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A climate neutral Swedish industry – An inventory of technologies

The four industrial sectors with the largest climate gas release in Sweden, Iron and steel, Cement, Chemicals and Refineries, have several possible pathways to become climate neutral. An overview of the technical choices is presented in this report along with estimation of technical readiness levels and a summary of remaining emissions which will require carbon capture and storage.

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Preface

This report serves as input to a project with the aim to develop a database for technical opportunities for climate mitigation for the process industry. The data for the technologies will be used to update the energy model TIMES-Sweden and analyse scenarios for Sweden to become climate neutral Sweden year 2045. The project is performed in cooperation between IVL Swedish Environmental Research Institute and Luleå Technical University.

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Summary

In year 2017, about 27 percent of the greenhouse gas emissions in Sweden originated from the industries. This equals to 17,203 thousand tonnes carbon dioxide equivalents. Within the Swedish industry, the four industrial sectors with the largest climate gas release are Iron and steel, Cement, Refineries and Chemicals. This report focuses on these four sectors which together emit 80 % of the industrial greenhouse gas emissions in Sweden. Each of these sectors have several possible pathways to become climate neutral. In this report some possible pathways are described and discussed.

In order to reach climate neutrality, transformative changes such as new processes and use of new raw material are needed. This is because a vast part of the emissions in all the sectors in question originates from the processes themselves or the use of fossil feedstock, not only from energy use. Many of the options are technically immature and there are many years of development left before they could be implemented in large scale.

Several technical challenges exist which are related to the processes, but in addition, there are several barriers of non-technical nature for the transformation. For example, supply and price of raw materials, uncertain market for new products and even some legal barriers. Furthermore, some of the options require development of infrastructure, for example the electrification of steel and cement production demands strengthening of the electric grids and increased production of renewable electricity.

Some of the technical options will not be ready for full-scale implementation in many years, even decades. But the climate challenge needs to be tackled quickly. Therefore, an aspect to consider is the demand for additional CO₂ reduction technologies during a transition phase. These technical options may not reduce all the emissions but still make an important contribution. Carbon capture and storage or usage (CCS/CCU) is inevitable during the transition phase, but also in a future scenario where all the new technologies are implemented. In particular, this applies to the cement industry since it will not be possible to produce climate neutral cement without CCS/CCU. It should be noted that CCU does not remove the CO₂ but transfers it elsewhere. However, it could partly reduce the climate impact from the use of new fossil resources.

CCS

A full-scale CCS solution requires the three parts 1) capture, 2) transportation and 3) storage, to work in conjunction. Most of the individual parts of the CCS chain are considered proven technologies, as they have been used for other applications. In addition, pilot- and demonstration scale implementations of the CCS chain has been tested as well, proving the CCS concept on the scale of megatons of CO₂ stored annually. The remaining barriers are related to risks associated with costs, up-scaling of existing technologies, problems related to infrastructure networks

involving multiple actors, public acceptance and storage related uncertainties. Uncertainties regarding the long-term viability of storage sites also generates barriers. There is also a legal barrier to transport CO₂ across national borders.

Steel and iron

The steel and iron industry accounts for 36 % of the industrial GHG emission in Sweden. Of this, the blast furnaces account for 85 %. The remaining part of the emissions mainly originates from fuel use and could to be replaced by renewable fuels without major technical development. However, in order to mitigate the emissions from the blast furnace, the steel making process needs to be evolved, which is a major challenge.

Currently, the main focus for CO₂ mitigation from the blast furnaces in Sweden is to develop a direct reduction (DRI-EAF) process using hydrogen as reducing agent instead of coal. The process is called Hydrogen Breakthrough Ironmaking Technology (HYBRIT). The process will be ready to implement at the earliest year 2035.

As another option, syn-gas (a mixture of CO and H₂) could be used as reducing agent in a direct reduction process. To use syn-gas in DRI is technically straightforward but it is expensive due to the production cost of high-quality gas. Furthermore, it is possible to use bio-coal as reducing agent in DRI with available technology.

An additional alternative reduction process is smelting reduction (SR-BOF). In the smelt reduction process, coke making and iron production are integrated in a single process. These alternatives are under development in other countries.

Furthermore, there is ongoing development of technologies for replacing part of the fossil coal by biogenic coal in the blast furnaces (BF-BOF). However, not all of the fossil coal could be replaced and therefore it needs to be combined with CCS to achieve the goal of climate neutrality.

Cement

The cement industry accounts for 18 % of the industrial GHG emissions in Sweden. Replacing fossil fuels in the cement production has the potential to reduce the CO₂ emissions by approximately 30 %. Fossil fuels could be replaced by either biofuels or electricity. However, the process related greenhouse gas emissions which account for 70 % are not removed by this measure.

The process related emissions mainly originate from clinker production and could be reduced by substituting clinker with other materials. However, even with a combination of clinker substitution and fuel switch, 30-60 % of the CO₂ emissions remain. Therefore, CCS is inevitable in order to produce a climate neutral cement.

With this conclusion in mind, the alternative to switch from fossil fuels to electricity has a major advantage compared to switching to bio fuels. With electric heating, the CO₂ stream from clinker production will be pure and there is no need for scrubbing. This radically reduces the investment cost for carbon capture, and the operation and maintenance costs. However, electric heating in the cement industry will be ready for large-scale implementation at the earliest in 2035.

Chemical industry

The chemical industry accounts for 8 % of the industrial GHG emissions in Sweden. Of this, the company Borealis, which produces polyethylene, accounts for the single largest source of greenhouse gas emission within Swedish chemical industry, representing 72 %. Since the fuel use in the chemical industry is based on the by-products from the production, a switch from fossil to

renewable feedstock is necessary in order to phase out the use of fossil fuels. The options for feedstock switch are described in this report are:

- Biobased feedstock to the steam cracker (bio-naphta, bio-LPG or bio-oils)
- Methanol-to-olefin (MTO)
- The ethanol-to-ethylene route (E2E)
- Oxidative coupling of methane for ethylene production (OCM).

The first three in the list are mature technologies which are running at large scale in different parts of the world. But they all depend on production of bio-based feedstock production processes which are less mature. Particularly to produce feedstock from forest biomass requires further development. The OCM technology is less mature. The concept relies on the production of SNG through either biomass gasification or upgraded biogas from fermentation of biomass and biomass waste. All the alternatives could be implemented incrementally.

Refineries

The refinery industry accounts for 17 % of the industrial GHG emissions in Sweden. There are five crude oil refineries in Sweden today. Three are typical fuel refineries while Nynas AB's refineries in Nynäshamn and Gothenburg are refineries for production of heavy petroleum products such as bitumen for asphalt and lubricant oils.

Since the CO₂ emissions are related to energy use at the refinery and they use their own by-products for energy purpose, focus in this report is switch of feedstock. Both alternative feedstock to the existing refineries and alternative processes for fuels production are possible options. In addition, biogas, hydrogen and electricity are feasible options for parts of the transport sector. In this report, alternative liquid fuels for engines are described:

- Fischer-Tropsch diesel
- Ethanol
- Methanol
- Dimethyl ether (DME)
- Biodiesel based on fatty acid methyl esters (FAME), e.g. Rapeseed Methyl Ester (RME)
- Hydrogenated vegetable oils (HVO)

Some of the technologies are mature (e.g. FAME and HVO) while others need more development, particularly in order to be able to use forest biomass. Also, the substitution of aircraft kerosene is a challenge that requires extra attention.

Sammanfattning

År 2017 kom utsläppen av växthusgaser i Sverige till cirka 27 procent från industrierna, vilket motsvarar 17 203 tusen ton koldioxidekvivalenter. De fyra industrisektorerna med den största klimatgasutsläpp i Sverige är järn och stål, cement, raffinaderier och kemi. Denna rapport fokuserar på dessa fyra sektorer som tillsammans släpper ut 80 % av de industriella utsläppen av växthusgaser i Sverige. Var och en av dessa sektorer har flera möjliga vägar för att bli klimatneutrala. Beskrivning och diskussion av dessa vägar är fokus för denna rapport.

Med bakgrund av klimatutmaningen är slutsatsen att det inte är möjligt att nå tillräckligt långt enbart med effektivisering av nuvarande industriprocesserna. Eftersom en stor del av utsläppen inte härstammar från energianvändning utan från processerna i sig samt användningen av fossil råvara, finns det behov av transformativa förändringar som nya processer och användning av nytt råmaterial. Många av alternativen är tekniskt omogna och det är många års utveckling kvar innan de kunde implementeras i stor skala.

Förutom de tekniska utmaningarna finns det ytterligare hinder för transformationen. Till exempel tillgång och pris på råvaror, osäker marknad för nya produkter och även juridiska hinder i viss mån. Dessutom kräver några av alternativen utveckling av infrastruktur. Till exempel kräver elektrifiering av stål- och cementproduktion förstärkning av elnätet och ökad produktion av förnybar el.

Vissa av de tekniska alternativen kommer inte att vara färdiga för fullskalig implementering på många år, ibland till och med årtionden. Men klimatutmaningen behöver hanteras snabbare än så. Därför det viktigt att även beakta möjliga övergångsteknologier. Dessa kanske inte reducerar hela utsläppet men utgör ändå en viktig pusselbit. Behovet av koldioxidinfångning och lagring eller användning (CCS/CCU) är oundvikligt under övergångsfasen, men också i ett framtida scenario där all transformation är genomförd. Särskilt som det inte är möjligt att producera klimatneutralt cement utan CCS/CCU. CCU är dock inte en varaktig lagring utan snarare ett sätt att flytta utsläppen till ett annat ställe. Det kan dock delvis ersätta användning av fossil råvara och därmed bidra till minskning av nya fossila växthusgasutsläpp.

CCS

En CCS-lösning i full skala kräver att de tre delarna 1) infångning, 2) transport och 3) lagring fungerar tillsammans. De flesta av de enskilda delarna av CCS-kedjan betraktas som beprövad teknik, eftersom de har använts för andra applikationer. Dessutom har CCS-kedjan testats i pilot- och demonstrationsskala, vilket bevisar CCS-konceptet i skalan megaton CO₂-lagring per år. De återstående hinder är relaterade till risker i samband med kostnader, uppskalning av befintlig teknik, problem relaterade till infrastrukturnätverk med flera aktörer, allmän acceptans och osäkerhet gällande lagrens funktion på lång sikt. Även vissa juridiska hinder finns.

Järn och stål

Järn- och stålindustrin står för 36 % av den industriella växthusgasutsläppen i Sverige. Av detta står masugnarna för 85 %. Den återstående delen av utsläppen kommer främst från bränsleanvändning och skulle kunna ersättas av förnybara bränslen utan någon större teknisk utveckling. För att eliminera utsläppen från masugnarna måste nya processer utvecklas, vilket är en stor utmaning.

För närvarande är huvudfokus för ersättning av masugnarna i Sverige att utveckla en direktreduktionsprocess (DRI-EAF) som använder vätgas som reduktionsmedel istället för kol. Processen kallas Hydrogen Breakthrough Ironmaking Technology (HYBRIT). Processen kommer att vara klar att implementeras tidigast 2035.

Förutom vätgas kan icke-fossil syntesgas användas som reduktionsmedel i en direkt reduktionsprocess som möjlig väg till klimatneutral stålframställning. Att använda syntetgas i DRI är inte ett tekniskt problem men mycket dyrare på grund av produktionskostnaden för högkvalitativ gas. Det är också möjligt att använda biobaserad kol som reduktionsmedel i DRI.

En ytterligare reduktionsprocess är smältreduktion (SR-BOF). I smältreduktionsprocessen integreras koksframställning och järnproduktion i en enda process. Det är möjligt att använda biobaserad koks och kol men vissa klimatgasutsläpp kvarstår så CCS är nödvändig för en helt klimatneutral produktion. Utveckling för dessa alternativ pågår i andra länder.

Dessutom utvecklas teknologier för att ersätta en del av fossila kol med biogen kol (BF-BOF). För att uppnå målet om klimatneutralitet måste det dock kombineras med CCS. Även om denna åtgärd alltså inte räcker hela vägen, är den ett tänkvärt alternativ som övergångsteknik.

Cement

Cementindustrin står för 18% av de industriella växthusgasutsläppen i Sverige. Att ersätta fossila bränslen i cementproduktionen kan minska koldioxidutsläppen med cirka 30 %. Fossila bränslen kan ersättas med antingen biobränslen (med mogen teknik) eller el (ej färdigutvecklad teknik). De processrelaterade utsläppen av växthusgaser som står för 70 % avlägsnas emellertid inte med denna åtgärd.

De processrelaterade utsläppen härrör huvudsakligen från klinkerproduktion och skulle kunna minskas genom att klinker ersätts med andra material. Men även om både fossila bränslen helt tas bort och klinker delvis ersätts, kvarstår 30–60 % av koldioxidutsläppen. För att producera en klimatneutral cement är det därför oundvikligt att CCS behövs i viss utsträckning.

Med denna slutsats i åtanke har alternativet att byta från fossila bränslen till el en fördel jämfört med att byta till biobränslen. Med elektrisk uppvärmning kommer CO₂-strömmen från klinkerproduktionen att vara ren och det finns inget behov av skrubbing. Detta minskar både investeringskostnaderna och drifts- och underhållskostnaderna för koldioxidinfångning.

Kemisk industri

Den kemiska industrin står för 8 % av de industriella växthusgasutsläppen i Sverige. Av detta står företaget Borealis, som producerar bland annat etylen och propylen till plastproduktion, för den enskilt största källan för utsläpp av växthusgaser, 72 %. Eftersom bränsleanvändningen i den kemiska industrin baseras på biprodukterna från produktionen är det nödvändigt att byta från fossil till förnybar råvara för att utveckla användningen av fossila bränslen. Alternativen för råvarubyte som beskrivs i denna rapport är:

- Biobaserad råvara till ångkrackern (bio-nafta, bio-LPG eller bioolja)
- Metanol-till-olefin (MTO)
- Etanol-till-etylen (E2E)
- Oxidativ koppling av metan för etylenproduktion (OCM).

De tre första i listan är mogna tekniker som används storskaligt i olika delar av världen. Men de är alla beroende av produktion av biobaserade råvaror vars produktionsprocesser är mindre mogna. Särskilt för att producera råmaterial från skogsbiomassa krävs ytterligare utveckling. OCM-tekniken är mindre mogen. Konceptet bygger på produktion av SNG genom antingen biomassafergasning eller uppgraderad biogas från jäsnings av biomassa och biomassaavfall. Alla alternativ kan implementeras stegvis

Raffinaderier

Raffinaderiindustrin står för 17% av de industriella växthusgasutsläppen i Sverige. Det finns fem oljeraffinaderier i Sverige idag. Tre av dessa är bränsleraffinaderier medan Nynas AB:s raffinaderier är raffinaderier för produktion av tunga petroleumprodukter som bitumen för asfalt och smörjolja.

Eftersom koldioxidutsläppen är relaterade till energianvändning på raffinaderiet och de använder sina egna biprodukter för energisyfte är fokus i denna rapport både alternativ råvara till de befintliga raffinaderierna och alternativa processer för bränsleproduktion. Alternativa flytande bränslen för motorer som beskrivs i denna rapport är:

- Fischer-Tropsch diesel
- Etanol
- Metanol
- Dimetyleter (DME)
- Biodiesel baserad på fettsyrametylestrar (FAME), t.ex. Rapsfrömetylester (RME)
- Hydrerade vegetabiliska oljor (HVO)

Utöver dessa är även biogas, vätgas och el viktiga möjligheter för transportsektorn. En del av teknologierna är mogna (t ex FAME och HVO) medan andra behöver mer utveckling, särskilt för att kunna använda skogsbiomassa som råvara. Dessutom är ersättning av flygplansfotogen ett problem som kräver särskild uppmärksamhet.

1 Introduction

This report is part of a project¹ that aims at taking a holistic approach when identifying cost-efficient pathways for Swedish industry to become CO₂ neutral. This implies looking at the process industry in detail while at the same time consider the comprehensive Swedish energy system. To facilitate this, we will: 1) identify low-carbon technologies and CO₂-capturing within the process industry, 2) gather the techno-economic & environmental data of those technologies into a database, and 3) run TIMES-Sweden with the database to identify critical technologies for carbon neutrality. The result will be both the identification of potential technology pathways and an updated TIMES-Sweden model that can be used in future energy system analyses for e.g. policy development. In this report the results of step 1 is presented. For each technological alternative, the process is described, its development level is estimated and its system consequences analysed. Eventually, barriers for Swedish industry to become CO₂ neutral are discussed. The result of step 2, the data-base, will be available from LTU, and the result of step 3 will be published in academic papers.

TIMES-Sweden is a national energy system model with detailed descriptions of both energy conversion (electricity, district heating, biofuels) and user sectors (industry, residential, commercial, agriculture and transport sector). As TIMES-Sweden has a detailed representation of both supply and demand sectors it can be used to identify cost-efficient technology pathways to meet environmental targets. In this project the TIMES-Sweden technology database for process industry will be updated to better describe state-of-the-art and emerging technologies for greenhouse gas emission mitigation.

The four industrial sectors with the largest climate gas release in Sweden - Iron and steel, Cement, Chemical and Refineries - have several possible pathways to become climate neutral. An overview of the technical options is presented in this report.

To a great extent, energy efficiency measures have already been made within the Swedish industries. To reach the goal of climate neutrality until year 2045, major leaps are now needed. In all sectors, new technologies need to be developed. Therefore, the focus in this report is on major technology leaps.

However, even with major process technology development, carbon capture and storage or usage (CCS/CCU) will be a necessary part of the strategy towards climate neutrality. In the TIMES-Sweden model, CCS/CCU is an alternative which could be used at any emission point. This report describes which technologies need to be combined with CCS/CCU to reach climate neutrality and pinpoint those emissions that cannot be removed even with new technologies and hence demand CCS/CCU to reach climate neutrality. In addition, alternative carbon capture technologies are described for the cement industry.

¹ Project 44678-1, Swedish Energy Agency.

1.1 Overview of greenhouse gas emissions from the Swedish industry

In Figure 1 the historic development of greenhouse gas emissions is shown from year 1990 to 2017². In year 2017, the greenhouse gas emissions in Sweden originated to about 27 percent from the industries, which equals to 17,203 thousand tonnes carbon dioxide equivalents. This is in level with the amount of greenhouse gas emissions from the domestic transport, and about three times as much as the energy sector and building sector together. However, the industrial sector has decreased its emissions of greenhouse gases by about 20 percent since the mid 1990's until the 2010's.

Within the Swedish industry, the four industrial sectors with the largest climate gas release are Iron and steel, Cement, Refineries and Chemicals. This report will focus on these four sectors which together emit 80 % of the industrial greenhouse gas emissions in Sweden. In Figure 2 the distribution of the emissions is shown in percentage. Three of these four sectors have remained at the same level or increased the emissions, while other industrial sectors have decreased their greenhouse gas emissions since the 1990's even though the production level has increased. The exception is the chemical industry, which has decreased its emissions by about 50 percent during the period.

The industrial greenhouse gas emissions originate both from the production processes, use of fossil fuel and fugitive emissions. The most significant sources are the use of coke in steel production, calcination of limestone and dolomite in cement production, and combustion of excess gases and fugitive emission within refineries.

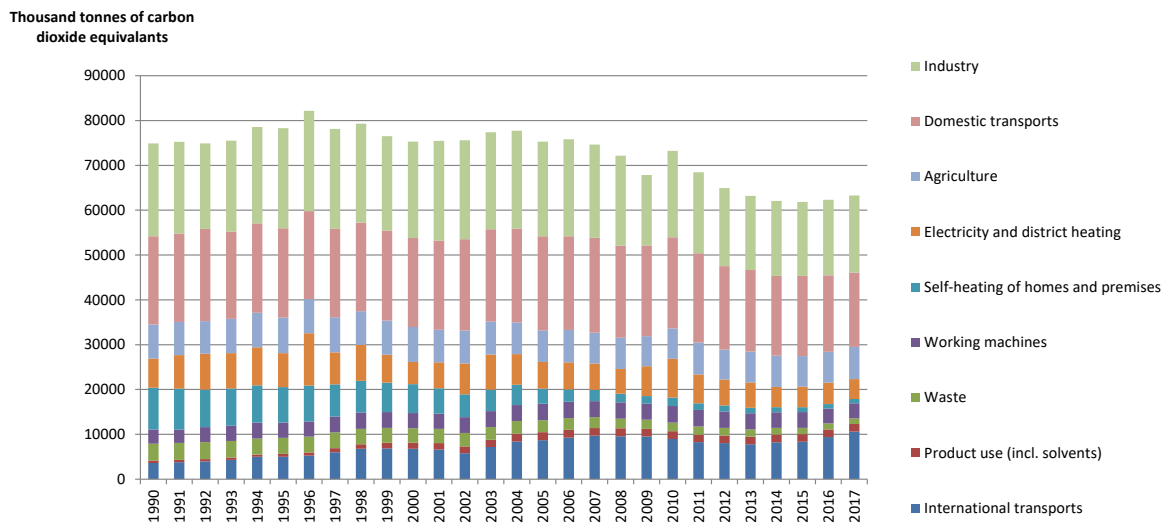


Figure 1 Territorial emissions of greenhouse gases in Sweden 1990 – 2017. Source: Swedish Environmental Protection Agency [1].

² Swedish Environmental Protection Agency, 2019.

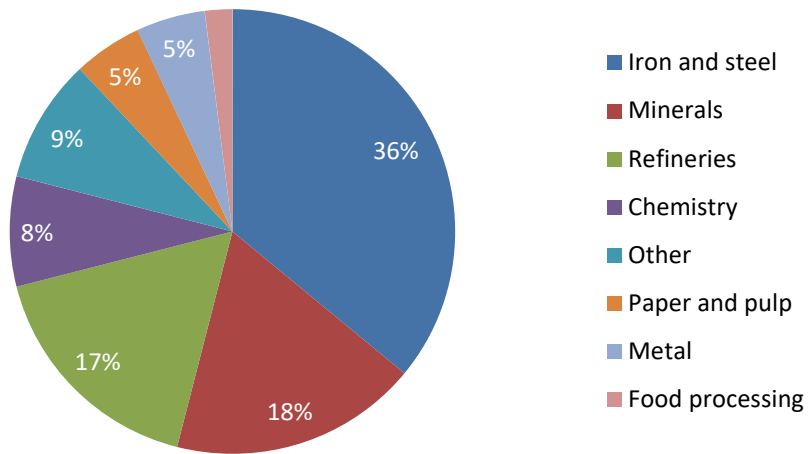


Figure 2 Distribution in percentage of greenhouse gas emission from all industrial sectors in Sweden year 2017. Source: Swedish Environmental Protection Agency [2].

2 Method

In this report, only the direct CO₂ emissions from the industries are considered. That excludes the downstream emissions from use of the products which are produced by the industries, e.g. use of fuels from the refineries, and destruction of the product at end-of-life, e.g. incineration of plastic products from the chemical industry. However, since the emissions at both refineries and in the chemical industry mainly relates to fuel use, and the fuel origins from their own by-products, the switch to renewable raw material is the focus for those sectors in this report. Consequently, the emissions from downstream use and end-of-life destruction will be reduced as well.

2.1 Inventory of technical options

The inventory of industrial technology options is based on literature studies for each industrial sector and discussions with industry representatives and researchers. The written sources are scientific publications, national statistical databases, the industrial sectors' climate roadmaps, environmental reports from companies, and reports from industrial development projects. However, due to the low technical maturity for many of the technologies, significant data uncertainties are still connected to the technologies studied.

The inventory has focused on description of the processes, their advantages, system consequences and obstacles. Furthermore, indirect technical obstacles related to the technologies, e.g. demand for new infrastructure, has been highlighted. A complete and publicly available database with estimations of investment costs and operational cost, and demand for energy and other resources for each technology will be set up within the framework of this project. However, energy performance for most of the technologies, such as fuel, heat and electricity demand per ton product has been described by Sandberg et al [3].

In addition, the inventory has summarised how mature each technology is. Some technologies are already commercially off-the-shelf, but many needs further development, or are even just available on lab-scale. The Technology Readiness Level (TRL) describes how mature each technology is. High TRL means very mature. Also, estimates of the year in which full scale processes could be running have been available for some of the technologies.

3 Steel and iron industry

3.1 Current situation

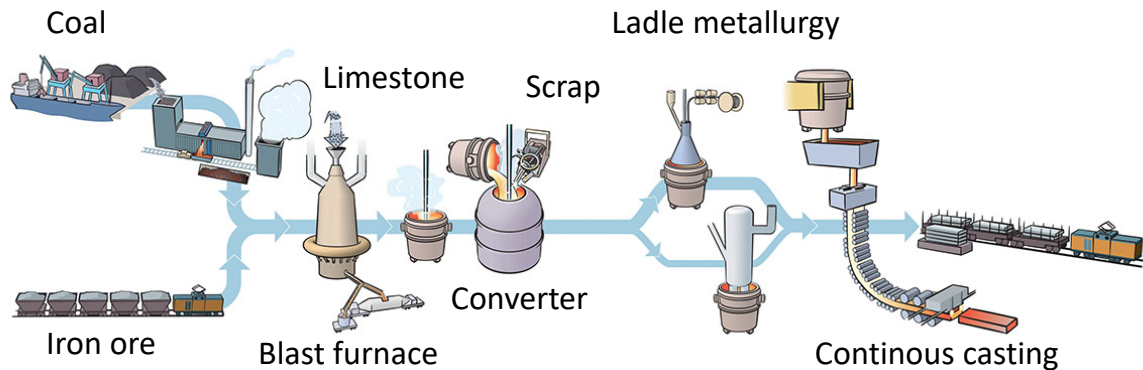


Figure 3. Illustration of the steel making process. Most of the CO₂ emissions origin from coal and coke use in the blast furnace. Image from SSAB, processed by IVL.

There are thirteen plants producing iron and steel in Sweden: Ten scrap-based steel production plants, two integrated iron and steel production plants with blast furnaces (BF) and one ore-based direct reduction plant (DRI). The raw iron produced in the blast furnace must further be processed in a basic oxygen furnace (BOF) to become steel. In addition, there are about eighteen plants for the processing of steel.

The steel production at the two blast furnaces sites is around 3,000 ktonne/y. The emissions from those sites, Luleå and Oxelösund, was 2,825 ktonne CO₂ in year 2017 [4]. However, the flue gases from the Luleå site are used by the local energy company for heat production. Therefore, a great part of the emissions are localised to that energy company in the national emission data base. If all the CO₂ emissions are included, the total was 4,998 ktonne CO₂ in year 2017. If all emissions are included, it is found that the specific emissions, recorded as tonnes CO₂ per ton crude steel, are similar in Luleå and Oxelösund. This is seen in Table 1.

The DRI plant is located in Höganäs and has a production of iron and steel powder of about 300 ktonnes/y. The CO₂ emissions were 197 ktonnes in year 2017 [5]. About 70% of the emissions originates from the reduction process in which fossil coke and anthracite are used to reduce iron ore. At Höganäs, there are ongoing test to replace some of the fossil feedstock and energy use [6]. A pilot plant for production of biobased syngas and production of bio-coke was constructed in year 2018.

The CO₂ emissions at the two blast furnaces sites are presented in Table 1. The specific emissions are around 1.2 tons CO₂ per ton produced hot rolled coil [7]. As comparison, on a global level the emissions from the steel industry are around 1.8 tons CO₂ per ton produced hot rolled coil [8]. The blast furnaces account for 85 % of the emissions from the Swedish iron and steel industry [9], see Figure 3. The remaining part of the CO₂ emissions, mainly origin from fuel use and could be replaced by renewable fuels without major technical development. Natural gas could for example

be replaced by biogas. To mitigate the emissions from the blast furnace, the steel making process need to be evolved, which is a greater challenge. Since the vast part of the emissions originates from the blast furnaces and the technological challenge is greater in relation to them, this report will focus on alternative iron reduction processes.

Table 1 Swedish steel plant data 2017 [2, 4]

	Specific CO₂ emissions (tonne CO₂-eq/tonne crude steel)	Steel production (ktonne/y)	Annual CO₂ emissions (ktonne CO₂-eq/y)
Luleå (inclusive of emissions located to the local energy company)	1.68	2,069	3,468
Oxelösund	1.72	888	1,530

3.2 Alternative pathways to climate neutrality

Currently, the main focus for CO₂ mitigation of the steel industry in Sweden is to develop a direct reduction (DRI) process which uses hydrogen as reducing agent instead of coal. The process is called Hydrogen Breakthrough Ironmaking Technology (HYBRIT). According to the goal for the HYBRIT project, the process will be ready to implement at the earliest year 2035, [10].

In addition to hydrogen DRI, natural gas, syngas or biogas could be used as reducing agent in DRI. If biogas or biogenic syngas is used, most of the fossil CO₂ emissions from the process is removed. Also, an additional reduction process is smelting reduction (SR-BOF). These alternatives are under development in other countries.

Furthermore, in parallel to the development of DRI processes, there is ongoing development of technologies for replacing part of the fossil coal by biogenic coal (BF-BOF). Biomass based charcoal have the potential to replace 100 % of the coal used [11, 12], but only up to 10 % of the metallurgical coke. Therefore, in order to make steel production climate neutral, this technology needs to be combined with CCS.

Additional development projects are ongoing, e.g. electrolysis of iron ore using electricity, but the expected time for full commercialisation is beyond the time frame of this project (EUROFER, 2013) and therefore it is not presented in this report.

In summary, the optional paths to reach a climate neutral steel production discussed here are:

1. Blast furnace (BF-BOF Charcoal): Replace fossil coal by biogenic charcoal in the blast furnace, combined with CCS.
2. Direct reduction (DRI-EAF): Direct reduction and electric arc furnaces, using
 - a. Hydrogen

- b. Syngas
 - c. Bio-charcoal
3. Smelting reduction (SR-BOF Charcoal): Smelting reduction, using bio-charcoal

The options are described separately below.

3.2.1 Blast furnace (BF-BOF Charcoal)

The blast furnace is an energy intensive process that uses primarily coal, coke and fluxing agents (e.g. dolomite and limestone) to produce raw iron from sinter, lump ore or pellets (i.e. agglomerated ores). The working principle of the blast furnace makes it reliant on metallurgical coke. The mechanical properties of metallurgical coke support the burden, i.e. the furnace content, while simultaneously enabling preferred hearth permeability for slag, gases and iron to flow through [13]. While metallurgical coke is required in the process, the fossil coal could be replaced by e.g. bioderived coal, oil, natural gas or plastic waste [14]. In the process, energy rich blast furnace gas is produced as a bi-product. The blast furnace partly re-uses the blast furnace gas as fuel for the process, but exports most of the gas for use in other processes (e.g. CHP plant as in the Luleå case described earlier) or for flaring. The raw iron produced in the blast furnace must further be processed in a basic oxygen furnace (BOF) to become steel.

The conventional blast furnace is close to reaching its theoretical minimum fuel use, and further reductions requires alternative blast furnace concepts [15]. One such alternative is the top gas recycled blast furnace (TGRBF). In the TGRBF, the blast furnace gas is conditioned and recycled in the process, thus re-introducing carbon monoxide and hydrogen in the process, which acts as reducing agents. The TGRBF is not yet a commercialised technology, but it has already been proven in pilot scale, and a full-scale deployment is assumed possible sometime after 2020 [16].

As long as the blast furnace process uses coke and coal as fuels, CO₂ emissions are unavoidable, but it is possible to reduce them considerably. Alternatives for reducing fossil CO₂ emissions in blast furnaces includes using biomass and CCS. Biomass, and especially biomass-based charcoal, has the potential to reduce subsequent CO₂ emissions from the blast furnace partially. Biomass-based charcoal have the potential to replace 100 % of the coal used [11, 12], but only up to 10 % of the metallurgical coke [17, 18]. In total this implies up to 30 % reduction of CO₂ emissions for steel making [9]. This alternative could be interesting if the quality of biomass-derived char is developed for blast furnaces and the price is low enough. Even though this measure does not help all the way, it is an interesting option to implement meanwhile other technologies are developed.

In order to achieve the goal of climate neutrality it needs to be combined with carbon capture and storage (CCS). CCS applications to the blast furnace varies with blast furnace technologies. In top gas recycled blast furnace concepts, CCS processes are required for conditioning of the blast furnace gas and therefore a convenient solution for carbon capture. This process also exports CO₂ lean blast furnace gas to other processes, acting as a pre-combustion capture unit for other processes. Conventional blast furnaces export most of the carbon to other processes with the exported blast furnace gas. Post combustion capture is one option, suitable for capturing CO₂ from the flue gas generated from air heating in the blast furnace. The CO₂ reduction of this alternative is only minor as this solution relies on the use of CCS in other processes for major emission reductions.

3.2.2 Direct reduced iron (DRI-EAF)

Direct reduction technologies utilise either gaseous fuels or solid fuels to produce direct reduced iron (DRI) from iron pellets, lump iron ore or iron ore fines. The result is DRI, a solid iron product also known as sponge iron. The produced DRI needs further processing, typically in an electric arc furnace (EAF), to become steel.

Gaseous fuel based DRI processes normally use natural gas as fuel, but other types of gaseous fuels such as e.g. syngas from gasification, coke oven gas or pure hydrogen are possible to use as well [19, 20]. Solid fuel based DRI production typically uses rotary kilns or rotary hearth furnaces to produce the DRI. In the furnace, iron ore fines or pellets are mixed with solid fuels and fluxing agents. Since the purpose of the solid fuel is mainly to provide carbon (which is gasified to carbon monoxide in the process), various carbon dense fuels are possible to use [21]. In the DRI process the reducing agents reacts with the iron ore without melting the iron.

Both gas-based DRI and coal-based DRI can achieve fossil free steel production, depending on the origin of the gas and coal respectively. The possibility of using syngas and pure hydrogen as reducing agents in gas based DRI technologies makes them potentially carbon neutral alternatives for DRI production as long as the syngas and hydrogen is produced using either biomass gasification or power-to-gas technologies. Due to the low share of fossil energy in the Swedish electricity mix, hydrogen DRI has been considered a feasible route for the Swedish steel industry to become carbon neutral and development efforts are focused on this route. In addition, many concepts using gaseous DRI production have an incorporated CCS step for gas conditioning, making these technologies suitable for CO₂ reductions using carbon capture [19].

The technology related challenge lies in the upscaling of power-to-gas and biomass gasification concepts and the full-scale coupling of these processes with the DRI-production technology. Estimations regarding the hydrogen pathway using electrolysis points towards a potential commercialisation of this process by 2035 [10]. In order to replace the Swedish blast furnaces with hydrogen- DRI, a vast hydrogen production is necessary which involves a high demand of electricity and capacity for hydrogen storage. In addition, the electric arc furnace in the second step of the process demands electricity. Hence, a prerequisite for the DRI-Hydrogen process, is that the electric grid capacity is strengthened to the production sites.

At present, a pilot plant is under construction for hydrogen-DRI in Sweden[10]. More development is required, both regarding the DRI process itself and the hydrogen production which would require electrolyzers of a scale which is not used anywhere in the world yet. The large-scale storage of hydrogen is another question which need to be further investigated. According to the feasibility study of the HYBRIT project, the production cost for steel would be about 20-30 percent higher compared to the reference case with blast furnaces [10].

The biomass-based syngas concept is more similar to current coal- or natural gas-based shaft furnaces and would assumingly be available earlier than 2025. Natural gas DRI is used at various places in the world already, particularly in places where natural gas is available at a low price. To use biomass-based syngas instead of natural gas in DRI is not a technical problem but would be much more expensive due to the production cost of syngas.

In solid fuel based DRI production, the added coal primarily works as a source of carbon and a full substitution of coal to bio-charcoal should therefore be possible, as suggested by [22]. The future deployment of fossil free production solid fuel based DRI production concepts is foremost depending on the possible large-scale production of bio-charcoal.

3.2.3 Smelting reduction (SR-BOF)

Smelt reduction is an alternative to blast furnaces which integrates coke making and iron production in a single process. The need for preparation of ore is reduced compared to blast furnaces. However, since fossil coal is used it is not possible to achieve carbon neutrality with this technology. To obtain a CO₂ reduction the waste gases need to be captured. A number of different smelting reduction processes are under development. The COREX technology is the most mature and in operation, e.g. in South Africa. Conventional smelt reduction is a technology which is considered to be particularly interesting in small- and medium-scale plants in development countries. This is due to possibility of small-scale units which require less time and cost for construction and the flexibility associated with this. Advanced smelting technologies are not yet commercialised and deployment of full-scale operations are not expected until 2030-2035 [23].

A typical smelting furnace consists of two interconnected units, a pre-reduction unit and a smelting unit. In a smelting furnace, iron ore and fluxing agents (and in some cases oxygen) are fed into the pre-reduction unit. The pre-reduction unit uses off gas from the smelting unit to reduce the iron ore partially. The partially reduced iron ore then enters the smelting furnace, where coal and oxygen are added to completely reduce and melt the iron ore, producing liquid raw iron. The raw iron is thereafter further processes in a basic oxygen furnace (BOF) to become steel.

While the working principles are the same for different smelting furnaces, the actual setup of technologies varies between different smelting furnace concepts. In conventional smelting furnaces (e.g. COREX technology), a direct reduction shaft used for pre-reduction, using a setup where the pre reduction unit and the smelting unit are separated from each other [24]. Meanwhile, in more advanced smelting technologies (e.g. HIsarna), other concepts such as a cyclone furnace are used is a setup where the pre reduction unit and the smelting unit are more integrated into each other [23, 25]. Consequently, the energy performance also varies. Conventional smelting furnaces are energy intensive, and even though the smelter off-gas is used for pre-reduction of iron ore, the conventional smelting concept produces high calorific export gas. This gas has to be used in e.g. a CHP plant to improve the energy performance of this concept. Meanwhile, advanced smelting concepts are more efficient, using approximately 80 % of the energy required for BF concepts while only producing CO₂ as off-gas.

Unlike the blast furnace, smelting furnaces operations do not rely on the mechanical properties of metallurgical coke, which allows for full utilisation of biomass substitutes [18]. Using biomass can potentially remove all of the fuel-based CO₂ emissions, but not the emissions related to the use of limestone and dolomite. The use of CCS differs between smelting technologies. In conventional smelting reduction, additional equipment for CO₂ removal is required to remove CO₂ content in the export gas. This is a sort of pre-combustion CCS concept, where CO₂ is removed before use in e.g. a CHP, as explored by [26]. The alternative for CO₂ reduction from combustion of the export gas is to apply post-combustion CCS options where the export gas is utilised. For advanced smelting reduction technologies, the situation is completely different. Due to the CO₂ rich flue gas, these technologies only requires the addition of a CO₂ compression step for CO₂ capture [25].

Hydrogen plasma smelting is another concept, which could drastically reduce CO₂ emissions. This technology is still under development, but have shown potential for improved cost- and environmental performance [27]. However, data regarding this technology is scarce and therefore not explored further within this report.

3.2.4 Summary Steel and iron industry

Table 2 summarises the technological options for the iron and steel industry to reach the goal of climate neutrality. The technical readiness level is high for several of the options, but they are then depending on the availability of bio-charcoal or biomass gasification which has a lower TRL.

Table 2 Summary of the technical options for the steel and iron industry to become climate neutral. Technical readiness level (TRL) is estimated as low (+), medium (++) or high (+++).

Process	TRL (+, ++, +++)	Earliest year of full-scale implementation	Comment	Source
BF-BOF Bio-charcoal	+++ (++)	2020	Depends on the availability of bio-charcoal. No known large-scale implementations. Needs to be combined with CCS in order to reach climate neutrality, since not all fossil coal can be replaced.	
TGR-BF-BOF-CCS	++	2020-2025	Proven in pilot scale.	EUROFER, 2013 [16]
SR-BOF Bio-charcoal	+++ (++)	2020	Depends on the availability of bio-charcoal. No known large-scale implementations.	
Advanced SR-BOF Bio-charcoal	+	2030-2035		Abdul Quader et al., 2016 [23]
DRI-EAF H2 (shaft furnace)	+	2035	Currently under development. Estimates according to the HYBRIT project.	HYBRIT, 2018 [10]
DRI-EAF Syngas	+++ (++)	2025	Commercially available with coal gasification (e.g. MXCOL). DRI + bio	

(Shaft furnace)			syngas depends on biomass gasification TRL.	
DRI-EAF Bio-charcoal (Rotating kiln)	+++ (++)	2020	Depends on the availability of bio-charcoal. Steel – production technology is known but not commonly used. No known large-scale implementations.	

4 Cement industry

4.1 Current situation

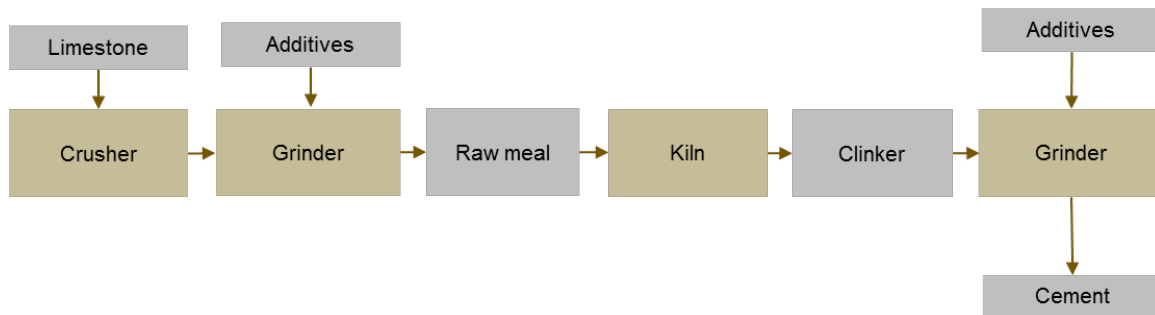


Figure 4 Schematic flow chart of the cement production process. The main part of the process related CO₂ emissions is released from the clinker production in the rotary kiln.

Historically, emissions from the cement industry have been approximately 1 tonne CO₂-eq/ton cement of which 50 % was process related, i.e. originating from the raw lime material. Energy efficiency improvements and fuel switching has led to significantly lower levels in Sweden today. Specific emissions do show a weakly decreasing trend, from 722 to 701 kgCO₂-eq/ton cement 2010-2016. The main reason for this improvement is an increased share of biofuels from 13 % to 21 % [28], which can be compared to 11 % in an average Nordic plant according to Rootzén et al [29] (Table 4). However, the total emissions are constant or increasing due to increasing production volumes.

There are three cement plants in Sweden, all run by Cementa AB, producing around 3,000 ktonne/y of cement in total. Swedish mineral industry emissions in 2016 were 3,199 ktonne CO₂-eq., which is 19% of total industry emissions. The main part, 2,348 ktonne, comes from cement industry with 810 ktonne CO₂-eq. from fuel combustion and 1,538 ktonne CO₂ are process emissions [28, 30].

The process emissions originate from the calcination in the rotary kiln in which limestone is turned into clinker. During heating of limestone (mainly CaCO₃), solid CaO and gaseous CO₂ is formed. These emissions cannot be reduced by fuel switching but need carbon capture in order to be removed. In year 2016 the average clinker content in Swedish cement was 86 %. With the development of new cement blends, the clinker content is about to be lowered, which also may reduce the CO₂ emissions from cement production.

Table 3 Swedish cement plant data 2016 [5]

	GHG (kg CO₂-eq/ton clinker)	GHG (kg CO₂-eq/ton cement)	% clinker	Production (kton/y clinker)
Skövde	851	714	84	434
Slite	792	679	86	2,198
Degerhamn	947	878	93	250
Weighted average	814	702	86	

Table 4 CO₂ emissions, feedstock and energy use in average Nordic cement plant [29]. The Swedish part of this data is from 2007-2011.

Emissions		
Specific CO₂ emissions	0.7	tonne CO ₂ /tonne cement
Feedstocks		
Limestone	1.4	tonne/tonne cement
Other feedstock materials	0.2	tonne/tonne cement
Energy carriers		
Coal	416	kWh/tonne cement
Pet coke	167	kWh/tonne cement
Fuel oil	<30	kWh/tonne cement
Alternative fuels	111	kWh/tonne cement
Biomass	83	kWh/tonne cement
Electricity	120	kWh/tonne cement

4.2 Alternative pathways to climate neutrality

In the roadmap towards fossil free cement industry in Sweden [31], it is described that the main CO₂ mitigation measures are fuel switching and development of new types of cement. Furthermore, carbonating is presented as a CO₂ mitigation measure. Since carbonating is a process which occur later during the lifetime of cement, not during the production phase, that measure is not included in this report. However, with or without carbonating, a significant part of the emissions will still remain and carbon capture and storage or usage (CCS/CCU) will be required in order to reach the zero vision.

In addition to the options described in the roadmap, there is an ongoing development of technology for electric heating in the cement production. Note that in order for electrification to be a CO₂ reduction measure, it is assumed that electricity is produced in a climate neutral way.

There are five main alternative pathways:

1. Improved thermal and/or electric efficiency
2. Switch fossil fuel to biofuel
3. Switch fossil fuel to electricity
4. Blended cement and/or clinker substitution
5. CCS

Improvement of energy efficiency has a relatively small potential to reduce the greenhouse gas emissions from the Swedish cement industry. Replacing fossil fuels has the potential to reduce the greenhouse gas emissions by approximately 30 %. Fossil fuels could be replaced by either biofuels or electricity. The CemZero project is developing technology for electric heating of clinker production and aim for large scale implementation year 2030. However, the process related greenhouse gas emissions are not removed with these measures.

Process related emissions could be reduced by substituting clinker with other materials. Viewed from a circularity perspective, an attractive alternative material is blast furnace slag which is a by-product from steel making. Using slag to substitute clinker could reduce the emissions with about 15-60 %, depending on if only Swedish slag is used or if slag is imported as well. However, if the steel industry change process from blast furnaces to direct reduction, as described as an option in Chapter 3.2.2, this will no longer be an alternative. Anyhow, carbon capture and storage will still be a necessary measure for the remaining emissions if the cement industry should reach the goal of climate neutrality. If both fossil fuel is replaced and clinker is substituted, 30-60 % of the CO₂ emissions still remain.

With this conclusion in mind, the alternative to switch from fossil fuels to electricity has a major advantage compared to switching to bio fuels. The CO₂ stream will be pure and there is no need for scrubbing. This radically reduces the investment cost for CCS, and also the operation and maintenance costs.

4.2.1 Improved energy efficiency

Compared to the best available technology, energy saving measures within the current cement production in Sweden could contribute to about 2-3 percent of CO₂ emission reduction [28].

Improved thermal and/or electric efficiency is considered an important path towards decreased CO₂ emissions globally, as illustrated in Figure 5. Efficiency measures can reduce emissions by 10-20 % in the absence of other technologies. The global average for thermal heat consumption of 3.5 [32] – 3.8 [33] GJ/ton clinker can be compared to Swedish data from 2013: Slite 3.7 GJ/ton clinker, Skövde 4.0 GJ/ton clinker and Degerhamn 4.8 GJ/ton clinker [34], indicating that the smaller Swedish cement plants are less energy efficient than the global average.

Cementa uses an energy efficient dry kiln process with precalcining³ and only estimates that energy efficiency improvements will contribute with 2-3 % of emission reductions to reach a CO₂ neutral process [28]. This corresponds to a little bit less than the savings that would be obtained by improving the smaller Degerhamn and Skövde plants to the same energy efficiency as the bigger Slite plant.

US EPA [35] states that a typical average heat input for a modern dry kiln process with precalcining is 3.3 GJ/ton clinker. Nordic average energy use according to Rootzén et al [29] (Table 4) is 3.3 GJ/ton clinker thermal energy consumption. It is known that energy demand is influenced by for example raw material mineralogy and chemical characteristics as well as plant size [32].

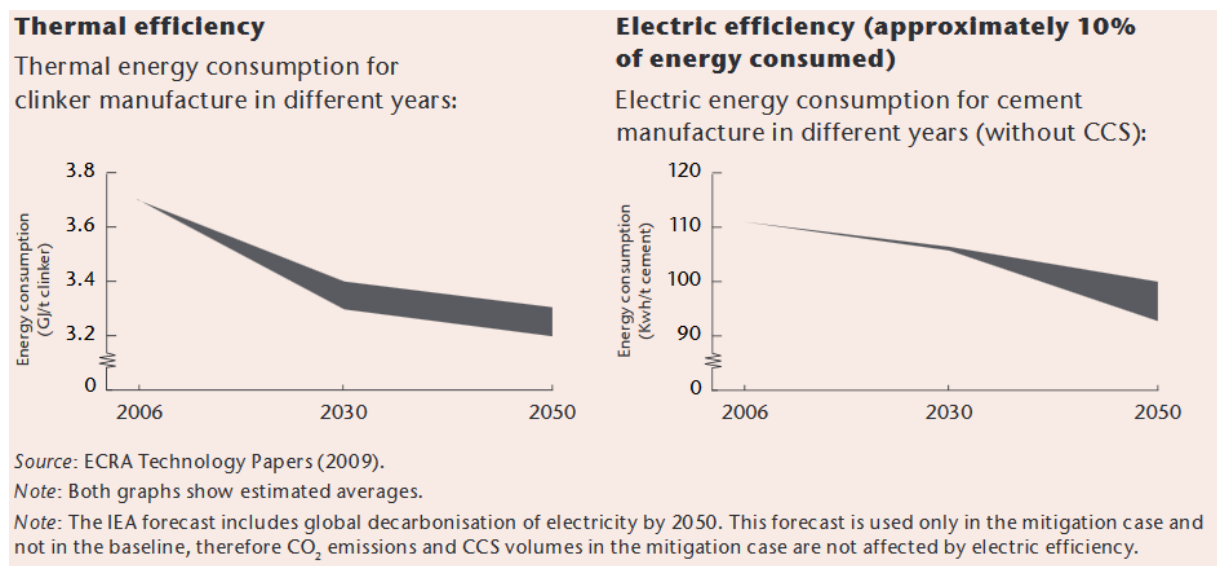


Figure 5. Projected energy efficiency increase until 2050 [36].

A similar comparison for electricity shows that the Swedish plants consume 120-130 kWh/ton cement, which is slightly higher than the global average in Figure 5 and the Nordic 120 kWh/ton cement (Table 4). Madloul et al [37] have shown for a specific plant that close to 90 % of the electricity consumption originates in mashing (34 %), fans/coolers (18 %) and cement milling (35 %). Remaining electricity consumers are raw material crushing (3 %), dust collector (5 %) and

³ Typically gives around 20% lower emissions than an old wet kiln process [7].

transportation (6 %). ECRA [32] states that the division between the process sections is raw material preparation 25 %, clinker production 25 %, cement grinding 43 %.

In addition to making the existing plants more efficient, a major reduction of energy use would be achieved if a part of the clinker would be replaced by other material. This is described in Chapter 4.2.4.

4.2.2 Fuel switching

The main fuels used in the Swedish clinker manufacture are coal and petcoke. The use of alternative fuels, which can be either biogenic or fossil, can decrease fuel related GHG emissions. Potential biomass fuels include for example woody biomass, sewage sludge, textiles, paper residues and agricultural residues. Potential alternative fossil fuels include pre-treated industrial and municipal solid waste, discarded tyres, waste oil, solvents and plastics. Tyres are partly made from biomass, about 20-30 % natural rubber. Technically 100 % of conventional fuel can be substituted and individual plants with 95 % yearly average exist [32]. The global average was 16 % alternative fuels 2014, of which 6 % was biomass [32].

A new burner was installed in Skövde 2013 to enable a larger fraction of alternative fuels with improved heat efficiency. An identical burner is also in place in Slite [34]. The Slite plant increased the alternative fuel fraction from 40 % to 55% 2012-2014 and 55 % is also the average alternative fuel fraction for Cementsa in total 2016 (21 % biomass, 34 % other fossil) [28]. The Skövde plant is behind in this development with 35 % alternative fuels reached 2016 [38].

4.2.3 Switch from fossil fuel to electricity

If the electricity is produced in a climate neutral way, switching from fossil fuel to electricity is a climate mitigation option which could reduce the CO₂ emissions from cement production by about 30 %.

There are several options for converting the fuel use in clinker production to electric heating. One example is to use plasma burners. This has been studied by Cementsa in cooperation with Vattenfall in the project CemZero [39]. The challenge is to develop efficient heat transfer to achieve the required temperature 1,450°C. According to the feasibility study, the electrification of the cement production seems technically possible but need to be verified in larger scale tests. They conclude that the production cost would be about doubled compared to today's technology. However, the cost for carbon capture would decrease significantly since the CO₂ emissions will be pure and scrubbing will not be needed. The aim for the CemZero project is that technology for electric heating of clinker production should be implemented in large scale year 2030.

Another alternative which is under development is electric direct separation reactor (DSR). A pilot project for this technology, the EU Horizon 2020 pilot project LEILAC, will present its results in May 2019.

Table 5 presents data for cement production with electricity compared with a reference plant. According to the CemZero report [39], the cost for carbon capture will be reduced in the case of electric heating of the clinker production. This is because the CO₂ stream will be pure and there is no need for scrubbing. Especially the capital cost is reduced, from about 130 MEuro to 24 MEuro in a plant with capacity 1 million tons clinker per year, but also the operation and maintenance cost.

Hence, the additional capital cost of 40 MEuro for electric heating of the cement production, is more than compensated by the less expensive carbon capture cost.

Table 5 Capital cost, fuel demand, electricity demand and operation and maintenance cost for a reference cement production plant and an alternative cement production plants with capacity of 1 million tonnes clinker per year (1.35 million tonnes cement), with 5 stage pre-heater and pre-calciner dry feed technology and at a clinker/cement ratio of 73.7 %. Scenario Amine represent a conventional cement plant with post combustion amine scrubber with electrical boiler. Scenario Plasma represent the electric cement production which use plasma heating. [39]

Technology	Capital cost, not related to carbon capture (MEuro)	Fuel demand MWh/tonne clinker ^a	Electricity demand kWh/tonne cement ^a (approximately 86 kWh/tonne clinker ^c and 34 kWh/tonne cement for cement grinding)	Operation and maintenance cost (Euro per tonne cement)
Reference plant	210 ^a	0.83-0.92 MWh/tonne clinker ^a	98 kWh/tonne cement ^a (approximately 86 kWh/tonne clinker ^c and 34 kWh/tonne cement for cement grinding)	20.2 ^a
Reference plant + Carbon capture (Case Amine)	210 ^a	0.83-0.92 MWh/tonne clinker ^b	98 kWh/tonne cement ^b (approximately 86 kWh/tonne clinker ^c and 34 kWh/tonne cement ^b for cement grinding)	20.2 ^b
Electricity + Carbon capture (Case Plasma)	252 ^a	0 ^a	1.2-1.3 MWh/tonne clinker ^a + 34 kWh/tonne cement ^b for cement grinding	20.2 ^b

^a CemZero report [39]

^b Derived from data in the CemZero report [39]

^c Clinker-cement ratio 73.7 %.

4.2.4 Feedstock and clinker substitution

Feedstock substitution denotes an additive that is mixed with the normal feedstock before the kiln while clinker substitution denotes an additive that replaces clinker in the cement milling process. Blast furnace slag and coal fly ash are the most commonly used materials, both as feedstock substitution and as clinker substitution [32].

Clinker substitution can potentially use a wider range of materials. The average clinker fraction in Swedish cement 2016 was 86 % [29] (Table 4) but globally it was 78 % 2009 [36] and 75 % 2014 [32] with large variability between regions (58 % in China [31], 68 % in Brazil, 92 % in North America [33]). Kajaste and Hurme [33] calculated that a change in the world average clinker substitution fraction to the level of Brazil would decrease greenhouse gas emissions from cement industry by approximately 10 % and point at clinker substitution as the best short term greenhouse gas mitigation strategy.

Limits to implementation include regional availability, prices, product properties, standards and common practice. Technically, 60 % clinker content in cement as a global average is feasible [31]. A new product (“Bascement”) with 6-20 % fly ash as a component was introduced in the Slite plant in 2013 and is claimed to give 10 % lower CO₂ emissions [34]. However, due to quality factors, the fly ash that could be used for this purpose is limited to fly ash originating from coal combustion [40]. Hence, the fly ash is not climate neutral. As coal combustion is planned to be phased out from the energy sector, fly ash will be a limited resource in the future.

On the European market, a high-quality cement product called Ecocem cement (CEM III/A), is available. Ecocem consists of a minimum of 50 % blast furnace slag and is classified in the European Cement Standard [41]. Ecocem could be used for all types of construction. However, there are limits in the availability of blast furnace slag.

In Sweden, the blast furnace slag production is about 450,000 ton per year which is about 15 % of the clinker production (2,900,000 ton per year). If all blast furnace slag was used for cement production, the clinker content could be reduced to 73 %. A clinker substitution of that magnitude would reduce the greenhouse gas emissions from cement production by approximately 15 % as well, since both process related and energy related emissions would be reduced. Viewed from a circularity point of view, blast furnace slag is an attractive alternative material since it is a by-product from steel making. However, this opportunity depends on blast furnace technology use in the iron and steel industry. If the iron and steel industry is transformed to new processes, the opportunity to use slag is reduced.

In addition to the blast furnace slag that is produced in Sweden, it is also possible to import slag from other EU countries. It should be noted that this slag would be produced in fossil-based blast furnaces and that even though it did not contribute to emissions in Sweden, it is not climate neutral. Currently, less than half of the slag in EU is used for cement [42]. If that opportunity is fully exploited, an average of 50 % slag content could be assumed. Compared to the current clinker content of 86 %, that would imply a clinker content reduction of about 60 % and a CO₂ emission reduction of the same size. Both process related emissions and energy related emission would be reduced when less clinker is needed.

4.3 Carbon capture technologies in the cement industry

With a continued production of the same types of cement as we are currently using, the only way of reaching low or net-zero emissions of CO₂ in the cement industry is to use CCS technologies. Existing literature typically targets three main alternative CCS technology concepts for the cement industry. These are 1) post combustion capture (PCC), 2) oxyfuel combustion (OXY) and 3) carbon looping. None of these CCS technologies are deployed commercially and the readiness level varies

depending on the technology of choice. CCS-technologies for the cement industry are estimated to be available by 2025 (PCC) – 2035 (OXY) [43]. A cost range of 40-90 €/ton CO₂ captured is realistic. As mentioned in Chapter 4.2.3, replacement of fuel combustion with electric heating could reduce the investment cost for carbon capture to about one fifth since the CO₂ stream will be pure [44].

Each of the three technologies for CCS have their own advantages and disadvantages. The first alternative, PCC, typically relies on flue gas cleaning technologies using amine-based scrubbers. Amine-based scrubbers have a quite high requirement of process steam for heating. While waste heat from the cement manufacturing process can partly reduce the required steam, dedicated steam generation technologies (i.e. boilers or combined heat and power plants (CHP) are still expected to be required to cover the remaining steam deficit [45]. The second alternative for CCS in the cement industry, OXY, uses oxygen to replace the air required for the combustion of fuels. This creates a flue gas that is rich in CO₂. The CO₂ rich flue gas only requires an additional compression stage for CO₂ handling (which, in any case, is required for all CCS applications) and does not require any dedicated separation technologies for the capturing process. Instead, the trade-off, compared to a conventional furnace, is the additionally required electricity for producing oxygen. The third option, CL, takes advantage of the reverse calcination process. The reverse calcination process captures the CO₂ in the flue gas by using quicklime (CaO) and the CO₂ to produce lime (CaCO₃). The produced lime is reheated using oxyfuel combustion to regenerate the CaO in a separate reactor, which, in turn, generates a CO₂ rich flue gas suitable for capture and storage without further flue gas processing. This option does not require steam but increases the fuel demand of the process and has a slightly increased electricity demand because of the required oxygen.

4.3.1 Summary cement industry

In Table 6 the technical options for the cement industry to become climate neutral are summarised. A biofueled process has high TRL but would need to be combined with one of the three CCS options in order to reach climate neutrality. The CCS technologies have low or medium high TRL.

Table 6 Summary of the technical options for the cement industry to become climate neutral. Technical readiness level (TRL) is estimated as low (+), medium (++) or high (+++).

Process	TRL (+, ++, +++)	Earliest year of full-scale implementation	Comment	Source
Biofueled	+++		Uses current technologies, depends on biofuel availability.	
Electric	+	2035	Currently investigated. Estimates according to the CemZero project.	CemZero, 2018 [39]
CCS – Post combustion capt.	++	2025	Pilot installations exist.	Hills et al., 2016 [43]
CCS – Oxyfuel	+	2035		Hills et al., 2016 [43]
CCS – Chemical looping	+	2030	Pilot installations exist.	Hills et al., 2016 [43]

5 Chemical industry

5.1 Current situation

The Swedish chemical industry represents 9 % of total energy use in Swedish industry [46]. Furthermore, the sector represents 6 % of the total GHG emissions from Swedish industry [47].

The Stenungsund cluster is an important part of the Swedish chemical industry. The cluster is located on Swedish west coast and entails industries such as AGA Gas AB, Nouryon (former AkzoNobel Sverige AB), Borealis AB, INEOS Sverige AB and Perstorp Oxo AB [48]. AGA produces industrial gases, Akzo Nobel produces amines and surfactants, Borealis produces ethylene and polyethylene (PE), INEOS produces polyvinyl chloride (PVC), and Perstorp Oxo produces specialty chemicals (ibid).

Another important chemical industry in Sweden is Yara. Yara mainly produces fertilizers [49] and is located in Köping, 150 km west of Stockholm. However, the production of ammonia, which is the most energy demanding step in fertilizer production, is located outside of Sweden.

The company Borealis represents the single largest source of greenhouse gas emission within Swedish chemical industry, representing 72 % of total emissions [5]. Thus, this description focuses first and most on this company and its possibilities to reduce emissions as well as use of fossil fuels.

5.1.1 Steam cracker

A steam cracker such as the one at Borealis uses hydrocarbon feedstocks such as ethane, liquefied petroleum gas (LPG), naphtha or gas-oil to produce ethylene and propylene. The output from the steam cracker consists of both ethylene and propylene, but the amounts and composition varies with the feedstock. As a comparative example, the yield from ethane feedstock is mostly ethylene while the yield from naphtha feedstock constitutes both ethylene and propylene. Apart from the ethylene and propylene, energy rich gas fuels are co-produced in the process. These energy rich gases are used in the process to satisfy the energy demand in the process. External sources of fuels might be required depending on feedstock. The use of these derived gases is the main source of fossil CO₂ in the steam cracker process, not accounting for the carbon release associated with potential downstream combustion of the produced olefins.

The ethylene produced by Borealis is used for polyethylene (PE) production. Ethylene is also provided to other industries in the Stenungsund cluster, see Figure 9. In addition, other products from the ethylene production, such as propylene and flue gas, are provided to industries in the cluster, see section 5.3.4. The Borealis cracking plant consists of nine steam crackers.

Figure 6 below shows the cracking process from naphtha, ethane (and other feedstocks) to ethylene [50].

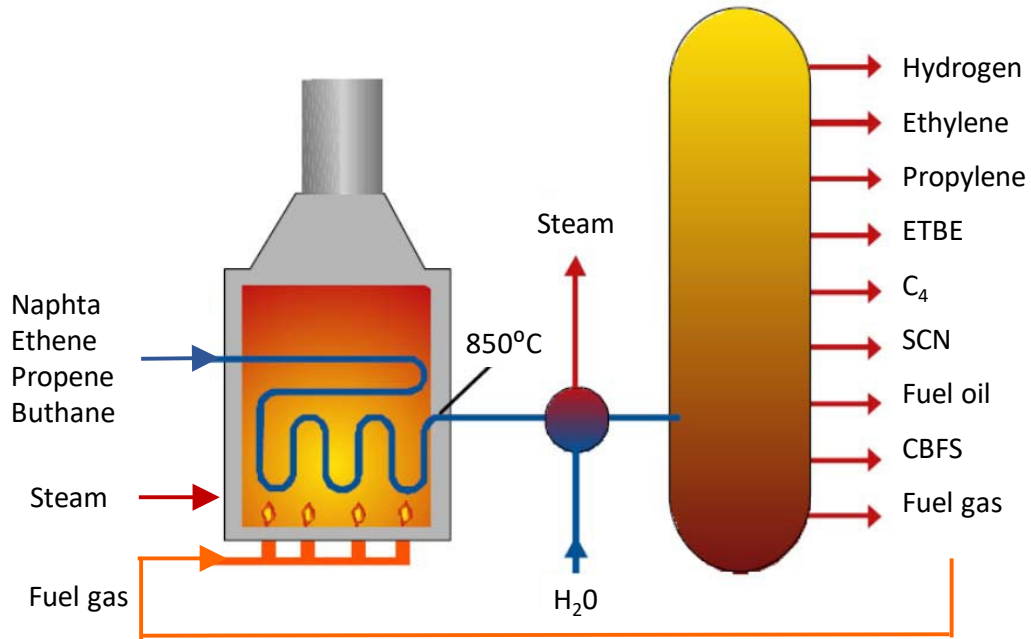


Figure 6 Borealis' cracking process [50].

5.1.2 Energy use in cracking process

According to Borealis environmental report [50], 3,532 GWh was used in the cracking process year 2016. The main part was fuel use and a smaller part was electricity use, see Table 7.

Table 7: Total energy use in cracking process at Borealis year 2016 [50]

Fuel use (GWh)	Electricity use (GWh)	Total energy use (GWh)
4,147	350	4,497

According to Figure 6 from Borealis environmental report year 2016, the fuel used in the cracking process is fuel gas, which is a by-product from the cracking process [50]. By switching to a non-fossil feedstock in the cracking process, a non-fossil fuel gas is obtained.

5.1.3 Emissions from cracking process

The carbon dioxide emissions from Borealis cracking process amounted to 664 kton year 2016 [50]. The emissions are directly related to the production level [51].

5.2 Alternative pathways to climate neutrality

The CO₂ emissions related to plastic use is highly related to production of new plastic material from fossil raw material. Hence, increased recycling of plastic and replacement with biobased materials are important puzzle pieces in reaching climate neutrality. There is also opportunity for process improvements, described in Chapter 5.2.1. However, the third main piece is to produce new plastic from biobased raw material instead of fossil. A feedstock switch is necessary to phase out the use of fossil fuels in the plastic production and the release of fossil CO₂ at the end-of-life of plastic when it is incinerated for “energy recovery”. In Chapter 5.3 the alternatives for feedstock switch are described.

Different processes to produce renewable feedstock may cause different emission volumes. Liptow et al. (2015) have performed a life cycle analysis (LCA) for production of ethylene from forest biomass [52]. They have compared different production routes, including gasification, wood and sugar cane fermentation, and conventional production based on fossil feedstock. They concluded that wood gasification is the least emitting pathway, followed by wood fermentation, and sugar cane fermentation. All the renewable pathways evaluated emit less than the conventional fossil-based pathway.

5.2.1 Process improvements

Ethylene is currently produced from steam cracking of fossil naphtha, ethane, and other feedstocks. The cracking process represents a large share (55 – 65 %) of the energy use in ethylene production [53]. Using Best Available Technology (BAT) may reduce the energy use in the cracking process, e.g. using different materials in furnace and cracking tubes.

5.3 Feedstock switch

According to the Swedish Energy Agency [46], there are two main paths to replace fossil feedstock in the chemical industry processes. One path is to produce “building blocks” from renewable feedstock that can be used in existing processes. Another path is to use a completely new process to produce the same end-product based on renewable feedstock. For example, gasification can be used to produce building blocks (syngas), which can be used to produce different molecule (e.g. methane or Fischer-Tropsch diesel). In Figure 7 this is described schematically. The former part of the processes (to produce the building blocks) is less mature and more expensive according to the Swedish Energy Agency (ibid). Therefore, alternatives for completely new processes to replace the steam cracker will be in focus in the following.

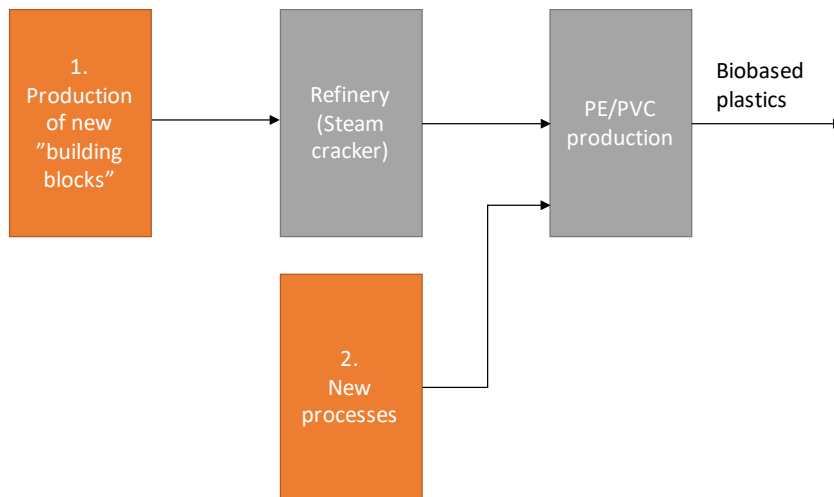


Figure 7 Schematic of the two main paths towards fossil free plastic production. Grey symbolises existing production units, orange symbolises new production units. The schematic is further elaborated in Figure 8. (Source: IVL and LTU, this report)

The Skogskemi project has investigated several routes based on gasification of forest biomass that can be used to produce feedstock for the chemical industry [54]. The project has identified different routes to produce olefins from forest biomass. Ethylene and propylene are the olefins which are produced in the steam cracker at Borealis and then used for polyethylene production. The routes to replace the steam cracker which were identified by the Skogskemi project are:

1. Methanol-to-olefin (MTO).
2. The ethanol-to-ethylene route (E2E).
3. Oxidative coupling of methane (OCM).

These alternatives are described separately in the following chapters.

Regarding production of new “building blocks”, biomass-based naphta derived from the Fischer-Tropsch process as a co-product from the production of bio-diesel is one option, and biomass-based LPG co-produced in the methanol-to-gasoline (MTG) process another (see e.g. (Hannula and Kurkela, 2013)). Another option is to use various forms of bio-oils, such as vegetable oil, tall oil or pyrolysis oil, that have undergone pre-processing, e.g., via hydrodeoxygenation (HDO) as studied by (Pyl et al., 2012).

In Figure 8, the alternative routes are illustrated. As shown in the figure, the feedstock (Methanol, Ethane or Methane) to the new processes which replace the steam cracker needs to be produced in some manner. The processes for this could be digestion, fermentation or gasification. For example, both plastics and forest residues could be gasified in waste refineries (in Swedish: “returraffinaderier”) [55]. An advantage is that this method can make use of plastic, which is not suitable for mechanical recycling.

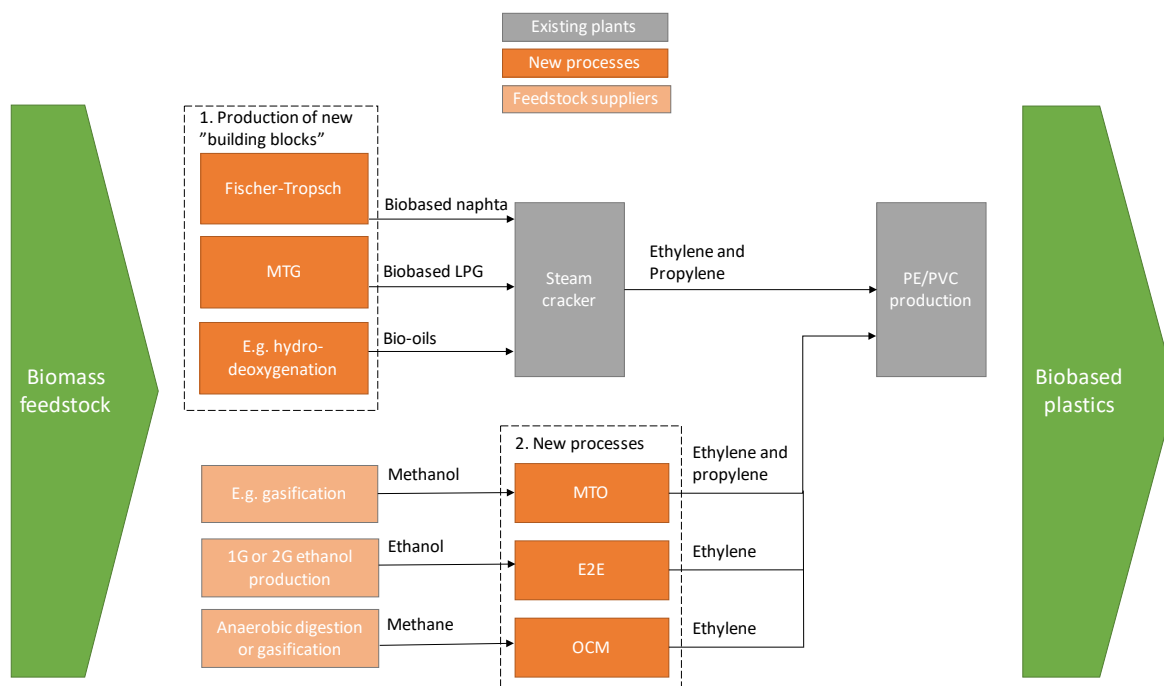


Figure 8 Elaboration of Figure 7. Schematic of pathways towards biobased plastic production. (Source: IVL and LTU, this report)

5.3.1 Ethanol-to-ethylene

The fossil ethylene that is currently used in the production of polyethylene can be replaced with biogenic ethylene produced from bioethanol [48, 49]. The ethanol-to-ethylene (E2E) technology is a commercially proven technology that uses dehydration of ethanol to produce ethylene. In the E2E process, ethylene is produced from bioethanol through dehydration. The process is endothermic and involves a catalyst.

Ethylene production from ethanol has been proven in large scale by a Brazilian company, Braskem [49]. Brazil is one of the world’s largest producers of ethanol. First generation ethanol is produced based on sugar cane in Brazil. Hackl and Harvey have evaluated production of bioethanol from lignocellulosic feedstock that could be used for biogenic ethylene production [48]. Ethanol production based on lignocellulosic feedstock is often called second generation and is not yet commercially mature. The production of bioethanol represents the major part of the production cost of biogenic ethylene [56] making it hard for biogenic ethylene to compete with fossil ethylene.

However, the E2E process produces only ethylene [57]. This means that the E2E process would require supplementary production of propylene using e.g. the methanol-to-olefins (MTO) process or an olefin metathesis process, as shown for biomass based production of propylene by Machado et al. [58]. In the olefin metathesis process, olefins are fragmented by the scission and regeneration of carbon-carbon double bonds.

5.3.2 Methanol-to-olefins

The methanol-to-olefin (MTO) process converts methanol mostly into light olefins such as ethylene, propylene and butylene, but also into water. In this way, ethylene from a renewable

source could be provided to the PE and PVC production. Accordingly, renewable propylene can contribute to renewable polypropylene production. The operation of the MTO process can be altered to change this ratio between ethylene and propylene somewhat, with the ratio of ethylene to total output (ethylene and propylene) typically ranging between 0.43-0.61. Since the ratio between ethylene and propylene in the process is restricted, make-up production of ethylene or propylene from other processes could be required, such as the E2E or OCM process for ethylene or the olefin metathesis process for propylene. Commercial installations of the MTO process do not exist yet, but is not that far away [57].

Since the MTO process uses methanol as feedstock, there are many possibilities for olefin production with reduced CO₂ emissions depending on methanol production. Methanol can be produced using biomass (including black liquor gasification) or coal gasification concepts, power-to-gas concepts or via steam reforming of natural gas. Both the biomass gasification and power-to-gas options allows for fossil free production of olefins. The methanol production in power-to-gas options requires CO₂ as input, making the MTO process a possible carbon capture and usage (CCU) option. The coal and natural gas-based options is not fossil free but could potentially lower overall emissions of olefin production if the methanol production step is combined with CCS technologies.

The research company Processum has investigated an MTO route based on methanol produced from forest biomass [54]. They have assumed a yearly production of 300 ktonne olefins based on an input from 100 tonne dry methanol per hour (equivalent to 800 ktonne per year assuming 8,000 operating hours). They also conclude that the production cost of methanol is considerably higher than fossil methanol (ibid).

5.3.3 Oxidative coupling of methane

The oxidative coupling of methane (OCM) process uses methane to produce ethylene. Just as the ethanol-to-ethylene process, the OCM process is only capable of producing ethylene. Complementary production of propylene e.g. with the MTO process, is therefore required. Even though the OCM process could be a potential option for ethylene production, current technologies battles problems with low yields and high energy requirements [59].

By using methane – the main constituent in natural gas and substitute natural gas (SNG) – the OCM process makes it possible to have a fossil free production of ethylene entirely based on biomass. The biomass-based concept relies on the production of SNG through either biomass gasification concepts or upgraded biogas from fermentation of biomass and biomass waste. The electricity-based concept relies on the production of SNG in power-to-gas technologies. The power-to-gas route requires CO₂ as feedstock to produce the SNG, which is stored in the produced ethylene via the OCM process making the concept a possible CCU solution. As the OCM process also is inherently equipped with CCS technologies, emission reductions through CO₂ storage is possible as well. The carbon capture will be less expensive since separation of CO₂ is a process step in OCM. However, the OCM technology itself is highly expensive.

5.3.4 Effect on Stenungsund cluster

The steam crackers at Borealis produces not only ethylene as input for Borealis production of polyethylene but also other intermediates (propylene, hydrogen, butylene, and fuel gas) used in the Stenungsund cluster. Thus, if a new process replaces or is integrated with the existing cracker process, this would affect several (or all) of the industries in the cluster. Some of the chemicals and

fuels currently obtained from the cracker would have to be produced in new processes and/or be imported.

The current flows of chemicals between industries are illustrated in Figure 9 below [60]. Please notice that the company Inovyn shown in the figure is part of company Ineos. Also, Akzo Nobel is named Nouryon since year 2018.

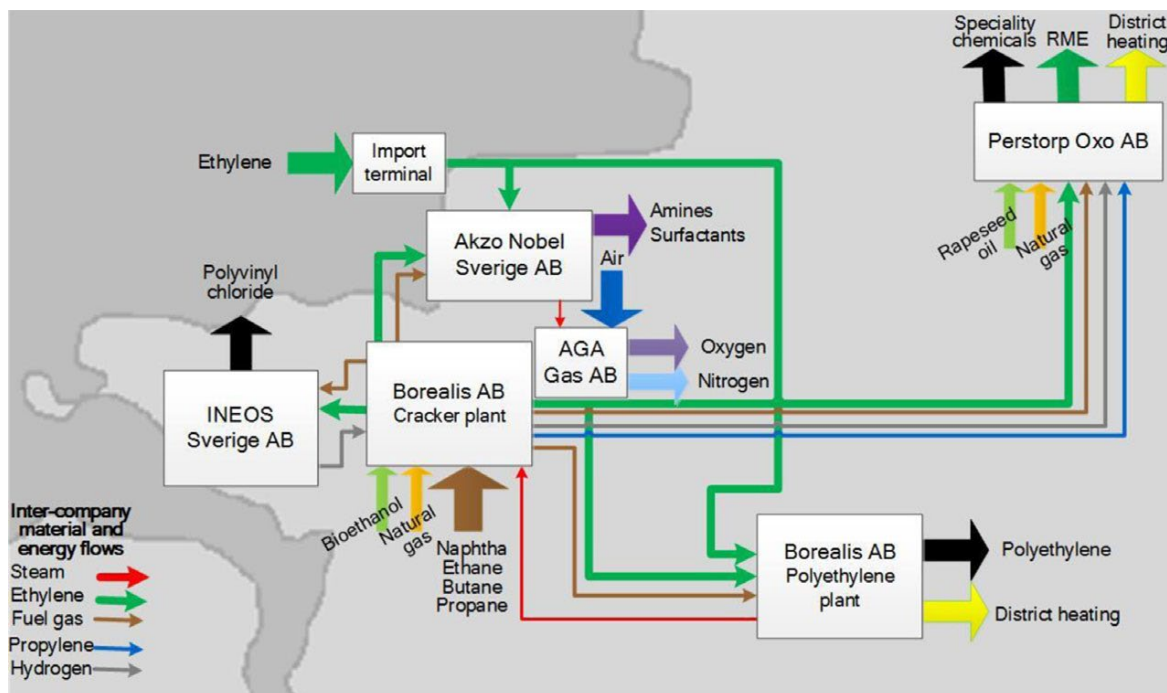


Figure 9 Flow of chemicals and energy between industries in the Stenungsund cluster (Source: Hackl, 2014 [60]).

The ethanol-to-ethylene process would, if replacing a cracker, leave the cluster with a deficit of propylene, butylene, and hydrogen. However, the methanol-to-olefins generates several flows, e.g. ethylene, propylene, and butylenes. These olefins are also produced in the current cracking process [51]. Thus, the MTO process has a similar output to the cracking process. This is an advantage when replacing the cracker, compared to the ethanol-to-ethylene process that only produces ethylene. However, the cracker also generates hydrogen. Hydrogen and some of the olefins produced in the cracker are sold to other chemical industries in the Stenungsund cluster. Thus, hydrogen would have to be obtained from another source if the cracking process would be replaced by an MTO process.

5.3.5 Possibilities to integrate proposed measures with the existing cracker furnaces

There are nine cracking furnaces in use at Borealis today. The proposed processes described above could be implemented gradually without completely exchanging the current cracking furnaces at Borealis. E.g. Royne et al. [61] have analyzed the possibility to replace one third of the conventional feedstock currently used in the cracking furnaces with biogenic olefins produced through the methanol-to-olefins as well as the ethanol-to-ethylene processes. The strategy evaluated by Royne et al. [61] would lead to the production of 200 ktonnes (25 %) olefins through the methanol-to-olefins route; 30 ktonnes (4 %) through the ethanol-to-ethylene route and 560 ktonnes (71 %) through cracking of fossil feedstock. The strategy relates to methanol produced through

gasification of wood chips, which generates a heat surplus, which would be used in the cracking furnaces. In this way, the excess heat from gasification would replace all the natural gas currently used in the cracking furnace. The heat could as well replace some of the fuel gas currently produced in the cracking furnaces (ibid).

5.3.6 Summary Chemical industry

In Table 8 the technical options for plastic production within the chemical industry to become climate neutral are summarised. Several of the processes have high TRL themselves, but they depend of production of bio-based feedstock which may have much lower TRL.

Table 8 Summary of the technical options for the chemical industry to become climate neutral. Technical readiness level (TRL) is estimated as low (+), medium (++) or high (+++).

Process	TRL (+, ++, +++)	Earliest year of full-scale implementation	Comment	Source
Steam cracker	+++	2020	Commercially available. Bio-products depends on the availability of bio-naphta (FT process), bio-LPG (bi product of the MTG process) and bio-oils.	
Methanol-To-Olefins	+++	2020	Commercial installations exist, but not widespread. Bio-MTO depends on bio-methanol production.	Tian et al., 2015 [62]
Ethanol-To-Ethylene	+++	2020	Commercial installation in Brazil. Bio-E2E using woody biomass depends on ethanol production.	
OCM	+	2035	Unclear readiness level, but it is low. High cost + low efficiency makes this technology questionable.	Spallina et al., 2017 [63]

6 Refineries

6.1 Current situation

There are five crude oil refineries in Sweden today (year 2017). The three refineries in Table 9 are typical fuel refineries while Nynas AB's refineries in Nynäshamn and Gothenburg are refineries for production of heavy petroleum products such as bitumen for asphalt and lubricant oils.

Table 9 Refining capacity and CO₂ emissions in the Swedish fuel refineries

	Refining capacity, barrels per day (1 barrel=159 litres)	CO₂ emissions, tonne/year (2017)
Preem refinery, Lysekil	220,000	1,583,787
Preem refinery, Gothenburg	125,000	461,299
St1 refinery, Gothenburg	78,000	522,459
Nynas AB, Nynäshamn	90,000	147,379
Nynas AB, Gothenburg	13,000	30,308
TOTAL	526,000	2,745,232

A crude oil refinery is an industry which separate and transform components in crude petroleum oil using mainly process technology and energy in form of heat and electric power. The heat is usually generated internally at the refinery by burning surplus products such as refinery gas or heavy products. This means that the heat emanates from the crude oil and the CO₂ from combustion must be treated as fossil-based CO₂. The main contributing greenhouse gases for a refinery are fossil-based CO₂, methane (CH₄), and dinitrogen oxide (N₂O). CH₄ and N₂O can both be formed in minor amounts at combustion and CH₄ can also occur as leakage from organic sources in the processes.

6.2 Alternative pathways to climate neutrality

For greenhouse gas reduction to a near zero level, there are two main possibilities to consider: 1) stop using fossil fuels, or 2) a net zero addition of fossil-based CO₂ to the atmosphere, which then allows a certain use of fossil fuels, but requires that the fossil-based CO₂ emission generated is collected and stored in the bedrock, i.e. CCS technology. Since carbon capture technologies are not applicable for vehicles, it will be necessary to stop using fossil fuels in the transport sector if the goal of climate neutrality should be reached.

It is difficult to predict how refinery operations will develop until the year 2050 if total climate neutrality is to be achieved. As shown by the climate-neutral alternatives available, it is likely that this production will be more delocalized depending on the availability of raw materials such as biomass, rapeseed oil, agricultural products for ethanol production, etc.

A good starting point for an analysis of possible pathways for the refinery industry towards climate neutrality should be based on the products and functions that a refinery delivers to society. Based on this, one can then analyse possible alternative products, processes, or development orientations that could reduce fossil-based CO₂ or other greenhouse gases.

Refinery products used for heating: These products include fuel oils, refinery gases, LPG etc. but also surplus heat used in for example district heating. These products can usually be replaced by solid biofuels but also with electric power.

Refinery products used to produce mechanical work (engines): These products include gasoline, diesel oil, aircraft kerosene, marine gas oil, light and heavy fuel oil, LPG etc. These products are much more specific and need a special quality to meet each engine specification. For some application, these products can be replaced by electric power or gas fuels such as biogas or hydrogen. For the latter alternatives, conventional vehicles cannot be used. Either modification of engines or totally new vehicles are needed. However, by “new” we do not mean that they do not exist, only that they could be considered less conventional. A schematic of alternative pathways to replace fossil transport fuels is shown in Figure 10. In the figure, “biogas” represents methane produced from different sources and processes, such as digestion of organic waste or gasification of forest biomass.

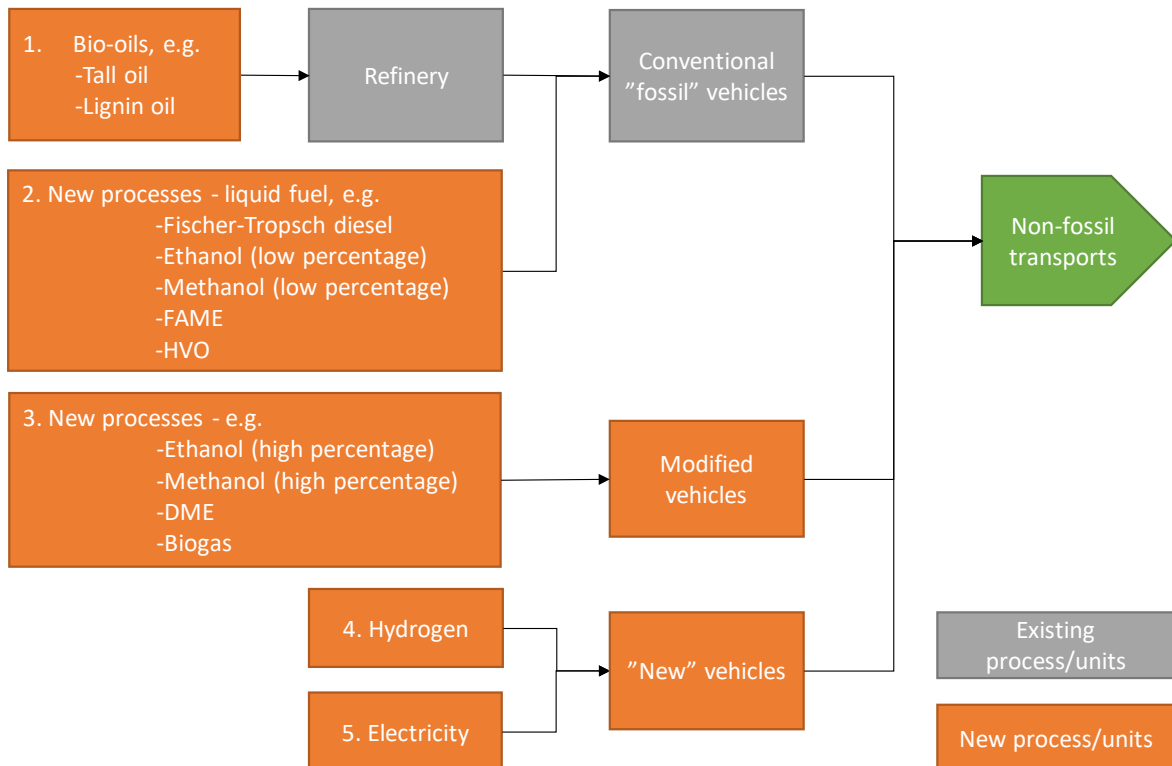


Figure 10 Schematic of the alternative pathways to replace fossil transport fuels. All input such as raw material and electricity is assumed to be non-fossil. Ethanol and Methanol in both box 2 and 3 are

produced by the same new processes. The difference is that if it is blended with fossil fuel to a low percentage, it could be used in conventional vehicles, but if it is a high percentage the vehicles need to be modified. (Source: IVL and LTU, this report)

Alternative liquid fuels for engines (box 1, 2 and 3 in Figure 10) are:

- Fischer-Tropsch diesel
- Ethanol
- Methanol
- Dimethyl ether (DME)
- Biodiesel based on fatty acid methyl esters (FAME), e.g. Rapeseed Methyl Ester (RME)
- Hydrogenated vegetable oils (HVO)

These alternatives are based on biomass but could in some cases also be produced by electrolysis of water for hydrogen production followed by synthesis reactions. Examples of this are synthetic methanol production from H₂ and CO₂ and DME production by dehydration of synthetic methanol. [64]

The substitution of aircraft kerosene is a problem that needs special attention. There are many requirements on jet fuels that are difficult to meet with a single bio-fuel (Bio-jet fuel). Many tests have been carried out but very few fuels have been used for operation of aircrafts. A common fuel is a mixture of ordinary kerosene with FAME. Other alternative designs are possible, e.g. a specially designed, A1-like, fuel can be developed based on Fischer-Tropsch synthesis with synthesis gas (CO + H₂) produced from biomass by gasification.

In the following sub-chapters, the production of these alternative fuels is described.

Refinery products used as materials or chemicals: These products include bitumen, lubricants, paraffin waxes, sulfur, petroleum coke, BTX, olefins, aromatic petrochemicals etc. These products can usually be replaced by alternative production from crude petroleum oil or by using alternative processes and sources.

6.2.1 Production of methanol

Methanol can be used directly as a motor fuel to replace gasoline but can also be used in the production of RME and DME. Methanol from gasification/syngas of wood has shown to be one of the most efficient ways of producing a liquid fuel based on renewable resources.

Large-scale production plants for methanol from wood gasification are rare. The company VärmlandsMetanol AB has estimated the production cost of methanol for such a case to 6 SEK per gasoline equivalent litre in year 2009 [65]. When methanol is produced by gasification of biomass, 60 % of the biomass is converted into methanol, giving 60 % conversion efficiency. Estimated production costs for methanol from wood are given in [66] to on average ~0.235 SEK/MJ corresponding to 7.6 SEK per gasoline eq. litre.

6.2.2 Production of FAME and RME

FAME (Fatty Acid Methyl Ester) is a group of products where different types of, usually, vegetable oils or animal fat are esterified to produce a more stable and useful fuel. A common oil to use is

rapeseed oil, which gives the corresponding fuel product, RME (Rapeseed Methyl Ester). RME is a fuel to be used in diesel engines and can also be mixed with ordinary diesel oil. It has similar properties as ordinary diesel but can gel at low temperatures especially in wintertime.

In the production of for example RME, the rapeseed oil is reacted with methanol (from e.g. gasification of biomass) in a transesterification reaction. The most common method is to use a base-catalyst such as sodium hydroxide, potassium hydroxide, or sodium methoxide. This process takes place at low temperatures (~60 °C) and pressures and gives a yield of almost 98 %. Rapeseed oil, methanol, and NaOH/KOH are mixed and heated to 60 °C at which the reaction takes place. The heat energy for the esterification process has been estimated by IVL to 0.2 MJ/kg RME and the use of electricity has been estimated to 0.1 MJ/kg RME. The exact process design with heat exchanger is important for the overall energy use. Glycerol is also formed during the reaction process and is separated after the chemical reaction. A typical mass balance for the esterification process is shown in Table 10.

Table 10 Mass balance for esterification

Substance	Quantity
Input	
Rapeseed oil	1,000 kg
Methanol	110 kg
NaOH/KOH (catalyst)	Small amounts
Output	
Rapeseed Methyl Ester (RME)	1,000 kg
Glycerol	110 kg

Density for RME is usually 0.87-0.9 kg/litre and the lower heating value is approximately 38 MJ/kg or 33 MJ/litre.

In [66], production costs for RME from rapeseed oil are presented, giving an average cost of 0.25 SEK/MJ corresponding to 9.0 SEK per diesel litre equivalents.

6.2.3 Production of HVO

To some extent, pure vegetable oils can be used directly as a fuel in diesel engines. However, the high viscosity of the oils causes several different problems such as poor atomisation of the fuel and clogging of the fuel system. To prevent this, the oil can be heated, diluted, or chemically modified. One type of modification is hydrogenation of the vegetable oil, which results in a product that is very similar to ordinary diesel and can be used directly as a diesel substitute or mixed with ordinary diesel. Hydrogenated vegetable oil (HVO) is produced from almost the same raw materials as FAME but another conversion process is used resulting in a different product. HVO is produced by a catalytic hydrogenation of different types of vegetable oils such as rapeseed oil, olive oil, palm oil, tall oil, and sunflower seed oil. Waste products such as used cooking oil can also

be used as a raw material. Normal process conditions are 350-450 °C at about 40-150 bar. A catalyst of Mo with Ni or Co is usually used [67, 68]. This can yield a product with a Cetane number of 55-65. The hydrogenation reaction is exothermic and the reaction with vegetable oils releases about 105 kJ/mol. However, the activation energy of the reaction is usually high, and a catalyst is needed. The use of electricity for the hydration process has been estimated by IVL to 0.2 MJ/kg HVO and the H₂ use has been estimated to 3 wt-% of the vegetable oil.

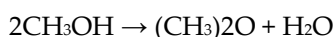
In [66], production costs for HVO diesel from different sources are presented as follows:

- HVO diesel from rapeseed oil: 0.225 SEK/MJ corresponding to 8.1 SEK per litre petroleum diesel equivalents.
- HVO diesel from palm oil/PFAD: 0.18 SEK/MJ corresponding to 6.5 SEK per litre petroleum diesel equivalents.
- HVO diesel from tall oil: 0.275 SEK/MJ corresponding to 9.9 SEK per litre petroleum diesel equivalents.
- HVO diesel from recycled waste veg. oil: 0.225 SEK/MJ corresponding to 8.1 SEK per litre petroleum diesel equivalents.

6.2.4 Production of DME

Dimethyl ether (DME) is the simplest of ethers with the chemical formula CH₃OCH₃. The boiling point is -24 °C and melting point -141 °C. DME is thus gaseous in most application temperatures. In fuel applications, it is mainly used to replace diesel oil, but it can also be used in gas turbines and to replace propane in LPG. DME liquefies at a pressure of approximately 5 bars. However, to replace diesel oil in diesel engines, special fuel systems are required. DME is known to have low emission levels when used in diesel engines, especially low in particulate matters and free of sulfur. A high cetane number of 55 compared to ~40-53 for ordinary diesel oil is also an advantage.

The production of DME takes place by dehydration of methanol according to the reaction below.



The required methanol is produced from synthesis gas (syngas), which can be produced from biomass to obtain a fossil free alternative. It can also be made from biogas (methane) produced of organic waste or agricultural products.

The dehydration reaction takes place at somewhat elevated temperature, usually less than 300 °C, over a solid acidic catalyst (e.g. Al₂O₃). The reaction is usually very selective and unreacted substances are recycled in the process. The process will also include distillation of the products. According to the reaction, 1.391 kg methanol is needed to produce 1 kg DME and 0.391 kg water is also formed. The overall dehydration reaction of methanol from liquid state is endothermic and 50.87 kJ/mol DME is needed if methanol is liquid and H₂O is at gaseous state at the end of reaction and 6.87 kJ/mol DME is needed if H₂O is at liquid state at the end of reaction and the condensation energy can be used. If the higher gaseous state of water is assumed, the energy needed for the reaction is about 1.104 MJ/kg DME. With losses, one can assume a thermal energy use of 1.5 MJ/kg DME. In addition, according to the typical relation between electricity and thermal energy in chemical processes, one can also assume a use of 0.2 MJ electric energy per kg DME for process and

handling. Lower heating value is about 28.4 MJ/kg for DME compared to 43.1 MJ/kg for diesel. Large production facilities exist in e.g. China, Japan, Korea, and Brazil.

In [66], production costs for DME from wood resources have been estimated to 0.225 SEK/MJ corresponding to 8.1 SEK per diesel litre equivalents.

6.2.5 Production of Fischer-Tropsch diesel

The Fischer-Tropsch process was developed in 1925 and is used in commercial scale in for example Malaysia and South Africa using fossil feedstock. However, it is also possible to use biomass-based feedstock and there are examples of pilot and demonstration sites for this, e.g. the LTU Green Fuels site in Piteå, Sweden. The feedstock to the Fischer-Tropsch process is carbon monoxide and hydrogen which is produced by gasification of coal, natural gas or biomass. In the Fischer-Tropsch process, the feedstock is converted into liquid hydrocarbons in the presence of metal catalysts, such as cobalt or iron.

In [66], production costs for Fischer-Tropsch diesel production from wood resources are given to 0.31 SEK/MJ corresponding to 11.1 SEK per diesel litre equivalents.

6.2.6 Production of ethanol

The company VärmlandsMetanol AB has estimated the cost for large-scale production of ethanol by fermentation of Swedish agricultural products to 10 SEK per gasoline equivalent litre in year 2009 [65]. The equivalent figure for ethanol produced by fermenting sugar made from decomposed wood cellulose (CASH method) is about 14 SEK per gasoline equivalent litre. In reference [66], production costs for ethanol from different sources are presented giving ethanol from wheat ~0.26 SEK/MJ and ethanol from sugar cane ~0.15 SEK/MJ. Expressed in gasoline eq. litre corresponding to 8.4 SEK respectively 4.9 SEK.

6.2.7 Summary refineries

In Table 11 the technical options for a climate neutral liquid fuel production is summarised. Several of the options have high TRL but some are depending on production of feedstock which have a lower TRL. All the alternative processes depend on availability of bio-based feedstock.

Table 11 Summary of the technical options for the refinery industry to become climate neutral. Technical readiness level (TRL) is estimated as low (+), medium (++) or high (+++).

Process	TRL (+, ++, +++)	Earliest year of full-scale implementation	Comment	Source
Fischer tropsch	++	2025	The FT-process is well known. Coupling with biomass gasification is not. Assumed same as methanol.	
Methanol	++ (6-7)	2025	Pilot scale exists. The syngas to methanol	Jafri et al., 2019 [69]

			process is well known. Coupling with biomass/black liquor gasification is not.	
DME	++	2025	Pilot scale exists. The syngas to DME process is well known. Coupling with biomass gasification is not. Assumed same as methanol.	
HVO Tall oil in RAF	+++	2020	Commercial installations exist.	
HVO Lignin oil	+ (3-7)	2035		Jafri et al., 2019 [69]
HVO Pyrolysis oil	+ (3-6)	2035		Jafri et al., 2019 [69]
FAME	+++	2020	Commercial installations exist.	
MTG	+++	2020	Same as the MTO process.	
Ethanol 2G	++	2020		Chudziak et al., 2017 [70]

7 How close is the transition to a climate neutral industry?

Many of the options for climate mitigation of the Swedish industries are technically immature and there are many years of development left before they could be implemented in large scale. For example, the technology for direct reduction of iron with hydrogen will be ready for implementation at the earliest in year 2035 and electric heating in the cement production is ready at the earliest year 2030. In Figure 11, the technical readiness level is generically estimated for the technological options for climate mitigation for the Swedish industries. In addition, the existing scale of implementation of each technology somewhere in the world is presented on the x-axis. However, regarding some of the bio-fuel and biobased plastic processes, the processes themselves may be relatively mature, but they rely on biobased feedstock production which is less mature. Those cases are marked with a black dot in the figure.

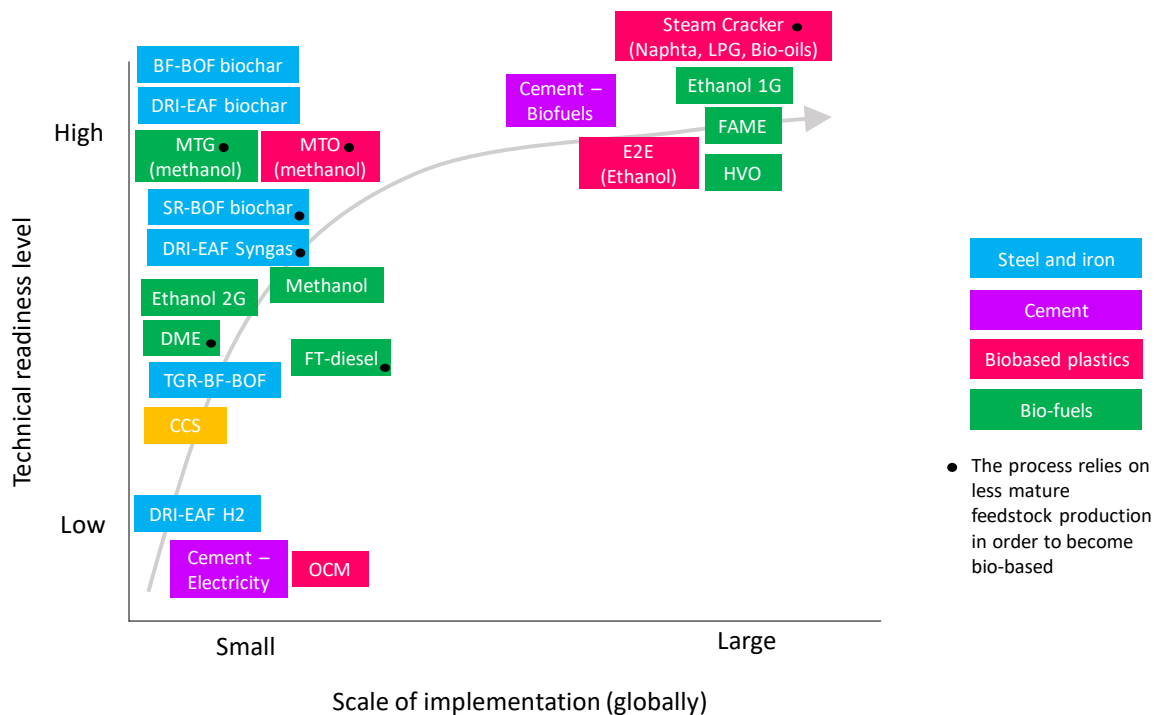


Figure 11 Estimated technical readiness level and existing scale of implementation for the technological options for climate mitigation of the Swedish industries. (Source: IVL and LTU, this report)

A general observation from Figure 11, is that the technologies are much spread-out regarding both TRL and scale of implementation. Depending on where in the diagram a technology is found, it could be assumed that different forms of support is needed to make them commercially viable. For the technologies with low TRL, such as Cement-Electricity, research funding and support for scaling up from lab to pilot scale, or pilot to demo scale is needed. However, relatively many of the technologies have medium or high TRL. The barriers to reach full-scale implementation tend to be more complex since they depend on many actors and uncertainties regarding market for new products or price for alternative energy and raw material. In addition, there could be legal barriers and lack of infrastructure to support a full-scale implementation. In Table 12, different kinds of barriers are described and exemplified by the technologies in question. Barriers which are general

for all new technologies (barrier 1-5) need to be addressed in parallel. Legal barriers and lack of infrastructure are barriers which national authorities need to act on.

Table 12 Barriers to reach full-scale implementation for new technologies.

Type of barrier	Explanation/Examples
1. Perceived risk with regards to new technologies	<i>An investor may perceive a risk related to be the first to invest in a new technology at a large scale.</i>
2. Lack of knowledge about the new technologies	<i>Industries may lack knowledge about new technologies. E.g. there are uncertainties regarding long term behaviour of leakages from carbon storage.</i>
3. Uncertain markets for new products	<i>E.g. Is there a market for green steel? Would a customer be willing to pay a premium?</i>
4. Price uncertainty for alternative raw material	<i>Fossil feedstock may be cheaper than the renewable alternative, e.g. chemical industries and refineries.</i>
5. Price uncertainty for renewable fuel	<i>E.g. natural gas is cheaper than biogas (at least in large quantities).</i>
6. Interdependency	<i>E.g. in the Stenungsund cluster there are many connections and dependencies between different industries in form of material and energy flows. It may be difficult to change a process if another industry depends on your bi-products.</i>
7. Co-ordination failure	<i>E.g. in the CCS version of the “chicken and egg” problem private actors investing in capture technologies require a working infrastructure, while actors investing in infrastructure require established capturing units to ensure their investment decision.</i>
8. Legal barriers	<i>E.g. legal constraints for transporting CO₂ between countries.</i>
9. Lack of infrastructure	<i>E.g. electric grid capacity for hydrogen production.</i>

8 Concluding remarks

All the studied industrial sectors have several technical options for greenhouse gas mitigation. However, across all sectors within the industry, efficiency measures applied to current processes are insufficient to reach deep emission reductions. In order to reach a dramatic emission reduction, a transformative change to new processes and/or use of new raw material is required.

Most processes that are required for deep reductions in CO₂ emissions require further development before full-scale implementation, thus some options might not be available during approximately the coming decade. For short-term reductions of CO₂ emissions in the industry, a switch of fuels or implementation of CCS is required. However, fuel switching is not always a feasible solution due to process requirements or because of non-mature fuel production processes. Process emissions can be captured by CCS, which are available for some selected technologies (mostly technologies using post combustion capture (PCC), while more advanced CCS options require further development.

CCS is not only a potential key transition technology, but also a key technology for achieving deep reductions in CO₂ emissions in the long-term perspective, as it is required for mitigation of process related CO₂ emissions in the cement- and the refinery industry. In the cement industry, at least 30 % of the CO₂ emissions will remain, regardless of cement production technology chosen because of process emissions related to the use of cement clinker. In refineries, a minor part of the CO₂ emissions from refineries, about 5 %, will also remain since they origin from production of asphalt and lubricants which are likely to still be produced in the future.

The transition to a climate neutral industry in Sweden will require further support for research and development for the technologies with low or medium technical readiness. General barriers to scaling up new technologies, such as market uncertainties, need to be addressed for technologies with high technical readiness but which are not yet implemented in large-scale. A particular important role for national authorities is to remove legal barriers and ensure that the necessary infrastructure is in place, for example remove the legal barrier to transport CO₂ over national borders and ensure the capacity demand in the national electric grid.

Many questions remain, such as how to use biomass and renewable electricity to meet the carbon mitigation targets to the lowest socio-economic cost. These limited resources are desired by all sectors within the energy system (for transportation, for heat generation etc.) and the decision of how to allocate these resources is complex. The scenario analysis using the TIMES-Sweden model in the latter part of this project can help to shed light on this resource optimisation problem.

References

1. Swedish Environmental Protection Agency. *Territoriella utsläpp och upptag av växthusgaser [Territorial emissions and uptake of greenhouse gases]*. 2019; Available from: <http://www.naturvardsverket.se/klimatutslapp>.
2. Swedish Environmental Protection Agency, *Fördjupad analys av svensk klimatstatistik [Detailed analysis of Swedish climate statistics]*. 2018.
3. Krook-Riekkola, E.S.A.T.A., *A bottom-up study of biomass and electricity use in a fossil free Swedish industry*. Energy, 2018. **167**: p. 1019-1030.
4. SSAB, *Annual report*. 2017.
5. Swedish Environmental Protection Agency, *Lista över utsläpp per anläggning [List of emissions per plant]*. 2018.
6. Höganäs. 2019; Available from: <https://www.hoganas.com>.
7. Pardo, N., *Prospective scenarios on energy efficiency and CO2 emission in the EU iron and steel industry*, in *JRC Scientific and Policy Report, JRC74811*. 2012.
8. JP, B., *Global Technology Roadmap for CCS in Industry - Steel Sectoral Report*.
9. Jernkontoret, *Jernkontorets forskning, Rapport D 869. Klimatfärdplan för en fossilfri och konkurrenskraftig stålindustri i Sverige [Climate roadmap for a fossil-free and competitive steel industry in Sweden]*. 2018.
10. HYBRIT, *Slutrapport HYBRIT - Hydrogen Breakthrough Ironmaking Technology, Genomförbarhetsstudie, Energimyndighetens projektnr 42684-1*. 2018.
11. Mousa, E., et al., *Biomass applications in iron and steel industry: An overview of challenges and opportunities*. Renewable and Sustainable Energy Reviews, 2016. **65**: p. 1247-1266.
12. Wang, C., et al., *Biomass as blast furnace injectant – Considering availability, pretreatment and deployment in the Swedish steel industry*. Energy Conversion and Management, 2015. **102**: p. 217-226.
13. Díez, M.A., R. Alvarez, and C. Barriocanal, *Coal for metallurgical coke production: predictions of coke quality and future requirements for cokemaking*. International Journal of Coal Geology, 2002. **50**(1): p. 389-412.
14. Ahmed, H., *New Trends in the Application of Carbon-Bearing Materials in Blast Furnace Iron-Making*. Minerals, 2018. **8**(12): p. 561.
15. van der Stel, J., et al., *Developments of the ULCOS Low CO2 Blast Furnace Process at the LKAB Experimental BF in Luleå*. 2011: p. 8.
16. Eurofer, *A steel roadmap for a low carbon Europe 2050*. 2013, EUROFER.
17. MacPhee, J.A., et al., *Possible CO2 mitigation via addition of charcoal to coking coal blends*. Fuel Processing Technology, 2009. **90**(1): p. 16-20.
18. Norgate, T., et al., *Biomass as a Source of Renewable Carbon for Iron and Steelmaking*. ISIJ International, 2012. **52**(8): p. 1472-1481.
19. Duarte, P.E., J. Becerra, and V.P. Projects, *Decrease of GHG emissions through the Carbon Free Emissions ENERGIRON DR Scheme in Integrated Mills*. 2018: p. 8.
20. Pauluzzi, D. and A. Martinis, *Sustainable decrease of CO2 emissions in the steelmaking industry by means of the ENERGIRON direct reduction technology*. 2011: p. 7.
21. Kekkonen, M. and L. Holappa, *Comparison of different coal based direct reduction processes*. 2000, Espoo: Helsinki University of Technology.
22. Han, H., et al., *Biomass reducing agent utilisation in rotary hearth furnace process for DRI production*. Ironmaking & Steelmaking, 2015. **42**(8): p. 579-584.
23. Abdul Quader, M., et al., *Present needs, recent progress and future trends of energy-efficient Ultra-Low Carbon Dioxide (CO2) Steelmaking (ULCOS) program*. Renewable and Sustainable Energy Reviews, 2016. **55**: p. 537-549.
24. Wang, N., et al., *Analysis of Material and Energy Consumption of Corex C3000*. steel research international, 2008. **79**(7): p. 547-552.
25. Junjie, Y., *Progress and Future of Breakthrough Low-carbon Steelmaking Technology (ULCOS) of EU*. International Journal of Mineral Processing and Extractive Metallurgy, 2018. **3**(2): p. 15.
26. Lampert, K., A. Ziebig, and W. Stanek, *Thermoeconomical analysis of CO2 removal from the Corex export gas and its integration with the blast-furnace assembly and metallurgical combined heat and power (CHP) plant*. Energy, 2010. **35**(2): p. 1188-1195.
27. Hiebler, H. and J.F. Plaul, *Hydrogen Plasma Smelting Reduction - an Option for Steelmaking in the Future*. Metalurgija, 2004. **43**(3): p. 155-162.

28. Cementa, *Nollvision för koldioxid [Zero vision for carbon dioxide]*. 2018.
29. Rootzén J, J.F., *Managing the costs of CO2 abatement in the cement industry*. . Climate Policy, 2017. **17**: p. 781–800.
30. Statistics Sweden, *Official Swedish Greenhouse gas emission statistics*. 2016.
31. Cementa, *Färdplan cement för ett klimatneutralt betongbyggande [Roadmap cement for a climate-neutral concrete building]*. 2018.
32. ECRA, *Development of State of the Art Techniques in Cement Manufacturing: Trying to look ahead*. 2017.
33. Kajaste R, H.M., *Cement industry greenhouse gas emissions–management options and abatement cost*. Journal of Cleaner Production 2016. **112**: p. 4041–4052.
34. Cementa, *En vision om noll koldioxidutsläpp. Utsikt - Skövdefabrikens informationsblad till närboende [A vision of zero carbon dioxide emissions. Skövde Factory information leaflet to nearby residents]*, in. 2014.
35. EPA, U., *Available and emerging technologies for reducing greenhouse gas emissions from the Portland cement industry*. US Environmental protection agency - Office of Air and Radiation. 2010.
36. IEA, *Cement Technology Roadmap*, in 2009: Paris, France.
37. Madlool, N.A., et al., *A critical review on energy use and savings in the cement industries*. Renewable and Sustainable Energy Reviews, 2011. **15**(4): p. 2042-2060.
38. Cementa, *En vision om noll koldioxidutsläpp. Utsikt - Skövdefabrikens informationsblad till närboende*, in. 2016.
39. Wilhelmsson, B., et al., *Cemzero - A feasibility study evaluating ways to reach sustainable cement production via the use of electricity*. 2018.
40. Erlandsson, *Minskad klimatpåverkan från nybyggda flerbostadshus [Reduced climate impact from new residential buildings]*. 2018.
41. standard, S., *Cement - Del 1: Sammansättning och fordringar för ordinära cement, SS-EN 197-1:2011*.
42. Jernkontoret. 2019; Available from: <https://www.jernkontoret.se/>.
43. Hills, T., et al., *Carbon Capture in the Cement Industry: Technologies, Progress, and Retrofitting*. Environmental Science & Technology, 2016. **50**(1): p. 368-377.
44. Cementa, V., *CemZero – A feasibility study evaluating ways to reach sustainable cement production via the use of electricity*. 2018.
45. IEA GHG, *Deployment of CCS in the Cement Industry*. 2013. p. 139.
46. Swedish Energy Agency, *Nulägesanalys ER 2017:04 [Current status analysis]*. 2017.
47. Swedish Energy Agency, *Energiläget i siffror 2018 [Energy situation in figures 2018]*. 2018.
48. Hackl, R.H., Simon, *Design Strategies for Integration of Biorefinery Concepts at Existing Industrial Process Sites: Case Study of a Biorefinery producing ethylene from Lignocellulosic Feedstock as an Intermediate Platform for a Chemical Cluster*. 2010, Chalmers University of Technology: Gothenburg
49. Satti, S., *Greenhouse Gas Abatement Strategies for the Chemical Industry in Sweden*. 2018, KTH.
50. Borealis, *Borealis Annual Report*. 2016.
51. Borealis, *Borealis Annual Report*. 2015.
52. Liptow, C., Tillman, AM. & Janssen, M., *Life cycle assessment of biomass-based ethylene production in Sweden — is gasification or fermentation the environmentally preferable route?* Int J Life Cycle Assess 2015. **20**(632).
53. Worrell, E., Bernstein, L., Roy, J., Price, L., Harnisch, J., *Industrial Energy Efficiency and Climate Change Mitigation*. Energy Efficiency, 2009.
54. Processum, *Skogskemi – Final report [Forest chemistry]*. 2014.
55. Kemiföretagen i Stenungsund, *Hållbar kemi [Sustainable chemistry]*. 2018.
56. Mohsenzadeh, A., Zamani, A. & Taherzadeh, M., *Bioethylene Production from Ethanol: A Review and Technoeconomical Evaluation*. ChembioEng, 2017. **4**(2).
57. Zacharopoulou, V. and A.A. Lemonidou, *Olefins from Biomass Intermediates: A Review*. Catalysts, 2018. **8**(1): p. 2.
58. Machado, P.G., A. Walter, and M. Cunha, *Bio-based propylene production in a sugarcane biorefinery: A techno-economic evaluation for Brazilian conditions: Techno-economic analysis of bi-propylene*. Biofuels, Bioproducts and Biorefining, 2016. **10**(5): p. 623-633.
59. Holmen, A., *Direct conversion of methane to fuels and chemicals*. Catalysis Today, 2009. **142**(1): p. 2-8.
60. Hackl, R., *A methodology for identifying transformation pathways for industrial process clusters: Toward increased energy efficiency and renewable feedstock.*, in *Department of Energy and Environment*. 2014, Chalmers University of Technology,; Gothenburg, Sweden.

61. Røyne, F., et al., *Environmental Evaluation of Industry Cluster Strategies with a Life Cycle Perspective: Replacing Fossil Feedstock with Forest-Based Feedstock and Increasing Thermal Energy Integration*. Journal of Industrial Ecology, 2017.
62. Tian, P., et al., *Methanol to Olefins (MTO): From Fundamentals to Commercialization*. ACS Catalysis, 2015. **5**(3): p. 1922-1938.
63. Spallina, V., et al., *Techno-economic assessment of different routes for olefins production through the oxidative coupling of methane (OCM): Advances in benchmark technologies*. Energy Conversion and Management, 2017. **154**: p. 244-261.
64. Madej-Lachowska, M., *Methanol Synthesis from Carbon Dioxide and Hydrogen over CuO/ZnO/ZrO₂ promoted catalysts*. 2014. p. 61–68
65. Gillberg, B.O., *Memorandum: Methanol factory in Hagfors January 2009, VärmlandsMetanol AB/Miljöcentrum*. . 2009.
66. Furusjö, E. and J. Lundgren, *Utvärdering av produktionskostnader för biodrivmedel med hänsyn till reduktionsplikten, Rapport från ett f3-projekt [Evaluation of production costs for bio fuels with regards to the reduction obligation]*. 2017.
67. Akhlaq Mughal, A., *Hydrogenation of Vegetable Oil over NiMo-S/ γ -Al₂O₃, Pt/ β -Zeolite & Pd/C Catalysts for Biodiesel Production*. 2011: Göteborg, Sweden.
68. Smejkal Q., S.L., Kubicka D., *Thermodynamic balance in reaction system of total vegetable oil hydrogenation*. Chemical Engineering Journal, 2009. **146**: p. 155-160.
69. Jafri, Y., et al., *Multi-aspect evaluation of integrated forest-based biofuel production pathways: Part 1. Product yields & energetic performance*. Energy, 2019. **166**: p. 401-413.
70. Chudziak, C.A., Geneviève; Bauen, Ausilio, *Ramp up of lignocellulosic ethanol in Europe to 2030*. 2017.



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