THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

CO_2 transportation infrastructure and biomass supply systems for carbon capture and storage

A modeling study of Swedish industry

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Abstract

Rapid decarbonization of the industrial sector is crucial if the world is to manage to meet the target set in the Paris Agreement of limiting global warming to "well below 2°C". The main technological pathways for achieving a low-carbon industry are the substitution of fossil feedstocks and energy supply with bio-based alternatives, electrification, and implementing carbon capture and storage (CCS). This thesis investigates the deployment of CCS and bioenergy CCS (BECCS) in industry, using Sweden as a case study. CCS involves the capture of CO_2 at the emissions source, transportation of CO_2 to a storage location, and storage in a deep geologic formation. This work considers CO_2 capture and transportation infrastructure and the potentials and costs for supplying regional logging residues – branches and tops left in the forest after logging operations – to act as an enabler of BECCS in the pulp and paper industry by supplying the additional heat demand imposed by CO_2 capture, assuming maintained production levels.

To evaluate the potential for logging residues to supply heat for the capture process, heat balance calculations on the site level were combined with an assessment of regional availability and existing use of logging residues. This work shows that the potential for regional logging residues to act as an enabler of BECCS is dependent upon regional conditions, primarily the existing biomass use in the district heating sector. The cost of transporting logging residues is highly distance-dependent, therefore, the ability to mobilize large volumes of these residues as close as possible to the plant applying capture is important. The costs for supplying logging residues to the plants investigated are in the range of 21–28 €/tCO_2 captured. These costs increase rapidly per tCO_2 captured and end up with higher costs in southern Sweden than in the north of the country.

The development of a large-scale CCS system that includes the capture, liquefaction, truck transport on-shore and ship transport off-shore was investigated by developing and using a cost-minimizing optimization model. To incentivize capture, CO_2 pricing, emission budgets and targets for capture were implemented. The use of an integrated CO_2 transportation infrastructure that connects several CCS plants with a CO_2 storage site is shown to be cost-efficient at emissions price levels of around 80 €/tCO_2 (excluding the cost for final storage). As the cost structure of CCS systems, including the capture, liquefaction, and transportation infrastructure, is primarily composed of the cost for capture and liquefaction, the system build-up over time and the total cost are most sensitive to cost uncertainties in relation to the on-site installations. Ships for offshore transportation also make up a significant part of the cost, so smaller sites located close to the final storage location can be favored over larger sites, despite having a higher cost for capture. The incentive structures chosen for motivating capture influence which sites are economically optimal to implement CO_2 capture at, and at which point in time. Waste-fired heat and power plants are economically feasible when capture targets are set for biogenic CO_2 in combination with a cost for fossil CO_2 emissions. Including BECCS in emission budgets reduces the system cost but tends to delay investments in mitigation and compensate at a later stage with BECCS. To facilitate technology development and near-term implementation of CCS and BECCS, it is important to consider that including carbon dioxide removal into the same policy regime that controls fossil CO_2 emissions, may result in the cost optimal strategy entailing a delay in fossil fuel mitigation.

Keywords: CCS, BECCS, industry, infrastructure, CO_2 transportation, cost optimization, biomass supply, incentives

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 **2021** https://doi.org/10.3389/fenrg.2021.738791

II. Karlsson, S.; Normann, F.; Odenberger, M.; Johnsson, F. *Modeling the development of a carbon capture and transportation infrastructure for Swedish industry.* Submitted for publication **2022**

III. Karlsson, S.; Normann, F.; Johnsson, F. *Cost-optimal CO_2 capture and transport infrastructure – A case study of Sweden.* Submitted for publication **2022**

Author contributions

Sebastian Karlsson is the principal author of all the papers. Dr. Anders Eriksson contributed with the biomass supply system analysis and discussion and editing of **Paper I**. Associate Professor Mikael Odenberger contributed with discussion on the development of the CCS system model used in **Papers II** and **III**, and discussion and editing of **Paper II**. Professor Fredrik Normann and Professor Filip Johnsson contributed with discussions and editing of all the papers.

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To my family and friends, thank you for your support and all the great moments that we have spent together, and an especially warm thank you to my parents, Mikael and Magdalena, for your constant love and encouragement. Finally (*das Beste kommt zum Schluss*), from the bottom of my heart, thank you Angelika for being a wonderful partner, for supporting me during my ups and downs throughout this journey and for always being there. I have learned so much from you, and I am truly grateful for all the amazing memories that we have created together. May there be many more.

Sebastian Karlsson, Göteborg, November 2022

Table of contents

1. Introduction

Climate change is a major challenge. The Paris Agreement commits the signing parties to limit the global temperature increase to "well below" 2°C relative to pre-industrial levels, and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels [1]. Keeping the global temperature increase below these limits with 50% certainty means that the estimated remaining carbon budgets with Year 2020 as a baseline are 500 and 1,150 $GtCO_2$ for the 1.5°C and 2°C global warming targets, respectively [2]. Considering that the current global level of CO_2 emissions is around 44.6 ± 7.6 $GtCO_2$/y [2], which includes CO_2 emissions from land use and land use change (LULUCF), it is clear that substantial and rapid emissions reductions are needed. Although the global energy system is still dominated by the use of fossil fuels, with coal, oil and gas constituting around 80% of the world's total energy supply [3] there are positive trends in the electricity generation sector. In Year 2021, wind and solar power contributed 10.2% of total electricity generation, surpassing 10% of global power generation for the first time [4]. Globally, the industrial sector contributes around 29% of greenhouse gas (GHG) emissions, of which around 82% are related to industrial energy use, with the remainder being direct process-related emissions [5]. Large industrial emission sources are found in the refinery, chemical, cement and iron and steel industrial sectors.

In the Swedish context, the climate policy framework adopted by the government states that in Year 2045, Sweden should reach net-zero GHG emissions, whereby 85% of the emissions reduction will be reductions in fossil-related emissions and up to 15% will be permitted from so-called 'supplementary measures', i.e., different types of carbon removal and mitigation measures in other countries [6]. In Sweden, electric power is generated mainly via hydropower and nuclear power, and similar to the global trend, there is a steadily increasing share of wind power, surpassing 17% of the total electricity generation in Year 2020 [7]. When combined, hydro, nuclear, and wind power account for just over 90% of the total electricity production in Sweden [7], contributing to a low-emissions intensity from the power generating sector, as compared to the global average. Industrial plants in Sweden, make up about one-third of the total domestic fossil GHG emissions, which amount to 51 $MtCO_2$/y [8]. In addition, there is extensive use of bio-based energy in Sweden at 141 TWh/y, with the pulp and paper industry being the largest industrial user, using about 52 TWh/y [7], leading to large biogenic emissions. Therefore, in Sweden, in addition to reducing emissions in the transportation sector, decarbonization is to a large extent about the decarbonization of industry. Carbon capture and storage (CCS) has been identified as one technological option to reduce drastically the level of emissions from the industrial sector. To date, major steps in the direction of large-scale deployment of CCS in industry have not been taken. The price levels in the European Union Emissions Trading System (EU ETS) have historically been too low to motivate large investments from industrial actors. Furthermore, to deploy CCS at scale, the appropriate infrastructure, the development of which is often left to actors other than the industries themselves, needs to be created.

With decisions regarding infrastructure development and incentives for motivating carbon capture often taking place on the national level, the scope of this thesis is to study national systems. This work attempts to complement the existing literature on the techno-economic aspects of CO_2 capture implementation by taking a systems perspective, providing an analysis that links CO_2 capture at different industrial sites with an infrastructure for CO_2 transportation to a storage location. Moreover, this thesis investigates the potential for regional forest biomass (in the form of logging residues) to act as an enabler of carbon removal via BECCS by supplying the additional heat demand for capture at existing industrial sites, assuming that production levels are maintained.

1.1 Aim and scope

The work presented in this thesis investigates the interactions between the implementation of carbon capture on the site level and the required CO_2 transportation infrastructure and biomass supply. The work aims to highlight important infrastructure- and supply system-related parameters that constitute enablers of or barriers to CCS implementation. These parameters involve biomass supply constraints and cost sensitivities in CCS systems, including both capture and transportation. The impacts of the identified parameters are quantified based on their influences on the deployment, configuration, and cost of the CCS system. Furthermore, the work investigates the impacts of employing different pathways towards incentivizing fossil CCS, BECCS and combinations thereof. More specifically, the thesis aims to contribute to method development by:

- Developing a cost-minimizing model for the implementation of CCS at existing industries that takes into account the cost-optimal deployment of capture, as well as the transport infrastructures required under different incentive structures for the motivation of fossil and/or biogenic CO_2 capture.
- Developing a methodology for quantifying the potential biomass supply and its related costs to supply bio-energy carbon capture – or other new biomass needs – based on biomass availability and existing uses in other sectors.

The developed methods are applied to a case study that applies CO_2 capture to Swedish industrial plants, addressing the following questions:

- How do CCS systems build-up over time in relation to national incentives for capture?
- How do different cost parameters in the CCS chain influence the CCS system build-up over time?
- To what extent can regional logging residues enable BECCS by supplying the additional heat demand imposed by capture implementation at existing industrial sites?

1.2 Outline of the thesis

This thesis is based on the three appended research papers and an essay that consists of six chapters. Chapter 1 introduces the thesis and places the work in context. Chapter 2 gives a brief background of topics related to the thesis. Chapter 3 gives an overview of the methodology used and modeling performed in the work. Chapter 4 presents and highlights some selected results from the appended papers. Chapter 5 discusses the work in a broader context. Chapter 6 draws conclusions from the thesis and contemplates the directions of future research endeavors building upon the work presented here.

2. Background

2.1 Achieving low CO_2 emissions from Swedish industry

Table 1 presents the large emitting Swedish industrial sectors and potential mitigation options that are unlikely to be (red), could potentially be (yellow) or are likely to be (green) implemented for each sector. For most sectors, implementing CO_2 capture constitutes a potential or likely mitigation option.

The direct CO_2 emissions from the iron and steel industry in Sweden were 6.2 Mt in Year 2019, of which around 85% emanated from the reduction of iron ore [9]. The steel industry has several potential technological options to reduce direct emissions. Reduction of iron ore in a blast furnace can be replaced with natural gas or hydrogen direct reduction. To replace existing Swedish blast furnaces, hydrogen supplied via electrolysis would create an electricity demand of around 15 TWh/y and an additional demand of 35 TWh/y if the Swedish mining company LKAB realizes its plans for reducing currently exported iron ore in Sweden [9]. Reduction of iron ore in blast furnaces could also be done by substituting coke with biochar (see [10], [11]). However, replacing coke with biochar requires that the biochar has certain mechanical and reactive properties that are appropriate for the process, which requires further refinement of biochar production processes [9]. In addition, the supply of sustainable biomass for such processes is a limiting factor. For heat treatment, the electrification of processes that currently use fossil fuels is an option; this is considered most feasible for processes that require heat at temperatures <1,000°C [9]. Implementation of CCS to mitigate site emissions is also possible and could prove cost-efficient due to the large CO_2 flows (see [12]). For the iron and steel industry in Sweden, electrification and the use of green hydrogen represent the path chosen for CO_2 emissions reductions [13]. In this steelmaking route, called the hydrogen direct reduction - electric arc furnace route (DR-EAF), iron ore is reduced with hydrogen using direct reduction (DR) to produce sponge iron, which is then fed into an electric arc furnace to produce steel. The use of CO_2 capture as an emissions reduction option is different in principle, in that existing production processes with maintained or increased carbon intensities are kept in place, and CO_2 capture is implemented as an end-of-pipe solution to reduce emissions to the atmosphere. In contrast, hydrogen DR-EAF would entail decarbonization of the process.

The Swedish cement industry emitted around 2.2 MtCO_2 in Year 2017 [14]. For the cement industry, around two-thirds of the emissions are associated with the calcination of limestone and the remaining one-third are linked to the combustion of fossil fuels to generate heat for the process [14]. The emissions associated with fuel use have historically been reduced by increasing the shares of bio-based and waste-based fuels in the process, and these shares could, potentially, be increased further [15]. Alternatively, the heat supply system for the process could be electrified, which would remove the direct CO_2 emissions associated with fuel use. Regardless of the fuel used for heating, the process emissions remain and need to be captured so as to mitigate fully the site emissions. However, the choice of technology for process heating has implications for the CO_2 capture process, in that electrification of the heat supply would result in better conditions for CO_2 capture, due to the flue gas in that case being mostly composed of CO_2 [16]. In the Swedish context, the cement manufacturer

Cementa has announced plans to implement CCS at their Slite site by Year 2030, aiming to become the world's first CO_2-neutral cement plant [17].

The refinery sector stands out in that most of the emissions related to its activity do not stem from the production process itself, but rather from the use of the product, i.e., Scope 3 emissions from the use of fossil fuels in the transportation sector. This implies that for refineries to have a place in a zero-emissions economy, they will eventually need to shift their feedstocks to biogenic sources. Currently, the Swedish refining sector produces around 4 million m^3 of bio-based transportation fuels [18], and the total amount of energy in the transportation fuels produced for the Swedish market is around 85 TWh, of which around 20 TWh are of bio-based [19]. The direct emissions from the Swedish refinery sector amounted to 2.9 $MtCO_2$ in Year 2017 [15]. The direct emissions can be mitigated through a combination of: (i) phasing out the fossil fuels used for process heating, using blue or green hydrogen instead of unabated steam methane reforming (SMR); and (ii) implementing CCS at the emissions point sources at the refinery site where the CO_2 concentration and flow are sufficiently high. Preem, which is one of the two Swedish refinery companies, has ambitions to explore and exploit a wide range of options to reduce direct and value chain emissions, and plans to phase in bio-feedstock to produce 5 million m^3 of bio-based transportation fuels annually by Year 2030, shifting their hydrogen production away from unabated SMR and implementing CO_2 capture with the aim of creating a climate-neutral value chain by Year 2035 [20].

The chemical sector in Sweden, which encompasses diverse processes that produce a wide range of products, including plastics, paints, pharmaceuticals and cleaning products, emitted around 1.3 $MtCO_2$ in Year 2017 [15]. In Sweden, the largest chemical manufacturing cluster is located on the west coast, in Stenungsund. To mitigate the direct emissions, CCS can be implemented at point sources on-site, although it is likely that capturing CO_2 from some stacks will entail high costs, due to the relatively low CO_2 flows and concentrations from these stacks. Since chemical manufacturing relies heavily on fossil feedstocks to produce its products, switching feedstocks to either biogenic alternatives or recycled materials is necessary [15]. Research is being conducted on thermochemical recycling of plastics, to transform plastic production from a linear to a circular material flow by breaking down plastic waste to its basic components, which can then be used to replace virgin fossil feedstocks [21]. This concept is also being investigated for the co-recycling of synthetic carbon materials with natural carbon materials (e.g., biomass) [22].

Heating for residential and service sector buildings in Sweden has shifted from using high numbers of domestic fuel oil boilers in the 1960s to being dominated by district heating [23]. The production of district heating has increasingly applied forestry residues and municipal waste as fuels, and current CO_2 emissions from the heating sector are around 10% of what they were in Year 1970 [24]. Municipal waste is used in some district heating plants and the waste is of mixed origin, roughly 65% biogenic and 35% fossil, with the fossil share being made up mostly of plastics in the waste stream. To reduce the levels of fossil emissions associated with waste incineration, the fossil part of the waste, such as plastics, needs to be sorted out; alternatively, CCS may be implemented. There is a large potential for BECCS from the biomass- and waste-fired heat and power plants in Sweden, estimated to more than 10 $MtCO_2$/y of biogenic origin [25].

The Swedish pulp and paper industry is large and consists mostly of chemical pulp plants. The pulp and paper industry uses around 50 TWh of bio-based energy [7] and emits around 20 Mt of biogenic CO_2 yearly, mostly from a few large stacks per site. Only around 4% of the total energy use in this sector is attributed to the use of fossil fuels [15]. Due to the large volumes of biogenic CO_2 emitted from a relatively low number of point sources within the sector, it presents an interesting opportunity for implementing bio-energy carbon capture and storage (BECCS) at existing sites.

The options for reaching a low-carbon industry in Sweden have different advantages and associated challenges. The use of biomass, to substitute for fossil energy or fossil feedstocks, is at present regarded by most of the industrial sectors as a partial solution for mitigating fossil emissions. At the same time, biomass, including the various versions that are suitable for energy purposes, is a limited resource. The potentials for increased out-take of biomass forms suitable for energy purposes from the forestry sector for Year 2030 and Year 2050 have been estimated as 27–37 and 34–45 TWh/y, respectively [26]. The current use of forest-based biomass for energy purposes is around 51 TWh/y [27]. With shortage of supply, the willingness to pay for biomass determines to which sectors the biomass will be allocated. Electrification of industrial processes could present interesting options for deep decarbonization of multiple sectors (for instance, iron and steel and cement production in combination with CCS). Industrial electrification is highly dependent upon the development of both electricity generation and the transmission grid. Utilizing hydrogen is necessary for those sectors in which hydrogen is required for the process, e.g., for the reduction of iron ore, chemical manufacturing, and refining. From the site perspective, deployment of CCS using absorption methods entails high capital costs and high additional energy demands, to cover the heat required for separation of the absorbed CO_2 from the solvent and the electricity needed for CO_2 conditioning.

Table 1. Overview of technological options to reduce direct CO_2 emissions from the large emitting industrial sectors in Sweden. Green shading indicates a planned or likely development, yellow shading indicates a possible or alternative option to the planned option, and red shading indicates an unlikely development.

	(Increased) biomass use	**Indirect electrification (green hydrogen)**	**Direct electrification**	**(BE)CCS**
Iron and steel	Alternative path	Hydrogen direct reduction	EAF	Alternative path
Cement	Partially		Partially	Necessary
Refinery	Necessary	Necessary	Potentially	Planned
Chemicals	Necessary	Necessary	Potentially	Partially
Heat and power	For the few remaining fossil fuel-fired plants		Heat pumps and electric boilers	Waste incineration. Large BECCS potential.
Pulp and paper	For the remaining (very small) fossil energy use			Large BECCS potential

2.2 Conditions for CCS in Swedish industry

In order to reduce the emissions from Swedish industry, four overarching technological options (in addition to increased energy efficiency), i.e., biomass, hydrogen, electrification and (BE)CCS, have been identified by, among others, the Swedish Energy Agency [8] and the Royal Swedish Academy of Engineering Sciences [15]. This thesis focuses on the implementation of CCS for fossil-related emissions mitigation and BECCS for carbon dioxide removal (CDR). Previous research on the implementation of CCS in industrial processes has focused on the techno-economical aspects at the site level. For example, the costs for CCS implementation at large Swedish industrial sites have been presented by Garðarsdóttir et al. [28] and Johnsson et al. [29], reporting capture costs in the range of 40–110 €/tCO_2 that include both investment and operational costs. Biermann et al. [12] have investigated the concept of partial capture as a means to reduce the specific costs for CCS at a steel mill and, thereby, make implementation more-feasible. Eliasson et al. [30] have investigated the effect of heat integration of a capture plant into existing industrial plant processes, and have found that the use of residual heat is highly important for reducing the operating costs. Beiron et al. [25] have studied the potential and specific cost of capture implementation from the waste-fired and bio-fired heat and power sectors in Sweden, showing that around 10–13 MtCO_2/y could be captured from the sector at a cost of <100 €/tCO_2 (including the costs for capture, liquefaction and truck transportation to the closest harbor). On the transportation infrastructure side, Kjärstad et al. [31] have investigated potential transport solutions in the Nordic region, comparing ships and pipelines from potential transport hubs to possible storage locations. They have concluded that ship transportation is an attractive, low-cost option, especially during a ramp-up phase.

Some previous studies have included both the site and infrastructure perspectives in the European context. d'Amore & Bezzo [32] have investigated a potential cost-optimal CCS supply chain on the European level using a mixed integer programming (MIP) optimization model. They have shown that capture costs are the major contributor to the total system cost, with transportation and sequestration costs never exceeding 10% of the total system costs. Morbee et al. [33] and Kjärstad et al. [34] have investigated the deployment of pan-European pipeline networks for CO_2 transportation, considering large-scale deployment of CCS in the European power-generating sector. Developments in the power-generating sector, advancing towards more-renewable production, and the reduced level of acceptance of land-based storage of CO_2 in Europe have prompted national projects on CCS, many of which involve the process industrial sector and consider local/regional transport solutions, which often employ ship transportation.

2.3 EU policy context

2.3.1 Developments in biomass and bioenergy use

Within the EU, recently proposed amendments to the Renewable Energy Directive (RED) [35] and revisions to the LULUCF regulation [36] pave the way for shifting from the utilization of biomass for energy and industrial purposes. Under the new formulation in the RED, using "primary woody biomass" for energy purposes would not meet the requirements for classification as renewable, with the consequence that it would not be included in the EU's renewable energy targets and would not receive the related subsidies. Furthermore, the imposition of a cap and the phasing down towards Year

2030 of the use of "primary woody biomass" for energy purposes would be introduced. The 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 would result in Sweden needing to increase its natural carbon sink by almost 10 $MtCO_2$/y from Year 2030 onwards, which could have severe implications for the forestry industry, with one likely consequence being reduced harvesting rates [37]. The Government of Sweden has issued an explanatory memorandum on the suggested revisions to the LULUCF regulation, in which it takes the standpoint that the carbon sink assigned to Sweden for Year 2030 should be lowered to an amount that is compatible with both the Swedish climate policy framework and further development of the bio-economy [38]. The amount of forest-based biomass that is available for energy use is highly 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 these potential policy developments will strongly influence the possibility for Swedish industry to use biomass as a part of its strategies to reduce emissions by replacing fossil feedstocks and fuels. Reduced harvesting activity also has implications for BECCS, in that reduced harvesting rates 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.

2.3.2 EU ETS

The EU ETS is the cap-and-trade system that was introduced for large sources of fossil CO_2 emissions in the European Union in 2005 [39]. It is one of the fundamental policy structures implemented in the EU to reduce fossil CO_2 emissions from energy-intensive activities within the EU. The system works by imposing a cap on the emissions from the activities included in the system and 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 the emissions during that period. If they fail to do so, they will be fined. An actor within the system that does not have sufficient allowances to cover their emissions can choose to either reduce their emissions or buy more allowances from another actor in the system during the trading period. The reasoning behind the cap-and-trade system is that the market mechanism for trading emission allowances is designed such that emissions reductions within the system take place where the cost associated with emissions mitigation is lowest. To ensure that the emissions from the system decrease over time, the allowances are reduced over time. During Phase 3 of the EU ETS, for the period of 2013–2020, the cap decreased by 1.74% yearly. In Phase 4, for the period of 2021–2030, the allowances continue to decrease with a linear reduction factor of 2.2% per year [40]. Recently proposed amendments to the EU ETS are to include more sectors in the ETS, increase the linear reduction factor to 4.2%, and gradually phase out the free allowances within the system [41]. 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 [41]. To mitigate the risk of increased carbon leakage as the number of free allowances is reduced, the European Commission has proposed a Carbon Border Adjustment Mechanism (CBAM). This mechanism 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 [41]. 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 as a consequence of changes within the EU ETS will be crucial in determining the relative cost of implementing CO_2 capture, and the costs of other emission mitigation technologies, as compared to the cost of emitting CO_2 at any given point in time. In addition to motivating investments in fossil CO_2 mitigation technologies, 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. [42], 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.

3. Method

Figure 1 shows an overview of the methodology used in this thesis. The overarching aim is to combine site-level perspectives with perspectives from the infrastructure and interacting systems (e.g., policies and energy markets) needed to support the implementation of CO_2 capture and storage. The work of this thesis looks at the implementation of CO_2 capture at existing sites, assuming that production and emissions levels will remain constant. The implementation considers capture using monoethanolamine (MEA) absorption, which can be implemented at existing sites without major process modifications. The site data are from the Chalmers Industrial Case Study Portfolio (ChICaSP) (for detailed information on ChICaSP, see [43]). The case study portfolio consists of a summary file, a case files folder, and a publications folder. In the summary file, publicly available data from, for example, emissions registries or environmental reports, are available. For example, the summary file contains information on yearly CO_2 emissions (fossil and biogenic), yearly electricity use, yearly production levels, and the location of the site. The case files folder contains results from case studies that have been performed at the site. These contain more-detailed information, such as information about the on-site energy system (pressure levels in a steam network), the distribution of emissions from different stacks on site, and their respective CO_2 concentrations. Finally, the publications folder contains the source publications (environmental reports and detailed case studies) from which the data in the ChICaSP are gathered.

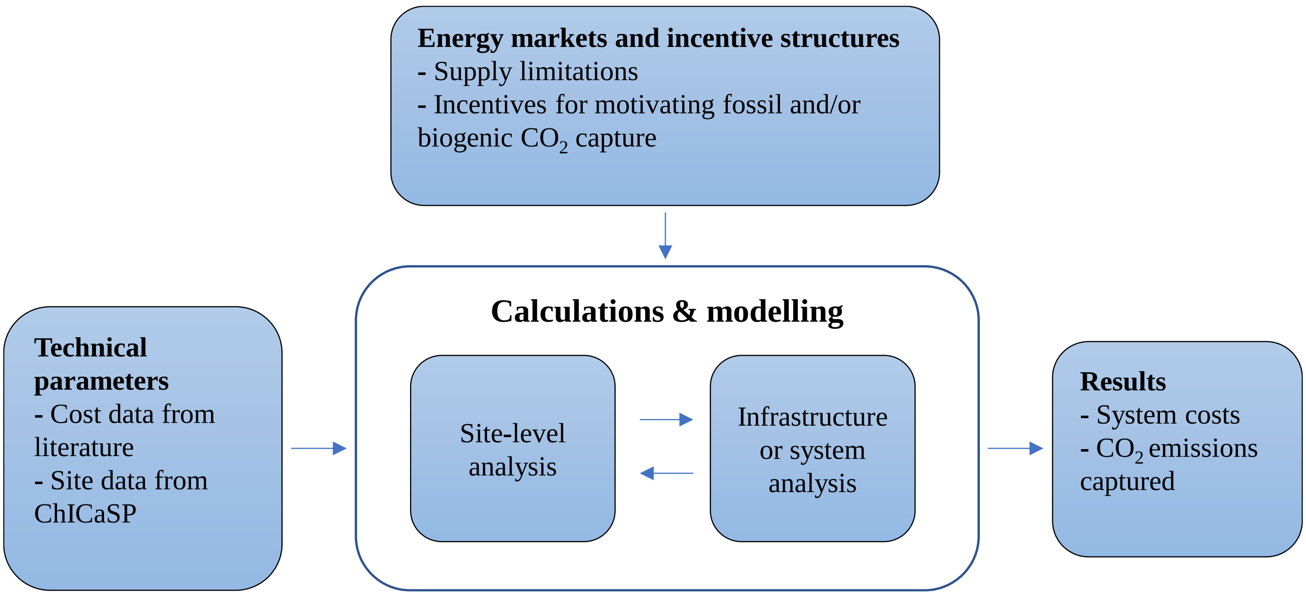

Figure 1. Conceptual overview of the methodology used in this thesis.

Figure 2 shows the industrial system considered in this thesis. The system includes sites in Sweden that emit more than 100 ktCO_2/y in the pulp and paper, heat and power, refinery, chemical, cement and steel industrial sectors. In **Paper I**, four of the pulp mills in this industrial system were chosen as case studies for BECCS implementation, to evaluate the potential for regional logging residues to act as an enabler of BECCS. In **Papers II** and **III**, all the sites shown in Figure 2 were included in the modeling, in addition to those harbors that could act as transport hubs for CO_2. Although some of the sectors in Figure 2, particularly the iron and steel sector, have other mitigation options as their focus, they were included in this work for most of the model runs, to assess the effect of implementation of CCS in an industrial system that comprises a wide variety of spatially distributed emission sources of different sizes.

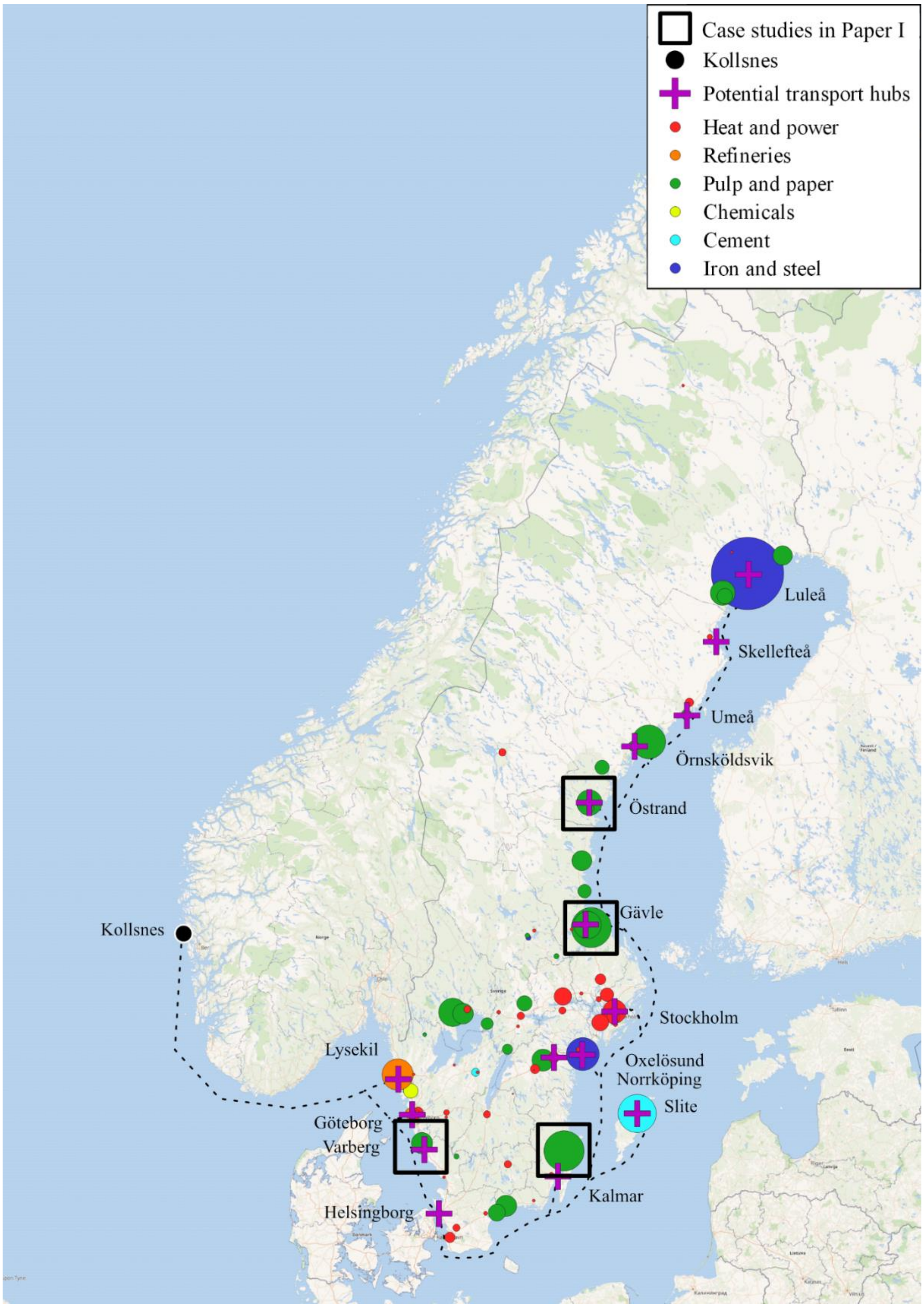

Figure 2. The industrial system considered in this thesis. The size of each site corresponds to the level of emissions from that site, which is in the range of0.1–3.3 MtCO_2/y. The map also includes harbors that could act as CO_2 transport hubs, and the ship routes from the harbors to Kollsnes in Norway. The pulp mills chosen for the case studies in Paper I are also marked.

3.1 Assessment of regional logging residues as an enabler of BECCS

Paper I uses the method shown in Figure 1 by combining an analysis of the site conditions for implementation of CO_2 capture at existing pulp and paper mills with an analysis of the potential and cost for supplying logging residues to supply heat for the capture process, assuming that the production levels at the pulp mills remain constant. On the site level, heat balance calculations to determine the reboiler heat demand for capture are performed. Site data from ChICaSP are used to determine the fuel requirement to supply the heat to the capture process at the relevant steam pressure level (~4 bar). Residual heat is only considered in so far that there is currently available unused steam at the appropriate pressure and temperature level for the capture process; no modifications to the site energy systems to free up heat are considered. For the biomass supply system, the availability of logging residues is evaluated in concentric circles around the pulp and paper mills, up to a radius of 200 km. The existing use of biomass in CHP plants that use biomass as fuel is included in the analysis and subtracted from the biomass that could be used by the pulp mills to fuel the capture process. The uptake radius for the CHP plants is based on the average transportation distance for trucks that deliver logging residues: 62.7 km in Year 2018 [44]. Logging residue costs are based on survey data [45] and costs for road transportation are calculated based on an hourly transport cost [46] and a calculation that considers the distance-specific average driving speed [47], [48].

3.2 CCS system modeling

For **Papers II** and **III**, the method shown in Figure 1 is implemented by studying CO_2 capture in conjunction with the CO_2 transportation infrastructure. Different incentives for motivating the capture of fossil and biogenic CO_2 are investigated. To map the development of a CCS system, including capture, liquefaction and transportation, an optimization model was developed and applied to Swedish emissions sources in the pulp and paper, heat and power, cement, refinery, chemical and iron and steel sectors. Figure 3 shows an overview of the model. The model is a cost-minimizing Mixed Integer Programming (MIP) model based on the mass balances for the CO_2 flow, from capture at a stack at a given industrial site, through a liquefaction plant located on-site, intermediate on-site storage, truck transportation, and intermediate storage at a transport hub to ship transportation to the endpoint. The model is limited to yearly time-steps.

The objective function of the modeling is to minimize the net present value (NPV) of the sum of all the annual costs, according to Equation (1):

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

where c_y^{annual} is the annual cost, including both investment and operating costs, for the equipment purchased in the model (capture, liquefaction, intermediate storage tanks, ships) and, in the case where it is included, the costs for emitting CO_2. The term y indicates the year, i.e., time period, y_0 is the reference year (the starting year of the modeled period), and r is the discount rate.

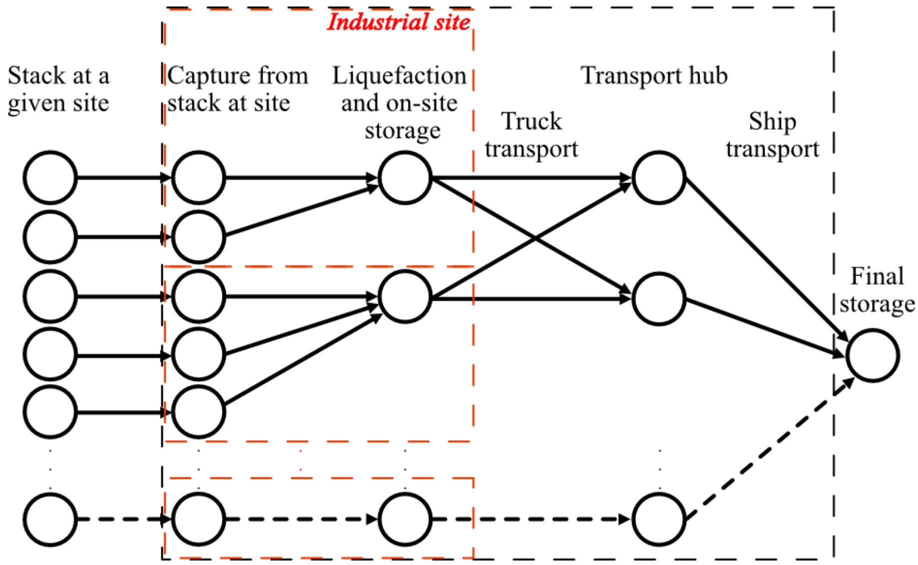

Figure 3. Flowsheet for the model developed and used in Papers II and III. CO_2 capture can be implemented at one to three stacks at a given site (depending on the industry sector). After capture, the CO_2 is liquefied, transported by truck to a coastal transport hub and finally, transported by ship to the endpoint in the model. The dashed black lines show the parts of the system for which costs are included in the model, and the red dashed lines indicate the activities that take place on-site. Source: Paper II.

The energy demand, costs and capture rate are based on post-combustion absorption, using MEA as the solvent. The specific heat demand is assumed to be 3.6 MJ/kgCO_2 and the capture rate is set to 90%. At each site, CO_2 capture can be implemented at 1–3 stacks (see Figure 3), depending on the type of site and how many capture-suitable stacks are located at the site. After capture, the CO_2 is liquefied on-site and stored in a buffer storage, after which it is transported by trucks to a transport hub located on the coast where it is stored in an intermediate storage facility. From the transport hub, the CO_2 is transported by ships to Kollsnes in Norway, which is considered the endpoint in the modeling. Costs for injection of the CO_2 into the final storage unit under the seabed, and for the permanent storage itself are not included in the modeling.

4. Selected results and discussion

4.1 Regional logging residues as an enabler for BECCS

The technical potential for BECCS in Sweden is significant, owing to the presence of several large biogenic point sources of CO_2 in both the pulp and paper and heat and power sectors, as described by Garðarsdóttir, et al. [28] and Beiron et al. [25]. However, in those studies, the implications for biomass supply systems of the increased demand for biomass for energy purposes resulting from capture implementation have been largely unexplored. **Paper I** explores this issue and highlights the possibilities for regional logging residues to act as an enabler of BECCS in different parts of Sweden. Recent developments within the EU regarding biomass and bio-energy use (see Section 2.2.1) are highly relevant for the results presented here, since they could result in a reduction of harvesting activities and thus, a reduced potential for logging residue out-take.

Figure 4 shows the amounts of logging residues available for the four pulp mills included in the case study, which take into account the existing demands from regional CHP plants by subtracting the biomass already used at the CHP plants from the biomass available for BECCS at the studied pulp mills. The mills denoted as '4.7-GWh plant' and '5.3-GWh plant' are located on the west and east coasts in the southern part of Sweden, respectively. The 3-GWh plant is located near Gävle and the 3-GWh plant, North, is located in Östrand (for site locations, see Figure 2). 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. The part of Sweden south of Stockholm contains the majority of the population and has more urban areas, and district heating systems are more-developed than in the parts of the country north of Stockholm. This, combined with the fact that Sweden to a large extent has moved away from fossil fuel use in the heating sector [23], means that the competition for logging residues for energy purposes is significantly higher in the southern parts of the country.

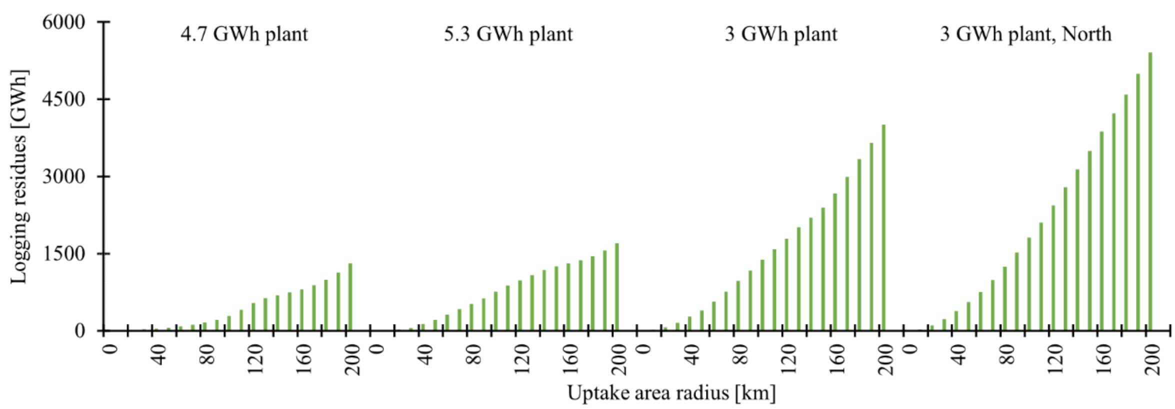

Figure 4. Available levels of logging residues for the case study mills included in Paper I as a function of the radius of the uptake area around the plant. Existing use of logging residues from bio-fired CHP plants in the uptake area is also considered. Source: Paper I.

Figure 5 shows the specific logging residue cost 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 in **Paper I**. The costs for supplying logging residues are highly distance-dependent, with increasing transportation distances leading to increased costs. This results in the sites that are situated in the south facing higher costs at 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 explained by the fact that a lower availability of logging residues implies mobilizing logging residues over a larger area to reach a given volume. This effect leads to a lower OPEX for driving the capture process at the two plants situated in the north of Sweden. Therefore, in addition to the costs for capture and the conditions for transportation of CO_2, regional differences in energy supply costs are important considerations when deciding where to implement CO_2 capture.

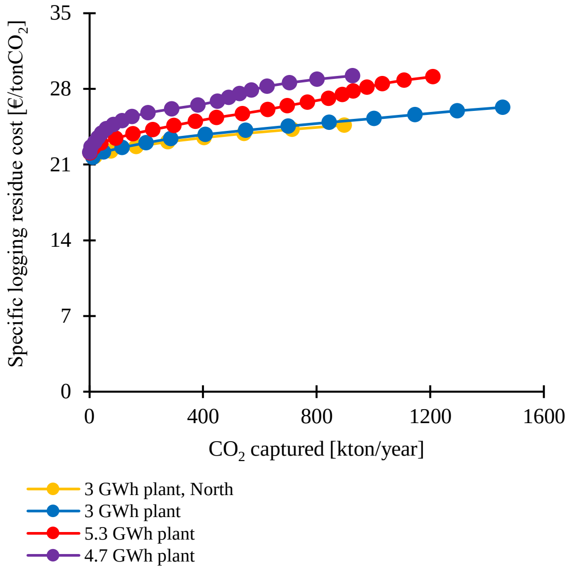

Figure 5. Specific cost of logging residues as a function of the CO_2 captured at the four case study mills in Paper I. The costs are highly distance-dependent, showing that more logging residues can be mobilized closer to the sites of the two plants located further north in Sweden (3-GWh plant and 3-GWh plant, North).

4.2 Impacts of incentive structures on CCS system development

Site-specific techno-economic conditions for CO_2 capture implementation, and ways to reduce capture costs in Swedish industry have been extensively studied, for instance by Biermann et al. [12] and Eliasson et al. [30]. Furthermore, CO_2 transportation and storage in the Nordic region have been investigated by Kjärstad et al. [31]. However, the two perspectives of transportation infrastructure and capture implementation have mostly been studied separately. **Papers II** and **III** attempt to combine these perspectives and investigate the potential development of an industrial CCS system in Sweden and which form it would take, depending on the incentive structures used to motivate the implementation of CCS and BECCS and how these incentives interact.

4.2.1 Combining incentives for fossil CCS and BECCS

Figure 6 shows the CCS system configurations for Year 2030 and Year 2045 for two different incentive scenarios. Panels 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 a public inquiry titled *The path to a climate positive future* (*Swedish: Vägen till en klimatpositiv framtid,* SOU 2020:4): 1.8 $MtCO_2$/y in Year 2030 and 10 $MtCO_2$/y in Year 2045. In panels c) and d), this incentive for biogenic capture is combined with an increasing cost for emitting fossil CO_2 in accordance with the *Net Zero Emissions by 2050* scenario in the International Energy Agency's World Energy Outlook [49]. From Figure 6, it is clear that in the incentive case that ascribes a price for emitting fossil CO_2 and implements capture targets for biogenic CO_2 [panels c) and d)], capture is shifted away from sites that emit large amounts of only biogenic CO_2 to sites in the waste-fired heat and power sector that emit a mixture of biogenic and fossil CO_2 (assumed as 65% biogenic and 35% fossil in the modeling). This shows that waste-fired heat and power plants become interesting for capture when specific incentives that target fossil CO_2 and biogenic CO_2 are combined.

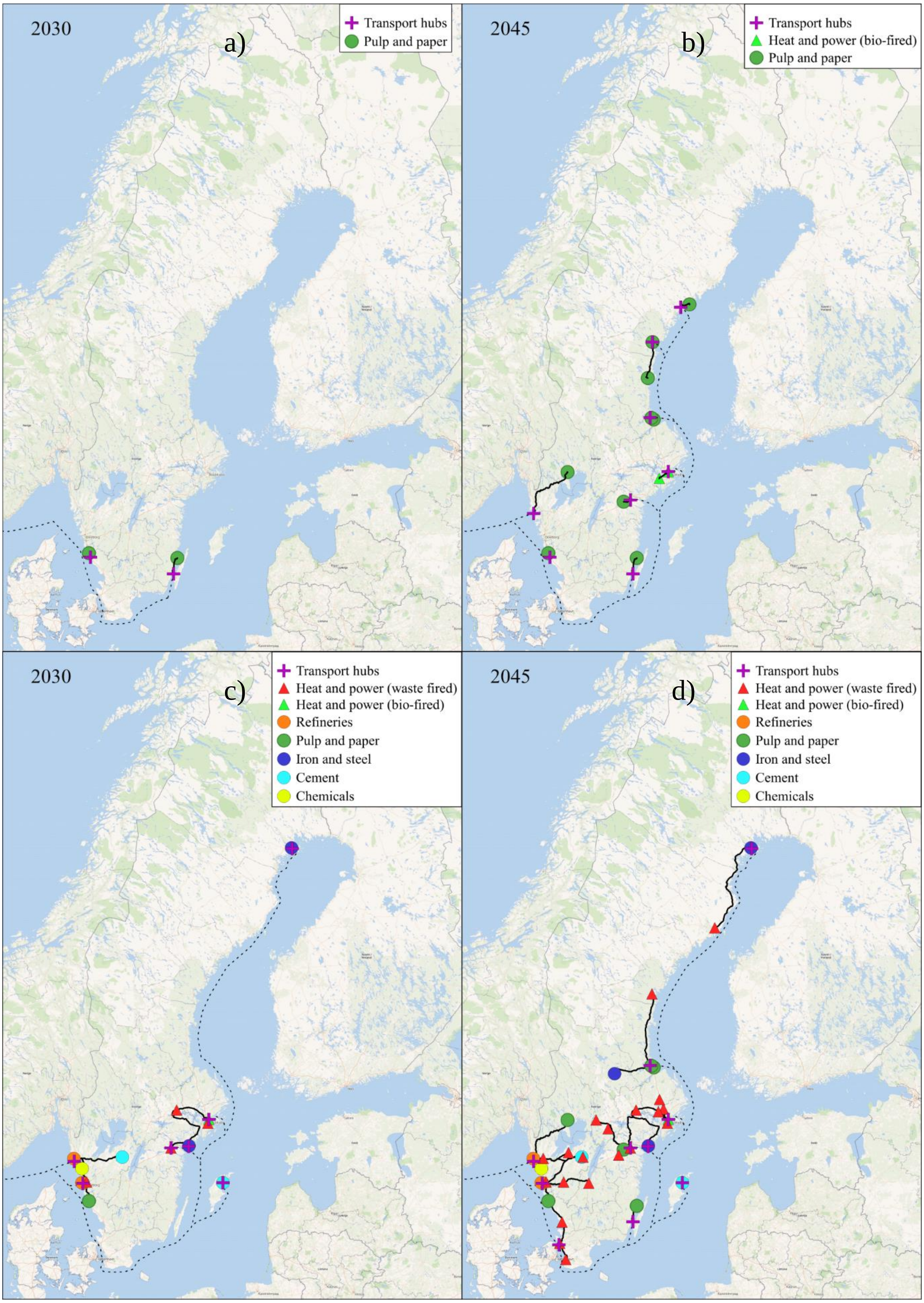

Figure 6. CCS-system configuration in Year 2030 and Year 2045 for two different incentive structures. In panels a) and b), only capture targets for biogenic CO_2 are used to incentivize capture implementation, whereas in panels c) and d),both biogenic capture targets and costs for emitting fossil CO_2 are used to incentivize capture implementation. Adapted from Paper II.

The effect of shifting the focus for capture implementation from large pulp mills to the heat and power sector, as shown in Figure 6, is explained by the relative costs and values of capturing CO_2 from pulp and paper mills, as compared to waste-fired heat and power plants, when fossil CO_2 pricing and biogenic capture targets are combined as incentives. Figure 7 shows the site costs for biogenic capture, with all the costs allocated to the captured biogenic CO_2 at a waste-fired CHP and in a pulp mill's recovery boiler, as well as the value associated with avoiding fossil emissions from the installed capture plant. The cost of capturing biogenic CO_2 from a waste-fired CHP is higher than the cost of capturing biogenic CO_2 from a pulp mill's recovery boiler. However, for each tonne of biogenic CO_2 captured from the waste-fired CHP plant, there are roughly 0.5 tonnes of fossil CO_2 in the flue gas that are also captured, resulting in an added value due to the emissions price for fossil CO_2. The value of mitigated fossil emissions is calculated by considering the fossil CO_2 emission price and allocating the value linked to avoiding the fossil CO_2 price to each tonne of biogenic CO_2 captured. While this reasoning is somewhat simplistic, given that the transportation infrastructure is not included it nonetheless illustrates that the cheapest way to meet the biogenic capture target might not always be to zoom in on the largest source of purely biogenic CO_2. Instead, in a context where fossil CO_2 mitigation can create value, sites that emit a mixture of fossil and biogenic CO_2 can become cost optimal.

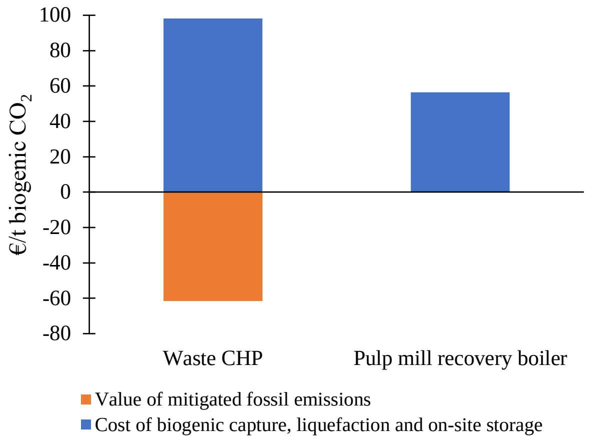

Figure 7. The cost for biogenic capture and the value of mitigated fossil emissions using capture targets to incentivize BECCS and fossil emission costs to motivate fossil CCS. The value of the mitigated fossil emissions is calculated by considering the fossil CO_2 emissions price and allocating the value accrued from avoiding the fossil CO_2 cost to each tonne of biogenic CO_2 captured. Source: Paper II.

4.2.2 Including BECCS in emissions budgets

The incorporation of carbon removal, for instance via BECCS, into incentive structures for motivating fossil CO_2 mitigation could motivate the implementation of such technologies at scale, and might provide cost benefits compared to only mitigating fossil CO_2 emissions. However, integrating carbon removal into existing incentive structures might have implications for the build-up of a large-scale CCS system. In the Swedish context, where a large fraction of the industrial sector emits biogenic CO_2, the effect of including BECCS into an emissions budget for the Swedish industrial system was evaluated.

Figure 8 shows the amounts of CO_2 that are captured to stay within the different sizes of emissions budgets considering the industrial system shown in Figure 2, with and without the possibility for the model to include BECCS to stay within the emissions budgets. When the system is allowed to do so, it starts to rely heavily on BECCS to offset fossil-related emissions. This happens for two reasons. First, in the Swedish industrial system, there are many sources of biogenic CO_2 in the pulp and paper and heat and power sectors. Many of these emissions sources have large CO_2 flows, resulting in low specific costs for capture. Second, the model tends to postpone investments in CO_2 mitigation and use large amounts of BECCS in the later stages to compensate for early fossil emissions, which is cost-effective since the model minimizes the net present value. These results highlight that inclusion of CDR into incentive structures for motivating fossil CO_2 mitigation might lead to a strategy where the cost optimal solution is to delay fossil emissions mitigation. This is an undesirable effect, which could be countered with specific policy measures targeting the implementation of CDR technologies. In Sweden, the planned policy for motivating BECCS is to secure BECCS outcomes through a reverse auctioning system using public finances. Implementing such a policy avoids the risk of delaying fossil CO_2 mitigation, however, there are other possible drawbacks with such a system. Securing BECCS outcomes using public finances entails a high cost for the taxpayer, which may be unfeasible in the longer term, and creates a low demand for BECCS as compared to what could be achieved if CDR were integrated into a broader policy regime for CO_2 mitigation [50].

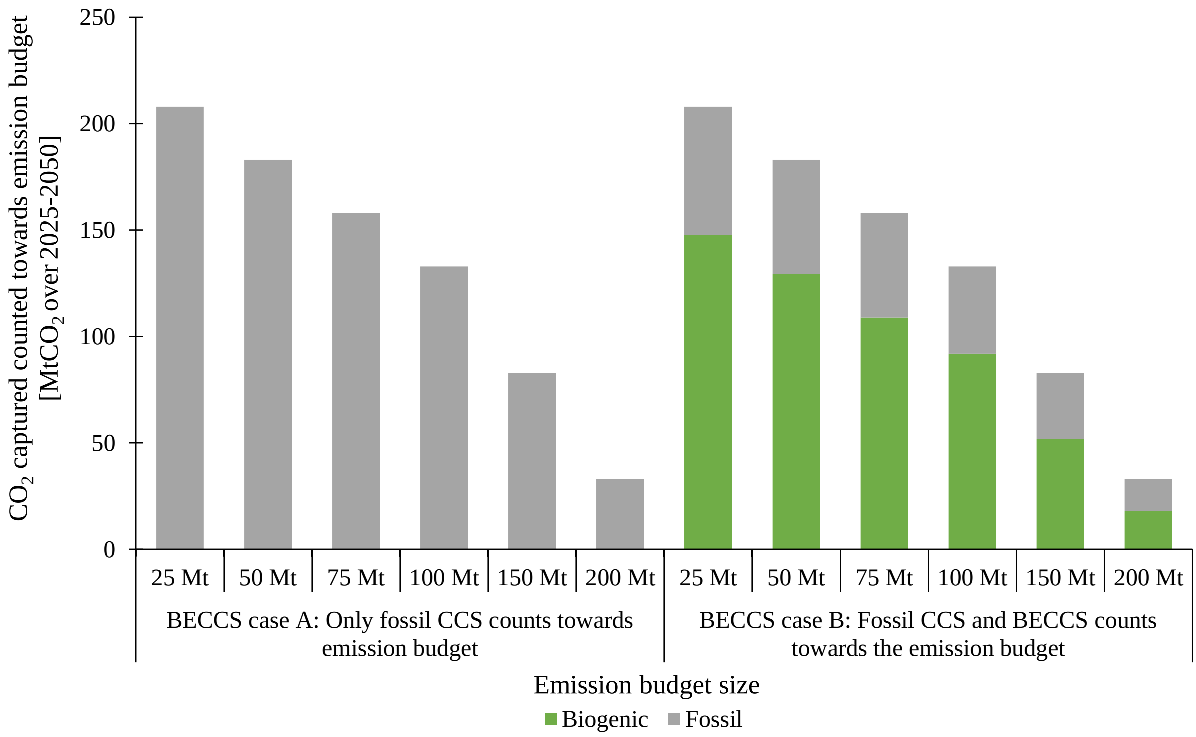

Figure 8. Levels of fossil and biogenic CO_2 captured that are counted towards the emissions budget depending on the emissions budget sizes with and without the possibility for the model to use BECCS to stay within the emissions budget. Adapted from Paper III.

4.3 CCS system sensitivity to cost elements

In addition to the incentive structures implemented to motivate capture, the development of a large-scale industrial CCS system is influenced by uncertainties related to the cost structure. Figure 9 presents selected results from the sensitivity analysis performed in **Paper II**. To incentivize capture implementation, the sensitivity cases were 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. The specific cost of the system is in the range of 69–94 €/tCO_2 in the sensitivity analysis. The sensitivity cases shown in Figure 9 assume that: the investment costs for site installations are increased by 50% (*Site CAPEX*1.5*); the transportation fuel costs are doubled (*Fuel cost*2*); and heat integration is performed, thereby decreasing by 50% the reboiler heat demand that needs to be covered by external energy sources (*Heat integration*). It is not unusual for cost estimations to have uncertainty levels of around ±30% to ±40%. Therefore, a case at the very high end with 50% increase in site investment costs was chosen to represent the effects on the system in case the assumptions relating to capture and liquefaction costs in the base case turned out to be highly optimistic. The baseline transportation fuel costs are set at 1.4 €/L for truck diesel and 420 €/t for ship fuel. A doubling of the fuel prices is motivated by potential developments whereby fuel prices increase due to, for instance, increased fuel taxes or carbon pricing. At the time of writing, the diesel price is around 2.5–3.0 €/L, which is in line with the levels applied in this sensitivity case. 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. These cases have in common that they modify the costs of site installations (capture and liquefaction). This implies that the total system cost is most-sensitive to cost uncertainties at the site level. The *Fuel cost*2* case decreases the emissions from the transportation infrastructure due primarily to a decrease in truck fuel use.

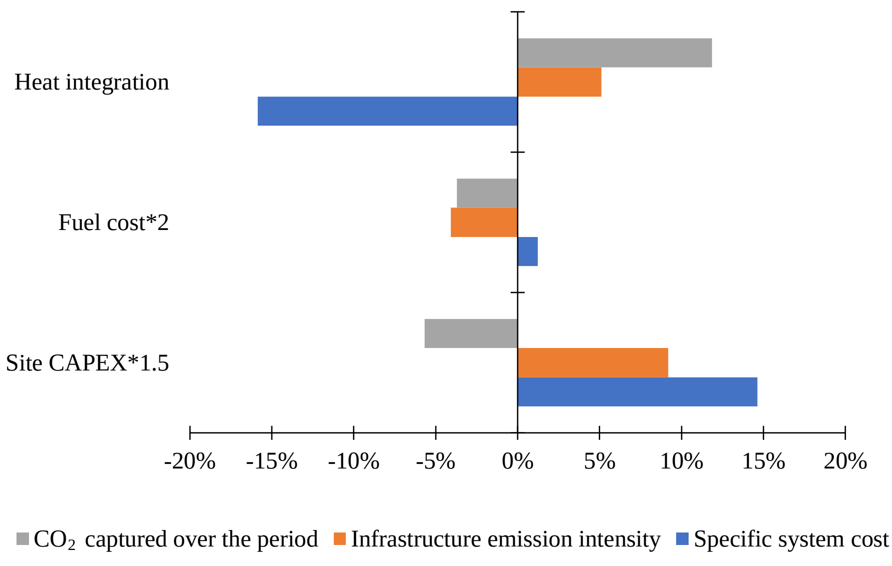

Figure 9. Sensitivity analysis for some performance indicators of the CCS system. Three sensitivity cases are shown in comparison to the base case. To incentivize capture implementation, the sensitivity cases are modeled with biogenic capture targets of 1.8 $MtCO_2/y$ by Year 2030 and 10 $MtCO_2/y$ by Year 2045, along with a cost for fossil emissions that increases throughout the period.

Figure 10 shows the cost structure of the system for the sensitivity analysis presented in Figure 9. The total cost of the system is dominated by the costs for capture and liquefaction, in terms of both CAPEX and OPEX. The transportation infrastructure is dominated by the cost of ship transportation. This further explains the results regarding the variations observed for the specific system cost in Figure 9, being mostly influenced by the *Site CAPEX*1.5* case, which significantly increases the specific CAPEX for site installations, and the *Heat integration* case, which greatly reduces the OPEX.

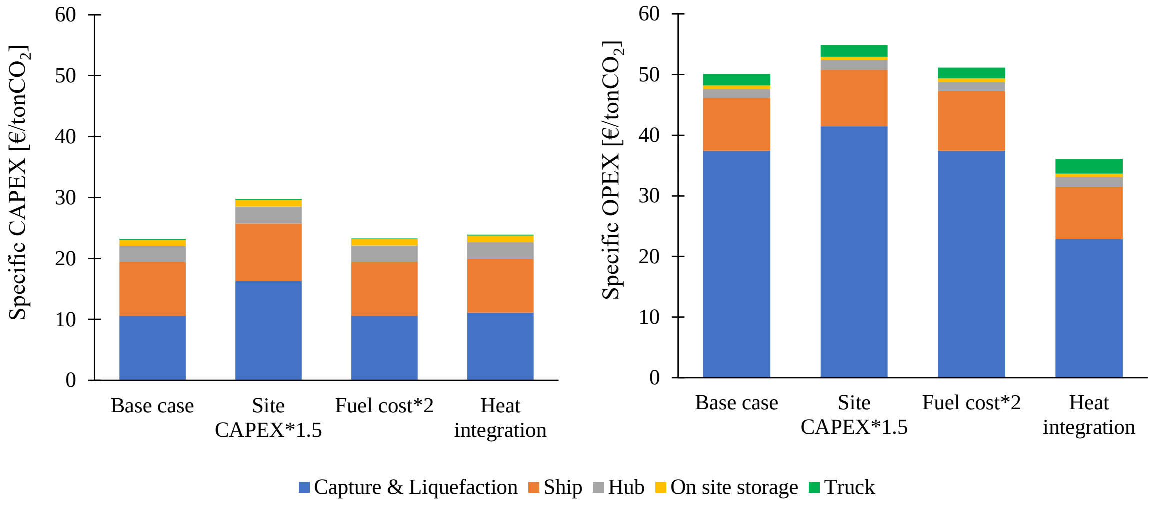

Figure 10. Cost structure of the industrial CCS system for the different sensitivity cases modeled in Paper II. To incentivize capture implementation, the cases are modeled with biogenic capture targets of 1.8 $MtCO_2$/y by Year 2030 and 10 $MtCO_2$/y by Year 2045, along with a cost for fossil emissions that increases throughout the period. Adapted from Paper II.

In addition to uncertainties regarding the costs for CCS equipment and for energy to drive the capture process and the associated transportation infrastructure, economic assumptions are likely to affect the deployment of large-scale CCS systems. Figure 11 shows the sensitivities of 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) to the discount rate. The emissions budget used allows emissions of 50 $MtCO_2$ over the period of 2025–2050. The higher the discount rate used, the greater the tendency to postpone investments in CO_2 capture and 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 look economically unfeasible in the near-term.

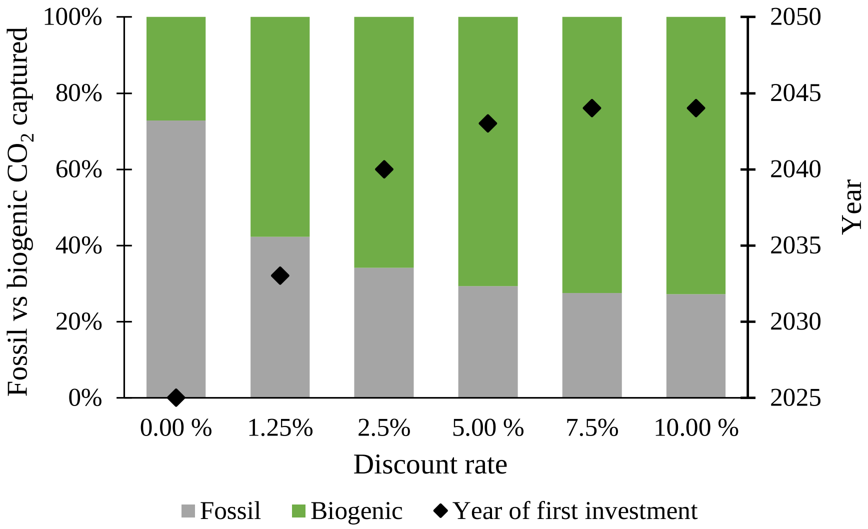

Figure 11. Share of biogenic vs fossil captured CO_2 (left y-axis) and year in which the first investment in CCS equipment is made (right y-axis) for an emissions budget of 50 $MtCO_2$, with the possibility for the model to use BECCS, for different discount rates.

5. Summary of results and discussion

5.1 Combining the site and infrastructure perspectives

In this work, combining the site perspective and the infrastructure or supply system perspective demonstrates the value of complementing techno-economic evaluations of CO_2 capture on the site level with information on the barriers to or enablers of implementation in the forms of regional conditions and national incentive structures. The work shows that the supply of logging residues is a limiting factor for the implementation of BECCS in the southern regions of Sweden, given that regional logging residues are to be used to supply heat for the desorption of CO_2. Furthermore, the work considers one at a time the additional demands for logging residues arising from BECCS implementation at the pulp mills, without considering any overlap of their respective uptake areas. If capture was to be implemented at several facilities in the south of Sweden that aim to use logging residues to drive such a capture process, the availability of biomass would present an even greater constraint. However, implementing capture at multiple sites in the same region is beneficial from the CO_2 transportation perspective, since the infrastructure can be shared, thereby reducing the costs. This presents a tradeoff between different system aspects that needs to be considered when the locations of capture plants are decided upon.

In addition to biomass availability being a limiting factor, the results show that the cost for the logging residue supply differs depending on the location of the site. This is attributed to the variable availability of logging residues and the highly distance-dependent cost structure for transporting logging residues. The cost of supplying logging residues varies between 21 and 28 €/tCO_2 captured, and it varies not only between regions, but also in relation to the amount of CO_2 captured. Thus, representing the energy penalty for carbon capture simply as a running cost that is proportional to the amount of CO_2 captured results in some potentially important aspects being missed. An analogy can be made to increased demand for electricity as a result of capture implementation, where regional conditions and marginal effects on the electricity market may influence the suitability of capture implementation at a given location. Regarding the results described in **Paper I**, it should be noted that energy sources other than regionally sourced logging residues could be considered for supplying heat to the capture process. Nonetheless, complementing techno-economic analyses of CO_2 capture with analyses of supply systems provides additional information that could be crucial in deciding how and where to implement CO_2 capture.

This thesis also reveals that the CO_2 transportation infrastructure is important to consider in conjunction with the cost for capture implementation on-site. The cost structure of a CCS system is largely made up of the costs for capture and liquefaction, although ship transportation also represents a significant part of the costs. A low cost for ship transportation could be a deciding factor in tipping the balance in favor of a smaller site with less-favorable capture costs.

5.2 Infrastructure and supply system perspectives on the development of a low-carbon industry in Sweden

Figure 12 illustrates the current conditions in Sweden in relation to the availability of biomass (logging residues) (panel a), the price of electricity (panel b), and the cost of transporting CO_2 (panel c). Note that these maps are supposed to be indicative and do not represent the conditions in every region. The logging residue availability is based on the findings from **Paper I**. The qualitative estimations of "high" and "low" CO_2 transportation costs are based on the work performed in **Papers II** and **III** and represent ship transportation to Norway. The electricity prices shown are the average values taken from the last 14 days of October 2022 from the NordPool spot market [51]. These conditions are all interconnected and relevant for the CCS and BECCS perspectives, biomass availability for supplying BECCS, electricity for compressing or liquefying CO_2, and CO_2 transportation for moving the captured CO_2 to storage.

Another way of looking at the three maps in Figure 12 is to consider that they represent important infrastructure and supply system considerations that will influence the costs of the main technology options for achieving a low-carbon industry in Sweden, i.e., electrification, biomass use, and CCS. The conditions for the supply of energy, with respect to both logging residues and electricity, are favorable in the north of Sweden. Meanwhile, the transportation of CO_2 is favorable in southern Sweden. The costs for CO_2 transportation could potentially be lowered by investigating alternative transport modes, such as pipeline or train transportation by land from central and northern Sweden to Norway. Alternatively, storage of CO_2 in the Baltic Sea could be explored to minimize the ship transportation distances for sites located further north. However, at present, ship transportation of CO_2 to Norway is the most likely pathway, at least in the near term, with the Northern Lights project being at the forefront of developing a CO_2 transportation and storage infrastructure [52].

The availability of logging residues primarily in the north of the country raises some important questions for a future bio-economy in Sweden. The refinery and chemical industries in Sweden, which are expected to increase significantly their demands for biomass feedstocks in the future, are concentrated in the southern part of Sweden on the west coast. This means that these industries will need to mobilize large volumes of biomass from the northern parts of the country or rely on imports. Alternatively, new industries could be established in the north of Sweden to benefit from the strong availability and lower cost of forest biomass. Electrification, both direct and for supplying green hydrogen, is likely to be important for the iron and steel, refinery and chemical sectors. With refineries and chemical manufacturing being located on the west coast, additional electricity generation and transmission capacity need to be procured in order to match the future demands. The electricity price levels in northern Sweden (SE1 and SE2) are currently lower than in the south of Sweden (SE3 and SE4), hinting at favorable conditions for electrification of industry that is located in the north, such as the iron and steel industry. However, the expected additional demand from electrification in the iron and steel industry of around 15 TWh/y, with an additional 35 TWh/y required if LKAB (the Swedish mining company) realizes its plans to produce iron from currently exported iron ore in Sweden [9]. Such a drastic increase in demand is likely to change the regional market conditions for electricity.

All the developments towards a low-carbon industry will entail large additional demands being placed on the associated infrastructure and supply systems. This thesis contributes to the research landscape by developing methods for mapping out these important aspects related to CCS and BECCS in Swedish industry. Future work should be aimed at addressing the interconnections between the site and system aspects so as to identify the barriers and opportunities that are not only connected to CCS, but also to other low-carbon technologies that are relevant for industry, to achieve net-zero GHG emissions.

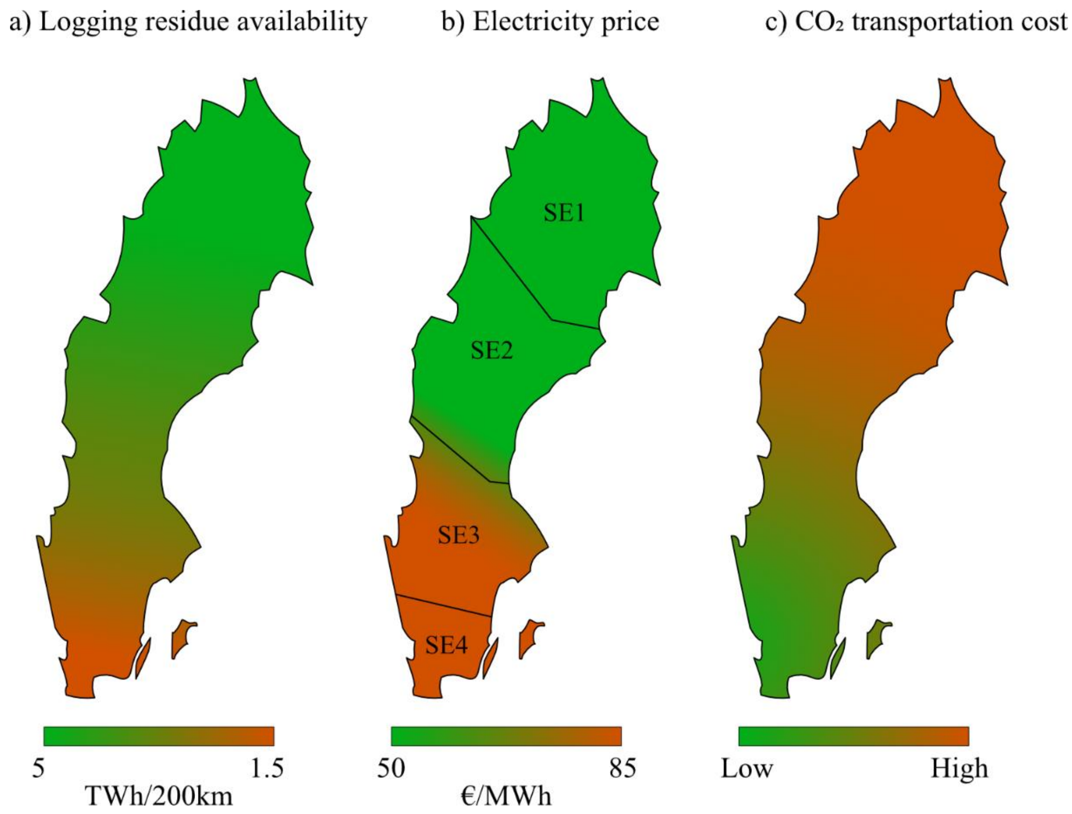

Figure 12. The conditions for supplying biomass, electricity and transportation of CO_2 in Sweden. Logging residue availability is based on the findings from Paper I. The qualitative estimation of "high" and "low" CO_2 transportation costs is based on work performed in Papers II and III and represents ship transportation to Norway. Electricity prices are the average values for the last 14 days of October 2022, as obtained from the NordPool spot market [51]

6. Conclusions and future work

This thesis investigates the interactions between CCS implementation from a site perspective and the required CO_2 transportation infrastructure (**Papers II** and **III**), and the regional supply of logging residues to generate heat for BECCS at existing industrial sites (**Paper I**). For this purpose, methods are developed to: 1) study the development of national CCS systems, including CO_2 capture and transportation, under regimes with different incentives for motivating capture installations; and: 2) quantify the potential biomass supply and associated costs for supplying new uses based on existing levels of availability and demand.

The present work shows that the potential for regional logging residues to act as an enabler of carbon removal via BECCS is highly dependent upon regional conditions, mostly in relation to existing use in the district heating sector. In northern Sweden, where availability is high and existing demand is low, the potential is large, whereas in the south of Sweden, the potential supply of logging residues is a limiting factor for reaching full capture, due to the high existing demand from the heat and power sector. The cost of transporting logging residues is highly distance-dependent and, therefore, having the ability to mobilize large volumes within a small radius of the point of use is crucial. The costs for supplying logging residues for BECCS vary in the range of 21–28 €/tCO_2 captured, increasing more rapidly and ending with higher costs in southern Sweden.

Large-scale CCS systems in Sweden for fossil CO_2 capture are shown to be motivated by emissions price levels of around 80 €/tCO_2 (excluding final storage). The cost structure of CCS systems mainly comprises the cost for capture and liquefaction, although ships also represent a significant contributor, such that access to short-distance ship transportation can tip the balance in favor of sites that are smaller and, therefore, have a slightly higher capture cost than larger sites. Increasing the costs for site installations postpones investments, whereas an increased cost for transportation fuels reduces the overall transportation distances and, thereby, the emissions intensity of the transport infrastructure.

The incentive structures chosen for motivating capture determine which sites are economically optimal for the capture of CO_2 and at what point in time. Waste-fired heat and power plants are economically feasible when incentives for both fossil and biogenic CCS are combined, as shown in Section 4.2, where capture targets are set for biogenic CO_2 and fossil CO_2 emissions are priced. Including BECCS as in emissions budgets reduces the system cost but tends to postpone the making of investments in CCS technology. The effect of postponing investments is highly dependent upon the discount rate. To facilitate timely implementation of CCS and BECCS, it is important to consider that including CDR into the same policy regime that controls fossil fuel emissions, might result in the cost optimal strategy being a delay in fossil fuel mitigation.

6.1 Future work

To gain further insights into the infrastructural and system considerations associated with decarbonizing industry, further model development work is needed. This thesis gives an overview of some system aspects that are relevant for BECCS and CCS in Swedish industry. However, as noted in Sections 2 and 5, substituting fossil feedstocks and energy with bio-based alternatives and electrifying industry are important potential pathways for many sectors. Thus, the modeling framework developed and used in **Papers II** and **III** of this thesis should be expanded to include these technological options. This will entail accounting for the expansion of electricity production and transmission that will be necessary for extensive electrification. In addition, it will need to take into account the limitations of different mixes of biomass and their associated transportation and conversion costs, so as to enable future use at the relevant sites.

Furthermore, the non-technical aspects of the build-up of the large infrastructures required for industrial decarbonization are likely to be crucial. Multiple actors with incentives that are not always aligned need to be involved in the build-up of the different integral parts of large systems. In the case of CCS, this is exemplified by a given industrial actor that is unlikely to want to invest heavily in capture equipment before knowing that there is a suitable, reasonably priced storage location with sufficient capacity available. Conversely, a storage operator is unlikely to want to invest heavily in CO_2 storage and injection capacities without knowing that there will be capture plants that will want to purchase this storage. While such considerations are not captured in cost-minimizing models such as the one applied in this thesis, they are crucial for achieving the ramp-up required to work towards meeting the climate targets. Furthermore, we see that the cost optimal ramp-up rates in this work are unreasonably high when implementing CO_2 pricing. The first steps of including limits on the deployment rate of the capture technology towards achieving a more-realistic system build-up have been taken in **Paper III**. However, future work should aim to complement the modeling results with a wider variety of such considerations, or better yet, find a way to represent more of these uncertainties endogenously.

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