväxande e-metanolanläggningar att bli mer flexibla i sin elanvändning som ett sätt att minska bördan på elsystemet och bättre korrelera med tillgången på förnybar el. Detta görs främst genom att undersöka tekniska och ekonomiska aspekter av flexibel e-metanolproduktion. Andra centrala faktorer som politiska styrmedel och elsystemets utveckling berörs också.

Den tekniska utvärderingen genomfördes främst genom att samla information från litteratur och industrin, och bekräftar att metanolsyntesen sannolikt är den primära flaskhalsen för flexibel e-metanolproduktion. Den öppet tillgängliga information som finns om metanolsyntesflexibilitet är dock motsägelsefull, vilket försvårar möjligheterna att dra tillförlitliga slutsatser. Vissa industrikällor pekar i en mycket positiv riktning, men den data som hade behövts för att bekräfta detta finns dessvärre inte öppet tillgänglig.

Den ekonomiska analysen genomfördes genom att beräkna produktionskostnader för anläggningskonfigurationer med varierande flexibilitetsgrad. Detta gjordes för åtta olika fall för att kunna utvärdera påverkan av olika antaganden för investeringskostnader, elpriser och CO_2-källa. Den ekonomiska analysen har likt den tekniska stora osäkerheter, men tyder på att under de flesta antaganden kan anläggningar designas med åtminstone viss flexibilitetskapacitet utan att produktionskostnaderna ökar jämfört med att designa för konstant produktion. Även en liten grad av flexibilitet kan dock vara värdefullt ur ett elsystemperspektiv. Under de mest gynnsamma antagandena för investeringskostnader var designer med mycket hög flexibilitetsgrad ekonomiskt genomförbara, och produktionskostnaderna kunde minskas med upp till 12% jämfört med att designa för konstant produktion. Dessa antaganden är dock i nuläget mycket optimistiska, åtminstone att döma av information från industri och näringsliv. Utöver investeringskostnader visar analysen även att elpriser har en stor påverkan på resultatet. Framtiden är dock svår att förutspå, både för investeringskostnader och elpriser.

Eftersom e-metanol sannolikt inte kan konkurrera ekonomiskt med fossila alternativ är politiska styrmedel centrala för att gynna implementeringen. EU-styrmedel som förnybartdirektivet, utsläppshandelssystemet, FuelEU Maritime och ReFuelEU Aviation har potentialen att skapa viktiga markader och mer gynnsamma marknadsförhållanden för e-metanol. Dessa skiljer dock inte på e-metanol och andra jämförbara förnybara alternativ, så e-metanolen kommer fortfarande behöva konkurrera med dessa. EU:s delegerande akter om förnybara bränslen av icke-biologiskt ursprung sätter tydliga ramar för produktionen av e-metanol, och de mer stränga kraven på korrelation med förnybar elproduktion från 2030 kommer sannolikt öka vikten av flexibilitet i framtiden.

En storskalig utbyggnad av e-metanolproduktion skulle ha en betydande påverkan på elsystemet. Omställningen av all svensk sjöfart till e-metanol skulle kunna innebära drygt 50 TWh extra elkonsumtion om året, runt en tredjedel av Sveriges nuvarande elproduktion. Utbyggnad och upprustning av elnätet och en storskalig utbyggnad av fossilfri elproduktion kommer därmed sannolikt vara förutsättningar för att kunna genomföra

en storskalig uppbyggnad av e-metanolproduktion. Ökad flexibilitet hade kunnat underlätta integreringen av nya anläggningar i elnätet.

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List of Abbreviations

AEL - Alkaline electrolysis

CAPEX - Capital expenditure

CHP - Combined heat & power

EU ETS - EU emissions trading system

GHG - Greenhouse gases

LCOM - Levelized cost of methanol

LHV - Lower heating value

LRC - Lined rock cavern

MeOH - Methanol

OPEX - Operational expenditure

PEMEL - Proton exchange membrane electrolysis

RED - Renewable Energy Directive

RFNBO - Renewable fuel of non-biological origin

SOEL - Solid oxide electrolysis

SAF - Sustainable aviation fuel

SVK - Svenska Kraftnät

TSO - Transmission system operator

Introduction

In order to combat climate change, large emissions reductions are required throughout society. This is reflected in climate goals - both Sweden and the EU have ambitions of being climate neutral within a few decades, Sweden in 2045 and the EU in 2050 (Swedish Environmental Protection Agency, 2024; European Commission, 2024b). As long as enough low-carbon electricity is available, large parts of this decarbonization can be achieved through direct electrification or by the use of renewable hydrogen. However, these are not viable alternatives for all sectors, leaving important parts of the transition to be achieved through other means. One potentially important tool in these cases is the use of so-called *electrofuels*, or *e-fuels*, which are produced using renewable hydrogen and sustainably sourced carbon. A core benefit of e-fuels is that in contrast to biofuels (which can also be used to decarbonize these sectors), they are produced without using biomass, which is a limited resource (International Energy Agency, 2023).

One type of e-fuel is *e-methanol*, which has the potential to play a crucial role in the transition of some hard-to-abate sectors, such as shipping (International Energy Agency, 2023), chemical industry (IRENA, 2021) and (if upgraded further) aviation (IRENA, 2021). Because of the size of these sectors, this would require a large amount of sustainable methanol, and subsequently also large-scale production facilities. Renewable H_2 for e-fuels is expected to be produced via electrolysis of water, which would make these facilities into very large electricity consumers.

In the future, the Swedish electricity system will likely contain more intermittent renewable production, and at the same time electricity demand is projected to increase dramatically (Swedish Energy Agency, 2023b). This combination will present new challenges for the electricity grid, and increase the need for demand flexibility (Svenska Kraftnät, 2024b). To alleviate in possible periods of grid stress, it would therefore be very valuable from a grid standpoint if large consumers, such as e-fuel producers, were able to be flexible in their electricity consumption.

There are however several question marks regarding to what degree e-methanol producers would be able to be flexible in their electricity consumption, both technical and economical. Electrolysis is already demonstrated to be relatively flexible (Lange et al., 2023; Edvall et al., 2022), but conventional methanol synthesis is characterised by inertia and a large amount of full-load hours (Bellotti et al., 2017; Van Antwerpen et al., 2023). Combined with the high costs associated with H_2-storage and the high investment costs for the facility as a whole (Ramboll, 2023; Danish Energy Agency, 2024a; Danish Energy Agency, 2024b), this could make it difficult for emerging production facilities to be flexible, both technically and economically. It is therefore interesting to examine if new e-methanol production plants could be flexible from a technical standpoint, and whether it could be economically viable.

The aim of this thesis is to examine and evaluate the possibilities for emerging e-methanol production facilities to become more flexible in their electricity consumption in order to lessen their burden on the electricity system. This will be done through examining both technical and economical aspects of the facilities themselves, as well as external factors such as regulations and electricity price.

The research questions are:

- How flexible can future e-methanol plants be from a technical standpoint?
- What are the economic conditions for flexible operation of e-methanol production?
- How are external factors such as electricity price and policies likely to affect the conditions for e-methanol?

Chapter 2

E-methanol

This chapter presents some background information on methanol and e-methanol, including properties, production, environmental impacts, and e-methanol's relation to the electricity system.

2.1 Methanol

Methanol is the simplest alcohol, consisting of a single carbon atom linked to three hydrogen and a hydroxyl group, and has the chemical formula CH_3OH. At ambient conditions, it appears as a colourless, relatively volatile, flammable liquid, and has an alcoholic odor similar to ethanol (National Center for Biotechnology Information, 2024). It is polar and water soluble. It can cause severe skin irritation and can be acutely toxic if inhaled or ingested, but is not carcinogenic (National Center for Biotechnology Information, 2024; Swedish Knowledge Center for Renewable Transportation Fuels, 2017).

It has a volumetric energy density of 15.8 MJ/L (lower heating value, LHV) (Swedish Knowledge Center for Renewable Transportation Fuels, 2017). This is about twice as high as liquid hydrogen, but only around half as much as gasoline (Office of Energy Efficiency & Renewable Energy, n.d.), meaning methanol only needs half the storage volume compared to liquid hydrogen, but twice the volume compared to gasoline.

Since methanol is water soluble and biodegradable, the environmental risks associated with leakage and spills is lower compared to many other fuels (Swedish Knowledge Center for Renewable Transportation Fuels, 2017).

Currently, methanol is mostly used for various energy applications, in pharmaceutical industry, and as feedstock for chemical industry (Palma et al., 2018).

2.1.1 Conventional methanol synthesis

Conventional methanol is produced from fossil feedstocks, most commonly natural gas and coal (Methanol Institute, 2022). The feedstocks are reformed into synthesis gas (commonly referred to as "syngas"), mainly consisting of hydrogen and carbon monoxide (Palma et al., 2018). The syngas is reacted under high pressure in the presence of a catalyst (National Energy Technology Laboratory, 2023). Conventional methanol synthesis is characterized by a high amount of full-load and high inertia (Bellotti et al., 2017; Van Antwerpen et al., 2023; Hulteberg, 2023).

For conventional fossil methanol, the Methanol Institute (2022) report life cycle greenhouse gas (GHG) emissions of 110 g CO_2e/MJ (396 g CO_2e/kWh) for natural gas based methanol, and 300 g CO_2e/MJ (1080 g CO_2e/kWh) for coal-based methanol. As a comparison, fossil diesel and gasoline have life cycle emissions of around 85-100 g CO_2e/MJ (305-360 g CO_2e/kWh) (Eriksson and Ahlgren, 2013).

2.2 E-methanol

"E-fuels", or "electrofuels", is a collective term for synthetic fuels produced using hydrogen from electrolysis. Most commonly, the hydrogen is then combined with carbon (from a non-fossil source) to produce various hydrocarbons, although combining it with nitrogen to produce e-ammonia is also possible (International Energy Agency, 2023).

E-fuels are chemically identical to their fossil counterparts, but instead of getting the needed hydrogen and carbon from fossil feedstocks, they are obtained by electrolysis of water and captured CO_2 (International Energy Agency, 2023).

There are several different electrolyzer technologies, but the two that are most mature and commercially available on a large scale are *alkaline electrolysis* (AEL) and *proton exchange membrane electrolysis* (PEMEL). Development of newer technologies such as solid oxide electrolysis (SOEL) (also referred to as high-temperature electrolysis (HTEL)) is interesting for the future, as they have the potential to be more efficient and use less critical materials (Danish Energy Agency, 2024b).

E-methanol is one of the e-fuels that have gathered the most interest, mainly because of its potential as a shipping fuel, as a feedstock in chemical industries, or as a precursor for more advanced hydrocarbons (e.g. aviation fuel) (International Energy Agency, 2023; IRENA, 2021). Currently, one e-methanol production facility is under construction in Sweden (Ørsted, 2024), and several projects are in different stages of planning or permitting processes (Liquid Wind, 2024a; Liquid Wind, 2024b; Uniper, 2024).

2.3 Greenhouse gas emissions of e-methanol

As long as the carbon feedstock is non-fossil, the life cycle emissions of e-methanol are almost exlusively determined by the carbon intensity of the electricity used for the electrolysis (Methanol Institute, 2022). This leads to very large variations depending on electricity source. Some examples of resulting emissions from the electricity used in e-methanol production are presented as blue bars in Figure 1. The emssions are based on the following assumptions:

- Electrolysis electricity consumption of 45 kWh/kg H_2 (IRENA, 2020; Ali Khan et al., 2021)
- 0.19 kg H_2 per kg methanol (Schemme, 2020)
- Methanol energy content (LHV) of 19.8 MJ/kg (Danish Energy Agency, 2024b)
- CO_2 emissions from electricity of 26 g/kWh for Sweden (Swedish Energy Agency, 2023c), 90 g/kWh for Nordic mix (Sandgren and Nilsson, 2021), 242 g/kWh for EU mix (EMBER, 2024), 371 g/kWh for Germany (EMBER, 2024), and 531 g/kWh for China (Statista, 2024)

Fossil methanol (from natural gas and coal) and the EU's fossil fuel comparator for renewable transport fuels of 94g CO_2e/MJ (338g/kWh) are also included for reference (brown bars). This comparator value represent emssions of fossil alternatives in the transport sector, and was first specified in the EU's renewable energy directive of 2018 (RED II) as a comparator for biofuels used in the transport sector (European Union, 2018). GHG emissions must be reduced by at least 70% (represented by red line) compared to this value in order to qualify as a renewable fuel of non-biological origin (RFNBO) (European Union, 2023b). This is covered more in-depth in Chapter 3.

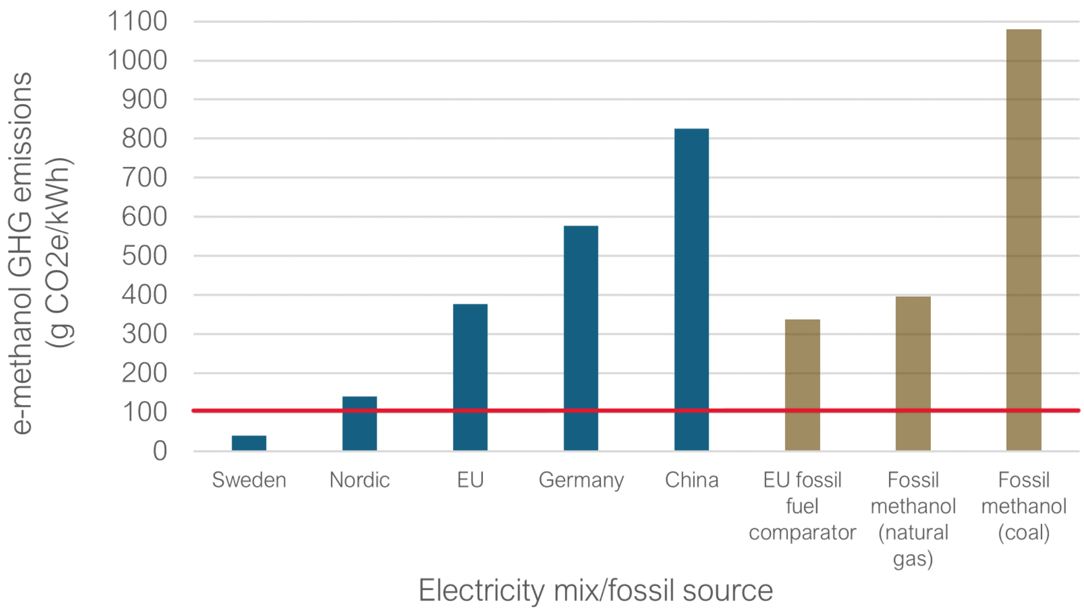

Figure 1: Calculated GHG emissions of e-methanol production using different electricity mixes (blue bars). The EU's fossil fuel comparator value and the target that must be reached (red line) to qualify as RFNBO is included for reference. Fossil methanol from natural gas and coal also included for comparison.

As Figure 1 shows, e-methanol is only environmentally viable if the electricity has low GHG emissions, and can actually have a higher climate impact than fossil counterparts in cases with carbon-intensive electricity. This means that e-methanol production must either be located in areas where electricity in the grid is very low in emissions (such as Sweden), or ensure low-emission electricity by other means, such as co-constructing a wind farm or solar plant.

2.4 E-methanol and the electricity system

Because of the large electricity consumption of electrolysis and carbon capture, e-methanol production will be very dependent on the conditions in the electricity system. Electricity prices will determine operating costs, and power availability, grid stability and transmission capacity will determine the possibility for new facilities to connect to the electricity grid. Predicting how the electricity system will develop is however difficult, as the electricity system (and the energy system as a whole) is undergoing a period of dramatic change, and the range of potential outcomes is very wide.

One thing that is clear is however that an increase in electricity demand is very likely as a result of the climate transition, and this in combination with an increased share of intermittent renewable electricity production is likely to present unprecedented challenges to the Swedish electricity system. The Swedish electricity consumption in 2023 was 134 TWh, but the Swedish transmission system operator (TSO) Svenska Kraftnät (SVK) predict an increase to between 178 and 271 TWh in 2035, and between 204 and 347 TWh in 2045 (Svenska Kraftnät, 2024b). The Swedish Energy Agency present relatively similar predictions of 175-250 TWh in 2035, and 220-320 in 2045 (Swedish Energy Agency, 2023b). In several reports, SVK predicts that construction of new electricity production may not be able to keep up with this demand increase, and discuss serious concerns of power shortages and balancing issues within just a few years (Svenska Kraftnät, 2023b; Svenska Kraftnät, 2023c; Svenska Kraftnät, 2023d). On the same note, a joint report between SVK, the Swedish Energy Agency, the Swedish Energy Markets Inspectorate, and the Swedish Board for Accreditation and Conformity Assessment states that current resources, infrastructure and balancing markets will not be sufficient to balance the electricity system in a few years (Swedish Energy Markets Inspectorate, 2023). As such, additional measures will be required to keep the balance and stability in the electricity grid in the future. Flexibility on the demand side, especially in electricity-intensive industry (such as e-fuel production), will be of great importance (Svenska Kraftnät, 2024a; Svenska Kraftnät, 2023e; Swedish Energy Markets Inspectorate, 2023; Swedish Energy Agency, 2023a). Both SVK and the Swedish Energy Agency suggest increasing incentives for demand flexibility, but exactly how is currently under discussion (Svenska Kraftnät, 2023e; Swedish Energy Agency, 2023a). Some suggestions include:

- Changing the rules for participating in ancillary service markets
- Flexibility markets
- Prioritizing flexible consumers over non-flexible ones for connection to the grid
- Changing grid fee and electricity contract structures to facilitate flexibility
- Signing non-firm connection agreements with new large consumers upon connection to the grid. This means that consumers could be mandated to reduce consuption during hours with very high overall consumption

(Svenska Kraftnät, 2023e)

The pathways to implementation for these suggestions are of varying length, and to what extent they will be eventually be materialized is currently unclear.

Introducing e-fuel production on a wide scale would mean a very substantial increase in electricity demand, as the energy use of previously non-electrified sectors would have to be covered by electricity. As an example, the Swedish shipping sector (domestic and international) used 27 TWh of energy in 2022 (Swedish Energy Agency, 2024c). If all this were to be converted to e-methanol, more than 50 TWh of electricity per year would be needed (assuming a power-to-fuel efficiency of around 50% (Rahmat et al., 2023)). This is roughly a third of Sweden's total electricity production in 2023 (Swedish Energy Agency, 2024a). An introduction of this scale would be challenging, and highly dependent on scale-up of electricity production and grid capacity, but flexibility could help facilitate new connections.

Lastly, as mentioned electricity prices will make up an important share of production costs of e-methanol. Average prices are by all means important, but the volatility is equally interesting, as it decides the potential economic gain from shifting consumption from expensive hours to cheaper ones (i.e. flexibility). Volatility will likely largely be decided by the balance between intermittent production (which increases volatility) and balancing factors such as energy storage or demand flexibility (which decreases volatility). Future price levels are however notoriously hard to predict. Recent events such as the COVID-19 pandemic and the Russian invasion of Ukraine, and their subsequent dramatic impacts on electricity prices, further goes to showcase the unpredictability. An increase in prices however seem the most likely outcome, mainly due to the higher demand and increased connections to the rest of Europe. Simulations by Svenska Kraftnät (2024b) show 2035 electricity prices of around €45-60 for all Swedish bidding areas, which would mean a significant increase for the two northernmost bidding areas SE1 and SE2. This increase is however highly dependent on to what degree new electricity-intensive industry establishment in northern Sweden becomes reality.

Chapter 3

Relevant EU and Swedish policy

Both Sweden and the EU have goals of climate neutrality within a few decades, Sweden in 2045 (Swedish Environmental Protection Agency, 2024) and the EU in 2050 (European Commission, 2024b). The net-zero GHG target for 2050 is a legally binding part of the European Climnate Law (European Union, 2021), which also includes the target of 55% GHG emissions reduction in 2030 (compared to 1990).

To achieve these targets, the EU has adopted the "Fit for 55"-package, a wide range of new and updated legislation targeting critical areas (European Council, 2024; European Commission, 2023a). An integral part of the package is the revised Renewable Energy Directive (European Union, 2023c) (also referred to as *RED III*), which includes binding targets for the overall share of renewables in the EU's total energy use. RED III updates the binding target for renewables in 2030, from 32% (in RED II), to 42.5% (with the aim of reaching 45%).

Included as renewable in the Renewable Energy Directive are what the EU calls *renewable fuels of non-biological origin*, or *RFNBO*s. This includes renewable hydrogen from electrolysis, along with renewable fuels produced using renewable hydrogen from electrolysis (such as e-methanol) (European Commission, 2023b). The conditions for when a fuel qualifies as an RFNBO (and thereby can be counted toward the EU's renewable energy targets) are set up in two delegated acts adopted in 2023. The first delegated act (European Union, 2023a) includes conditions to ensure that the electricity used in hydrogen production is renewable, and that scale-up of RFNBO production promotes *new* renewable energy production. From 2030, demands on hourly temporal correlation between renewable electricity production and electricity consumption are implemented, meaning that RFNBO plants must prove that electricity used was renewably produced during the same hour it was used.

The second delegated act (European Union, 2023b) includes the methodology for calculating GHG emissions from RFNBOs, along with the demand of at least 70 % reduction in GHG emissions compared to the EU's fossil fuel comparator of 94 g CO_2e/MJ (338 g CO_2e/kWh). It also specifies that carbon captured from non-sustainable sources may be counted as avoided emissions until 2035 (for carbon from electricity generation) or 2040 (for carbon from "other uses of non-sustainable fuels").

Included in the Fit for 55-package are also policies that more specifically target certain sectors. For e-fuels and e-methanol, the two most relevant ones are shipping and aviation.

For shipping, there are two important EU policies that affect the use of e-fuels. The first one is the inclusion of the shipping sector in the EU emissions trading system (EU ETS), the EU's flagship mechanism for carbon pricing. Since January 1st, 2024, the EU ETS includes all large ships entering EU ports (defined as ships with a gross tonnage above 5000) (European Commission, 2024a). During a phase-in period, only parts of the emissions will be covered, but from 2027, all emissions are included. This may benefit e-methanol, as it is one of the major alternatives that can be used to reduce GHG emissions in shipping. The second one, FuelEU Maritime (European Union, 2023d), includes mandates for GHG reductions for the shipping sector. The regulation mandates GHG reductions from 2025 onwards, starting at 2% (compared to 2020 average values), eventually reaching 80% in 2050. To incentivize early scale-up of RFNBO production (which includes e-methanol), emissions from RFNBOs are only counted as half between 2025 and 2033.

For aviation, the EU's key decarbonization legislation is called ReFuelEU Aviation (European Union, 2023e), and includes mandates for the inclusion of so-called sustainable aviation fuels (SAF) for aircraft operating from EU airports. The SAFs can be made up of either advanced biofuels (i.e. produced from non-food biomass) or RFNBOs. The mandates are gradually increasing, starting at 2% in 2025 and increasing to 70% in 2050. From 2030, the legislation also includes specific minimum percentages for RFNBOs, starting at 0.7% in 2030 and increasing to 28% in 2050. While e-methanol cannot be used directly as an aviation fuel (because of the low energy density), it can act as a precursor to more advanced e-fuels (Topsoe, 2024a).

In Sweden, the primary policy to reduce GHG emissions from transport has since 2018 been the Emissions Reductions Mandate ("Reduktionsplikten"), which includes mandates for emission reductions in gasoline, diesel and kerosene for aviation (Swedish Energy Agency, 2024b). In 2023, the mandates were 7.8% for gasoline, 30.5% for diesel and 2.6% for kerosene (Sveriges Riksdag, 2023b). However, in the fall of 2023, the Swedish parliament voted to lower the mandates of gasoline and diesel to 6% for 2024-2026, and from 2027 scrap the mandates for gasoline and diesel entirely (Sveriges Riksdag, 2023a). The mandate for kerosene however remains. It is currently 3.5% and is set to increase to 27% by 2030 (Sveriges Riksdag, 2023a).

Chapter 4

Methodology and input data

4.1 Technical analysis

The aim of the technical analysis was to examine whether it is, or could become, possible to design an e-methanol production plant that is flexible in its electricity consumption. This was done by gathering information from literature, industry, and communication with relevant people. All different production steps were evaluated, but with the main focus on the methanol synthesis. Results of the technical analysis are presented in Chapter 5.

4.2 Economic analysis

The purpose of the economic anylysis was to examine how flexible configurations (in which the plant runs for fewer hours but has a higher capacity) compare economically to the traditional static/constant operation case (where the plant runs for as many hours as possible, but has a lower capacity). The theory is that if the plant has the ability to be flexible, it can choose to operate during hours when electricity prices are lower and low-carbon electricity more abundant (and avoid hours when prices are high and the grid is likely more stressed), possibly providing an economic gain while also benefitting grid stability. This however comes with a larger investment cost, as a higher capacity is needed in order to produce the same amount of methanol.

The economic analysis focuses on an e-methanol production plant with the following characteristics:

- Constructed around 2030, but analysis will focus on the year 2035
- Located in the geographic area covered by electricity bidding zone SE2 (which roughly covers the southern half of northern Sweden)
- Production of 100 000 tonnes of methanol per year
- Alkaline or PEM electrolyzer
- CO_2 feedstock from pulp/paper mill or combined heat & power (CHP) plant

These conditions were provided by Uniper to provide a realistic scenario for a hypothetical e-methanol plant.

Excess heat and O_2 that is produced as byproducts were not considered as the potential utilization of these is highly dependent on local/regional conditions.

Full flexibility of the plant was assumed, meaning that the plant can freely ramp production up and down without limitations. This may seem odd at first, but was deemed the most reasonable assumption under the circumstances. Indeed, the original ambition was to perform a full simulation of a plant with H_2 storage capacity and limits for ramping and part-load. However, this was proven undesirable for a couple of reasons. Firstly, no clear picture of the technical operating conditions was obtained from the technical assessment (more on this in Chapter 6). This meant that rather dubious assumptions would have had to be made, introducing more uncertainties. The second (and main) reason was that including storage and ramping limits would have introduced very large optimization problems, as conditions for how the plant is to optimally "behave" would have to be set up. This includes things like optimizing when to fill and empty the storage and how the plant should ramp up and down in response to different electricity prices. Getting a plant that performs reasonably well would likely have been possible, but fully optimizing would have been very time consuming. Given that the assumptions for the technical flexibility would have been very uncertain anyways, drawing any interesting conclusions from the results would also likely have been difficult. Instead, assuming perfect flexibility has the potential to answer a few interesting questions. Firstly, it can indicate whether there is *any* economic potential for flexibility, since if there would be no economic room even under these best-case assumptions, it can (in theory) be ruled out. Secondly, if there is potential for flexibility, it can give an indication of the *maximum* potential, setting an upper limit for what could be achieved. Thirdly, it gives an indication of how the economic conditions may look if methanol synthesis becomes flexible enough to eliminate the need for costly H_2-storage.

To analyze the economic flexibility potential, data for capital expenditure (CAPEX) (also referred to as *investment cost*) and operational expenditure (OPEX) was used to calculate the *levelized cost of methanol* (LCOM) at varying amounts of full-load hours (and plant capacities). The LCOM is the cost of producing a specified unit of methanol, in this case one metric tonne. To test how different assumptions affect the results, the analysis was divided into 8 different cases, based on different assumptions of CO_2 availability, electricity prices, and CAPEX. A visualization of the cases is provided in Figure 2.

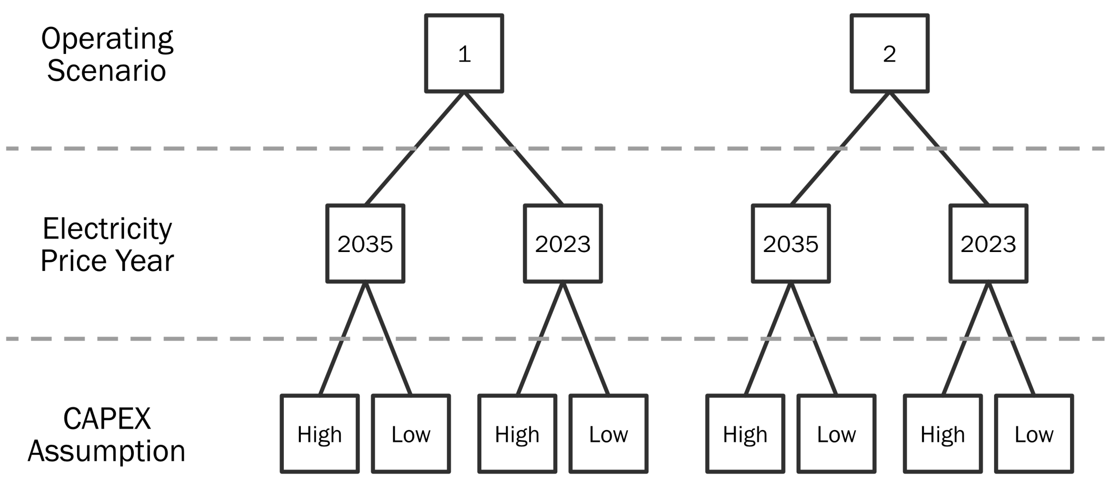

Figure 2: A visualization of the 8 different cases that are included in the economic analysis.

More information on the assumptions for the different cases is presented in Sections 4.2.1, 4.2.3, and 4.2.5.

4.2.1 Operating Scenarios (CO_2 availability)

The economic analysis is divided into two operating scenarios, based on the two most likely ways that non-fossil CO_2 could be supplied in Sweden. Since the e-methanol plant in this thesis is connected to the electricity grid (and therefore always has the ability to produce H_2), the CO_2 supply becomes the limiting factor deciding when methanol production is possible.

The first operating scenario, named "Operating Scenario 1", is based on CO_2 supply from a pulp/paper mill. These facilities typically operate year-round, without seasonal shutdowns. This means that the e-methanol production can be sustained throughout the year. To leave room for maintenance and unexpected disruptions, a maximum cap of 8000 full-load hours has been assumed instead of the 8760 that make up a full year. The 8000 hours that are deemed available have been chosen so that the average and median electricity price is unchanged compared to when including all 8760 hours.

The second operating scenario, named "Operating Scenario 2", is instead based on CO_2 supply from a combined heat and power (CHP) plant. CHP plants generally shut down during summer when heating demand is low, and typically have around 6000 operating hours (Levihn, 2017; Kraftringen, 2024). Consequently, this operating scenario caps the amount of full-load hours at 6000, with the 2760 unavailable hours occuring during the warmest months (May 19 to September 11, in this case). This means that the e-methanol plant will be unable to take advantage of the lower electricity prices and greater supply of renewable electricity that generally occurs during summer.

As shown in Figure 2, each operating scenario is divided into 4 cases, based on CAPEX assumptions (covered in Section 4.2.3) and electricity prices (covered in Section 4.2.5).

4.2.2 Technical data

In order to calculate production costs some technical data is needed, for example to calculate the capacities of the methanol reactor and electrolyzer, and the electricity consumption. The technical data used is presented in Table 1 below.

Table 1: Technical data used in the economic analysis.

	Value	Source(s)
Electricity consumption of electrolysis	45 MWh/t_{H_2}	Assumption based on RISE (2021) IRENA (2020) Ali Khan et al. (2021)
kg H2 / kg MeOH	0.19	Schemme (2020)
kg CO2 / kg MeOH	1.37	Schemme (2020)
Energy content of MeOH (LHV)	19.9 MJ/kg	Danish Energy Agency (2024b)

4.2.3 CAPEX

The capital expenditure (CAPEX) is made up by the investment costs needed to construct the facility.

As gathered sources on CAPEX costs for both electrolyzer systems and methanol reactors varied greatly, two different CAPEX cases are used. One is named "High CAPEX", and use cost estimates toward the higher end of the spectrum of collected sources. These should be relatively represenative of current costs, according to information from Uniper. The other is named "Low CAPEX", and instead use cost estimates toward the lower end of the spectrum, which should be relatively representative of the targets for 2030. According to Uniper, these are very far from current cost expectations, but figures in this range are not uncommon in literature, especially when referring to 2030 (and onwards). See for example IRENA (2020), Agora Energiwende (2023), Saba et al. (2018), Danish Energy Agency (2024b) & Ali Khan et al. (2021).

As the ranges of costs reported for AEL and PEMEL were very similar, these have not been differentiated.

The CAPEX figures used for the electrolyzer system and methanol synthesis system are presented in Table 2. The full list of collected sources on CAPEX costs can be found in Appendix.

Table 2: CAPEX figures used in the economic analysis.

	"High" CAPEX Assumptions	"Low" CAPEX Assumptions
Electrolyzer system	€2000/kW_{el}	€550/kW_{el}
Methanol reactor system	€1200/kW_{MeOH}	€500/kW_{MeOH}

4.2.4 OPEX input data

The operational expenditure (OPEX) is made up by a variety of different costs that are consequences of running the facility. Included operational costs are electricity price, CO_2-capture, grid fees (except connection fee), electrolyzer (including stack replacement), and methanol synthesis system.

CO_2 costs are loosely based on Energiforsk (2022) where both OPEX and levelized CAPEX costs are around €20/t at 8000 full-load hours. With fewer full-load hours, it is assumed that the CAPEX costs will double if the amount of full-load hours are halved (as twice the capacity is needed), while OPEX is assumed to stay constant. This is summarized in Equation 1:

$$CO_2 \text{ cost (EUR/t)} = 20 + 20 \times \frac{8000}{\text{nr. of full load hours}} \tag{1}$$

The grid fees are based on E.ON (2024). The connection fees and cost of potential needs for grid capacity expansion are not included, as no data could be found.

OPEX for the electrolyzer system (including stack replacement) was assumed to be 4% of CAPEX per year, based on Grahn et al. (2022). Other sources also report similar figures (Danish Energy Agency, 2024b; Agora Energiwende, 2023; Dieterich et al., 2020).

OPEX for the methanol synthesis system was assumed to be €30 000/MW_{MeOH}/year, based on Danish Energy Agency (2024b).

The cost of electricity varies greatly depending on the number of full-load hours and the year chosen. This is covered more in-depth in Section 4.2.5.

4.2.5 Electricity price data

In order to analyze the economic flexibility, electricity prices on an hourly basis are needed. For years in the past, hourly prices can be downloaded via the ENTSO-E transparency platform (ENTSO-E, n.d.). This is the way in which hourly prices for 2023 were obtained. Day-ahead prices were used as this represents the majority of traded electricity (Svenska Kraftnät, 2023a).

For the future, this is obviously not an option. Instead, some kind of simulation has to be performed based on assumptions of the future energy system. For this thesis, electricity price data for 2035 was purchased by Uniper from Gothenburg-based consulting firm Profu.

To model the electricity prices, Profu used two different optimization models, TIMES-NORDIC and EPOD. Most of the assumptions were based on the "lower electrification" scenario ("lägre elektrifiering") in Swedish Energy Agency (2023b). In that scenario, electricity demand in Sweden is assumed to increase to over 200 TWh in 2035. Nuclear power generation capacity was assumed to be unchanged compared to today. Assumptions for fossil prices and ETS credits were slightly adjusted compared to Energimyndigheten. Electricity grid expansion and maintenance was assumed to be in line with Svenska Kraftnät (2021). Storage capacity was assumed to be 13 GWh batteries and 229 GWh hydrogen storage, with hydrogen storage concentrated in northern Sweden. The weather year of 2016 was assumed for production profiles and weather-dependent electricity demand. An important limitation of the simulation is that negative electricity prices are not possible.

To visualize how the 2023 and 2035 electricity prices look, and how they compare to each other, their price duration curves are presented in Figure 3.

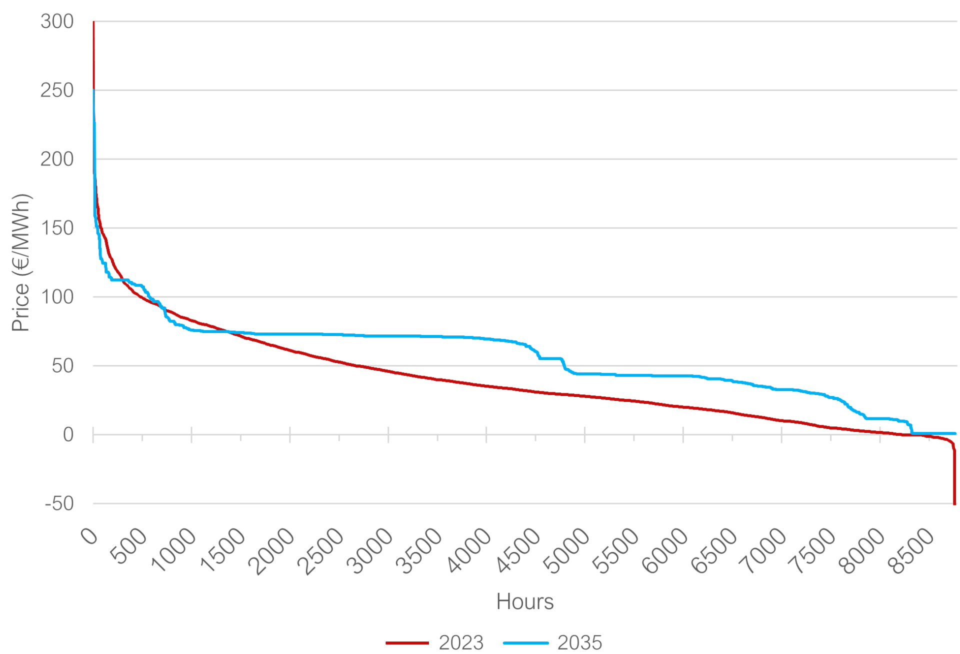

Figure 3: SE2 price duration curves for 2023 and 2035 (simulated by Profu).

As can be seen in Figure 3, the 2035 prices are generally higher than for 2023. For 2023, the average price is €40 and the median price €32. For 2035, the average price is €56 and the median price €66.

During LCOM calculations, what hours of the year that are included is determined by the amount of full-load hours. If for example LCOM is calculated for a case of 5000 full-load hours, the 5000 cheapest hours are included.

4.2.6 Other assumptions needed

Finally, a few more assumptions are needed in order to calculate costs. These are presented in Table 3.

Table 3: Miscellaneous assumptions needed for LCOM calculations.

	Value	Source
Construction time	1.5 yrs	Uniper
Interest rate	10%	Uniper
Lifespan electrolyzer	25 yrs	Agora Energiwende (2023)
Lifespan MeOH-reactor	25 yrs	Assumption based on Agora Energiwende (2023), Danish Energy Agency (2024b), Rivera-Tinoco et al. (2016)
Exchange rate SEK-EUR	11 SEK/EUR	Assumption based on recent exchange rate history

4.2.7 LCOM calculations

The LCOM is calculated by summing up all costs that can be attributed to a certain time frame, and dividing by the amount of methanol that is produced within that same time frame. In this thesis, the focus is on a single year where 100 000 t of methanol is produced, so the LCOM is simply calculated as such:

$$\text{LCOM} = \frac{\text{Yearly CAPEX costs} + \text{Yearly OPEX costs}}{100\,000\ \text{t}} \tag{2}$$

In order to estimate the yearly CAPEX cost, one must calculate the *equivalent annual cost*, which is done as follows:

$$\text{Equivalent annual cost} = \text{Investment cost} \times \text{A} \tag{3}$$

where A is the annuity factor, which is calculated as:

$$\text{A} = \frac{\text{r}}{1 - (1 + \text{r})^{-\text{n}}} \tag{4}$$

where r is the annual interest rate, and n is the economic lifetime of the investment in years (Skärvad and Olsson, 2013). The interest rate can be seen as the expected yearly return on investment if it was made elsewhere, so since that revenue is lost it is seen as a cost of the project in question. The investment cost will vary depending on the size of electrolyzer/methanol reactor (dictated by amount of full-load hours) and whether the "high" or "low" CAPEX scenario is used.

Something else that must be considered is that the plant is not operational immediately after the investment is made. Construction takes approximately 1-2 years (based on information from Uniper), and while these years will not carry any of the equivalent annual costs, interest expenses are still incurred during this time as capital is locked up in the project. Therefore, the original investment cost must be adjusted in order to also include the interest costs during construction. This is done by multiplying by

$$(1+\mathrm{r})^{\mathrm{t_c}}$$

where r is once again the interest rate and $\mathrm{t_c}$ is the construction time in years. This leaves us with the final equation for the CAPEX costs carried by each production year:

$$\text{Yearly CAPEX cost} = \text{Equivalent annual cost} = (1+\mathrm{r})^{\mathrm{t_c}} \times \text{Investment cost} \times \frac{\mathrm{r}}{1-(1+\mathrm{r})^{-\mathrm{n}}} \tag{5}$$

This equation is used to calculate the yearly CAPEX costs of both the electrolyzer system and methanol synthesis system.

For OPEX, some costs are static, but many are based on the amount of full load hours (either directly, or indirectly via electrolyzer/methanol reactor size). These are simply multiplied by the appropriate figure (except for the cost of electricity). For electricity, the cost is dictated by the amount of full-load hours. In a case with 5000 full-load hours, the 5000 cheapest hours are each multiplied by the power of the electrolyzer.

When all the yearly costs (CAPEX and OPEX) are calculated, the total cost is divided by the amount of methanol produced per year (in this case 100 000 tonnes) to obtain the LCOM.

For each of the 8 cases (Operating Scenario 1/2, high/low CAPEX, electricity prices from 2023/2035), the LCOM was calculated for different amounts of full-load hours (and thereby different electrolyzer/methanol reactor sizes) in order to analyze the effects of flexibility on LCOM. In each case, the lowest amount of full-load hours was 10, and the maximum amount was determined by the operating scenario (8000 in Operating Scenario 1, and 6000 in Operating Scenario 2). The LCOM was calculated for every 10 full-load hours (10, 20, 30, etc., up to the maximum cap), meaning that in every one of the 8 cases, costs were calculated for either 800 or 600 configurations (depending on operating scenario). The calculations were performed in Microsoft Excel, using a custom macro that was programmed in Visual Basic for Applications (VBA).

Chapter 5

Technical flexibility potential

In this chapter, the information gathered on the technical potential for flexibility in e-methanol synthesis will be presented. The information is divided into sections based on the different production steps.

5.1 Electrolysis

Electrolysis of water is generally regarded as flexible enough to be used for load-following operations, such as following wind profiles or adapting to fluctuating electricity prices (Edvall et al., 2022; Lange et al., 2023; Danish Energy Agency, 2024b). According to Edvall et al. (2022), both AEL and PEMEL are likely even quick enough to be able to provide all different ancillary services to the Swedish TSO Svenska Kraftnät. As such, it is unlikely for electrolysis to be the limiting factor for flexibility in e-methanol production.

5.2 Methanol synthesis

As described in Section 2.1.1, traditional methanol syntesis is characterized by large scale, constant operation, and the incentive has been to get as many hours of production as possible out of the investment. As such, flexible operation of methanol synthesis has only recently gathered more interest. This might be one of the reasons why very limited information seems to be publicly available in regards to the flexibility potential of methanol synthesis technologies. In addition, the information that is avaliable varies greatly, with some sources being very sceptical and others very optimistic. It has therefore proven difficult to get a comprehensive and accurate picture of the current state of flexibility capabilities in methanol synthesis technologies. In this section, some academic and some industrial sources on methanol synthesis flexibility will be presented.

Academic sources were found to be very mixed in their stance on flexible operation. Van Antwerpen et al. (2023) states that methanol synthesis has very limited flexibility due to process dynamics and reduced equipment lifetime, and that potential flexibility must be achieved by other means. Hank et al. (2018) state similar concerns over catalyst lifetime and reactor temperature. Bellotti et al. (2017) states that methanol reactors should be run at nominal capacity for as much as possible due to the high inertia. Hulteberg (2023) indicated that it might be possible to adjust production to as low as 30 % of capacity, but that this takes days, which is too slow to provide any significant benefits. Svitnič and Sundmacher (2022) states that it is uncertain whether methanol production could be operated flexibly.

Dieterich et al. (2020) has a more positive outlook on flexibility than the previously mentioned academic sources, and refer to three different sources to provide evidence of high flexibility. Unfortunately, neither Supp (1981) (supposedly demonstrating a Lurgi reactor with 10-15% part-load and ramping from 0-100% in a few minutes) or Valentin (n.d.) (supposedly referring to a simulation of an Air Liquide reactor adjusting production from 20 to 100% in 6-7 minutes) could be found or accessed. Heydorn et al. (2003) is the only one of the three that could be accessed, and refers to tests of an uncommon (Palma et al., 2018) type of liquid phase methanol reactor that indicated a possible ramping rate of around 5%/min.

Both Van Antwerpen et al. (2023) and Hulteberg (2023) mention the possibility of temporarily pausing production (often referred to as *hot stand-by*). This is done through recirculation and externally heating the reactor to maintain pressure and temperature, in order to be able to quickly resume production. For how long this can be sustiained is unclear, but Van Antwerpen et al. (2023) states that it might be possible for up to 24 hours.

Industry is generally more positive than academic sources, although more secretive in regards to actual numbers.

Topsoe (2024b) state the following about their ModuLite™ e-methanol synthesis:

> "Topsoe's eMethanol loop is a dynamic loop that consumes hydrogen directly as the electrolyzer produces it. This ability to adapt to fluctuations in hydrogen supply, and sustain production at low loads, reduces the risk of forced restarts and eliminates the need for costly hydrogen storage."

This seems to indicate a high degree of flexibility, but as no actual figures are presented publicly, it is unclear exactly what it means in terms of minimum part-load and ramping limits.

MAN Energy Solutions (2023) claim a minimum part-load of only 10%, and "fast ramping between 10–100% load to cope with potential fluctuations in the renewable electricity supply". Module sizes are however quite small, at only 10 or 20 MW.

Do et al. (2022) demonstrate an AirLiquide pilot reactor that was able to adapt to various load changes in under 10 minutes. The project was however very small-scale, with only a few kg produced per hour.

German start-up C1 claim to have invented a completely new methanol synthesis technology, which is supposed to have a high efficiency and selectivity, combined with good scalability and high flexibility (C1 Green Chemicals, 2023). The technology is currently projected to be commercially available in a few years.

Several industrial sources were contacted, but all declined to share more specific data on flexibility.

In Table 4, a summary of the information collected on the flexibility of methanol synthesis is presented.

Table 4: Collection of publicly available sources on the flexibility of methanol synthesis.

Source	Min. part load (%)	Ramping rate	Comment
Van Antwerpen et al. (2023)	100	-	Possibility of "hot stand-by" for up to 24hrs
Do et al. (2022)	?	Fast	Small-scale pilot
MAN Energy Solutions (2023)	10	"Fast"	10/20 MW modules
Heydorn et al. (2003)	?	5%/min	
Dieterich et al. (2020)	10-15	10-15%/min*	Based on inaccessible sources, one of which is from 1981
C1 Green Chemicals (2023)	"High flexibility"	"High flexibility"	Pilot stage successful
Topsoe (2024b)	"Low loads"	"consumes hydrogen directly as the electrolyzer produces it"	Large scale
Hulteberg (2023)	30%	very slow (days)	

*based on claimed capability of adjusting from 20-100% in 6-7 min.

5.3 Distillation

The raw methanol must be fed into a distillation unit in order to be upgraded to the desired standard. Flexibility in this part has however not been investigated, as methanol storage is relatively uncomplicated and likely eliminates the need for flexibility in the distillation.

5.4 Storage

Storage of H_2 (and potentially CO_2) can provide plenty of flexibility since it gives the opportunity to temporally decouple electricity consumption and hydrogen use, but exactly how much is dependent on how it is used. Storage is also very much limited by costs, as storage tanks and compressors are currently very expensive (Danish Energy Agency, 2024a). Because of compression, an extra 10-15 % of electricity is also needed for H_2 that is stored in tanks compared to H_2 that is used directly (Danish Energy Agency, 2024a). Due to the small molecular size and high flammability, H_2-storage in tanks is also complicated by the leakage risks. It is therefore accompanied by strict regulatory safety standards (Swedish Civil Contingencies Agency, 2024). Another drawback of leakage risks is that hydrogen is a very potent indirect greenhouse gas, with a GWP100 of 11.6 ± 2.8 (Sand et al., 2023), meaning that 1 kg of hydrogen emissions approximately cause as much warming as 11.6 kg of CO_2 emissions (over a 100-year time period). Minimizing leakage is of course not an issue exclusive for storage, but every production step added increases the leakage risk.

An alternative that is less expensive than tanks is storage in geologic formations. The most promising of these is storage in salt caverns, however such formations are not available at all in Sweden (Edvall et al., 2022). A more interesting alternative in a Swedish context is the use of so-called *lined rock caverns* (LRCs), which have less specific geologic demands (Masoudi et al., 2024). There is currently one such facility in

Sweden, a pilot that evaluates LRC as a method of lowering electricity costs for hydrogen production within the HYBRIT fossil-free steel project (Vattenfall, 2023). However, even the less specific geologic conditions of LRCs cannot generally be expected to be available on-site when constructing a new facility (Edvall et al., 2022).

Because of the high costs of tank storage, the uncertainty of LRC possibilities, and time constraints, flexibility from storage has not been evaluated further in this thesis.

Chapter 6

Economic flexibility potential

In this chapter, the results for the economic analysis of flexibility potential are presented. The results are primarily divided based on the two operating scenarios (pulp/paper mill or CHP plant). Each scenario is then divided into four cases based on electricity prices and CAPEX:

- 2035 electricity prices, "high" CAPEX
- 2035 electricity prices, "low" CAPEX
- 2023 electricity prices, "high" CAPEX
- 2023 electricity prices, "low" CAPEX

In total, six graphs and one table are presented for each operating scenario. Four of the graphs show LCOM and cost breakdown based on the four different cases listed above. The fifth graph shows the LCOM for all four cases together, and the sixth and final graph show costs/savings from flexibility compared to constant operation.

Finally, results are summarized in a table.

6.1 Operating Scenario 1: up to 8000 full-load hours, spread evenly across the year (pulp/paper mill scenario)

This scenario represents a case where the CO_2 feedstock is available throughout the year, for example if provided by carbon capture from a pulp/paper mill. 8000 hours have been assumed as the maximum amount of full-load hours instead of 8760 to provide room for maintenance of the e-methanol plant and possible disruptions in the CO_2 feed. The calculated LCOM results and cost breakdowns for the four different assumption combinations are presented in Figures 4, 5, 6 and 7 below. Calculations have been made from 10 to 8000 full-load hours, but to produce more effective figures only results from 3000 to 8000 full-load hours are presented. (For all cases, the results below 3000 full-load hours had higher LCOMs than the range included in the figures.)

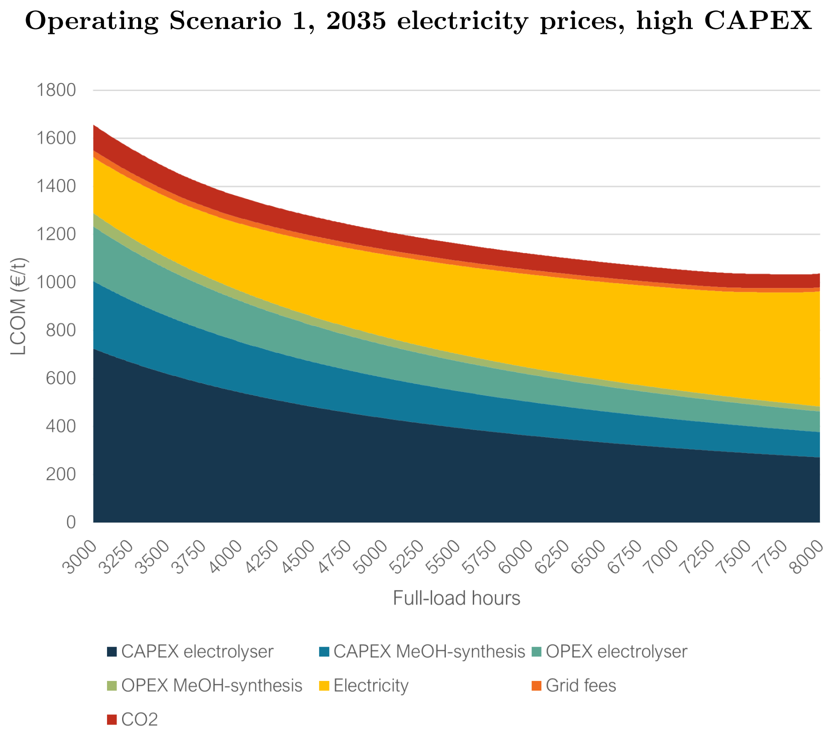

Figure 4: LCOM and cost breakdown results using 2035 electricity prices, the "high" CAPEX assumption, and Operating Scenario 1.

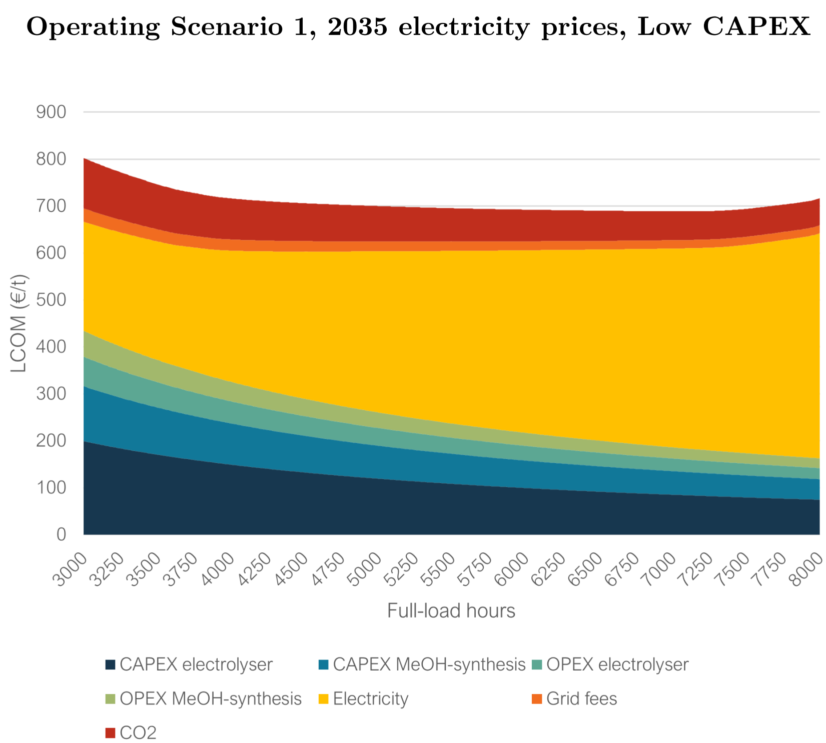

Figure 5: LCOM and cost breakdown results using 2035 electricity prices, the "low" CAPEX assumption, and Operating Scenario 1.

Operating Scenario 1, 2023 electricity prices, High CAPEX

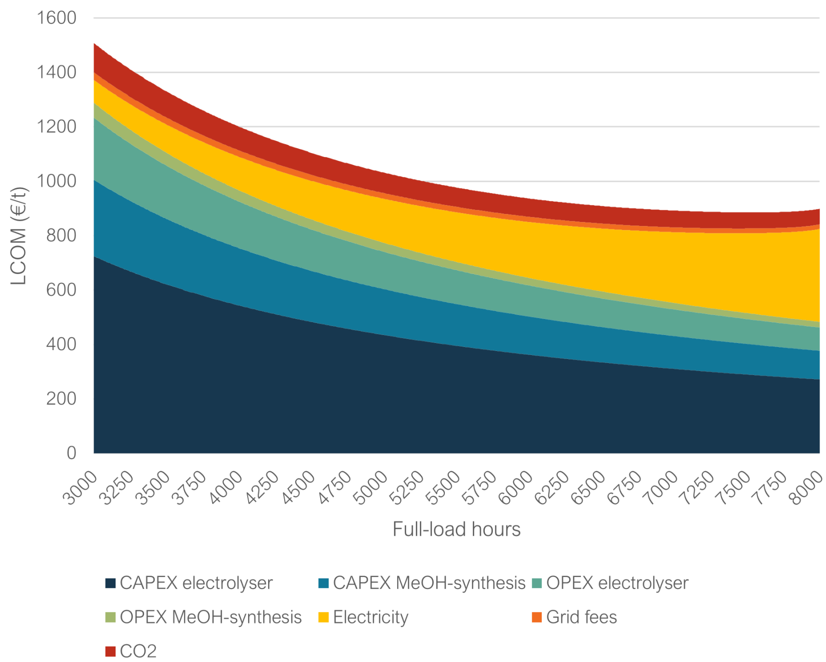

Figure 6: LCOM and cost breakdown results using 2023 electricity prices, the "high" CAPEX assumption, and Operating Scenario 1.

Operating Scenario 1, 2023 electricity prices, Low CAPEX

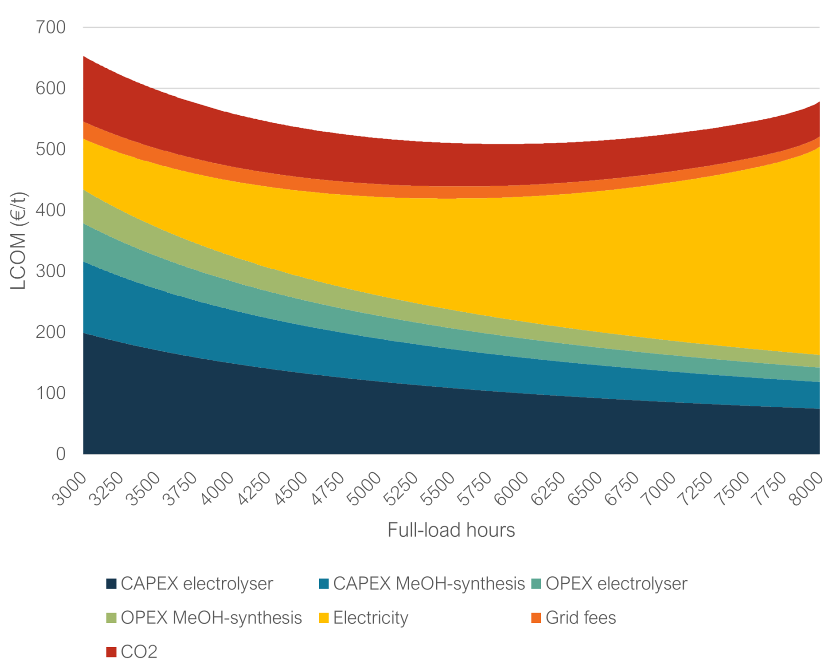

Figure 7: LCOM and cost breakdown results using 2023 electricity prices, the "low" CAPEX assumption, and Operating Scenario 1.

Figures 4 and 6 show that for the two high-CAPEX cases, LCOM generally decreases with more full-load hours. They do however flatten out towards the ends, where decreasing CAPEX costs and increasing electricity costs cancel each other out. They are both, perhaps unsurprisingly, heavily dominated by CAPEX costs, especially at lower amounts of full-load hours. The lowest LCOMs are €1033 (at 7850 hours) for the 2035 high-CAPEX case, and €885 (at 7540 hours) for the 2023 high-CAPEX case.

Figure 5 shows that the 2035 low-CAPEX case has a relatively flat cost profile, with LCOM of around €700/t in the range of 4000-8000 full-load hours. Costs are dominated by electricity price, especially at higher amounts of full-load hours. The lowest LCOM is €689 at 7100 hours.

The 2023 low-CAPEX case has its lowest LCOM at a medium amount of hours, with costs increasing in both directions. It has the lowest LCOM of all cases in Operating Scenario 1, with €509 at 5840 hours.

6.1.1 Summary of Operating Scenario 1

The Operating Scenario 1 LCOM results of the four different cases are presented in Figure 8 below.

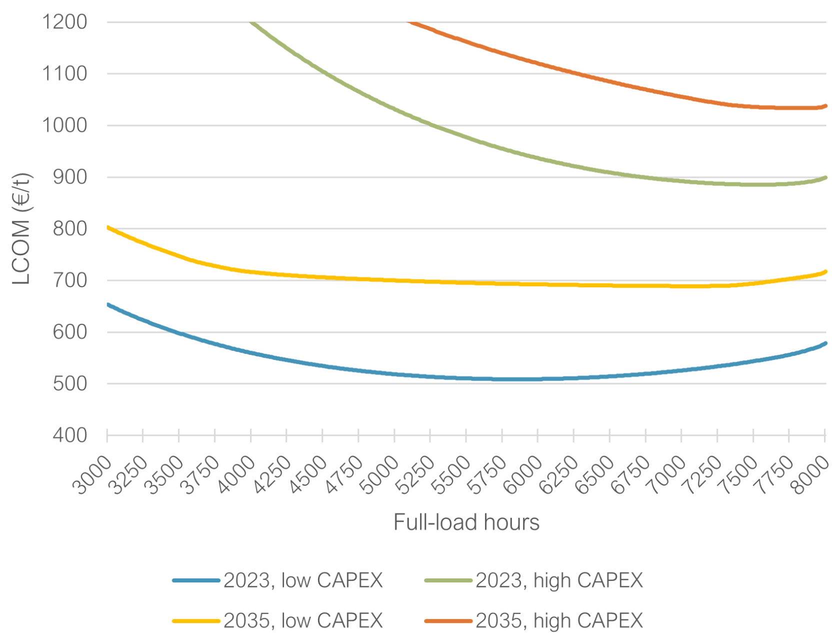

Figure 8: LCOM with varying full-load hours of the four cases in Operating Scenario 1.

It is clear that both the CAPEX and electricity prices have large impacts on the LCOM, with all four combinations being distinctly different, and the highest LCOM being roughly twice as high as the lowest. Cases where costs are decreased or constant when the amount of full-load hours are reduced have a higher economic flexibility potential. This is made clearer in Figure 9, where the change in LCOM compared to constant operation is presented:

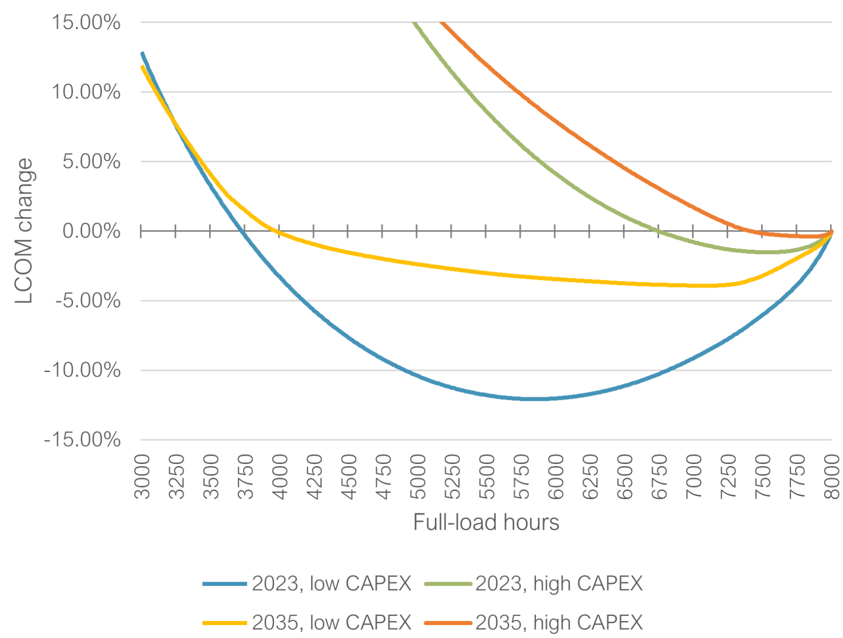

Figure 9: Cost/savings from flexibility in Operating Scenario 1, presented as LCOM change compared to constant operation (8000h).

Figure 9 indicates that all cases have at least some economic room for flexibility, since the number of full-load hours can be decreased from 8000 without the costs increasing. There is however a substantial difference in how large this potential is. The LCOM stays at or below that of constant operation down to 7400 full-load hours in the 2035 high-CAPEX case, down to 6750 hours for the 2023 high-CAPEX case, and down to around 4000 hours for both low-CAPEX cases. The four cases also differ widely in potential savings from flexibility. The savings in the lowest case (2035 High CAPEX) are negligible, while the highest case (2023 Low CAPEX) show savings of up to 12% compared to constant operation.

Important results from Operating Scenario 1 are summarized in Table 5.

Table 5: Summary of results from Operating Scenario 1.

	LCOM - Constant operation (8000h) (€/t)	Lowest LCOM (€/t)	Max. savings from flexibility	Optimal full-load hours	Optimal Electrolyzer size (MW)
2035, high CAPEX	1038	1033	0.4%	7850h	108.9 (+1.9%)
2035, low CAPEX	717	689	3.9%	7100h	120.4 (+12.7%)
2023, high CAPEX	899	885	1.5%	7540h	113.4 (+6.1%)
2023, low CAPEX	579	509	12.1%	5840h	146.4 (+37.0%)

6.2 Operating scenario 2: 6000 available hours with shutdown during summer (CHP plant scenario)

This scenario represents a case where the CO_2 feedstock is not available during summer. This would be the case if CO_2 is provided by a combined heat and power plant, which typically shut down during summer and have roughly 6000 operating hours per year (Levihn, 2017; Kraftringen, 2024). The assumed shutdown has been centered around July, lasting from May 19 to September 11. The calculated LCOM results and cost breakdowns for the four different assumption combinations are presented in Figures 10, 11, 12 and 13 below. Calculations have been made from 10 to 6000 full-load hours, but to produce more effective figures only results from 3000 to 6000 full-load hours are presented. (For all cases, the results below 3000 full-load hours had higher LCOMs than the range included in the figures.)

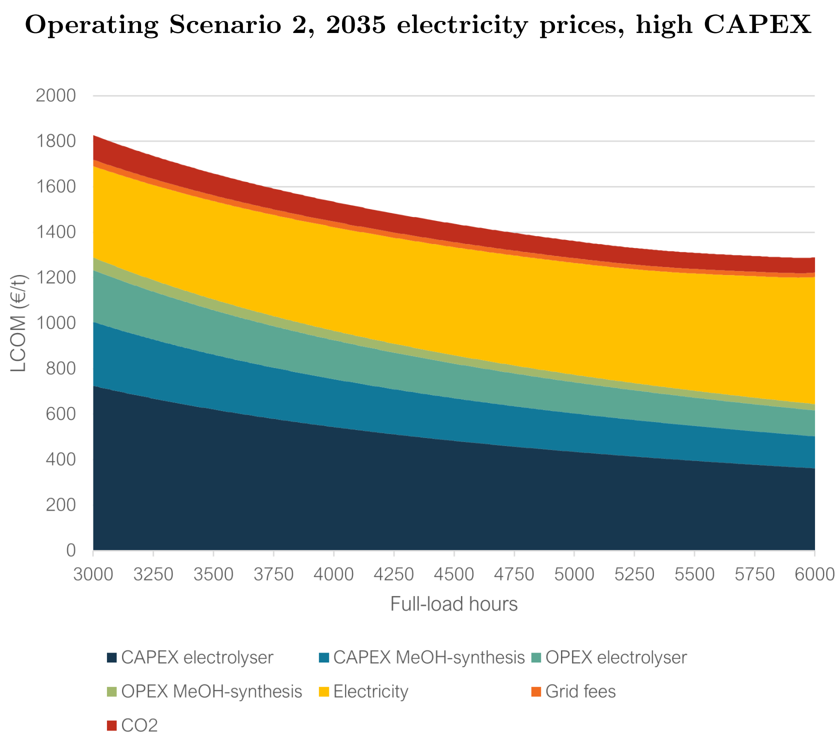

Figure 10: LCOM and cost breakdown results using 2035 electricity prices and the "high" CAPEX assumption.

Operating Scenario 2, 2035 electricity prices, Low CAPEX

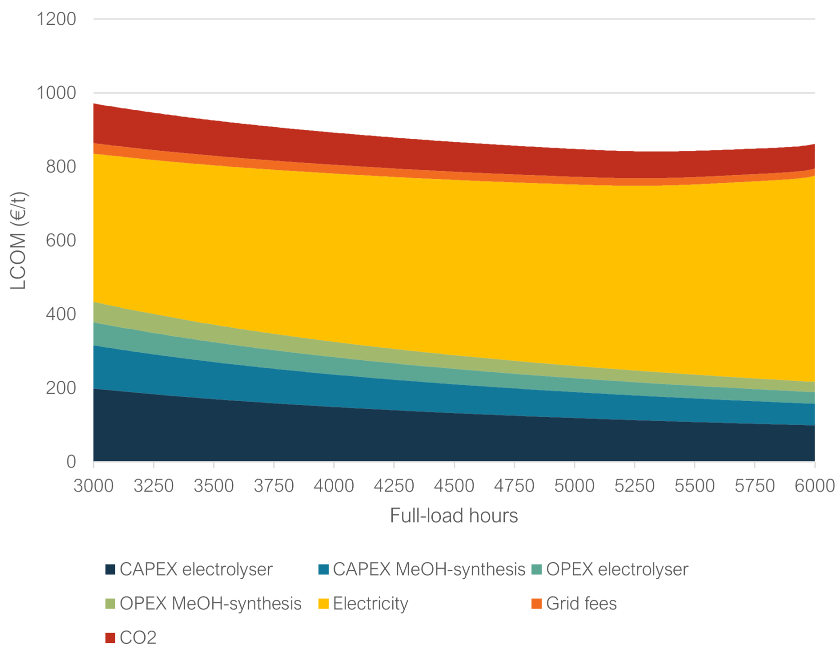

Figure 11: LCOM and cost breakdown results using 2035 electricity prices and the "low" CAPEX assumption.

Operating Scenario 2, 2023 electricity prices, High CAPEX

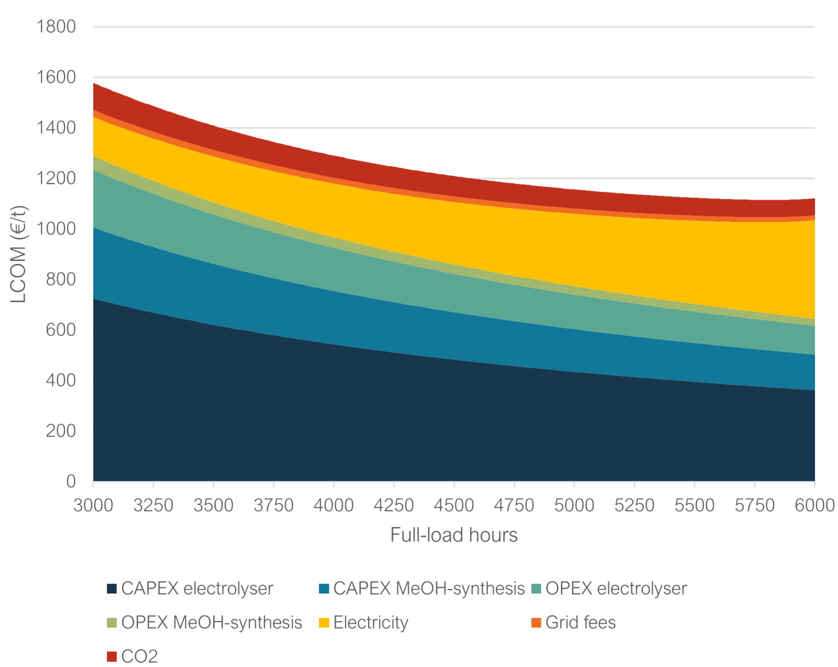

Figure 12: LCOM and cost breakdown results using 2023 electricity prices and the "high" CAPEX assumption.

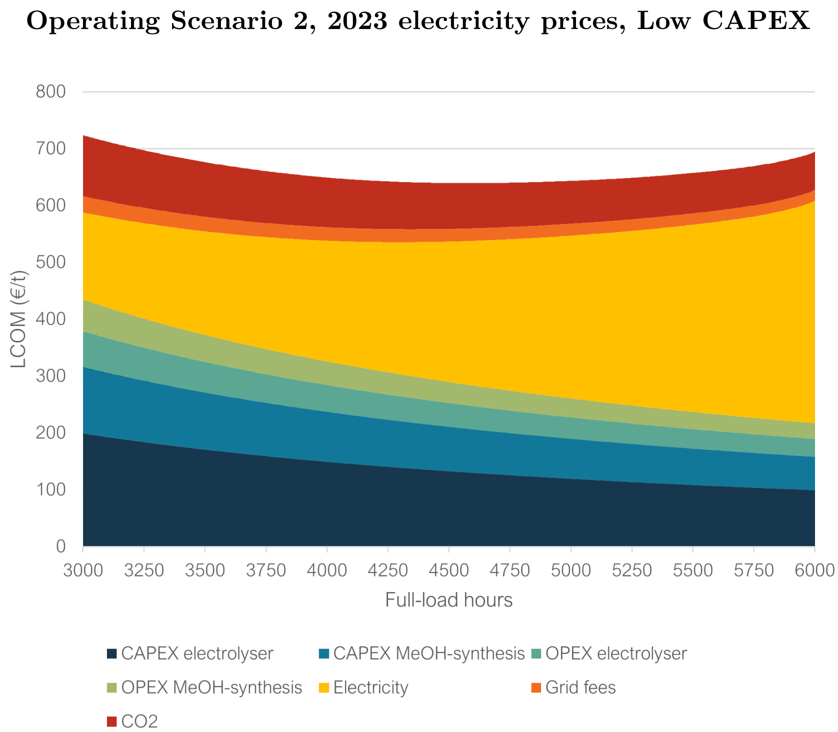

Figure 13: LCOM and cost breakdown results using 2023 electricity prices and the "low" CAPEX assumption.

The LCOM curves show similar behavior to Operating Scenario 1, with the two high-CAPEX cases once again having costs that decrease with more full-load hours, but flatten towards the upper end.

The 2035 low-CAPEX scenario is once again dominated by electricity costs, but now has a slightly less flat profile.

The 2023 low-CAPEX case again has its lowest LCOM at a medium amount of hours, and has the lowest LCOM of the four cases.

One crucial difference compared to Operating Scenario 1 is that for all cases, the LCOM is higher than for the corresponding case in Operating Scenario 1. This is mainly due to two reasons, one being that production is halted during summer when electricity prices are lowest, and the other that there are fewer available hours for production, meaning a higher capacity is needed to produce the same amount of methanol, leading to larger investment costs.

6.2.1 Summary of Operating Scenario 2

The Operating Scenario 2 LCOM results of the four different cases are presented in Figure 14 below.

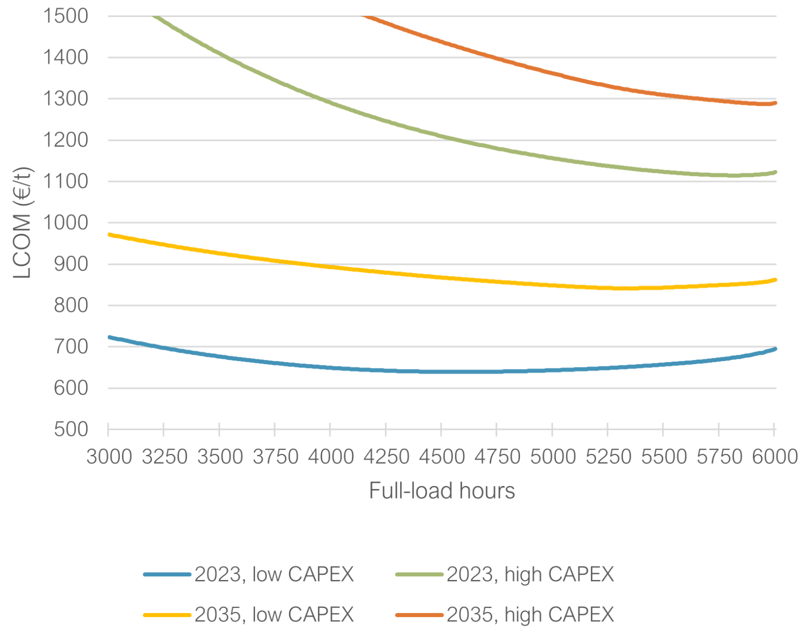

Figure 14: LCOM with varying full-load hours of the four cases in Operating Scenario 2.

From Figure 14, it is once again clear that both CAPEX and electricity price both had large impacts on the LCOM, with all four cases being distinctly different. As mentioned, the biggest difference compared to Operating Scenario 1 is that all cases have a higher LCOM than their corresponding case in Operating Scenario 1.

Figure 15 shows the change in LCOM compared to constant production:

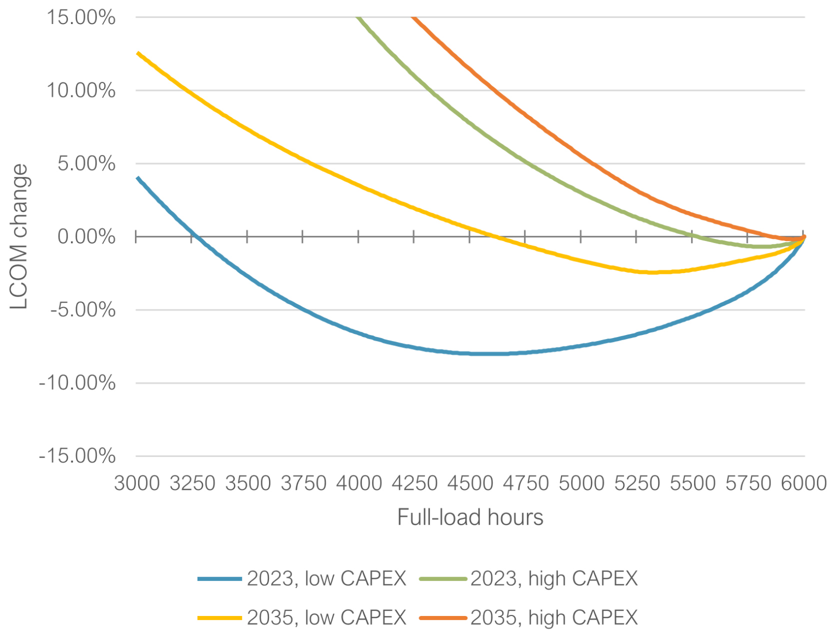

Figure 15: Cost/savings from flexibility in Operating Scenario 2, presented as LCOM change compared to constant operation (6000h).

In all four cases, there are now significant decreases in the amount of hours the production can be flexible without increasing costs, compared to Operating Scenario 1. This is especially clear for the 2035 high-CAPEX scenario, where there is now essentially no economic room for flexibility. The two low-CAPEX cases still show significant (although decreased) room for flexibility.

Important statistics from Operating Scenario 2 are summarized in Table 6.

Table 6: Summary of results from Operating Scenario 2.

	LCOM - Constant operation (6000h) (€/t)	Lowest LCOM (€/t)	Max. savings from flexibility	Optimal full-load hours	Optimal Electrolyzer size (MW)
2035, high CAPEX	1290	1288	0.2%	5950h	143.7 (+0.8%)
2035, low CAPEX	863	842	2.4%	5320h	160.7 (+12.8%)
2023, high CAPEX	1122	1115	0.7%	5810h	147.2 (+3.3%)
2023, low CAPEX	695	639	8.0%	4590h	186.3 (+30.7%)

Chapter 7

Discussion

In this chapter, the results and limitations of the technical and economic analyses, and what they could mean for e-methanol production, will be discussed. After that, the essential role that policy plays in shaping market and production conditions and the important interlinkage with the electricity system will be discussed.

7.1 Technical flexibility

The assessment of technical flexibility showed sources that were astonishingly far apart in regards to methanol synthesis, ranging from flexibility being essentially impossible to some sounding very positive. The results pointing in a positive direction were unfortunately mostly qualitative statements from industry that are somewhat open to interpretation, and they are unfortunately not keen on openly sharing more specific data. It is however unlikely that such statements would be made without at least some flexibility to back them up, so there may be some grounds for optimism looking into the future. Especially the statements by Topsoe (and to some degree MAN Energy Solutions) sound very promising. If flexible methanol synthesis is possible, flexiblity of an e-methanol plant as a whole is likely also possible as the remaining production steps are flexible enough.

To be able to make a complete and accurate assessment of the overall feasibility of flexibility, more accurate technical information would be needed. This is important also for making more accurate economic predictions, as the technical flexibility decides the limits for how the plant can operate.

It is possible that more accurate information could have been obtained with non-disclosure agreements with suppliers, however that was not attempted for this thesis as it would have meant that results could not have been published.

7.2 Economic analysis results

Much like the technical assessment, the economic analysis was also complicated by large disparities in available sources. This was especially true for CAPEX, where the highest sources were several times more expensive than the lowest ones. This of course makes it difficult to know what results could be expected in reality. According to Uniper, the "high" case is much more representative, which indicates that it might be more reasonable to value those results higher. The results of the "low" case are however also interesting as an indication of what could happen if CAPEX would decrease in the future. It is also worth emphasizing the major uncertainties that are a result of other assumptions, not least the electricity prices, the many other cost/calculation assumptions, and the assumption of "perfect" flexibility. The results should therefore be seen as an indication of how the conditions may look under different circumstances, rather than an accurate prediction of the future.

Generally, the economic results were very varied, which is not a suprise considering the variations in input data. In the most beneficial cases, the plant could be designed to operate for as little as about half the hours of the year without having a higher LCOM than for constant operation. In the least beneficial case (Operating Scenario 2, 2035, high CAPEX), only 50 hours of flexibility was possible before having a higher LCOM than for constant operation. Under the assumption that the high CAPEX scenario and the simulated 2035 electricity prices are most likely to be representative of actual conditions, it is likely that the actual potential is closer to 50 hours than to 4000. It is however interesting that all cases show at least a little economic room for flexibility, as even just a few hours of suspended electricity consumption can be very valuable for the grid during critical periods.

Potential savings from flexibility also varied greatly, from an essentially negligible amount in the two 2035 high CAPEX cases to more than 10% with 2023 electricity prices, low CAPEX and the pulp/paper mill scenario. Once again, the less optimistic figures are probably more likely. It is however interesting to see that flexibility could contribute to lowering the production costs of e-methanol if favorable conditions become reality.

One thing not considered are potential incomes that are generated as a result of having a flexibility capability, which may increase the flexibility potential. These include incomes from paricipating in potential future flexibility markets, and from providing ancillary services to the TSO Svenska Kraftnät. As it is very difficult to estimate how these will look a decade into the future, they were not included in the quantitative analysis. As long as such services are requested during hours of high electricity prices, any compensation would contribute to an increased economic flexibility potential.

In terms of CO_2-sourcing, the results showed clear benefits in partnering with a pulp/paper mill rather than a CHP plant. This was true for all four cases, both in terms of flexibility potential and overall LCOM. This is due to the pulp/paper mill scenario having a higher amount of available hours for production, and that the mostly-cheap hours of the summer are unavailable for the CHP scenario. Especially being unavailable during summer is a clear drawback of the CHP-sourcing, as this is also the period when it is likely easiest for the grid to handle a large consumer.

For LCOM, the economic analysis showed results of around €500-1300 per tonne, depending on assumptions (with what can probably be considered most realistic in terms of CAPEX and electricity prices being in the €1000-1300 range). Fossil methanol prices on the European market have been in the €300-500 range for the past few years (Methanol Institute, 2024), meaning that in the status quo, e-methanol from this hypothetical plant is likely economically uncompetitive compared to fossil methanol. Fossil methanol may however not be the main competitor to e-methanol, and it is also possible that fossil methanol will become more expensive in the future. These issues are discussed further in Section 7.3.

Not considered are also potential incomes from selling excess heat and O_2 that is produced. If it is possible to generate incomes from these depends on the local conditions, for example if it is possible to connect to a district heating network, and if there is a local/regional market for O_2 (as compression and transportation of O_2 is expensive). One potential drawback of partnering with a CHP plant is that if the methanol plant is feeding the district heating network with excess heat, it may lower the need for the CHP plant to operate, thereby reducing the CO_2-supply to the methanol plant. It is therefore important to consider the size of the CHP plant and the local heating demand when deciding on localization for an e-methanol plant.

The future electricity prices are also very important, as they are (especially in some of the cases) a very large part of the LCOM, and could therefore have a major impact on the production costs of e-methanol.

Another crucial aspect is the fluctuation of the electricity price, as it is the sole reason why cost reductions from flexibility are even possible in the first place. Future volatility is therefore important for the flexibility potential, with a higher volatility meaning a higher flexibility potential. The future volatility is however very uncertain. On one hand, a higher share of intermittent renewable production could increase volatility, but on the other hand, more electricity storage and flexibility on the demand side is also likely, which may smoothen prices.

7.3 Policy

It is clear that policy is one of the main factors determining the conditions for e-methanol, both in terms of market and production conditions.

Current and future policies mandating GHG emissions reductions or renewable energy use create market conditions in which e-methanol can compete not against its fossil counterpart, but against other renewable alternatives. It is likely that these may be the main markets for e-methanol, considering that e-methanol is likely economically uncompetitive compared to fossil methanol. It is however possible that policies such as the EU ETS or the Carbon Border Adjustment Mechanism may make fossil methanol more expensive in the future.

Policies such as FuelEU Maritime and ReFuelEU Aviation will be intergral in creating market conditions for renewable fuels, although the modest requirements in the near future means that the market size could remain relatively small until more significant demands become reality. FuelEU Maritime also has no specific mandates for RFNBOs or e-methanol, meaning that demand could be filled by other types of renewable fuels if proven more competitive. ReFuelEU Aviation have minimum RFNBO requirements from 2030, although these are also quite modest, at least in the early years. The fact that policies don't specifically target e-methanol means that a future market is not guaranteed if e-methanol is outcompeted by other renewables.

The effectiveness of EU ETS in creating favorable market conditions for e-fuels is hard to predict, as the carbon price is dictated by the market. If allowances become costly enough to push the cost of fossil fuels close to the price of e-fuels, the competitiveness of e-fuels will increase.

From 2030 onwards, the demands on hourly temporal correlation of electricity production and electricity use for RFNBO production means that flexibility in one form or another likely will become necessary in e-methanol production. This flexibility could be provided either by electricity/H_2-storage, sythesis flexibility, or a combination of both.

7.4 Electricity system

A lot is happening in the electricity system, and it is difficult to know how conditions will look in the future. A couple of things are however clear.

One is that the future of the electricity prices will be key for the production costs and economic flexiblity potential of e-methanol production.

The other is that a large-scale usage of e-fuels in the climate transition would require an immense amount of electricity, which means that it would be highly dependent on an increase of (low-carbon) electricity production and investments in transmission capacity. Flexibility would however make it easier for new facilities to be greenlit for grid connection, since they would have the capacity to reduce consumption if needed. This means that with flexibility, more electricity dependent energy/climate transition projects could potentially be realized.

Chapter 8

Conclusions

Evaluating the technical flexibility of e-methanol production was complicated by the fact that publically available information on methanol synthesis flexibility differed greatly. Other production steps were however deemed as flexible enough, meaning that if methanol synthesis can be flexible, entire e-methanol plants likely can be as well. Some manufacturers of methanol synthesis systems have made statements that possibly indicate a very high degree of flexibility, but to be able to make an accurate assessment this needs to be backed up by numerical data.

The economic analysis was also characterized by many uncertainties, not least from large differences in available cost data and limitations of the simulation. The results covered a wide spectrum, but in all simulated cases at least some flexibility was possible without increasing production costs. Under what is likely the most realistic assumptions at the moment, at most a few hundred hours of flexibility was possible without increasing costs. Even this can however be very positive for electricity grid stability. Under the most beneficial assumptions, the plant could be designed to operate for only around 4000 hours per year without increasing costs compared to constant operation.

Potential savings from flexibility ranged from 0.2-12.1%, with only the two cases with most beneficial assumptions reaching over 5%.

The analysis showed clear economic benefits of supplying the CO_2 demand from a pulp/paper mill compared to a combined heat and power (CHP) plant. Flexibility potential was also higher with the pulp/paper mill scenario.

LCOM ranged from €500 to €1300, with the higher end of that range representing what is likely currently the most realistic assumptions.

Policy support was deemed integral for the implementation of e-methanol, as it is by all indications uncompetitive on its own against fossil alternatives. Currently enacted policies do not favor e-methanol over other renewable alternatives, meaning a future market for e-methanol is not guaranteed.

The future development of electricity prices was also determined to have an important role in shaping conditions for e-methanol production, as they made up a significant share of the production costs. For flexibility, electricity price volatility is the main factor in determining whether it is economically viable.

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Appendix

AEL

Source	From year	For year	Size (MWel)	Cost/kWel (stack)	Cost/kWel (system)	Currency	Year currency	Lifespan stack	Lifespan BOP
8	2020	2018			**800-1500**	EUR	2018	55-120000h	
2	2020	2020	>10	270	**500-1000**	USD	2020?	60000h	
7	2023	2023	10-1000	6-14% of system	**2000-4500**	USD	2023?		
1	2023?	2025	100		**875**	EUR	2020	70 000h (2020)	
3	2023	2030	?		**566-664**	EUR	2022	15 years	20-25 years
6	2017	2030			**590-680**	EUR	2017		
1	2023?	2030	100		**550**	EUR	2020	70 000h (2020)	
9	2021	2030			**540-1548**	AUD	2021?	40 000h	20 years
2	2020	2050	>10	<100	**<200**	USD	2020?	100000h	

PEMEL

Source	From year	For year	Size (MWel)	Cost/kWel (stack)	Cost/kWel (system)	Currency	Year currency	Lifespan stack	Lifespan BOP
4	2016	2016	21.3		**600**	EUR	2015?	30 000h	
8	2020	2018			**1400-2100**	EUR	2018	60 000-100 000	
2	2020	2020	100	400	**700-1400**	USD	2020?	50000-80000h	
7	2023	2023	10-1000	15-29% of system	**1500-3000**	USD	2023?		
1	2023?	2025	100		**975**	EUR	2020	55 000h (2020)	
3	2023	2030	?		**807-943**	EUR	2022	15 years	20-25 years
5	2018	2030	12		**800**	EUR	2018?	50 000h	
6	2017	2030			**330-800**	EUR	2017		
1	2023?	2030	100		**650**	EUR	2020	55 000h (2020)	
9	2021	2030			**401-2039**	AUD	2021?	40 000h	20 years
2	2020	2050	100	<100	**<200**	USD	2020?	100000-120000h	

Methanol synthesis

Source	From year	For year	Size	Cost per kW (MeOH out)	Currency	Year currency	Lifespan
4	2016	2016	944kW (or 16 300 t/yr)	**1629**	EUR	2015?	100 000h
5	2018	2018	4000 - 10 000 t/yr	**1284**	EUR	2018?	?
1	2023?	2030	600 t/day	**1090**	EUR	2020	30 år
3	2023	2030	?	**623**	USD	2021	30 år
10	2020		300MW	**230**	EUR	2017	
10	2020		100MW	**300-400**	EUR	2017	

Table A1: Collected CAPEX sources for AEL, PEMEL, and methanol synthesis. Corresponding sources listed in Table A2.

Table A2: Corresponding sources for Table A1.

Nr.	Source
1	Danish Energy Agency (2024b)
2	IRENA (2020)
3	Agora Energiwende (2023)
4	Rivera-Tinoco et al. (2016)
5	Hank et al. (2018)
6	Saba et al. (2018)
7	Ramboll (2023)
8	Dieterich et al. (2020)
9	Ali Khan et al. (2021)
10	Schemme (2020)