THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Energy infrastructures for low-carbon-emitting industries

Modeling the deployment of electrification, carbon capture and storage, and biomass use

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Gothenburg, Sweden 2024

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ISBN 978-91-8103-113-3

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr 5571
ISSN 0346-718X

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Printed by: Chalmers digitaltryck
Gothenburg, Sweden 2024

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Abstract

The transition from a fossil-based to a renewable, low-carbon industrial system relies heavily on the parallel deployment of infrastructures and industrial developments. This thesis studies the linkages between the implementation of emissions reductions technologies (electrification, carbon capture and storage, and biomass use) at industrial sites and the required energy infrastructures. Within the scope of this thesis, optimization models, based on supply chain cost-minimization and CO_2 emissions-minimization, are developed and applied to study the deployment of mitigation technologies and energy infrastructures. These models are applied alongside case studies and scenario analysis to assess the transition of industry and its associated energy infrastructures to low CO_2 operation. The thesis highlights that the deployment of energy infrastructures can be a limiting factor in the transition of industry.

The results confirm that reducing permitting times and expanding the capacity to build up grid infrastructure in parallel with the electrification technology are crucial measures to meet climate targets. Poor conditions for electrification, in terms of long permitting times and low grid expansion capacity, may delay the electrification of Swedish industry by up to 15 years.

In the studied system, the costs for CO_2 separation and liquefaction make up ~65% of the costs for CO_2 capture and transport systems (albeit excluding the cost for final storage), rendering the mitigation option sensitive to CO_2 capture investments and technology performance. As CO_2 capture gives a high added cost for industrial operators, implementation is highly dependent upon incentives, and the modeled deployment in different sectors is sensitive to the incentive scheme applied. For example, carbon pricing mechanisms for fossil CO_2 and mechanisms that motivate capture of biogenic CO_2 result in different sectors targeted for capture when implemented in conjunction as opposed to separately. This highlights the importance of clear, long-term policies to create incentives for site operators to invest in mitigation technologies.

Future industrial biomass demands are likely to exceed the logging residue supply potential on a national level, and even more so in high-demand regions. The cost of logging residue supply is highly sensitive to the transport distance when utilizing current transportation modes. However, cost-effective long-distance transportation chains can connect high-demand and high-supply regions at relatively low cost increases compared to supplying logging residues regionally.

Keywords: Industry; transition; infrastructure; biomass use; electrification; carbon capture and storage; carbon dioxide removal; decarbonization; supply chains

List of publications

The thesis is based on the following papers, which are referred to in the thesis by their Roman numerals:

I. Karlsson, S.; Eriksson, A.; Normann, F.; Johnsson, F. *Large-Scale Implementation of Bioenergy with Carbon Capture and Storage in the Swedish Pulp and Paper Industry Involving Biomass Supply at the Regional Level.* Frontiers in Energy Research. 9, 738791. **2021**
https://doi.org/10.3389/fenrg.2021.738791

II. Karlsson, S.; Eriksson, A.; Fernandez-Lacruz, R.; Beiron, J.; Normann, F.; Johnsson, F. *Supply potential and cost of residual forest biomass for new industrial applications in Sweden.* Submitted for publication **2024**

III. Karlsson, S.; Normann, F.; Odenberger, M.; Johnsson, F. *Modeling the development of a carbon capture and transportation infrastructure for Swedish industry.* International Journal of Greenhouse Gas Control. 124, 103840. **2023**
https://doi.org/10.1016/j.ijggc.2023.103840

IV. Karlsson, S.; Normann, F.; Johnsson, F. *Cost-optimal CO_2 capture and transport infrastructure – A case study of Sweden.* International Journal of Greenhouse Gas Control. 132, 104055. **2024**
https://doi.org/10.1016/j.ijggc.2023.104055

V. Karlsson, S.; Beiron, J.; Normann, F.; Johnsson, F. *The role of permitting times and grid expansion capacity in industrial decarbonization – A case study of Swedish industry electrification.* Submitted for publication **2024**

Author contributions

Sebastian Karlsson is the principal author of all the appended papers. Dr. Anders Eriksson contributed with the biomass supply system analyses in **Papers I** and **II**. Dr. Raul Fernandez-Lacruz contributed with the biomass supply system analysis in **Paper II**. Associate Professor Mikael Odenberger provided assistance with the development of the CCS system model used in **Papers III** and **IV** and contributed with discussions and editing of **Paper III**. Dr. Johanna Beiron assisted with the development of the model applied in **Paper V** and contributed with discussions and editing of **Papers II** and **V**. Professor Fredrik Normann and Professor Filip Johnsson contributed with discussions and editing of all the included papers.

Other publications not included in the thesis

- Karlsson, S.; Eriksson, A.; Normann, F.; Johnsson, F. *CCS in the pulp and paper industry - implications on regional biomass supply.* In: Proceedings of the 15th International Conference on Greenhouse Gas Control Technologies (GHGT-15). **2021**.
- Beiron, J.; Karlsson, S.; Skoglund, H.; Svensson, E.; Normann, F. *The role of BECCS in providing negative emissions in Sweden under competing interests for forest-based biomass.* In: Proceedings of the 2nd International Conference on Negative Emissions. **2022**.
- Karlsson, S.; Normann, F.; Johnsson, F. *Policy implications on cost optimal CO_2 capture and transport infrastructure – A case study of Sweden.* In: Proceedings of the 16th International Conference on Greenhouse Gas Control Technologies (GHGT-16). **2022**.
- Skagestad, R.; Karlsson, S.; Kjärstad, J.; Johnsson, F.; Haugen, H-A.; Hovland, J. *Assessing the Suitability of CO_2 Reduction Technologies for Emission Intensive Industries – a Nordic Case Study.* In: Proceedings of the 16th International Conference on Greenhouse Gas Control Technologies (GHGT-16). **2022**.
- Toktarova, A.; Hörbe Emanuelsson, A.; Karlsson, S.; Normann, F.; Harvey, S. *Decarbonization strategies for the European steel industry - identifying decision-making factors.* In: Proceedings of the 37th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2024). **2024**

Acknowledgments

First off, I would like to thank my supervisory team, Fredrik Normann, Filip Johnsson and in the latter part of the thesis work, Johanna Beiron. Fredrik, I am grateful that you decided to take me on this journey, and thanks for all the mentoring and help that you have provided along the way. Not only has it been an inspiration to work with you, but I have also found great enjoyment in our conversations on a personal level. Filip, thank you for maintaining diligent oversight of the work, and always providing astute and detailed input – it has greatly increased the quality. Johanna, thank you for your insightful comments and input during the latter half of my PhD work, and especially for the help and ideas that you provided regarding method development. In addition to your efforts to increase the quality of my work, I also highly value your friendship, and I always look forward to our chats during the workday.

I also wish to extend my thanks to those who have been involved in and made possible the work leading up to this thesis. Jan, for all your knowledge and guidance on the topic of CCS infrastructure. Mikael, for the help that you provided during the development of the CCS system model. Anders and Raul, for sharing your knowledge of forestry biomass and providing extremely valuable contributions to various parts of this thesis work. And of course, to all the project partners in the ZeroC and ACCSESS projects, especially our collaborators at SINTEF Energy and SINTEF Industry, for valuable collaborations that I hope will continue in the future.

To all my coworkers, thank you for making the Division of Energy Technology a great place to spend my working hours. A special thank you to the IPS-group for being a great forum for discussion and feedback, and to the members of the Thermodynamics teaching team for making the many hours spent teaching a fun part of the PhD process. Ivana, thank you for being a great office mate for most of my PhD, I have truly enjoyed our conversations about big and small, significant and insignificant topics, and value your friendship greatly. To my new office mates, Ivan and Nidia, thank you for welcoming me into the office during the most stressful part of my PhD journey. Marie, Katarina and now Anna, thank you for ensuring that the Division functions. Without you, nothing would get done.

To my friends and family, thank you for your support and all the good times that we have spent together. Special thanks to my mother and father, Magdalena and Mikael, for always believing in me and encouraging me – you are greatly appreciated and loved. Finally, Angelika, thank you for being a wonderful partner and for your continuous love and support during this journey. I am incredibly grateful that I have gotten to spend the last eight years with you, and I look forward to many more decades on our journey of life together.

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1. Introduction

There are several drivers for the global economy to transition away from fossil fuels. From an economic standpoint, fossil fuels are a scarce resource, and prices will increase as the supply declines and the cost of extraction increases. In addition, geopolitical concerns regarding the regimes that control a large share of the world's fossil reserves make fossil resources unreliable. Finally, the continued use of fossil fuels entails substantial greenhouse gas (GHG) emissions, with the industrial sector currently accounting for roughly 30% of such emissions globally [1], increasing the effects of climate change.

The Paris Agreement, introduced at the 2015 United Nations Climate Change Conference, aims to limit global warming to well below 2°C and attempts to limit warming to 1.5°C [2]. The Paris Agreement operates with nationally determined contributions, where the signing parties submit their efforts to reduce the levels of their national emissions in line with the targets. The EU and all its Member States have signed and ratified the Paris Agreement, which means that in the European context, the aims of the treaty will be implemented in the forms of regulations and directives from the EU level, setting the direction for national policies. National legislation, along with EU regulations will in turn set the direction and targets for industry, often in the forms of industry roadmaps and decarbonization targets and plans for individual companies.

The transition of electricity and heat generation, transportation, and production of industrial goods to CO_2-free operation involves transformative changes of unprecedented magnitudes. To facilitate this transformation, the energy supply needs to be decarbonized, and the required infrastructure needs to be in place. For example, the electrification of transportation requires not only new vehicles, but also CO_2-free electric power generation, as well as an infrastructure comprising new electricity grids and charging stations. The exchange of the vehicle fleet, the build-up of new infrastructure, and the phase-out of the old infrastructure, each of which is controlled by different actors with different interests, must be performed in parallel. Biomass, as a CO_2-neutral hydrocarbon source, plays important roles in easing the transition through drop-in fossil fuel replacement and in niche applications that are difficult to electrify, such as certain shares of heavy road transport, shipping, aviation, and transport in remote areas.

Similarly to transportation, decarbonization of industry is not only reliant upon the upgrading and replacement of existing process units, but it also requires a low-carbon electricity supply and infrastructure deployment. In contrast to transportation, the individual units and, thus, the sizes of the investments, are substantially larger, and the investment cycles are longer, making the timing of infrastructure development even more important. In the industrial transition, carbon capture and storage (CCS) and the substitution of fossil fuels with biofuels and bio-feedstocks are important as bridging technologies to electrification, so as to ease the timing issue and reduce emissions from sectors that are not easily electrified. Expansion of the electricity grid infrastructure and deployment of CO_2 transport and storage networks typically entail large, costly projects that are associated with relatively low levels of public acceptance and long environmental permitting times [3], [4], which require coordination with changes made at the industrial site. The substitution of fossil fuels and feedstocks with biomass resources raises various challenges concerning constrained supply, future competition between different sectors, and the cost of supply, as compared to conventional fuels.

To summarize, the transition of industry towards low levels of CO_2 emissions is dependent upon the concurrent deployment and development of energy infrastructures, which face different challenges depending on the chosen technological pathway. To facilitate a timely transition of industry towards low-CO_2 operation, a better understanding of the deployment of energy infrastructures in conjunction with the implementation of CO_2 emissions reduction technologies at industrial sites is needed.

1.1 Aim and scope

This thesis considers the transition of industrial sites and supporting energy infrastructures, focusing on the main technological pathways for transformative emissions mitigation, electrification, carbon capture and storage, and biomass use. The thesis focuses on the system at the national level and connects process changes made at individual sites with the development of relevant energy infrastructures, to quantify the costs and important barriers for the industrial transition to low-carbon operation. Furthermore, the thesis integrates aspects of incentive structures and environmental permitting into the technical and economic analysis framework. In performing the assessment, the thesis contributes to method development by:

- Developing a cost-minimizing optimization model to study the development and cost of CO_2 capture and transportation chains; and
- Developing an emissions-minimizing optimization model to study the pace of industrial electrification, given the constraints in relation to grid infrastructure permitting times and construction capacity

By applying these methodologies alongside existing methodologies, the thesis aims to:

- Quantify the potential and cost for logging residues to supply future demands for energy, manufacturing, and bioenergy with carbon capture and storage (BECCS) applications at industrial sites (**Papers I** and **II**);
- Analyze the cost structure of large-scale (BE)CCS systems and how incentive structures for fossil CO_2 mitigation and carbon dioxide removal (CDR) impact their deployment in industry over time (**Papers III** and **IV**); and
- Relate electricity grid infrastructure expansion to the deployment of industrial electrification and identify conditions in terms of permitting times (connected to public acceptance), electricity grid expansion pace, and coordination between site electrification and infrastructure projects that allow for timely industrial electrification (**Paper V**).

The geographic scope is national systems, using Sweden as a test case. The national focus is motivated by the fact that many national decisions and climate policies govern the deployment of new technologies and infrastructures. However, the national focus is also a limitation as the Swedish context is not directly applicable to other countries or regions, even though the applied methodologies are. The temporal scope of the work primarily covers the present period (2020–2025), up until 2045–2050, given that the current EU and national climate targets are set for to these periods.

1.2 Outline of the thesis

This thesis consists of a summarizing essay and the five appended papers. The summarizing essay is divided into seven chapters. Chapter 1 contains an introduction that frames the thesis work and outlines the aim and scope of the work. Chapter 2 presents the background and gives an overview of the research landscape regarding the technological pathways that are studied and the policy context in which the transition of industry is set to take place. Chapter 3 presents an overview of the methodologies applied and developed within this thesis work. Chapter 4 presents selected results from the appended papers, and considers the overarching implications from the thesis work as a whole. Chapter 5 contains a summarizing discussion of the results presented in the thesis, and Chapter 6 draws conclusions in relation to the aims outlined in Chapter 1. Chapter 7 presents suggestions for future research, based on the work in the thesis.

The focuses of the appended papers are listed briefly below.

Paper I explores the potential for regional logging residues (branches and tops that can be extracted during roundwood harvesting operations) to act as energy supply for BECCS implemented at four large pulp and paper mills in Sweden. The focus is on the regional difference in logging residue supply potential and costs to supply logging residues to the case study pulp mills.

Paper II expands the analysis of logging residues, assessing the potential to cover developments in several sectors. National and regional supply potential of logging residues is assessed and mapped to estimated demands for bioenergy and biogenic carbon in current and future applications. Costs are calculated for logging residue supply according to current usage patterns, and for supplying high demand sites with excess logging residues from high supply areas.

Paper III presents and applies a cost-minimizing optimization model to study the development of and costs for CO_2 capture and transportation systems in the Swedish industrial system. **Paper IV** builds on the modeling work performed in **Paper III** and further investigates questions related to the deployment of large-scale cost-optimal (BE)CCS systems when different modes of incentivizing biogenic and fossil CO_2 capture is applied.

Paper V presents and applies an emissions-minimizing optimization model to study the development of electrification in industry under constrained infrastructure deployment capacity. Thus, the analysis complements the work performed in other parts of the thesis, by focusing on aspects of infrastructure deployment for the industrial transition that are not related to costs, but nonetheless of large importance for enabling a timely transition.

2. Background

This chapter presents background information relevant to the work performed in the thesis. Section 2.1 gives an overview of the Swedish industrial and district heating sectors and their CO_2 emissions. Section 2.2 gives an overview of the research related to electrification, CCS and biomass use, and their applications in the Swedish context. Section 2.3 gives a brief outline of the policy landscape of interest for the industrial transition. Section 2.4 summarizes the research landscape and places the work presented in this thesis in the context of existing research.

2.1 Sweden's industrial and district heating sectors

Sweden has a broad industrial sector with industries producing a wide range of basic materials. The largest point sources of emissions, emitting more than 100 $ktCO_2$/year of fossil or biogenic CO_2, comprise industrial sites involved in refining, chemical manufacturing, cement production, iron and steel production, and pulp and paper production. In addition to the process industrial sectors, Sweden also has well-established district heating systems, connected to several heat and power plants. The heat and power plants in Sweden are typically waste- or bio-fired, with a few remaining fossil fuel-fired plants operating for short periods when the heat or electricity demand is especially high.

Iron and steel

The iron and steel producing sector in Sweden consists of iron ore mining and processing and steel manufacturing. Iron ore mining and processing are carried out by the state-owned company LKAB, and steel is manufactured by multiple companies, with the largest one being SSAB. Iron ore is mined in the north of Sweden and pelletized before it is sold domestically, mostly to SSAB, or exported to the global market [5]. The pelletizing plants are fired mostly by fossil fuels. LKAB produces around 80% of the iron ore in the EU [6], and the site operations emit around 0.7 $MtCO_2$/year. Primary steel production in Sweden is based on the traditional blast furnace-basic oxygen furnace (BF-BOF) production route. In this process, iron ore is reduced using coke in the blast furnace (BF) to produce pig iron, which is then sent to the basic oxygen furnace (BOF) to be treated with oxygen, in order to reduce the carbon content of the steel to the desired level [7]. Both the BF and the BOF are large point sources of CO_2 emissions, and SSAB's primary steel production emits around 3.8 $MtCO_2$/year. In addition to primary steelmaking, there are production plants in Sweden for recycled steelmaking, based on electric arc furnaces (EAFs), in which scrap is melted to produce steel. In the global context, another steel production route is the direct reduction of iron (DRI) process, which is a common alternative to the BF-BOF production route. In the DRI process, iron ore is reduced in a solid state (without melting, as occurs in the BF) using syngas (carbon monoxide and hydrogen) as reducing agents to produce direct reduced iron [8]. The syngas used for the reduction is typically produced from the reformation of natural gas and, therefore, this production pathway is commonly implemented in steel mills with good access to a natural gas grid. The direct reduced iron can subsequently be melted in EAFs to produce steel.

Pulp and paper

Sweden is a large producer of pulp and paper, with 28 mills emitting 0.1–2 $MtCO_2$/year from producing market pulp, paper or a combination of the two. Most of the pulp produced in Sweden is virgin pulp, in contrast to the European pulp and paper industry, where a significant amount of the production involves recycled pulp. The total emissions from the sector are around 23 $MtCO_2$/year, of which more than 97% are biogenic. The largest pulp mills in Sweden use the Kraft pulping process, which utilizes chemical treatment of the pulpwood as opposed to mechanical treatment, which is the other main production pathway. In the Kraft process, the wood is broken down using a chemical mixture and heat to produce pulp. The chemical mixture used to break down the wood contains a large amount of lignin and some cellulose after the pulp production. This mixture, black liquor, has a high energy content and is combusted in a recovery boiler, so as to recover the cooking chemicals. During combustion, large amounts of heat are generated, and this heat is used to generate steam to supply the mill's internal processes with heat, as well as to produce electricity. At Kraft pulp mills, the recovery boiler is the largest source of CO_2 emissions. The second-largest source of CO_2 at a Kraft pulp mill is typically the lime kiln, in which the calcium carbonate formed while recovering the chemicals from the recovery boiler is calcined, which enables reforming of calcium hydroxide to be re-used in the chemical recovery process. The CO_2 concentration from the lime kiln is high, due to the pure CO_2 generated from the calcination process. The Swedish pulp and paper industry is already almost entirely free of fossil emissions, since most of the energy used comes from bioenergy and electricity [9].

Cement

There are two cement production plants in Sweden, one located in Skövde in southern central Sweden and one on the island of Gotland, which lies off the east coast of Sweden. Both cement plants are owned by the company Heidelberg Materials. The cement plant located in Slite emits around 2 $MtCO_2$/year and the one in Skövde emits around 0.4 $MtCO_2$/year. Cement production is based on heating a mixture of ground limestone and silicon, often in the form of sand or clay, to temperatures of around 1,450°C. During this process, the calcination reaction takes place, leading to the formation of cement clinker. The cement clinker is then pulverized to produce cement. The emissions from cement production comprise roughly two-thirds process emissions and one-third fuel-based emissions [10]. The process emissions come from the calcination of limestone, and as such, cannot be mitigated by switching the fuel source.

Refineries

There are three large refineries producing transportation fuels located on the Swedish west coast. Put together, these refineries have a processing capacity corresponding to around 16 Mt of crude oil per year and emissions of 2.1 $MtCO_2$/year from the site activities. At the largest refinery, located in Lysekil and owned by Preem, the largest point source of emissions is the flue gases emanating from the hydrogen production unit (HPU), utilizing steam methane reforming (SMR), accounting for almost 40% of the emissions [11]. Although the site emissions from the refineries are substantial, the largest part of the emissions associated with the refining activities, around 85%, is the downstream Scope 3 emissions associated with product use, namely the combustion of the fuels in the transportation sector

[12]. Preem, which is the largest refining company in Sweden, has a target to establish by Year 2035 a climate-neutral value chain, including the upstream raw material supply, site activities and downstream product use [12].

Chemicals

The Swedish chemical industry consists of several companies that are producing a wide variety of products, ranging from plastics, paint, and coatings to pharmaceutical products. The largest chemical manufacturing cluster in Sweden is in Stenungsund, on the west coast. The total of the emissions from the chemical cluster in Stenungsund is around 0.9 $MtCO_2$/year. The industry is characterized by a few large companies that are employing most of the workers in the sector and are highly export-dependent [13]. One of the largest production units in the Stenungsund cluster is the cracker plant that is owned and operated by the company Borealis. This cracker is one of the largest point sources of emissions in the cluster (around 0.6 $MtCO_2$/year); it produces ethylene and propylene for the production of polyethylene, which is used primarily for cable and piping applications.

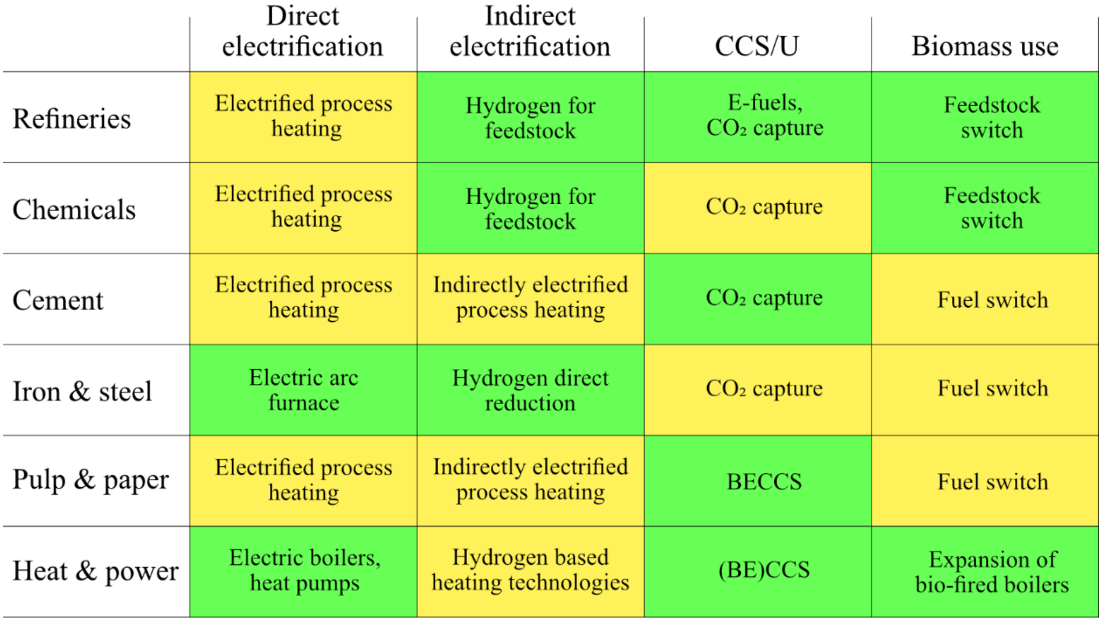
District heating

Sweden has well-established district heating systems, with combined heat and power (CHP) plants and heat plants supplying district heating to communities. The plants that deliver district heating are mostly waste incineration plants or biomass-fired CHP plants, and this development has reduced fossil fuel use in the Swedish heating sector [14]. Incineration of household waste leads to both fossil and biogenic emissions (typically around 30–40% fossil-based) due to the waste containing some share of plastics. In Sweden, district heating supplies around half of the heating in residential and commercial buildings, delivering around 50 TWh/year of heat with a fuel mix that is primarily made up of unrefined waste streams from forestry (e.g., bark, branches and tops and wood chips) and waste [15]. The remaining fossil emissions from Swedish district heating are low, only around 4 $MtCO_2$/year, with most of the fossil emissions originating from the fossil share of household waste, i.e., plastics. The biogenic emissions from CHP plants are substantial, around 13 $MtCO_2$/year.

2.2 Technological pathways for low-CO_2-emitting industry

Figure 1 shows the technology pathways for low-CO_2-emissions, with the possibilities to apply electrification, biomass use, and CCS in the considered sectors. Electrification is the primary long-term goal for many sectors, while biomass use and CCS may mitigate emissions that are otherwise difficult to avoid and function as bridging technologies if electrification is not possible in the planned timeframe of the transition. In addition, using biomass-based feedstock or captured carbon is a necessity for industries that are producing carbon-based products. Furthermore, the implementation of CCS at large point sources of biogenic emissions has the potential for CDR via BECCS. Each of these technologies come with their respective advantages and disadvantages, and therefore, have different roles to play in a future decarbonized industrial system.

At Swedish refineries, the switching of feedstock to biogenic carbon sources is already happening, with liquid biofuels being produced from mostly oils and fats. Hydrogen production from electrolysis, used to complement the current hydrogen production from SMR and enable further expansion of production from biogenic feedstocks, is likely. Additionally, CCS is likely to be implemented on high-CO_2 concentration emissions sources to mitigate site emissions. In chemicals manufacturing, electrified production of hydrogen is likely to be implemented in conjunction with substituting fossil carbon with alternative carbon sources. In the cement industry, CO_2 capture is necessary to mitigate process emissions, and CCS is planned for the largest cement plant in Sweden. The fuel-based emissions from cement plants could additionally be mitigated by fuel switching to electricity or biobased fuels. Electrification of the iron and steel industry is the chosen technology path in the Swedish context, involving hydrogen from electrolysis for iron ore reduction and EAF steelmaking. The Swedish pulp and paper industry is almost fossil-free, however the remaining fossil-based emissions could be phased out by further increasing the use of bioenergy or electrified heating. Providing CDR via BECCS is likely to be an interesting option for pulp and paper mills. While the heat and power sector in Sweden operates almost free of fossil fuels, it will likely undergo several changes in the coming decades. Some waste- and bio-fired CHP plants are already planning to implement CCS, in many cases motivated by municipal or regional climate targets. The electrification of some district heating supply, via for instance heat pumps (or electric boilers), is also likely to take place, while at the same time, new bio-fired CHP capacity is planned to be installed.



	Direct electrification	Indirect electrification	CCS/U	Biomass use
Refineries	Electrified process heating	Hydrogen for feedstock	E-fuels, CO_2 capture	Feedstock switch
Chemicals	Electrified process heating	Hydrogen for feedstock	CO_2 capture	Feedstock switch
Cement	Electrified process heating	Indirectly electrified process heating	CO_2 capture	Fuel switch
Iron & steel	Electric arc furnace	Hydrogen direct reduction	CO_2 capture	Fuel switch
Pulp & paper	Electrified process heating	Indirectly electrified process heating	BECCS	Fuel switch
Heat & power	Electric boilers, heat pumps	Hydrogen based heating technologies	(BE)CCS	Expansion of bio-fired boilers

Figure 1. Technological pathways towards low emissions and how they may be applied in the Swedish industrial and district heating sectors. Boxes shaded in green indicate a communicated or likely development, whereas boxes shaded in yellow indicate potential alternative developments.

2.2.1 Electrification

Electrification of industry primarily involves replacing heat generation from fossil fuels with heat generation from sources that are powered by electricity or that utilize hydrogen produced via electrolysis [16]. In contrast to the heat supply for buildings and residences, the high-temperature industrial heat demands that are currently covered by combustion (at upwards of 1,500°C) are more difficult to replace with direct electrification. In Europe, around half of the industrial heat demands are at temperatures >500°C, including the demands for sectors such as cement, lime, and iron and steel production [17]. Typically, electrification of the heat supply for high-temperature processes used in such materials processing industries, are at a lower technology readiness level (TRL) than, for instance, CCS technologies separating CO_2 from flue gases after combustion [18], [19]. It is important to note that the carbon footprint of any electrified process is dependent upon the carbon intensity of the grid, and thus, reliant on a low-CO_2-intensity electricity supply. Madeddu et al. [20] have shown that without further decarbonization of the EU electricity grid, the emissions from the industrial sector could increase with broad electrification of industrial processes.

Process level

In essence, electrification of processes can be divided into two categories. Direct electrification entails a switch to end-use technologies that utilize electricity directly, for instance electric boilers or heat pumps. Indirect electrification entails using electricity to produce hydrogen or synthetic fuels (utilizing hydrogen generated from electrolysis as one component), which are then used in processes to replace fossil fuels or feedstocks [16]. In general, direct electrification technologies tend to operate with high efficiencies. However, direct electrification of high-temperature processes (>500°C) tends to be difficult [21]. On the other hand, indirect electrification technologies can be used to produce hydrogen or fuels that are more easily integrated into existing processes and infrastructures, although the production of hydrogen or synthetic fuels entails higher conversion losses (e.g., around 70% energy efficiency for conventional alkaline electrolysis), making the overall system less efficient [21].

For cement manufacturing, different electrification approaches have utilized process analysis tools, typically considering direct electrification of the process heat supply [22], [23], [24], [25], while sometimes also considering indirect electrification [22], and often including CO_2 capture due to the process emissions [23], [24], [25]. Cost assessments of electrified cement manufacturing with CO_2 capture report mitigation costs in the range of 65–140 €/tCO_2 depending on the specific process concepts and the cost assumptions applied [22], [23], [25]. Since electrified cement production would require large amounts of electricity, the costs are sensitive to the electricity price. In the Swedish context, electrification of cement manufacturing has been studied in among other projects, the CemZero project [25].

The iron and steel industry can potentially fully mitigate all its CO_2 emissions by electrifying the entire process, replacing the current production units with a production pathway that is based on hydrogen direct reduction (HDR) of iron ore and EAFs for steel production[26], [27]. In the electrified process, the iron ore is reduced to produce direct reduced iron using pure hydrogen produced by electrolysis as a reducing agent instead of fossil fuels [28]. The direct reduced iron can then be smelted in an EAF to produce steel. Vogl et al. [26] have reported that HDR of iron ore can be cost-competitive with traditional steelmaking at a relatively modest carbon price of 34–68 €/tCO_2 and an electricity price of 40 €/MWh. The Swedish iron and steel industry is aiming for electrified steel production in order to decarbonize fully the process [29]. As part of the transition, LKAB is planning to take responsibility for the HDR part of the process, in that it will no longer sell iron ore pellets as its main product, but rather sponge iron. In doing so, LKAB also aims to reduce the iron that is currently exported as pellets, which would lead to a drastic reduction of downstream emissions at steel mills that currently buy the exported iron ore pellets.

For refineries and chemical manufacturing, direct and indirect electrification are relevant: indirect electrification to produce the hydrogen needed in the manufacturing processes, and direct electrification of the process heat supply. For ethylene and propylene production, traditional fossil fuel-fired steam crackers can be replaced with electrified steam crackers. Some studies have investigated the economic and environmental performances of electric steam crackers [30], [31]. Due to the high energy intensity of steam cracking, electrifying the process can yield substantial emissions reductions. As refineries transition away from the use of fossil fuels, the demand for hydrogen is likely to increase, due to the higher hydrogen demand for refining biomass resources or producing electrofuels, rather than processing crude oil [32]. Some of the increased hydrogen demand is likely to come from electrolysis, entailing an indirect electrification of the hydrogen supply.

Infrastructure and system perspectives

For electrification of industrial processes to be feasible, an improved grid infrastructure and new low-CO_2-emitting electricity generation capacity are required. Lechtenböhmer et al. [33] have investigated the impacts on the future EU electricity demand from the implementation of broad electrification in industry, and they conclude that the demand for electricity from industry could increase by around 1,500 TWh/year. This demand would be in addition to the roughly 900 TWh/year that are used by EU industry today [34].

The integration of electrified industrial processes into the energy system have been studied in previous works. For example, analyses have been conducted on the costs of [35] and interactions between electrified steel industry and the energy system [36]. Pimm et al. [35] have reported marginal abatement costs for hydrogen DR-EAF steelmaking in the range of 23–38 £/tCO_2 (27–45 €/tCO_2 applying the average € to £ exchange rate for Year 2021).

Electrified processes and new generation capacity are reliant on expansion of the electricity grid infrastructure. Energy system modeling approaches have been used to investigate the viability of expanding the electricity grid and transmission capacity from a cost perspective [37], [38], [39]. The results of these analyses indicate that from the system cost perspective, it would be beneficial to expand the electricity grid to connect high-demand areas with regions that have a high level of supply, rather than focusing solely on local production and storage.

However, current grid expansion is occurring slowly and previous research highlights that the main barriers to further grid expansion are lackluster regulatory frameworks and public acceptance, resulting in drawn out permitting procedures [40], [41], [42], [43]. It often takes 5–15 years to plan, permit and build a grid infrastructure in developed economies, highlighting the importance of enabling the integration of planning for transmission and distribution grids with long-term energy transition plans [4]. In addition, the pace of investments in the grid needs to be increased, and skilled workers in the relevant sectors, as well as secure supply chains for components are needed to meet the demands that are expected to be imposed on grids in the future [4].

2.2.2 Carbon capture and storage

Carbon capture and storage involves the separation of CO_2 from the flue gas, transportation of the high-purity CO_2 stream from the flue gas source to a storage site, and injection of the CO_2 for permanent storage in a suitable geologic formation. CCS has been performed since 1972, primarily for enhanced oil recovery in the oil and gas sector, and cumulatively, over 200 $MtCO_2$ have been stored globally [44].

CO_2 capture

There are several processes for the separation of CO_2 from other gases. The most-mature technology involves the separation of CO_2 from the flue gas stream after combustion of the fuel, using absorption with amine-based solvents. A major advantage of this technology is that it can easily be implemented as an end-of-pipe solution without major modifications to the process to which it is applied. However, separating CO_2 that is diluted to relatively low concentrations in a flue gas stream is costly in terms of energy expenditure [45].

Research on the implementation of CO_2 capture has focused largely on techno-economic considerations and the integration of specific capture technologies with processes. During the last decade, research studies have investigated CO_2 capture integration at specific sites, such as steelworks [46], [47], [48], [49], cement plants [23], [24], refineries [11], [50] and CHP plants [51]. Furthermore, some studies have made broader, sector- or industry-wide cost estimations [52], [53], [54]. Typically, such analyses come up with costs in the range of 40–200 €/tCO_2-captured, with costs often below 100 €/tCO_2 for emissions sources with higher annual emissions than a few hundred $ktCO_2$. Typically, the energy penalty imposed by a CO_2 capture process makes up a significant part of the cost. Thus, efficient heat integration has the potential to reduce significantly the cost of CO_2 capture. CCS can play an important role in mitigating emissions that are otherwise hard to abate (e.g., process emissions from cement production), or it can act as a technology that can be used in a nearer timeframe due to it being relatively easy to implement, as compared with more-transformative technologies. BECCS is expected to play an important role as a CDR technology. The pulp and paper industry, with large point sources of biogenic CO_2, is of interest for BECCS [55]. Large bio-fired heat and power plants, in similarity to the pulp and paper industry, are also of interest for BECCS.

Several CO_2 capture projects are under development in Sweden. Stockholm Exergi, a district heating plant operator in the Stockholm area, has announced the implementation of CO_2 capture in their bio-fired heat and power plant, designed to capture around 0.8 $MtCO_2$/year, with plans to start construction in Year 2025 [56]. There are several other municipal heat and power plants that aim to implement CO_2 capture technologies in the near term, often motivated by municipal or regional climate targets. Heidelberg Materials is planning to implement CO_2 capture at their plant in Slite, aiming to be the first climate-neutral cement plant by Year 2030 [57]. Preem plans to use CCS to mitigate some of the site emissions, specifically at a hydrogen production unit [11]. Large amounts of relatively highly concentrated CO_2 are emitted from the hydrogen production, making it a suitable target for CO_2 capture.

Transportation and storage infrastructure

CCS requires a new infrastructure for CO_2 transportation and storage. The transportation infrastructure for CO_2 includes trucks, trains and pipelines onshore, as well as ships, barges and pipelines offshore. The cost of CO_2 transportation depends primarily on the transportation distance and the volume of CO_2 to be transported. Much research has been carried out on CO_2 transportation, with some studies comparing different transportation modes from the cost perspective [58], [59], [60]. The obtained results indicate that for offshore transport, ships tend to be favored for long distances, whereas pipeline transport tends to be preferred for short distances and large CO_2 volumes. There is also a discussion as to whether ship transport of CO_2 should be carried out at 7 barg or 15 barg. Research indicates that costs are lower for the 7 barg system, especially for longer transportation distances [61]. However, near-term projects are likely to use the 15 barg system due to its relatively higher technological maturity, as is the case in the Norwegian Northern Lights project [62].

In the European context, storage of CO_2 is likely to be performed offshore, in suitable geologic formations, such as depleted oil and gas fields or saline aquifers. Onshore storage of CO_2 is more likely to encounter local opposition, as exemplified by the failure of the CCS project in Barendrecht in The Netherlands [63]. There is a large potential to store CO_2 in the North Sea due to the high prevalence of suitable geologic formations [64]. The Northern Lights project involves the most-developed commercial CO_2 storage, located off the west coast of Kollsnes in Norway. The project will sell CO_2 transportation and storage as a service and it is on track to complete its first phase during Year 2024, enabling the storage of 1.5 $MtCO_2$/year [65].

CCS supply chains

Previous research studies have analyzed the deployment of large-scale CCS systems using optimization approaches, with some of these evaluating the development of large pan-European CO_2 transportation networks. Kjärstad et al. [66] have considered carbon capture in the European power-producing sector and large pipeline networks, applying a modeling framework developed by Morbee et al. [67] to determine the cost-optimal transportation infrastructure. d'Amore et al. [68] have presented an optimization modeling framework for CCS supply chains, encompassing the capture, transport, and sequestration stages for European emissions sources in industry and power generation sectors. The lowest system cost achieved entailed total specific costs of 52 €/tCO_2, with capture making up around 80% of the costs.

In addition, several works have looked at national CCS supply chains using optimization modeling approaches in the European context. For example, Kalyanarengan Ravi et al. [69] have presented a total supply chain cost-minimizing model and applied it to capture 54 $MtCO_2$/year in The Netherlands for 25 years of operation. The costs reported are approximately 35–39 €/tCO_2, with the capture and compression stage accounting for most of the cost for the supply chain. Becattini et al. [70] have developed a CCS supply chain cost-minimizing model and applied it to study different emissions reductions pathways, involving linear reduction or cumulative reduction, for waste-to-energy plants in Switzerland. Two storage sites have been considered by Becattini et al. [70], one in Norway (corresponding to the Northern Lights project) and a hypothetical storage site in Switzerland that is assumed to be available for use later in time. They present supply chain costs of up to 174 €/tCO_2, with transportation making up most of the system costs, when captured CO_2 is transported all the way from Switzerland to Norway. However, with access to the hypothetical Swiss storage site, the cost of transportation is significantly reduced.

As outlined above, the economic conditions for CCS supply chains have been researched for several cases, at both the national and Europe-wide levels. The literature indicates that in most cases, most of the costs for CO_2 supply chains are linked to the capture and conditioning of CO_2. However, the reported total supply chain costs vary widely, in the range of 35–174 €/tCO_2, motivating further investigations of the cost and deployment of CCS supply chains in specific system contexts.

2.2.3 Biomass use

The EU bioeconomy strategy highlights the importance of sustainable usage of biomass and bioenergy to mitigate climate change [71]. According to Berndes et al. [72], bioenergy based on forestry waste streams is of special interest because it is typically found to contribute positively to climate mitigation even in the short term. However, it should be noted that there is an ongoing discussion regarding the best way to utilize forests for mitigation purposes, with on the one hand increased bioenergy use, while on the other hand forests are left standing to ensure carbon sinks, with several proponents of both sides (see for example [72], [73], [74], [75], [76], [77]).

Application in industrial processes

Biomass is an obvious substitute for fossil fuels, as it can be used both as a feedstock for the production of carbon-based materials and for energy purposes. Lignocellulosic biomass (biomass from plants, e.g., agriculture and forestry) can be converted to biofuels through thermochemical or biochemical production routes to produce biofuels, or alternatively to produce a wide range of chemicals or plastics. However, to enable novel industrial production and bioenergy applications, the composition of the biomass needs to be understood in greater detail [78]. For chemical and petrochemical applications, undesirable properties, such as a high oxygen content, can render the use of solid biomass problematic, in addition to requiring large storage capacities, making upgraded biomass a more-suitable solution [79]. In addition, to meet industrial heat demands, biomass can be combusted directly or processed into different solid, liquid or gaseous fuels, which vary significantly in their energy densities and combustion properties, which means that in principle, biomass-based systems could be used for most process heat demands [80]. Thus, the challenges associated with using biomass in industrial applications are different for different sectors.

For instance, biochar could be applied to replace or reduce the use of coal and coke in steelmaking [81], [82], requiring the pre-processing (using pyrolysis or gasification) of biomass for biochar production. In the Swedish context, Nwachukwu et al. [83], have performed an analysis that connects spatially explicit biomass supply to users in the Swedish iron and steel industry, showing that biomass use could reduce emissions from the sector by 43%, although this would be achieved with the penalty of an increase in the cost for energy supply compared with the use of conventional fuels. Even in fully electrified steelmaking, some carbon will be needed to replace the fossil carbon that is currently present in the steel.

Adding biomass to replace a share (20% or more) of the conventional fuel used in cement manufacturing has shown promising results, and the main constraints to further use in the sector have been identified as the need for pre-treatment, economic considerations, and local resource availability [84]. In addition to replacing fossil fuels for existing process heat demands, biomass could act as an energy source for BECCS through supplying the additional energy required to drive the CO_2 capture process.

Biomass supply potential

With the increasing interest in biomass use as climate mitigation strategy over the last few decades, numerous studies have assessed the potential for biomass out-take on the global [85], [86], EU [87], [88] and Swedish [89], [90] levels. Hänninen et al. [88] have performed a review of the bioenergy supply potential in the EU and come up with widely varying estimates of the forest biomass supply potential for Year 2030, in the range of 23–573 Mm^3/year. This broad range is explained by difference in the: definitions of terms such as *bioenergy*; assumptions regarding conversion factors (between mass, volume and energy content); and definitions of the supply potential (theoretical, technical or economic potential). In the Swedish context, the supply potential for forest-based bioenergy in the coming decades is typically estimated to be in the range of 15–40 TWh/year [90], [91]. Parklund [92] has estimated that there is a currently unutilized ecologic potential of logging residues (suitable for use in energy applications) of almost 14 TWh/year.

Biomass use in Sweden

Forest-biomass supply chains in Sweden are based on the forest industry producing high-value products from roundwood, such as sawn products for construction materials. Smaller or lower-quality trees are used by the pulp and paper industry for pulp production. In chemical pulp mills, the combustion of black liquor with the primary purpose of regenerating chemicals for the process generates large volumes of steam, which are used for process heat, electricity generation and, in some cases, district heating delivery. The assortments of biomass that are used for energy purposes are waste products from the harvesting and preparation of wood for higher-value uses. The main waste streams used for energy purposes are logging residues, which are branches and tops that can be gathered during harvesting, bark obtained from de-barking the trees before they are turned into products, and sawdust that is generated in sawmills that are producing construction materials [93]. Unrefined waste streams (bark, logging residues, sawdust and wood chips) used as fuel for heat production amounted to around 18 TWh in Year 2022 [15]. Börjesson et al. [94] have estimated that the additional demand for forest fuels and feedstocks could increase by over 60 TWh/year in Year 2050, although this estimate is associated with high levels of uncertainty due to unknown extents of energy efficiency measures and electrification in different sectors.

Forestry waste streams, such as the currently unutilized potential of logging, residues could be exploited and used to supply some of the future demands for energy or manufacturing purposes in industry. In order for logging residues to be used, they need to mobilized and transported to the end-user. The supply chains for logging residues are based on the extraction of branches and tops during roundwood harvesting, forwarding (terrain transport to a roadside), comminution, and onward transportation directly to an end-user or via a terminal. The most-common method for comminution in the Swedish context is chipping, which typically takes place in the forest before onward transportation, and the comminuted logging residues are almost exclusively transported by trucks [95]. The chipped material is either transported directly by truck to an end-user, which is the case for most logging residues extracted in Sweden, or to train terminals for onward transportation over longer distances.

2.3 Policy context

Figure 2 presents a timeline for meeting the emissions reduction targets of the EU and Sweden, as well as two examples of climate targets for Swedish industry. The EU and Swedish targets use the Year 1990 emissions levels as reference, although these have been recalculated to reference Year 2018 (the same as the industrial examples) for the purposes of Figure 2. The overarching framework at the United Nations level is the Paris Agreement, which sets the direction for the targets on the EU and national levels. The IPCC estimates the remaining carbon budgets for a 50% likelihood of limiting warming within the Paris Agreement target of 1.5°C to be 500 GtCO2 [96]. This means that if emissions remain at the same levels as in the last decade, the budget will be exhausted by the early 2030s.

To attempt to stay within the emissions budgets, ambitious targets have been set by several of the signing parties to the Paris Agreement. The EU as a signing party to the Paris Agreement has its own emissions reduction targets, where the long-term goal is to reach climate neutrality by Year 2050. Sweden, as a Member State of the EU and a signing party to the Paris Agreement, has its own climate policy framework and aims to reach net-zero GHG emissions by Year 2045 and net-negative emissions thereafter [97]. As a result of the policy directions on the EU and national levels, industrial actors in Sweden have established their own climate targets and roadmaps, typically aiming to reach net-zero emissions sometime in the period of 2035–2045. Some examples of these industry-set targets are: Heidelberg Materials, which aims to have one climate-neutral cement plant in operation in Year 2030; Preem, which aims to establish a climate-neutral value chain for their refining operations in Year 2035; and SSAB, which aims for climate-neutral steel production by Year 2045.

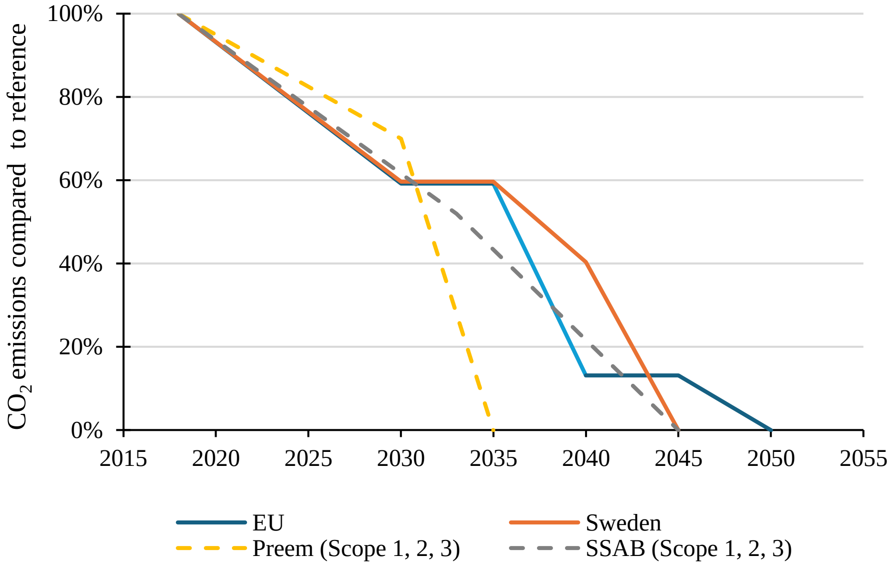


Figure 2. Timeline of CO_2 emissions reduction targets at the EU and Swedish levels. The dotted lines represent the climate targets for Preem and SSAB. Note that since the reference years for the EU and Sweden differ compared to those for the industrial actors, they have been recalculated to have the common reference year of 2018.

2.3.1 EU ETS

The EU ETS is the cap-and-trade system that was introduced for large sources of fossil CO_2 emissions in the EU in Year 2005 [98]. The system works by imposing a cap on the emissions from the activities included in the system, and by distributing emissions allowances in accordance with the cap through auctioning or free allocations for certain sectors at risk of carbon leakage. The allowances can be traded among the actors in the system, and at the end of the period, each actor must surrender allowances that correspond to its emissions during that period. If they fail to do so, they will be fined. The reasoning behind the cap-and-trade system is that the market mechanism for trading emissions allowances is designed such that emissions reductions within the system take place where the cost associated with emissions mitigation is lowest.

Figure 3 shows the development of the cap for emissions allowances in the EU ETS between Year 2025 and Year 2040. To ensure that the emissions from the system decrease over time, the number of allowances is reduced over time. During Phase 3 of the EU ETS, i.e., 2013–2020, the cap decreased by 1.74% annually. In Phase 4, for the period of 2021–2030, the allowances were set to continue to decrease with a linear reduction factor of 2.2% per year [99]. However, recent amendments to the EU ETS have included more sectors in the ETS, increased the linear reduction factor (LRF) to 4.3% for the period of 2024–2027 and 4.4% for 2028–2030, and will gradually phase out the free allowances within the system [100]. With the new LRFs, the emissions cap would reach zero in Year 2039 [101]. The free allowances are planned to be phased out between Year 2026 and Year 2034, in parallel with the phasing in of the Carbon Border Adjustment Mechanism (CBAM) [102]. The CBAM will assign a carbon price to certain basic materials (e.g., steel, aluminum, cement) that are imported into the EU. If an importer can prove that a carbon price has already been paid when the goods were produced, the corresponding amount can be deducted [103]. In addition, the European Commission has proposed a new ETS system to cover upstream emissions related to buildings and road transportation, and this would be separate from the already existing system for the industry, energy and aviation sectors [104].

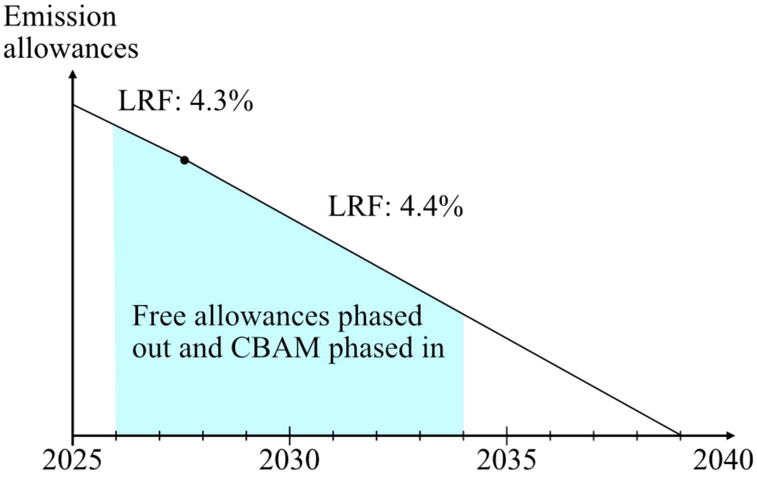


Figure 3. Evolution of emissions allowances in the EU ETS. The blue shading represents the period during which free allowances will be phased out and the CBAM mechanism phased in. LRF, Linear reduction factor; CBAM, Carbon border adjustment mechanism.

Large fossil CO_2 emitters in Swedish industry, including waste incineration, iron and steel production, cement production, refining, and chemical manufacturing, are included in the EU ETS. The development over time of emissions allowance prices due to changes made within the EU ETS is crucial to determining the relative cost of implementing mitigation technologies, as compared with the cost of emitting CO_2. In addition to motivating investments in fossil CO_2 mitigation, incentivizing the deployment of CDR technologies could be achieved by including CO_2 removal credits in the EU ETS. The legal and economic considerations related to integrating CO_2 removal credits into the EU ETS have been investigated by Rickels et al. [105], and they have shown that such an integration would lead to lower-cost net emissions reductions for a given emissions level from the system, or conversely, that more-ambitious net emissions reductions could be achieved at a given price for emissions allowances. From its inception until the 2020s, the EU ETS allowance prices have typically been <25 €/tCO_2, although in recent years, the price has increased and become more volatile, being currently around 60–70 €/tCO_2 [106].

2.3.2 EU regulations on biomass and bioenergy use, including LULUCF

Biomass use in the EU is generally guided by the so-called cascading principle, which holds that Member States should prioritize biomass use according to the following order: 1) wood-based products; 2) extending the service life of wood-based products; 3) re-use; 4) recycling; 5) bioenergy; and 6) disposal [107]. The cascading principle will likely be important in prioritizing how scarce biomass resources will be used. The EU’s third Renewable Energy Directive, RED III, has recently been approved, and sets the ambitious binding target that at least 42.5% of the energy use will be renewable in the EU in Year 2030, up from 23% in Year 2022 [108]. Despite earlier formulations in the directive that could severely limit the use of forestry-based biomass for energy purposes, the approved Directive is generally positive towards bioenergy. The Directive limits financial support for energy generation from saw logs, veneer logs, industrial grade roundwood, stumps and roots and highlights that waste prevention, reuse and recycling should be prioritized [109], which is in line with the cascading principle.

Accounting for the carbon stock in biomass is handled by the Land Use, Land Use Change and Forestry (LULUCF) sector. Land can act both as a carbon source and a carbon sink, where CO_2 can be absorbed from the atmosphere via, for instance, biomass growth and released through biomass harvesting. Thus, when biomass is used for energy purposes, the biogenic emissions are accounted for when the biomass is harvested as a change in the carbon stock, and not during combustion and release to the atmosphere. The EU LULUCF regulation contains commitments for the Member States regarding carbon sinks in the LULUCF sector [110]. The recent revisions to the LULUCF regulation change the rules regarding accounting and increase the magnitude of the proposed carbon sink in the LULUCF sector. The revisions to the LULUCF regulation will result in Sweden needing to increase its natural carbon sink, which could have implications for the forestry industry, with one likely consequence being reduced harvesting rates [111]. The amount of forest-based biomass that is available for industrial and energy use is dependent upon the activity level of the forestry industry, since the majority of bioenergy in the Swedish context is based on waste products from the forestry industry. Therefore, it is likely that developments that reduce harvesting activity will influence the possibility for Swedish industry to use biomass to reduce emissions by replacing fossil feedstocks and fuels. Reduced harvesting activity also has implications for BECCS, in that it will lead to reduced availability of logging residues that could be used to meet the increased energy demand imposed by capture implementation at existing sites, or as an energy source for new CHP plants equipped with CO_2 capture.

2.3.3 Incentives for sustainable fuel production in the EU

As a driver to produce aviation fuels, the RefuelAviationEU initiative is a regulation that mandates an increasing minimum share of Sustainable Aviation Fuel (SAF) and synthetic fuels in all fuels provided to aircraft operators at EU airports [112]. In Year 2025, a minimum share of 2.5% SAF is required, and in Year 2030, a minimum share of 1.2% synthetic fuels is mandated. For SAF, the proportion is increased to 6% in Year 2030 and 70% in Year 2050. For synthetic fuels, the proportion is increased to 35% in Year 2050. In addition to the incentives for aviation fuel, the initiative FuelEU maritime sets out targets to reduce the GHG emissions intensities of fuels used for shipping, by 2% in Year 2025 and up to 80% by Year 2050 [113]. Special incentives that allow the double counting of emissions reductions are included for renewable fuels of non-biologic origin (RFNBO), so as to increase their uptake in the sector.

Incentives targeted at phasing out fossil fuels from aviation and maritime transport will lead to an increased demand for alternative fuels, such as e-fuels or biofuels. This increased demand will drive the transition of the refining sector further towards utilizing non-fossil carbon sources. E-fuel production projects have also been announced and planned due to the expected demands in the coming decades.

2.3.4 Swedish climate policy framework and incentives for BECCS

In the Swedish context, the climate policy framework sets the goal of achieving net-zero GHG emissions by Year 2045, where at least 85% of the emissions reductions should come from the mitigation of fossil fuel emissions, and the remaining 15% could be achieved using "supplementary measures", i.e., CDR technologies and mitigation measures in other countries [97]. For these supplementary measures, BECCS is expected to play a significant role; it has been estimated that BECCS will provide 1.8 $MtCO_2$/year by Year 2030 and 3–10 $MtCO_2$/year by Year 2045 [114]. To incentivize BECCS, the Swedish Energy Agency is using a reversed auctioning procedure to acquire BECCS outcomes. The reversed auctioning system has a budget of 36 billion SEK (roughly 3.2 billion €) until Year 2046 and is planned to give support to any individual project for investment and operational costs over a period of maximum 15 years [115]. The Swedish Energy Agency is currently taking bids from potential BECCS providers. The reversed auctioning system has, together with municipal and regional climate targets (often targeting climate neutrality before the national target of Year 2045), resulted in increased interest in the implementation of CCS at waste- and bio-fired heat and power plants.

Although the reversed auctioning procedure for BECCS is used in the Swedish context, other policy models could be of interest. Zetterberg et al. [116] have considered the following five policy models to motivate BECCS: State guarantees (the reversed auctioning system is one form of this policy model); quota obligations from other sectors (e.g., transport and agriculture); allowing BECCS credits in the EU ETS; voluntary markets; and having other states as buyers of BECCS outcomes. The different models come with various advantages and disadvantages. Quota obligations, voluntary markets, and the integration of BECCS into the EU ETS all move the financing from State governments to private entities as the primary financer. In addition, quota obligations and the integration of BECCS credits into the EU ETS would likely lead to a greater demand for BECCS than would be reasonably achieved through State funding. However, with State funding, favorable conditions can be created for BECCS to ramp up implementation in line with near-term targets.

2.4 Summary of the research space

Table 1 presents an overview of the conclusions drawn from related research on CCS, electrification and biomass use and their respective system and infrastructure considerations, drawing upon the research outlined above. In summary, there is an extensive library of research on the technology, policy and systems aspects of the decarbonization of industry. As highlighted in Table 1, this thesis discusses the connections between process and infrastructure development, aspects that are currently under-explored in the literature and that are, nonetheless, important for the industrial transition from fossil fuel dependency.

Typically, techno-economic studies of the implementation of CO_2 capture in industry have focused on site-level considerations and costs. The costs are often <100 €/tCO_2 for emissions sources larger than a few hundred tCO_2 per year. Such analyses often set the system boundary after the conditioning of CO_2 or add a generalized value for transportation and storage. Likewise, techno-economic evaluations of CO_2 transportation system typically define the captured CO_2 to be transported as an input value. In addition to these approaches, some studies in the European context have combined these perspectives to investigate the full supply chains. However, the reported costs vary widely (35–174 €/tCO_2) depending on the context in terms of assumed capture technologies and transportation modes, considered emissions sources, how capture is incentivized, and the geographic scope. As such, further investigations of the deployment and costs of CCS systems in specific contexts, and their development when motivated by different emissions mitigation incentives, are motivated. The work of this thesis contributes to the research space by studying the concurrent deployment of CO_2 capture and transportation systems under different incentive structures for (BE)CCS in the Swedish context, which is characterized by relatively distributed emissions sources, high biogenic emissions, and relatively long transportation distances. In addition, the cost for the supply of heat to drive the capture process (typically represented as a running cost for steam) is further investigated by studying the potential and cost for supplying the heat demand for BECCS using regional logging residues.

Investigations of the usage of biomass in industrial applications, in conjunction with estimations of the supply potentials and demands, show that biomass could fulfill many industrial heat and feedstock demands going forward, although the future supply potential and demands are highly uncertain. Some work has been performed on connecting the supply to the demands. For instance, Nwachukwu et al. [83] have connected spatially explicit biomass supply to the demands in the iron and steel sector, revealing an emissions reduction potential of 43% from the sector. Further analyses that consider future developments in several sectors and that assess the spatially resolved costs, supply potential and demand are motivated. The work in this thesis provides an analysis of the spatially and temporally resolved supply of and demands for logging residues, relevant to industrial and bioenergy applications. In addition, the costs and potential to fulfill high demands from specific users on the regional level and using excess from high-supply regions are investigated.

Work on the electrification of industrial sites reveals a wide range of costs (often >100 €/tCO_2), with these being highly sensitive to electricity costs. At the same time, large-scale electrification of industry will require expanding the capacity of the electricity grid. Grid expansion is shown to be cost-efficient from a system perspective, connecting high-demand areas to regions with high-supply regions. In addition, the main barriers to grid expansion are connected to permitting and public acceptance. As such, investigating the connection between industrial electrification and the development of the electricity grid is motivated. This thesis contributes with analyses that quantify the impacts of barriers related to expanding the electricity grid, and the impact of coordination between implementation of site electrification and grid infrastructure deployment on the pace of industrial electrification.

Table 1. Related research and the contribution of this thesis work in the context of the existing research landscape.

Technology	Main conclusions from the site/industry perspective	Main conclusions from the infrastructure and system perspectives	Contribution(s) of the work in this thesis
Electrification	Mitigation cost of electrified process technology is around 35–140 €/tCO_2, and this is highly sensitive to the electricity cost (e.g., [22]-[24], [26], [30]). Electrified industries in energy systems can be cost-competitive with conventional production routes (e.g., [35], [36]).	Grid extension is cost-effective from the energy system perspective (e.g., [37], [38]). Main barriers to further deployment include low public acceptance, drawing out permitting procedures (e.g., [4], [41], [42]).	Studies the connections between industrial electrification and the development of the electricity grid. Quantification of how the main barriers identified in the literature impact the transition to electrified industry.
CCS	Cost of capture is typically in the range of 40–200 €/tCO_2 and is highly dependent upon the flue gas flow and CO_2 concentration. Heat integration is an important tool for cost reduction (e.g., [11], [46]-[50], [52]-[54]).	CO_2 transport cost is highly dependent upon the transport mode and distance. Ships typically have the lowest cost for long distances. Offshore pipelines are cost-competitive for large volumes (e.g., [58]-[61]). Reported CCS supply chain costs in the European context varies widely (35–174 €/tCO_2) (e.g., [67]-[70]) Different ways to incentivize BECCS come with different advantages and drawbacks (e.g., [105], [116]).	Considers the impact on cost of capture of utilizing regional logging residues to supply heat for BECCS. Studies the cost structure and deployment of (BE)CCS systems under different incentives in Sweden, characterized by distributed emissions sources, high biogenic emissions and long transportation distances.
Biomass use	Use cases for biomass and bioenergy in industry are broad. Challenges typically relate to pre-processing needs, required process conditions, and constrained biomass supply. Emissions reduction potential is high, although it entails a cost increase for energy supply due to low fossil fuel costs (e.g., [78]-[84]).	Supply potential estimates on the global, EU and national levels show a wide range: 15–40 TWh/year in Sweden (e.g., ([85]-[91]). The future demand for forest fuels and feedstocks in Sweden is upwards of 70 TWh/year in Year 2050, with associated high uncertainty intervals [94].	Analyzes the supply and demand with high spatial resolution and with consideration of future developments in several sectors. The supply costs and potential to fulfill future biogenic carbon and bioenergy demands with regional logging residues, and with excess logging residues from high-supply regions, are estimated.

3. Method

For evaluating the performance of technologies and infrastructures in line with the Research Aims outlined in Section 1.1, the key parameters are the costs for the technologies and systems, the CO_2 emissions (or emissions reduction), the deployment of a given technology or infrastructure over time, and the supply potential in the case of biomass. To generate these output parameters, this thesis utilizes case studies and scenario analyses, together with optimization modeling to identify the most cost- or time-efficient solutions. Figure 4 shows the relationships between the specific methods applied for the mitigation technologies. Industrial sites are motivated to decarbonize through the application of incentives for CO_2 reductions. Decarbonization can be performed by utilizing biomass, CCS or electrification. Costs are the focus of the investigation of the biomass supply and CCS, whereas permitting times, grid infrastructure expansion pace, and coordination between the site and infrastructure developments are the focus for electrification. Two of the methodologies applied, the cost-minimizing CCS supply chain model and the CO_2 emissions-minimizing model, have been developed within the scope of this thesis.

The work of this thesis focuses on the case of Sweden, due to the high prevalence of process industry in its different sectors, excellent access to forest biomass, and good conditions for a low-CO_2 electricity supply. The cost data and technology performances are based on techno-economic studies in the literature, covering process technologies and infrastructures. The site data for existing process industrial sites are primarily gathered from the Chalmers Industrial Case Study Portfolio (ChICaSP; for more information, see [117]), which contains information on yearly production, emissions, and electricity use, as well as more-detailed energy balances for some specific sites. Data for CHP plants used for estimations of CCS are based on the work performed by Beiron et al. [54].

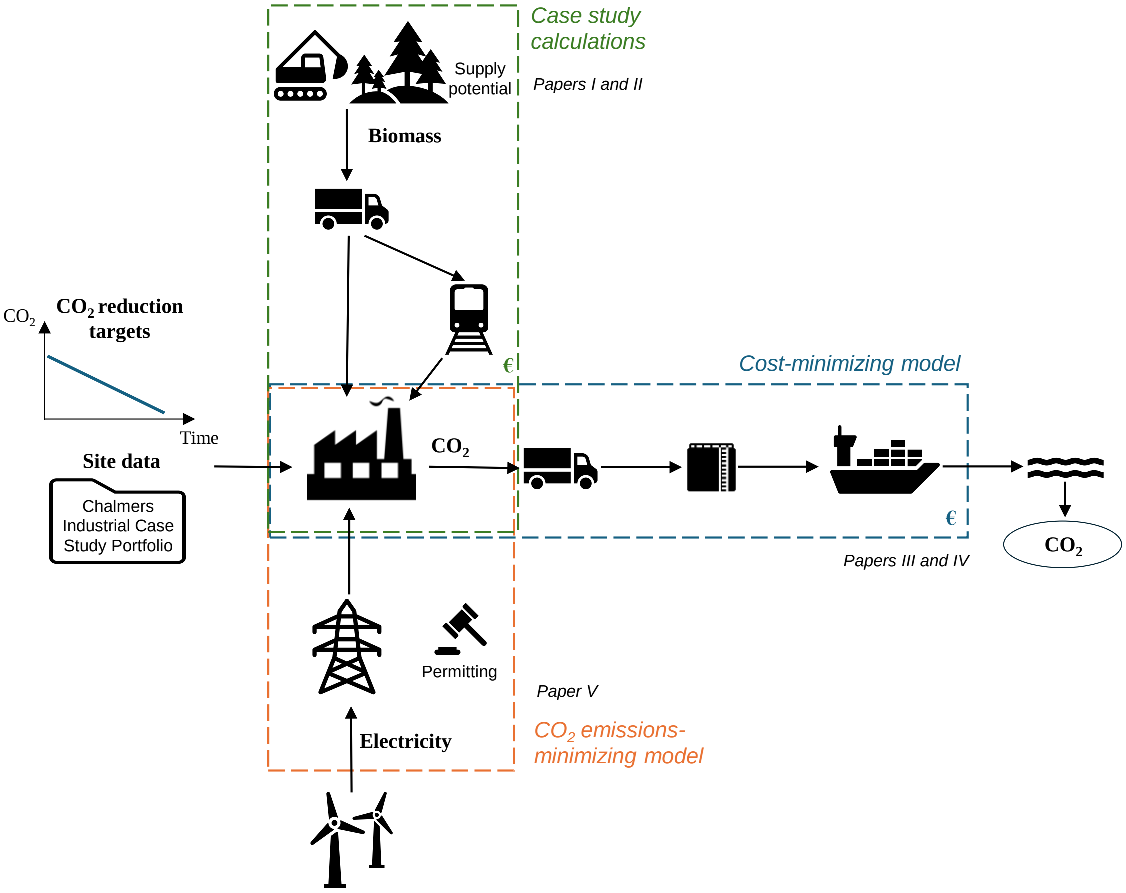


Figure 4. Schematic overview of the method applied in this thesis and the connections to the different systems investigated in the appended research papers.

3.1 Cost assessment tools applied in the thesis

To estimate the economic performances of technologies and systems, techno-economic assessment is a commonly used tool. Typically, a techno-economic assessment of a technology involves estimations of capital expenditures (CAPEX), operational expenditures (OPEX), and revenues (or cost savings), to allow for a cost-benefit analysis of a given technology, or to compare the cost performances of different technologies. In this thesis, techno-economic assessment tools are utilized to calculate the costs for technologies and supply chains, and the results are integrated into cost-minimizing optimization modeling. For decarbonization technologies, the goal of any given technology is to mitigate CO_2 emissions. Therefore, a common cost metric that is applied in literature is the levelized cost of carbon (LCOC) or the specific mitigation cost (€/tCO_2), where the cost of a given mitigation technology is levelized against the expected emissions reductions ΔCO_2 over its lifetime [118], as expressed in Equation (1):

$$LCOC = \frac{CAPEX_{annual} + OPEX}{\Delta CO_2} \qquad (1)$$

To calculate the specific mitigation cost, the CAPEX needs to be annualized to yield a yearly investment cost. The annualized CAPEX is calculated by obtaining an overnight investment need $C_{overnight}$ (M€), in this thesis from literature sources, for the relevant technologies. The investment cost is then annualized using the capital recovery factor (CRF) according to Equation (2). The CRF is obtained using the discount rate *r*, and the estimated lifetime *n* according to Equation (3).

$$CAPEX_{annual} = C_{overnight} * CRF \qquad (2)$$

$$CRF = \frac{r}{1-(1+r)^{-n}} \qquad (3)$$

The remaining part of the specific mitigation cost is the OPEX, which consists of several cost items that typically can be divided into fixed OPEX and variable OPEX. Fixed OPEX are cost items that remain the same regardless of how the technology is utilized over a given time period, for instance maintenance and insurance costs are often calculated as fixed OPEX. Variable OPEX is instead dependent upon the utilization of the technology, and includes, for instance, the fuel, electricity and utility costs.

3.2 Optimization modeling approaches

The two optimization models applied in this work have commonalities, in that they both are mixed integer linear programming (MILP) models, although they were developed to elucidate different parts of the Research Aims and the deployment of different infrastructures, as outlined in Figure 4. Both models were developed and implemented in GAMS.

To answer questions related to the cost structure and deployment under different incentives for CCS systems, cost-minimizing systems modeling is applied. In this approach, the cost of implementing CCS is weighed against the cost of emitting fossil CO_2, and the resulting deployment of CCS represents the cost-optimal implementation under a given set of assumptions regarding technology costs and CO_2 emissions pricing. In addition, BECCS can be motivated either by assigning a value to the captured biogenic CO_2 or by implementing targets for BECCS, in which case the sites chosen for capture implementation will represent the least costly way to reach a given capture target. Thus, cost-minimizing modeling is a useful tool to compare the costs and deployment of a technology in various scenarios.

The CO_2 emissions-minimizing model is applied to study aspects of the industrial transition related to the timing of infrastructure deployment. This modeling approach maximizes the pace of industrial electrification under a set of constraints imposed on the expansion of the supporting infrastructure, so as to understand the conditions for permitting times and infrastructure construction that facilitate a timely transition. In addition, coordination between developments on the site and the supporting infrastructure levels is investigated.

3.2.1 Cost-minimizing CCS supply chain model

The cost-minimizing model considers the: deployment of monoethanolamine (MEA)-based CO_2 capture followed by liquefaction at industrial sites; transportation of the CO_2 to a coastal harbor/hub; and onward offshore transportation to a permanent storage location. The costs and performances of the individual parts of the chain are included in the model, excluding the cost of final storage. The objective function of the cost-minimizing model is to minimize the net present value of the system costs over a period of 25 years, according to Equation 4:

$$\min c_{tot,NPV} \geq \sum_{y \in Y} \frac{c_y^{annual}}{(1+r)^{y-y_0}} \qquad (4)$$

where the annual cost, c_y^{annual}, includes the annualized CAPEX and OPEX for the system components in a year, as well as the cost for emitting CO_2 in year y. Furthermore, r is the discount rate and y_0 is the starting year of the modeling. The model is based on the mass balances of CO_2, ensuring that the captured CO_2 is transported from a site to the storage location via a coastal transport hub. The CAPEX and OPEX for the included parts of the CCS supply chain are calculated based on the flow of CO_2 in any given path from a site to the storage location. For the CO_2 capture and liquefaction CAPEX, the cost equations presented in the paper of Eliasson et al. [48] are applied, and a specific heat demand for capture of 3.6 MJ/kgCO_2 is assumed. For CO_2 shipping, the cost assumptions for 7-barg ships are applied, and a ship transport capacity of 8.6 ktCO_2 is assumed to represent smaller-sized vessels that may be used during a ramp-up phase of CCS. Trucks are utilized for the transportation of CO_2 from inland sites to harbors. The applied costs are based on "Nth of a kind" cost estimations.

To motivate the deployment of CCS in the modeling, different incentive structures are applied. For fossil CCS, a CO_2 price that increases over the period of 2025–2050 by 80–220 €/tCO_2 is implemented to reflect the EU ETS [119]. For biogenic CO_2, capture targets are imposed to reflect the levels of BECCS suggested as a complementary measure in Sweden, corresponding to 1.8 MtCO_2/year in Year 2030 and 10 MtCO_2/year in Year 2045 [114]. In addition to the capture targets, biogenic CO_2 can be assigned a monetary value to reflect a situation in which CDR is either integrated into existing policy frameworks, such as the EU ETS, or a voluntary market. A detailed model description can be found in **Paper III**, while the cost data and assumptions applied in the modeling are listed in **Papers III** and **IV**.

3.2.2 CO_2 emissions-minimizing model

The purpose of the CO_2 emissions-minimizing model is to study the electrification of industry given the constraints on the pre-study, permitting, design study, and construction times of the infrastructure. In addition, the model is constrained in terms of the amount of electrified industrial capacity that can be connected to the electricity grid annually, to reflect bottlenecks in the expansion capacity of the grid caused by low investment levels or the lack of availability of workers with the relevant skills. The objective function of the model is to minimize the levels of CO_2 emissions from the system through implementing electrification over the studied period, according to Equation 5:

$$\min \; CO_{2,initial} - CO_{2,electrified-mitigation} \qquad (5)$$

where $CO_{2,\text{initial}}$ is the sum of the baseline emissions from the considered sites and $CO_{2,\text{electrified-mitigation}}$ is the sum of the emissions reductions due to implementing electrification over the modeled timeframe. This objective function will ensure that electrification projects are deployed so as to maximize CO_2 mitigation, which means that the resulting deployment will reflect the most-rapid industrial electrification, given the constraints applied to infrastructure development. The main parameters that are varied in the modeling are; (i) the permitting times for infrastructure and site electrification projects; and (ii) the pace of installation of the grid infrastructure. In each scenario varying these parameters, the model will prioritize the implementation of projects that can deliver the greatest CO_2

reductions over time through electrification, given the assumptions applied. This results in a merit order where projects are implemented according to their emission mitigation potentials in relation to how much grid infrastructure capacity they require (tCO_2/MW).

In addition, coordination between developments on the industrial site and the supporting infrastructure is investigated, modeled as limitations as to when industrial site projects can be initiated in relation to infrastructure projects. A high level of coordination is modeled as a situation in which the pre-study, permitting, design study and construction phases are able to be performed in parallel for the site installations and infrastructure projects. A low level of coordination is modeled as sites not being able to initiate their pre-study procedures before the relevant infrastructure project is finished.

Applied permitting times are based on the statistics for environmental permitting that have been analyzed and published by the Swedish Environmental Protection Agency [120], and the yearly grid expansion capacity is based on the 5-year period with the largest increase in industrial electricity use in Sweden. The downstream part of Scope 3 emissions is included for the refinery and ironmaking sectors, since the aim of electrifying the operations at these sites also includes the mitigation of the downstream emissions.

In the model, CO_2 emissions budgets can be set, and CCS can be used as a bridging technology to mitigate emissions if the rate of electrification is not rapid enough to stay within the CO_2 budget. This is used to highlight the demand for bridging technologies in different scenarios. A detailed model description, along with the assumptions applied can be found in **Paper V**.

3.3 Case study calculations for biomass availability and costs

The case study calculations are applied to assess the supply potential and costs for biomass use at specific industrial sites. In this thesis, the focus is on logging residues (branches and tops), as this is a residual stream with a clear use case for bioenergy or industrial feedstock purposes.

To estimate the spatially explicit volumes of logging residues, forestry data from the Forest Impact Assessments are used [121], [122]. In this work, the assumption is made that current forestry practices are maintained. This is an important assumption because the logging residue potential is inherently tied to roundwood harvesting activities. The supply potential of logging residues is combined with the demands from different categories of users, to assess the potential of logging residues to substitute fossil feedstocks and to supply bioenergy both as an energy source for BECCS and for industrial processes. Logging residue transportation costs are based on transporting chipped logging residues by trucks (**Papers I** and **II**), trains and ships (**Paper II**). For more-detailed information on the data and assumptions applied, see **Papers I** and **II**.

In the case study in **Paper I**, a situation is explored in which four large pulp mills in different parts of Sweden implement CO_2 capture and supply the additional heat demand for the capture process through combusting logging residues. The existing use of logging residues in the district heating sector around the studied pulp mills is considered, so as to highlight the importance of regional energy supply conditions as an important part of the cost for CO_2 capture. For the case study performed in **Paper II**, the demands for bioenergy and biogenic carbon from future users are estimated based on announced projects for BECCS, heat and power generation, and liquid biofuel and DRI production. Current users of logging residues in the district heating sector are also included in the study. The potentials for logging residues to be used in the considered projects are assessed on a regional level, where supply-demand balances are established. Regional marginal cost curves are produced, based on maintained regional transportation and the use-patterns of logging residues, giving an indication of the supply cost as a function of the logging residue out-take in the region. The costs to transport logging residues from high-supply regions to high-demand sites are assessed.

3.4 Studied industrial system

Figure 5 maps out the system studied in this thesis. The considered existing industrial and CHP plants are sites with total emissions (biogenic plus fossil) of >100 ktCO_2/year. Different parts of the work study different selections of the sites shown on the map. The pulp mills chosen as case studies to assess the regional potential for logging residues to act as a heat supply for BECCS in **Paper I** are indicated with squares, and the nine existing industrial sites studied in **Paper V** are highlighted as red diamonds in Figure 5. Note that two of the refineries studied in **Paper V** are in the same city on the west coast (Gothenburg). Biomass terminals and new potential users of biomass considered alongside the already existing iron ore processing and refinery industries in **Paper II** are shown. In the CCS supply chain modeling performed in **Papers III** and **IV**, the existing sites are included, along with the harbors (marked as purple plus-signs) and the Kollsnes CO_2 storage hub.

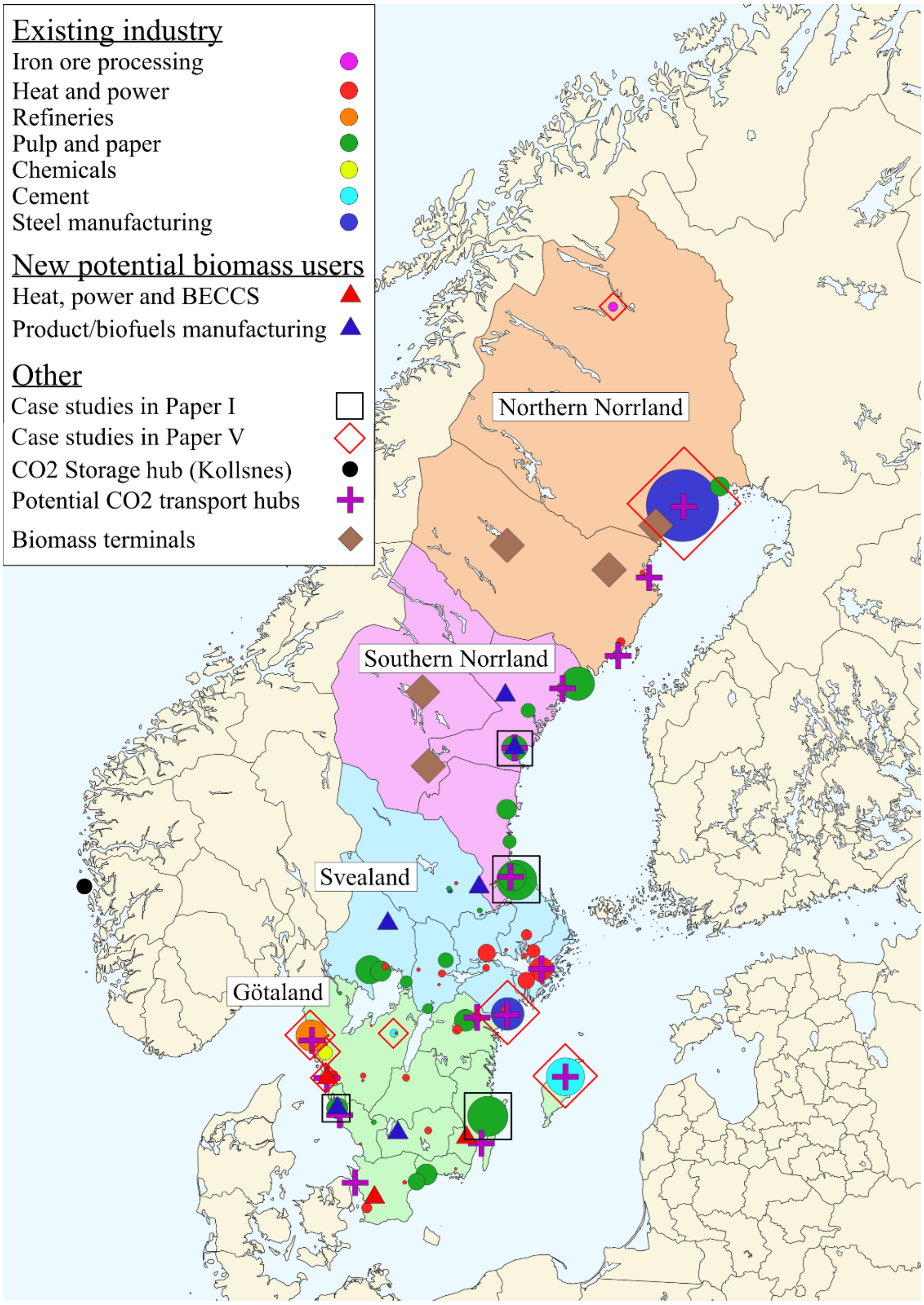


Figure 5. Map of the system studied in this thesis, with indications of the sizes of existing industries, scaled according to CO_2 emissions, ranging from 0.1 to 3.3 $MtCO_2$/year.

4. Results

This chapter highlights and discusses some of the results obtained from the work performed in this thesis, focusing on the Aims outlined in Section 1.1. Section 4.1 presents results regarding the supply potential and costs of using logging residues for industrial applications. Section 4.2 presents results in relation to the costs and deployment of CCS systems in Sweden under different incentive structures. Section 4.3 presents results on the impacts of permitting times and grid infrastructure expansion capacity on industrial electrification. Section 4.4 presents some summarizing results, combining different learnings from the thesis work.

4.1 Opportunities for logging residues to enable BECCS or substitute fossil feedstocks

In this section, the supply potential of logging residues is discussed and placed in perspective in relation to current use and potential future use cases. Developments in EU policy regarding biomass and bio-energy use (see Section 2.3.2) are relevant for the results presented here, since they could impact harvesting activities and, thus, alter the potential for logging residue extraction.

4.1.1 Marginal costs for logging residues with current use patterns

Figure 6 presents the regional marginal cost curves from **Paper II**, assessing the cost for logging residues in an analysis in which the current industrial landscape and logging residue use are assumed to be maintained without any changes. Note that the marginal costs only consider the costs for physical extraction and transportation of logging residues, and they do not reflect the market price, which additionally includes, for instance, administration costs and profit margins that can vary depending on the business agreement.

In total, the supply potential of logging residues in Sweden is estimated to be about 21 TWh/year, with 27%, 25%, 27%, and 21% of the estimated potential in Götaland, Svealand, southern Norrland, and northern Norrland, respectively. Although the supply potential seems to be relatively evenly distributed across the four regions, the northern and southern Norrland regions are significantly larger in terms of area than Svealand and Götaland. The differences in logging residue potentials between regions are due to varying forest conditions across the country, which reflect the area of productive forest land, the forest growth rate, and forest management and harvesting activities. The actual extraction of logging residues was 7.8 TWh in Year 2020 [60], corresponding to 37% of the calculated potential. The extraction of logging residues also differs substantially between the regions: 83% of the supply potential is used in Götaland, 48% in Svealand, 7% in southern Norrland, and 1% in northern Norrland.

Supply costs increase from south to north, mainly due to the longer transportation distances from the forest to the railway terminal or end-user. For an expected extraction of 3 TWh/year, the calculated supply costs from the southernmost to the northernmost region are 12.9, 13.8, 14.4, and 19.3 €/MWh, respectively. In Götaland and Svealand, logging residues are currently used extensively for district heating and power production [124], and the transportation distance between the forest and the end-user is relatively short compared to northern Sweden.

The results imply that it is cost-effective to prioritize the mobilization of logging residues close to new users when utilizing existing transportation modes, mainly truck transport directly to an end-user or via a terminal with onward train transportation, to keep the supply costs down.

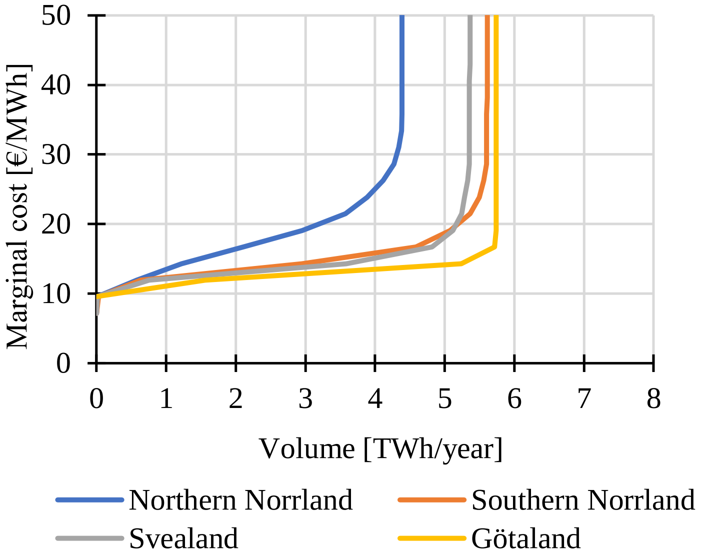


Figure 6. Calculated marginal costs for logging residues considering current use patterns. Note that the marginal costs only consider the costs for the physical extraction and transportation of logging residues according to current usage patterns, and they do not reflect the market price, which in addition includes, for example, administration costs and profit margins that can vary depending on the business agreement. Source: Paper II.

4.1.2 Future regional logging residue supply potential and biomass demand

Figure 7 provides estimations of the regional logging residue supply potential and biomass demand based on the work described in **Paper II**. The biomass demand is estimated based on announced projects for different categories of users. The other new users category displayed in Figure 7 summarizes several smaller liquid biofuel production and heat and power projects with estimated demands that are small compared to those for the existing refinery and iron and steel industries. The left-most part of the graph includes the demands only from heat, and power (and heat and power plants with BECCS) applications and the estimates of the supply potentials for the early 2030s. The right-most part of the graph includes the demands from manufacturing (liquid biofuels and carbon for ironmaking) and the estimates of the supply potentials for the early 2040s. Thus, the results represent a situation in which the near-term use of logging residues can be expected for heat and power, and the long-term use case will also include manufacturing.

When only the demands from heat and power applications are included, the supply potential in each region outweighs the demand. Logging residue use in heat and power applications is conventional and already extensively applied today, and since the regional balances indicate that the supply can meet the demand regionally, similar transportation solutions, mainly trucks, are applicable. However, when the demands for manufacturing are also included, the demand drastically outstrips the supply potential in Götaland (southern Sweden), with an excess of logging residues in three out of the four of the remaining investigated regions further north. This imbalance is primarily due to the large estimated demand for biogenic carbon from the refinery sector in Götaland. This regional difference between the logging residue supply and biomass demands highlights some important aspects. The excess logging residues in regions further north could be mobilized and transported to the south to supply some fraction of the biogenic carbon demand of the refineries. However, as established in Section 4.1.1, the marginal cost for the logging residue supply is highly dependent upon the transportation distance when current transportation solutions are applied (mainly trucks and limited use of trains from terminals). This presents a problem that needs to be overcome if long-distance transportation of logging residues is to be considered. Moreover, the supply-demand balances highlight that carbon sources other than logging residues are needed to supply the entire future demands. Thus, the import of biomass or the utilization of captured CO_2 should be explored, in addition to the use of other waste streams from forestry.

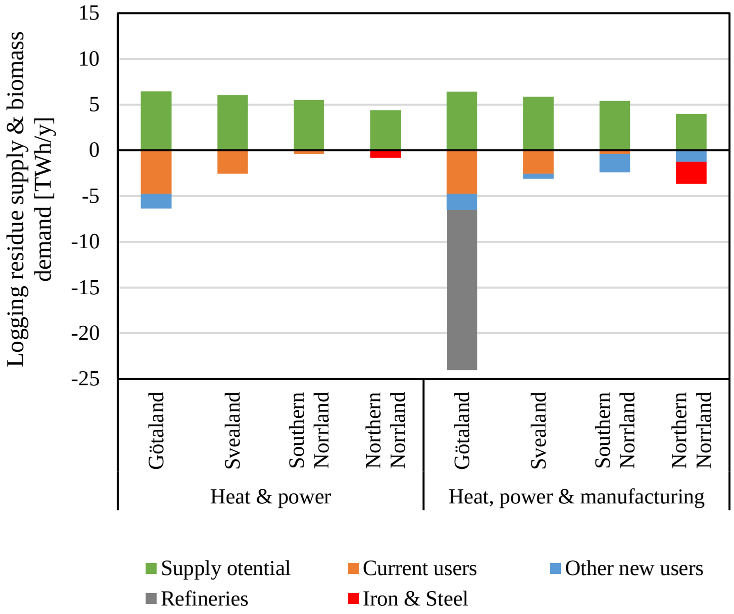


Figure 7. Regional supply-demand balances comparing the logging residue supply potentials with the estimated biomass demands in Götaland, Svealand, southern Norrland and northern Norrland. Adapted from Paper II.

To supply the refineries in southern Sweden with biogenic carbon from regions located further north, it might be beneficial in both practical and economic terms to supply methanol rather than chipped logging residues. Given the higher energy density of methanol compared to chipped logging residues, the transportation costs can be significantly reduced by transporting methanol. To highlight the cost reduction for methanol transport, as compared to logging residues transport, Figure 8 shows the costs (bars) for logging residue mobilization and onward transport at one specific terminal in Norrland, as a function of the onward train transportation distance. Furthermore, the reduction in cost derived from transporting methanol instead of logging residues (line) is shown. The train transport cost increases significantly with train transportation distance, from around 2.5 €/MWh for 250 km to almost 15 €/MWh for 1,500 km. Furthermore, for a train transportation distance of 250 km, the cost reduction is marginal, at only 2 €/MWh. However, as the train transportation distance increases up to 1,500 km, the cost reduction from transporting methanol by train instead of transporting logging residues increases to 12 €/MWh. These results highlight the potential for decentralized methanol production to reduce significantly the cost of transportation over long distances. Another interpretation is that for any given distance, the cost reduction shown corresponds to the economies of scale of centralized methanol production that would be needed to make the transportation of logging residues more cost-efficient. In addition to the potential benefit in terms of cost of transporting methanol to refineries as opposed to transporting logging residue chips, the former is likely to be significantly more practical, since methanol storage tanks are likely to take up a lot less space than a wood chip storage at the refinery.

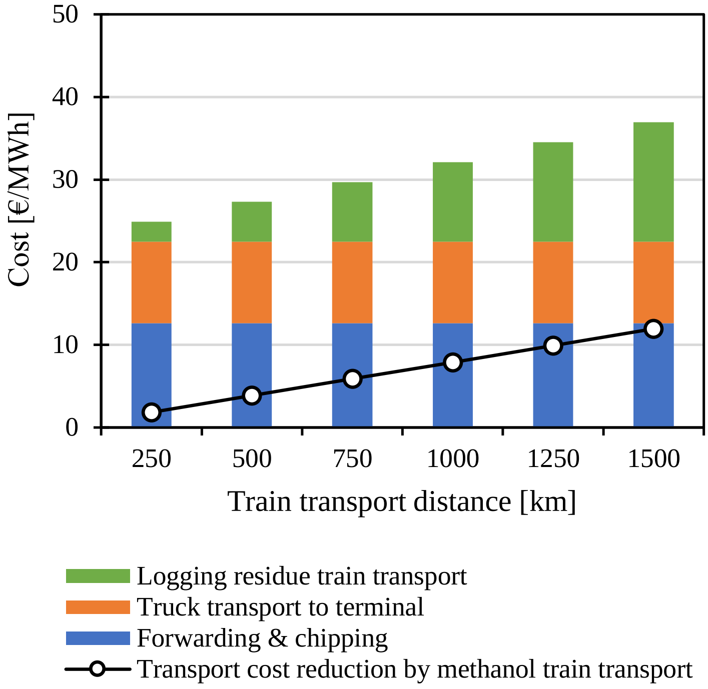


Figure 8. Costs (bars) for logging residue mobilization and onward transport along with the transportation cost reduction (line), as a function of the train transportation distance. Source: Paper II.

4.1.3 Logging residues to supply heat for BECCS

An alternative use for logging residues is as a fuel to supply the additional heat demand imposed by implementing BECCS at existing industrial sites. The potential for BECCS in Sweden is significant, with several large biogenic point sources of CO_2 in both the pulp and paper and heat and power sectors, as shown by Garðarsdóttir et al. [53] and Beiron et al. [54]. **Paper I** explores a scenario in which regional logging residues act as an enabler of BECCS by supplying the heat demand for capture at existing pulp mills located in different parts of Sweden.

Figure 9 shows the amounts of logging residues that are available for four pulp mills included in the case study, taking into account the existing demands from nearby CHP plants by subtracting the logging residues already used at CHP plants from the logging residues available for the studied pulp mills. The mills, which are called the '4.7-GWh plant' and '5.3-GWh plant', are respectively located on the west and east coasts in the southern part of Sweden. The 3-GWh plant is located near Gävle (around 150 km north of Stockholm) and the 3-GWh plant, North, is located in Östrand (around 350 km north of Stockholm). See Figure 5 for an indication of the case study mill locations. The two plants located in the south of Sweden (4.7-GWh and 5.3-GWh plants) have far lower amounts of logging residues available to them, since southern Sweden contains the majority of the population and has more district heating systems that utilize bio-fired heat and power plants than the northern parts of the country.

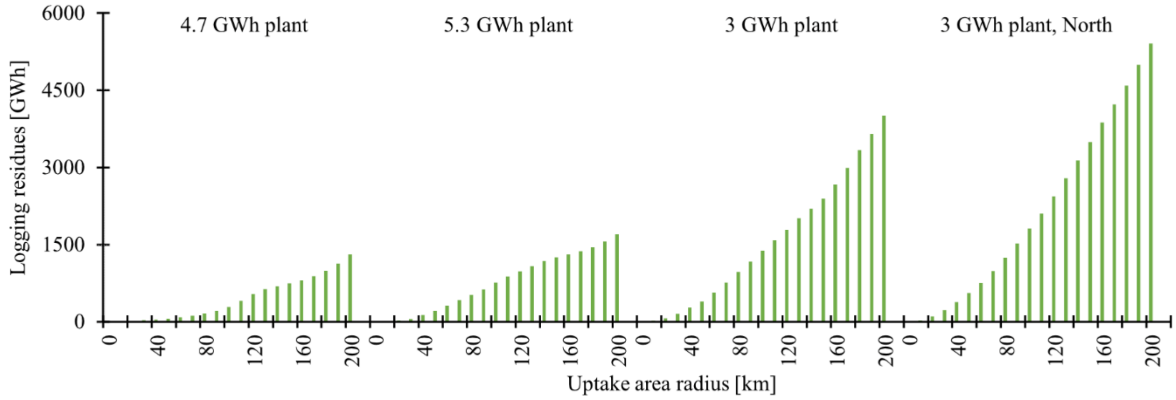


Figure 9. Available levels of logging residues for the case study mills included in Paper I as a function of the radius of the uptake area around the plant. Existing usage of logging residues from bio-fired CHP plants in the uptake area is also considered. Source: Paper I.

Figure 10 shows the resulting specific logging residue costs in €/tCO_2, i.e., the cost per tCO_2-captured for supplying heat using regional logging residues, for the four mills included as case studies. Since the costs for supplying logging residues are highly distance-dependent, increasing transportation distances lead to higher costs. This results in the sites that are situated in the south facing higher costs for lower volumes of CO_2-captured, in addition to having higher costs at the maximum capture potential. The more-rapid increase in costs and the higher cost for achieving maximum capture are attributable to a lower availability of logging residues, which implies mobilizing logging residues over a wider area to reach a given volume. Moreover, it should be pointed out that for the plants located in southern Sweden, the maximum capture potential in this analysis is limited by the logging residues that are available for supplying heat to the capture process, rather than the emissions of CO_2 from the site. These results highlight the fact that regional differences in energy supply potential play an important role when decisions are being made on where to implement CO_2 capture, particularly if regional biomass resources are planned to be used to fuel the process.

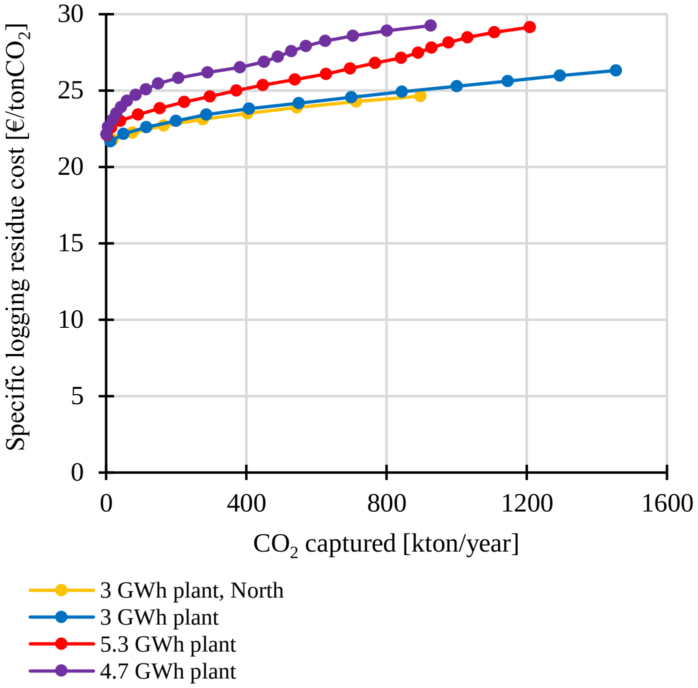


Figure 10. Specific cost of logging residues as a function of the CO_2 captured at the four case study mills in Paper I. The costs are highly distance-dependent, showing that more logging residues can be mobilized closer to the sites of the two plants located further north in Sweden (3-GWh plant and 3-GWh plant, North).

4.2 Deployment of CCS systems

The deployment of large-scale CCS systems is associated with high costs and relies on incentives to motivate the implementation of CO_2 capture. This section presents results in relation to the costs of CCS systems, along with the impact of specific incentives used to motivate the deployment on how such systems are deployed.

4.2.1 Cost of CO_2 capture and transport systems

Figure 11 shows a marginal cost curve calculated using the CCS supply chain model developed in this work, covering the existing industrial and heat and power plants shown in Figure 4. To generate the marginal cost curve, CO_2 capture and transportation infrastructure are implemented for one emissions source at a time, and sorted based on the total cost. Figure 8 shows that large parts of the CCS system could be implemented at a cost for capture, liquefaction and transportation of <100 €/tCO_2. Furthermore, it is evident that a few smaller projects have costs that are significantly higher, due primarily to the high specific cost for capture that result from low annual emissions. The costliest project has a calculated cost of around 720 €/tCO_2. Furthermore, it can be seen that the largest projects are not always the least-costly when transportation infrastructure is included, despite typically having the lowest cost for capture and liquefaction. This is due to the larger projects typically being implemented earlier, which means that they carry the costs for an infrastructure that can also be utilized by smaller projects that are implemented subsequently.

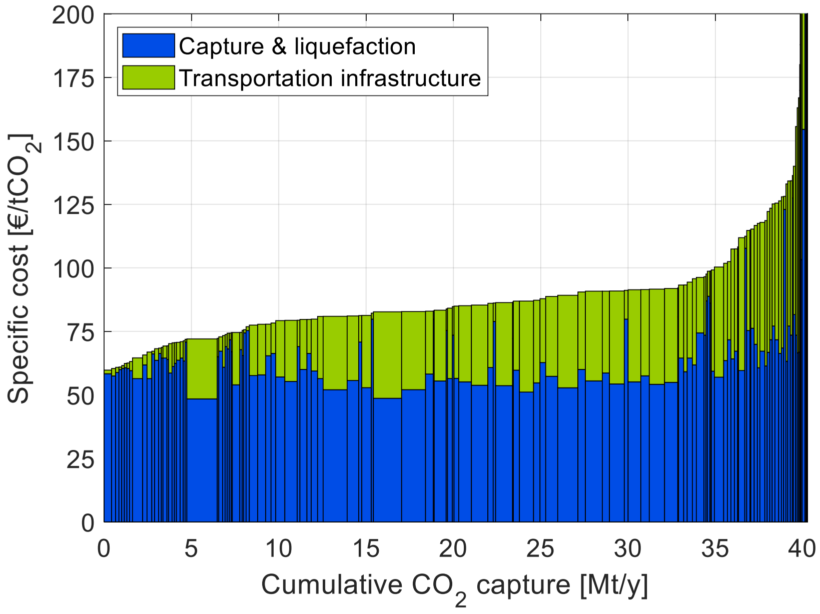


Figure 11. Marginal abatement cost curve calculated using the CCS supply chain model that includes the costs for capture, liquefaction and transportation of CO_2.

Figure 12 presents selected results from the sensitivity analysis performed in **Paper III**, to highlight the impacts of parameter changes on the cost structure of CCS systems. To incentivize capture implementation, the sensitivity cases are modeled with biogenic capture targets of 1.8 $MtCO_2$/y by Year 2030 and 10 $MtCO_2$/y by Year 2045, along with a cost for fossil emissions that increases throughout the period to reflect the EU ETS [119]. The specific cost of the system lies in the range of 69–94 €/tCO_2 for the different cases in the sensitivity analysis. The sensitivity cases shown in Figure 12 assume the following changes from the base case: investment costs for site installations (capture and liquefaction) are increased by 50% (*Site CAPEX*1.5*); the transportation fuel costs are doubled (*Fuel cost*2*); and heat integration is performed, decreasing by 50% the reboiler heat demand that needs to be covered by external energy sources (*Heat integration*). Looking at the cost structure of the system in Figure 12a, the cases with the strongest influences on the system cost are the *Site CAPEX*1.5* case on the high side, and the *Heat integration* case on the low side. The transportation infrastructure costs mostly comprise the cost for ship transportation.

The *Site CAPEX*1.5* and *Heat integration* cases have in common that they modify the costs of the site installations (capture and liquefaction), which make up the largest part of the total system cost. Thus, the total system cost is most-sensitive to cost uncertainties at the site level. Looking at Figure 12b, The *Fuel cost*2* case decreases the emissions intensity from the transportation infrastructure, primarily due to a decrease in truck fuel use, since the model is choosing to implement capture at sites that generally are located closer to the coast.

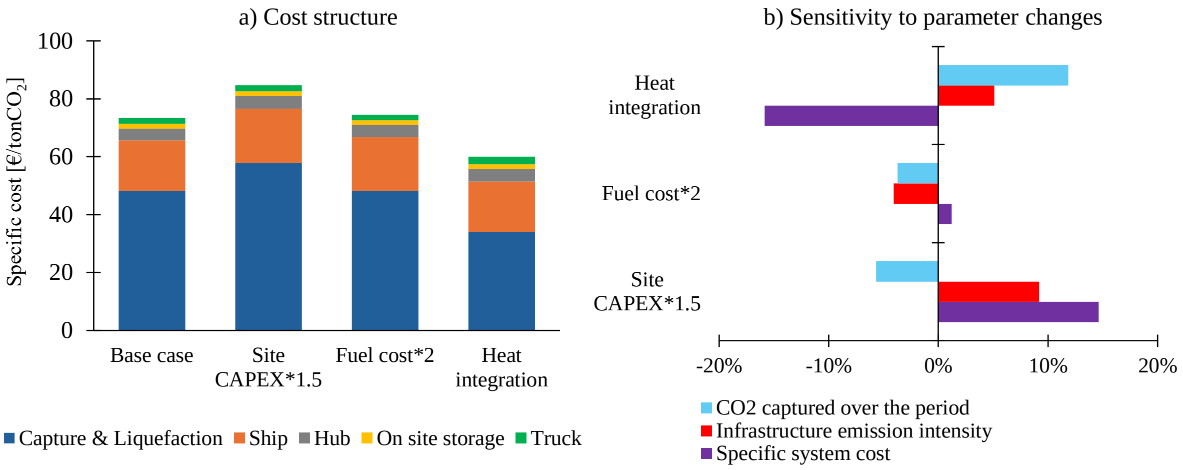


Figure 12. a) Cost structures of the industrial CCS system for the different sensitivity cases. b) Sensitivities for some performance indicators of the CCS system. Three sensitivity cases are shown in comparison to the Base case modeled in Paper III. To incentivize capture implementation, the cases are modeled with biogenic capture targets of 1.8 MtCO$_2$/year by Year 2030 and 10 MtCO$_2$/year by Year 2045, along with a cost for fossil emissions that increases throughout the period. Adapted from Paper III.

In addition to the costs for CCS equipment and the associated transportation infrastructure, the economic assumptions applied will impact which types of systems are deemed to be cost-optimal. Figure 13 shows the share of biogenic vs fossil CO$_2$-captured (left *y*-axis) and the year in which the first investment is made (right *y*-axis), as a function of the discount rate applied. The emissions budget used allows total emissions of 50 MtCO$_2$ over the period of 2025–2050, and BECCS can be used to offset fossil emissions. The higher the discount rate used, the greater the tendency to postpone investments in CO$_2$ capture and to rely on subsequent BECCS offsetting of early fossil emissions. The tendency to postpone investments mirrors the effect of using a high discount rate when performing investment calculations on an individual project level. A higher discount rate will require a higher profit margin for a given investment (e.g., a higher CO$_2$ price as an alternative cost), which will tend to make investments appear economically unfeasible in the near term.

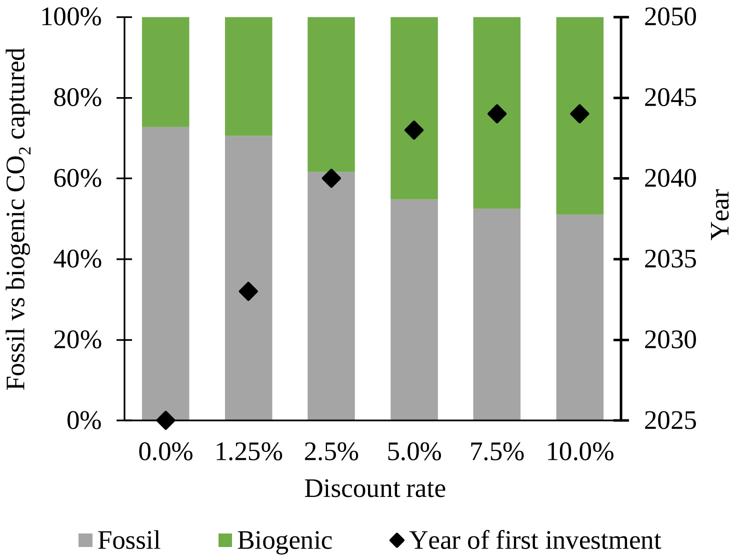


Figure 13. Shares of biogenic vs fossil captured CO$_2$ (left y-axis) and year in which the first investment in CCS equipment is made (right y-axis) for an emissions budget of 50 MtCO$_2$, with the possibility for the model to use BECCS, for different discount rates. Adapted from Paper IV.

4.2.2 Impacts of incentives on CCS system development

Figure 14 shows the CCS system configurations for Year 2030 and Year 2045 for two different incentive scenarios. Figure 14, a and b show the results when the only incentive used to motivate capture installations is setting capture targets for biogenic CO_2 in accordance with the levels proposed in the SOU 2020:4 public inquiry. These levels are 1.8 $MtCO_2$/y in Year 2030 and 10 $MtCO_2$/y in Year 2045. In Figure 14, c and d, the same capture targets for biogenic CO_2 are combined with an increasing cost for emitting fossil CO_2 to reflect the prices in the EU ETS. From Figure 14, it can be seen that in the case that combines a fossil emissions price and capture targets for biogenic CO_2, capture implementation is shifted away from sites that emit large amounts of only biogenic CO_2 (mainly in the pulp and paper sector) to sites in the waste-fired heat and power sector that emit a mixture of biogenic and fossil CO_2 (assumed to be 65% biogenic and 35% fossil in the modeling). Implementing CCS in the waste-fired heating sector instead of the pulp and paper sector with the introduction of a CO_2 price is explained by the fact that the captured fossil CO_2 helps to mitigate the system cost by reducing fossil emissions, at the same time as the biogenic share of the emissions helps to fulfill the capture target. This effect shows that implementing incentives that involve assigning different values to biogenic and fossil CO_2 capture can exert significant effects on the cost-optimal system composition. In this specific case, waste-fired heat and power plants become interesting for capture when the value to the system of mitigating fossil CO_2 to reduce system costs can be combined with fulfilling capture targets for biogenic CO_2.

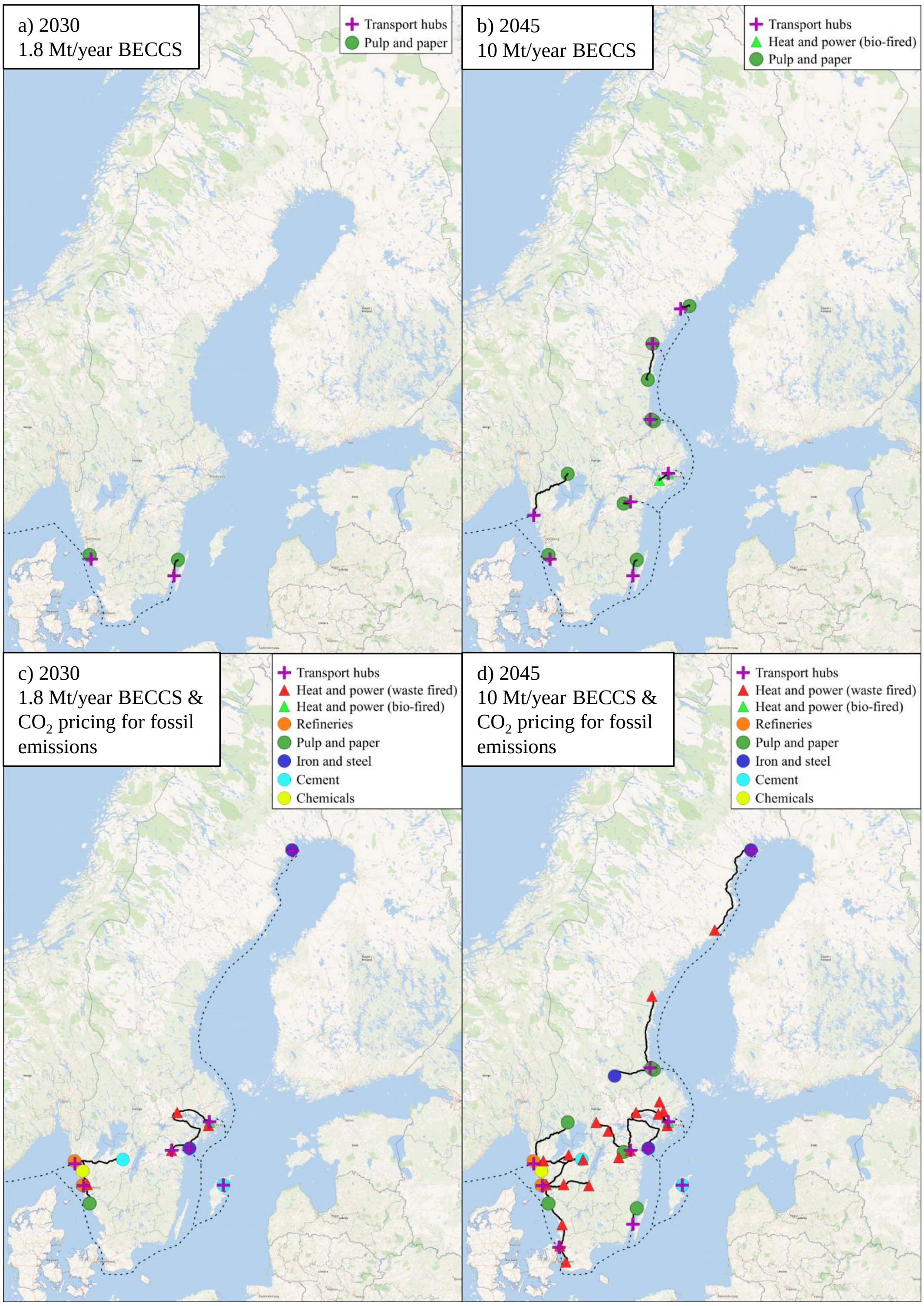


Figure 14. CCS system deployment in one case in which the only incentive for CO_2 capture is biogenic capture targets (panels a and b), and one case in which biogenic capture targets are combined with the CO_2 pricing for fossil emissions (panels c and d). Adapted from Paper III.

4.3 Industrial electrification under different permitting times and grid infrastructure construction capacities

Figure 15 shows: a) the number of sites electrified; and b) the cumulative unabated emissions over time for a *Base scenario* and two additional scenarios investigated in **Paper V**. The analysis utilizes the model described in Section 3.2.2. The *Best-case scenario* presents a scenario in which the grid construction pace is doubled and permitting times are halved compared to the *Base scenario*, i.e., good conditions for industrial electrification. The *Worst-case scenario* applies the opposite changes, i.e., bad conditions for industrial electrification.

Looking into the modeled *Base scenario*, the nine included industrial sites have electrified their operations by Year 2043, which is in line with the national Swedish target of reaching net-zero emissions by Year 2045. However, some of the industries included in the modeling have net-zero targets that are more ambitious than the national targets, aiming to decarbonize their operations already around Year 2035. Reaching such targets could prove challenging considering that four of the nine industrial sites included are electrified after Year 2040 in the *Base* case. In the *Best-case scenario*, all sites are electrified already in Year 2037, facilitated by rapid permitting procedures and a high grid expansion capacity. In the *Worst-case scenario*, however, one site cannot be electrified before Year 2055. If the modeling period is extended, all electrification projects cannot be completed until Year 2058 in the *Worst-case scenario*. Looking at the cumulative unmitigated emissions, there is a large difference between the *Best-case* and *Worst-case* scenarios, ranging from around 850 $MtCO_2$ over the period in the *Best-case scenario* to around 2,150 $MtCO_2$ over the period in the *Worst-case scenario*. In other words, going from short permitting times and a high capacity to expand the electricity grid to long permitting procedures and a low pace of expansion of the grid can cause the unmitigated system emissions to increase by a factor of about 2.5.

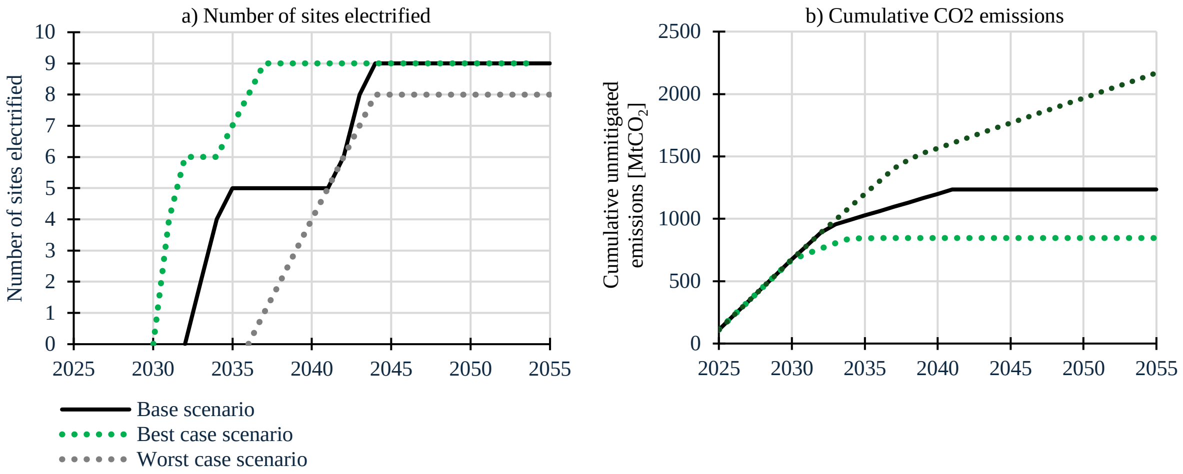


Figure 15. Numbers of sites electrified (panel a) and cumulative unabated emissions (panel b) over time (2025–2055) for three scenarios with varying permitting times and electricity grid expansion capacities. For the modeled Best-case scenario, the permitting times are doubled and the electricity grid construction capacity is halved compared to the Base scenario. The opposite changes are made in the Worst-case scenario. Adapted from Paper V.

Figure 16 shows the times required to electrify the considered industries for a wide range of permitting times and grid construction capacities. In addition, both *high* and *low coordination* cases (for a description of the coordination cases, see Section 3.2.2) are tested for each combination of grid construction capacity and permitting time. In Figure 16, the effect of diminishing returns in terms of the impact on the speed of the transition as a function of increased grid installation capacity can be observed. Once the grid installation capacity reaches 300 MW/year, the time taken for the system to transition is only marginally decreased with any further increase in capacity. On the other hand, for grid installation capacities below 300 MW/year, each addition of 100 MW/year yields a drastic reduction in the time taken to electrify the industry. This non-linear behavior shows the importance of ensuring sufficient grid capacity expansion to avoid outcomes in which the electrification takes multiple decades longer than the climate targets of Year 2045. The higher the competition for infrastructure expansion, the more important it will be to ensure a high construction capacity to get the projects, and thus the CO_2 mitigation, deployed. For the system to be able to electrify fully before Year 2050 for all of the investigated permitting times with high coordination, the possibility to accommodate at least 300 MW/year of additional industrial demand to the grid must exist. If a grid construction pace of 200 MW/year is applied, only permitting times of up to 3 years will ensure full electrification before Year 2050.

Furthermore, the impact of low coordination between actors has a stronger effect when permitting times are long (compare the dots and the crosses of the same color in Figure 16). This is because low coordination is modeled in such a way that permitting procedures on the site and infrastructure level must be run consecutively, meaning that two long permitting procedures need to be undertaken for any project to become operational.

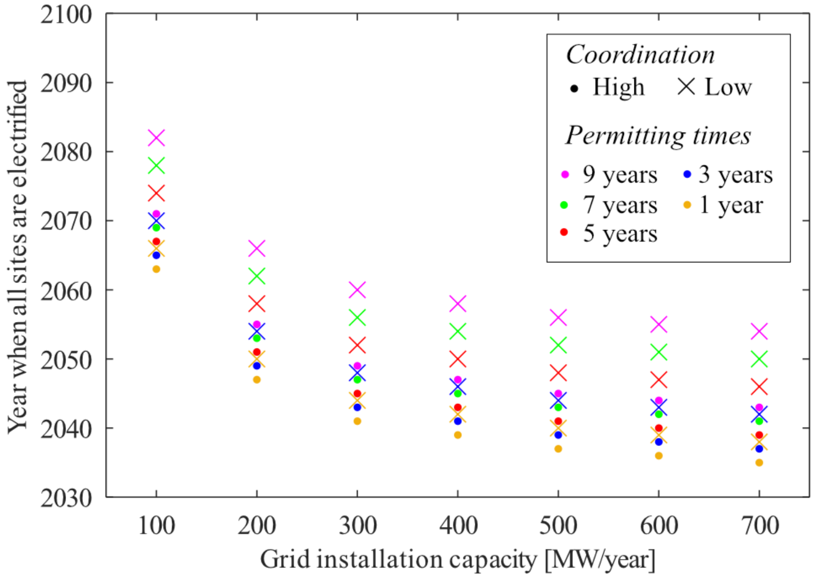


Figure 16. Permitting times of 1–9 years (color-coded) are modeled for grid construction capacities in the range of 100–700 MW/year. Each combination of permitting time and grid construction capacity is run with high (dot) and low (x) coordination between the industrial electrification projects and infrastructure development. The total estimated additional power demand from the included industrial sites is around 3.3 GW. Source: Paper V.

4.4 Summarizing results

The different technological pathways and infrastructures studied in this thesis are associated with different opportunities due to their cost structure and the regional conditions in which they are implemented. This section presents summarizing results that combine learnings from different aspect of the thesis.

4.4.1 Regional conditions for CO_2 transportation, logging residue out-take and the electricity grid

Figure 17a shows a heat map of the logging residue excess in Sweden, together with the CO_2 shipping costs from the harbors considered (see Figure 5). It highlights areas that are likely have a deficit of grid capacity going into Year 2030 (based on planned electrification and grid expansion projects, as assessed by the consultancy company SWECO [125]). Figure 17b shows a heatmap of the Year 2020 emissions from the Swedish industrial and district heating sectors, in addition to announced projects for CO_2 mitigation in existing industry, to enable a comparison of the conditions for infrastructures in emissions-intensive regions of Sweden.

The CO_2 shipping cost is higher in the north of Sweden, due to the longer distances to storage projects in the North Sea. Furthermore, the lower prevalence of utilization of logging residues due to a lower density of CHP plants in northern Sweden result in a higher logging residue excess, as well as a higher cost for mobilization. Thus, logging residue excess regions correlate with regions of high cost for CO_2 transportation. For new BECCS projects that are planning to use forest residues, this represents a potential tradeoff, where the benefit of higher logging residue availability in the north can be outweighed by higher costs for CO_2 transportation, and vice versa in the south of Sweden. For other decarbonization projects, the tradeoff between logging residue availability and CO_2 transportation costs could help inform decisions regarding which technological pathway to pursue between CCS and bioenergy use. Regarding the expected lack of grid capacity, the highlighted areas are typically urban areas, some of which are currently experiencing a lack of capacity. The situation is expected to improve until Year 2030 in some areas, such as Stockholm and the surrounding areas, while worsening in others, such as northern Sweden and the west coast, due to expected electrification projects outpacing the planned expansion of the grid.

Regions with a risk of insufficient grid capacity correlate with regions of high industrial activity. The overlap between the plans for expansive electrification projects in the industrial sector and the areas identified as likely to have grid capacity problems highlights again the importance of increasing the pace of grid infrastructure deployment to enable the decarbonization of industry. In addition, should electrification projects face delays due to a lack of grid infrastructure capacity, using logging residues to substitute fossil energy sources is more feasible in the north, while CO_2 transportation costs favor CCS in the south of Sweden.

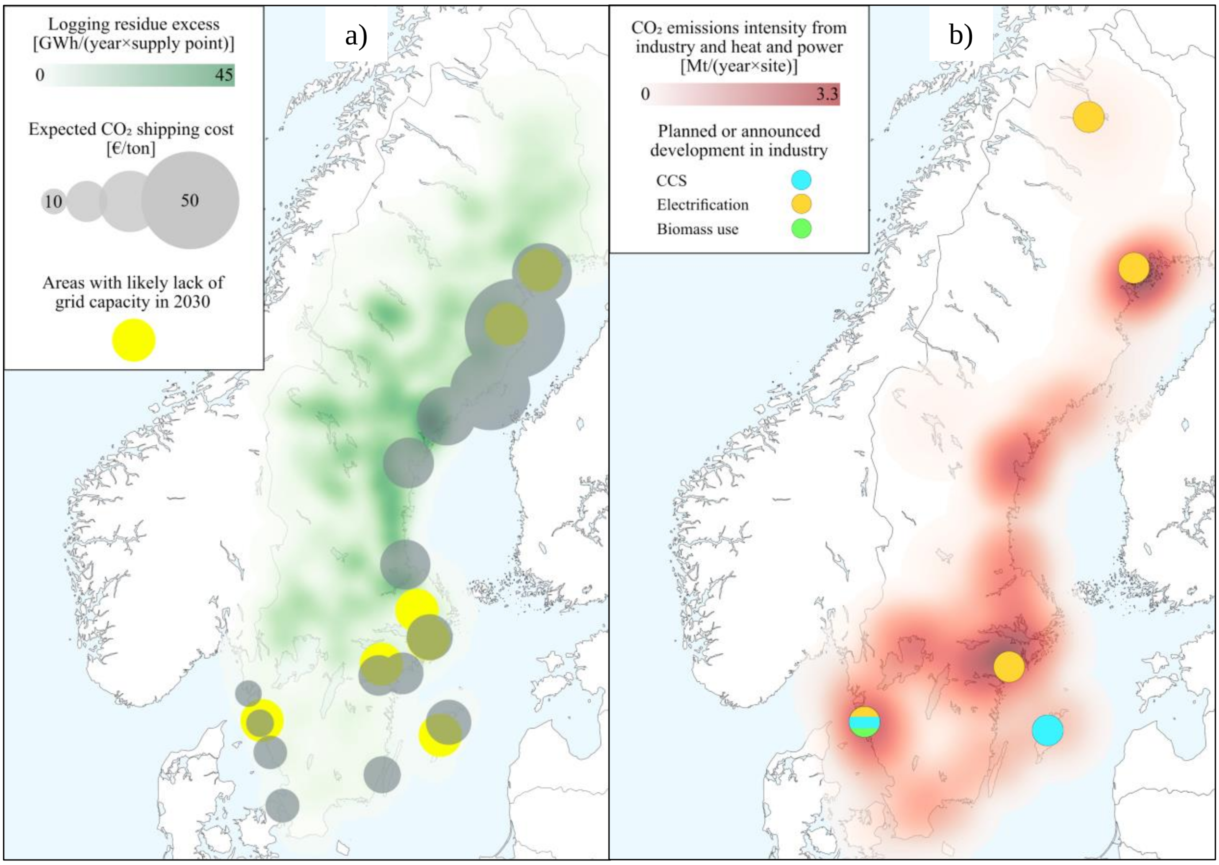


Figure 17. Map of Sweden displaying: a) estimated logging residue excesses, with calculated CO_2 shipping costs to Kollsnes, Norway and areas with expected deficit of electricity grid capacity in Year 2030 according to SWECO [125]; *and b) emissions intensities from industry and heat and power, along with announced developments in existing industry.*

4.4.2 Investment cost distribution

Figure 18 shows an indicative investment cost distribution for CO_2 mitigation between the site installations and the infrastructure for electrification (assumed plasma burners), CCS, and drop in logging residue use at the cement plant in Slite (on the island of Gotland), which emits around 2 $MtCO_2$/year. Note that since the costs used to produce the results presented in Figure 18 are based on different sources and are all associated with some level of uncertainty, they should be taken as indicative.

Electrification has a high share of the investments at the site level (even in a case where sub-sea cables must be installed), which highlights that even though electrification is the long-term goal for many industries, CCS and biomass are attractive short-term solutions for the plant owners. CCS and, to an even greater extent, biomass exhibit the opposite phenomenon, whereby a considerable share of the investment is in the required infrastructures and is not directly seen by the plant owner. In these cases, securing long-term financing for the actors supplying the required infrastructure is important, since the "lock-in" effect of high upfront investments at the site level is not present. On the other hand, for capital-intensive activities at the industrial site level, long-term and clear policies to ensure that the investments are worthwhile in the long term are of the utmost importance. High investment costs for the process technology, infrastructure or both further motivate high-level coordination between the actors, as shown to be necessary for a timely transition in Figure 16, to avoid unutilized capital-intensive assets and missed value generation.

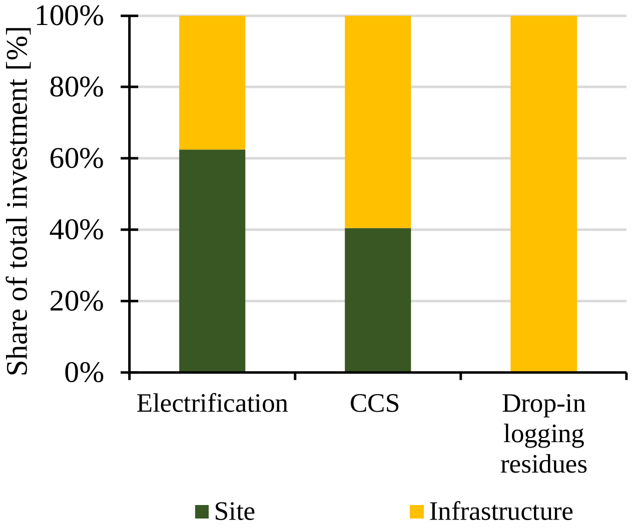


Figure 18. Indicative investment cost distributions between the site installations and infrastructure for electrification, CCS, and logging residue use at the Heidelberg Materials cement site in Slite. Note that the costs are associated with uncertainties and should be taken as indicative. Investment in plasma technology is based on the CemZero report [25]. Investment in grid infrastructure is based on an estimate from the Swedish TSO of 6 billion SEK (roughly 530 M€). Investment costs for CCS are taken from Paper III. Logging residue supply costs are from Paper II and assume there is the possibility to use some amount of chipped logging residues without process modification.

5. Summarizing discussion

This chapter discusses some relevant Master's degree thesis work that has been performed that further develop and utilize the cost-minimizing CCS supply chain model developed within the scope of this thesis work. Additionally, potential developments and barriers related to the transition of industry, of relevance for the thesis is discussed.

5.1 Further developments of the CCS supply chain model

The CCS supply chain model was further developed within the scope of several Master's degree theses that were completed by others during the period of this PhD thesis. This section highlights and discusses a few of the results from two such Master's degree theses.

5.1.1 Comparing different pressure levels for CO_2 transport

The 2024 Master's degree thesis of Gunnarsson [126], investigates (among other issues) the impact of allowing for different CO_2 conditions during transportation, opening up the possibility to compare the 7 barg, 15 barg and dense-phase pipeline cases. Figure 19 compares the costs of the system when the 7 barg, 15 barg, and pipeline systems are used and cannot be mixed. In the results shown in Figure 19, a cost for final storage of 50 €/tCO_2 was assumed. From Figure 19, it is clear that the pipeline system as modeled is not favorable from a cost perspective in the Swedish context, owing to the geographically distributed, relatively low-flow CO_2 sources that require transportation over long distances. It seems likely that the cost of pipeline transport could be significantly decreased if a backbone solution was to be deployed in Sweden, connecting most of the major emitters to the storage location. However, such a project would require extensive planning and coordination and would be much less flexible than a system based on ship transportation, especially during a ramp-up phase. Furthermore, from Figure 19, it can be seen that the cost for the 7 barg system is lower than that for the 15 barg system, which is in line with previous research [61].

Thus, for a large-scale Swedish CCS system, utilizing shipping for offshore transportation seems to be favorable from a cost perspective, in addition to the flexibility in ramping up that is afforded by ships as opposed to pipelines.

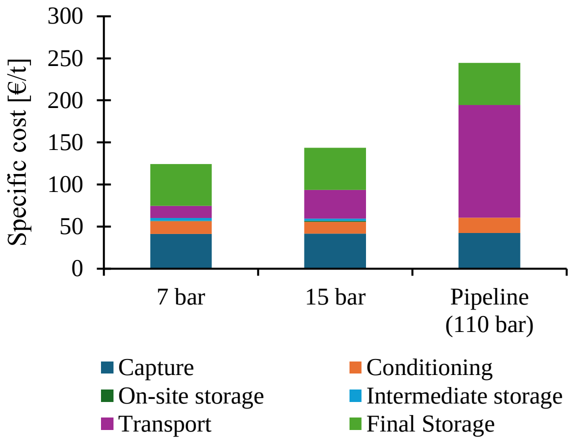


Figure 19. Comparison of the specific costs for a CCS system in Swedish industry based on the 7 barg, 15 barg and dense-phase pipeline transportation systems. Adapted from Gunnarsson 2024 [126].

5.1.2 Biogenic CO_2 or logging residues as a carbon source for refineries

In the 2023 Master's degree thesis of Martinez [127], the cost-minimizing CCS supply chain model was extended to account for CO_2 utilization at a refinery located on the Swedish west coast. Among other questions, the thesis investigates how high demands for both BECCS and bio-CCU influence the costs to supply CO_2 to the refinery for utilization through competition for the resource. Figure 20 compares the costs for supplying biogenic carbon to the refinery in the forms of logging residues and captured CO_2. The costs for logging residues are based on the results from **Paper II** in this thesis and the costs for supplying CO_2 are based on the work of Martinez [127]. The estimates for CO_2 supply present a situation where BECCS is motivated by a monetary value (equivalent to the cost of emitting fossil CO_2 in the EU-ETS). In the low estimate, the demand for carbon from the refinery is 0.6 Mt/year by Year 2035 and 0.8 Mt/year by Year 2040, while the high estimate has a carbon demand from the refinery of 12.8 Mt/year by Year 2035 and 16.5 Mt/year by Year 2040. For logging residues, the low and high estimates are based on the transportation distance, with the low estimate considering logging residue mobilization in southern Sweden, and the high estimate considering mobilization of logging residues in northern Sweden.

In Figure 20, the cost of supplying biogenic CO_2 for utilization increases when the carbon demand becomes high, which increases the costs by about 15%. The supply costs for biogenic CO_2 remain relatively constant for lower demands (up until the high estimate shown in Figure 20), as a lower demand allows for the capture of CO_2 from large biogenic emitters in the system (primarily pulp mills and bio-fired CHP plants), for which the specific costs are relatively low. Once the demands for BECCS and bio-CCU are sufficiently high, smaller sources of biogenic CO_2 need to be targeted for capture, thereby increasing the supply cost. This indicates that BECCS and bio-CCU can co-exist without dramatic cost increases up until the demands from both BECCS and bio-CCU become high, in which case the costs start to increase. For logging residues, the costs increase by around 34% going from the low estimate to the high estimate, demonstrating the sensitivity of the cost to transportation distance.

Furthermore, the cost of supplying carbon to the refinery in the form of logging residues is consistently lower than the cost of supplying CO_2. However, the supply potential of logging residues is more-distributed and constrained than that of biogenic CO_2, due to the prevalence of large pulp and paper mills and bio-fired CHP's in the Swedish system, resulting in a high level of supply of biogenic CO_2 from point sources. Furthermore, the results in Figure 19 do not consider any upgrading of either CO_2 or logging residues supplied to the refinery, so it is important to note that the costs for further processing can change the cost balance between the options. However, on a purely cost of carbon-supply basis, the results indicate that securing a logging residue supply so as to avoid the higher cost of carbon from CO_2 can be efficient.

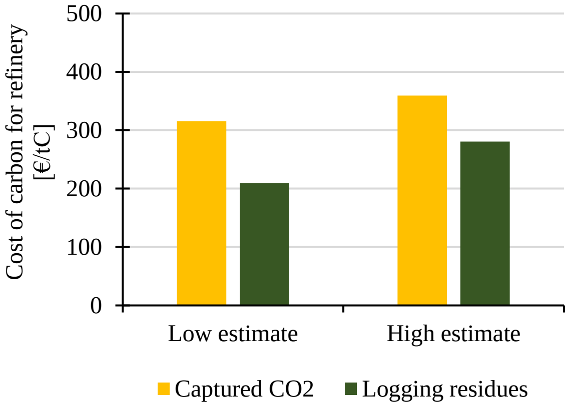


Figure 20. Comparison of the costs to supply carbon from logging residues and captured CO_2*. For captured* CO_2*, the estimation is based on the work of Martinez* [127]*. For logging residues, the estimation is based on Paper II.*

5.2 Experiences gained from recent CCS projects

The two most-advanced Nordic CO_2 capture projects, both of which are located in Norway and part of the Longship CCS project, involve CO_2 capture at a cement plant in Brevik and at a waste-to-energy (WtE) plant in Klemetsrud, Oslo and storage in the Norwegian North Sea. In 2023, the WtE project was put on hold while the costs are reviewed and a plan for cost reductions is put in place. The reasons for the cost increase were inflation, geopolitical instability affecting the energy and material supply chains, and an unfavorable exchange rate for the Norwegian currency. Furthermore, the project underwent a change of the initial port considered for CO_2 transportation. As of yet, it is unclear what the final cost of the project will be, although it is likely to be significantly higher than the typical range of 50–150 €/tCO_2 reported in the research literature, or the cost of 65–100 €/tCO_2 for most larger emitters in this work, also including transport.

This issue highlights important differences between the cost estimations performed in research studies and the actual cost for CCS experienced by early movers. One important difference is that CO_2 transportation and storage are typically calculated in the cost assessments (including the one in this thesis) as the physical cost for the infrastructure required to transport and store a given amount of CO_2. However, from an industry owners perspective, CO_2 transportation and storage will likely be purchased as a service, meaning that the price paid by the industrial operator will not only include the costs for the infrastructure, but also the costs related to profit margins, making the *market price* higher than the *cost*. Furthermore, the costs presented in the literature are typically based on N^{th}-of-a-Kind cost assessments, assuming that the technology has been implemented enough times in the past such that no further benefit from cost reductions can be derived through learning. Some recent works (e.g., [128], [129]) have accounted for this by calculating the First-of-a-Kind (FOAK) costs, in an attempt to account for the fact that technology learning will not yet have occurred for early movers implementing CCS. Taken together, these differences in methodology, along with unexpected cost increases due to the break-down of global supply chains resulting from geopolitical instabilities and pandemics, as experienced in the last few years, are likely to explain a significant part of the difference between the high costs reported by recent CCS projects and the typical range of costs reported in the research literature.

5.3 Uncertainties of forest-based bioenergy

Biomass from forestry has been shown to have the potential to fulfill at least some of the demands from future industrial manufacturing and energy. However, the future of forest-based biomass is uncertain. The supply potential of forestry residues that are suitable for use in future industrial applications is tied to the harvesting of roundwood. Harvesting activity is in turn highly influenced by policy developments, such as the carbon sink level prescribed by the LULUCF regulation or the classification of what constitutes renewable energy in the context of the RED III directive. Sweden has argued for a stance that is pro-forestry and supports bioenergy use in the context of such regulations, and so far, the outcome has been mostly favorable for maintained forestry and bioenergy use. However, this is not guaranteed to be the case in the future, especially with the ongoing discussions on the climate effects of biomass utilization versus increasing the carbon stock. The work related to logging residues in this thesis assumes that forestry practices are maintained, meaning that the results are sensitive to changes in policy that could reduce harvesting activity, and thus, the potential to supply logging residues. If harvesting activity was to be decreased, the estimated supply potential (around 20 TWh/year) of logging residues would be reduced roughly in proportion to the reduction in harvesting activity, due to logging residue outcomes being tied to roundwood harvesting. There would also be consequences for the pulp and paper industry, with reduced production levels as one primary effect.

5.4 Barriers to the industrial transition

Table 2 summarizes the main barriers identified within the results from the thesis work and the literature outlined in the *Background* section of the thesis. The transition of industry towards low CO_2 emissions faces different challenges depending on the technological pathway, and is reliant on the development and implementation of effective policies and infrastructures.

Electrification of industrial processes is costly, and the costs are highly sensitive to the electricity price. Additionally, direct electrification of high temperature processes is typically of relatively low TRL. Electrification also relies on expansion of the electricity grid, the timeliness of which has been shown in this thesis to be highly dependent upon rapid permitting procedures and a high pace of grid construction.

Implementing CCS means that industrial operators need to overcome high additional costs, particularly due to the OPEX associated with the energy penalty imposed by the capture process. This makes the deployment of CCS and BECCS reliant on incentives or the creation of markets for CO_2 to motivate deployment. The results in this work show that different incentives for motivating fossil CCS, BECCS or a combination thereof, yield different outcomes in terms of what sites and sectors are targeted for capture implementation. In addition, CO_2 storage capacity needs to be ramped up, and in the European context, offshore storage seems to be the most likely alternative at present, due to the relatively low public acceptance that can be expected for onshore storage projects.

Biomass use is primarily constrained by the supply potential and costs of suitable assortments, as compared with the low-cost fossil fuels used today. In addition, pre-treatment of biomass is needed for many applications, to suit the demands posed by the process. The results from this work indicate that increased competition is highly likely as fossil fuels are phased out in several sectors.

In addition to the specific barriers listed in Table 2, there are general barriers to the decarbonization of industry. Policy directions, on the national and EU levels, need to be clear in order to make investments in mitigation technology worthwhile in the long term [43]. This is important, since industrial operators work on long investment cycles, and they need to be certain that the policy landscape will yield sufficiently high costs for emitting CO_2 over time to motivate transitioning their production process to low-emissions operation. The recent amendments to the EU ETS discussed in Section 2.3.1 are aimed at creating this outcome, sending a signal to fossil emitters that continuing fossil fuel use will entail high costs, both in the near and longer terms. Moreover, the transition is dependent upon the timing between the deployment of CO_2 mitigation technologies onsite and infrastructure to avoid unutilized investments.

Table 2. Main barriers to further implementation of electrification, CCS, and biomass use identified in the literature and from the results in this thesis.

Technology pathway	**Barriers to further implementation - site level**	**Barriers to further implementation - infrastructure/system level**
Electrification	- Relatively low TRL - Often requires the replacement of conventional process units - OPEX is typically highly dependent upon electricity prices (which are uncertain) - Dependent on expansion of the electricity grid infrastructure	- Long permitting times for electricity grid expansion (linked to public acceptance and inefficient administrative procedures) - Requires skilled workers, secure supply chains and a sufficient pace of investment
CCS	- High upfront costs - High OPEX due to high energy penalty (post-combustion capture) - Dependent upon sufficient storage capacity being installed in parallel	- To make a business case, requires capture plants that supply CO_2 - Cross-border transportation of CO_2 is complicated from a regulatory standpoint - Onshore CO_2 storage is typically met with low levels of public acceptance
Biomass use	- Processes need to be adapted and/or feedstock may need pre-treatment - Bioenergy needs to be cost-competitive with alternative fuels - Requires supply systems for suitable biomass assortments	- Supply of suitable biomass assortments is constrained, resulting in competition and likely increased prices, if more sectors see a demand in the future - Susceptible to policy directions that limit the out-take of suitable biomass assortments

6. Conclusions

This thesis discusses the connections between the implementation of CO_2 emissions reductions technologies on industrial sites and their related infrastructures. Within the scope of this thesis, modeling tools are developed that provide increased understanding of the costs, pace, and development over time of the industrial transition under different incentive structures and constrained infrastructure deployment.

Barriers related to the pace of expansion of infrastructure are shown to have a significant impact on the timeliness of the transition. Poor conditions for the electrification of industry, in terms of long permitting times and low grid expansion capacity, can delay electrification of Swedish industry by around 15 years. The timeliness of the transition is also highly dependent upon having a high level of coordination between site-level projects and infrastructure projects, so that the developments onsite and of the infrastructure can be performed in parallel.

For CCS supply chains in Swedish industry, the costs for CO_2 capture and conditioning make up most of the system costs, while transport infrastructure makes up a comparatively small part. Since (BE)CCS represents high added costs for the industrial site, it is dependent upon incentives or the creation of markets for CO_2 capture to be implemented. The deployment of CCS in different sectors is shown to be sensitive to the incentives applied for BECCS and fossil CCS. For instance, a more-extensive deployment of CCS in the waste-fired heat and power sector is seen when the fossil CO_2 price is combined with biogenic capture targets, due to the value accrued to the system from reducing costs for fossil CO_2 emissions at the same time as biogenic capture targets are fulfilled. These results highlight the importance of clear, long-term policies that motivate the deployment of CCS, to signal to site owners that their investments in mitigation technologies will be economically viable over time.

Furthermore, even though biomass is a constrained resource, and the demand triggered by the phasing out of fossil fuels outweighs the supply potential on the national level, there is an as-yet undeployed potential in logging residues from forestry. The regional distribution of logging residue excess and demands for biomass is highly unbalanced. In regions where the supply potential outweighs the demand, the excess could be transported to high-demand areas. The cost for utilizing current logging residue transportation modes (primarily trucks) is highly sensitive to the transport distance. Thus, future users in regions with extensive current use can expect higher costs due to requiring mobilization over larger areas. Deployment of cost-effective long-distance transport can enable the connection of high-demand and high-supply regions at relatively low cost increases compared to supplying logging residues regionally.

Put together, the work in this thesis shows that infrastructure development is highly important in enabling the transition of industry to meet climate targets, and that regional variations between infrastructure conditions can make different technological pathways suitable. Furthermore, the thesis highlights that clear policy, secure financing and timely infrastructure development are crucial to enable the industrial transition.

7. Suggestions for future work

The work in this thesis investigates several aspects linked to the implementation of CO_2 emissions reduction technologies in industry and the connected energy infrastructures. However, to facilitate and understand the conditions for the transition in more detail, there are areas for improvement and further research questions.

The assessments performed in **Papers I** and **II** limit the analysis to logging residues. However, other assortments of biomass might be of interest for application in industrial processes, especially considering that the national supply potential of logging residues is shown to be outweighed by future demands for bioenergy and biogenic carbon. Performing similar analyses considering the inclusion of other suitable biomass assortments would thus be beneficial.

The cost-minimizing CCS supply chain model developed and applied in **Papers III** and **IV** in this thesis uses yearly time steps. However, several energy-market dynamics of relevance for the cost of CCS takes place on much smaller timescales. Cost-minimizing modeling on a more-resolved timescale would be of interest, to investigate the deployment and operation of CCS in industry considering intra-annual energy price variations, such as in an energy system characterized by higher shares of renewables.

Furthermore, this thesis applies a mix of individual methodological approaches. However, the analysis would benefit from also including a direct comparison between the technological options and their deployment. Such a model could be based on cost minimization and impose constraints on the deployment of technology and infrastructures inspired by the model developed in **Paper V**. Additionally, to understand more clearly the issue of coordination between site and infrastructure operators, agent-based modeling could be an interesting tool to apply to questions regarding the timing of deployment such as those studied in **Paper V**.

One major limitation of the work in this thesis is the focus on the national, and specifically, the Swedish context. As such, the results may not be transferable or generalizable to other contexts. A remedy for this issue could be the application of the thesis methods to other regions and conditions, or to expand the geographic scope to, for example, the European level.

A recurring theme in the research literature and in news coverage of the industrial transition is the demand from industrial actors for a clear policy landscape in which to make investments. Due to the long investment cycles in industry, the direction of climate policy needs to be predictable to render large investments in emissions mitigation technologies feasible. Further work on how such policies could be designed and implemented would be highly beneficial to facilitate the transition of industry.

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