Influence of carbon dioxide removal policies in CCUS-system development

A techno-economic assessment of Swedish industrial sectors

Master's thesis in Innovative and Sustainable Energy Engineering

Gustavo Ezequiel Martínez

DEPARTMENT OF SPACE, EARTH AND ENVIRONMENT

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
www.chalmers.se

MASTER'S THESIS 2023

Influence of carbon dioxide removal policies in CCUS-system development

A techno-economic assessment of Swedish industrial sectors

Gustavo Ezequiel Martínez

Department of Space, Earth and Environment
Division of Energy Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023

Influence of carbon dioxide removal policies in CCUS-system development
A techno-economic assessment of Swedish industrial sectors
GUSTAVO EZEQUIEL MARTÍNEZ

Supervisor:	Sebastian Karlsson, Department of Space, Earth and Environment (Chalmers)
	Mika Järvinen, Department of Mechanical Engineering (Aalto)
Examiner:	Fredrik Normann, Department of Space, Earth and Environment

Master's Thesis 2023
Department of Space, Earth and Environment
Division of Energy Technology
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone: +46 31 772 1000

Printed by Chalmers Reproservice
Gothenburg, Sweden 2023

Influence of carbon dioxide removal policies in CCUS-system development
A techno-economic assessment of Swedish industrial sectors
GUSTAVO EZEQUIEL MARTÍNEZ
Department of Space, Earth and Space
Chalmers University of Technology

Abstract

This master's thesis examines the effect of carbon dioxide removal (CDR) policies and need for CO_2 utilization on the development of a carbon capture, utilization, and storage (CCUS) system for the Swedish industry. The study aims to assess the impact of policy scenarios to promote biogenic carbon capture and storage (BECCS) on the total volume CO_2 captured and the levelized cost of CO_2 in the CCUS system as well as the impact on the levelized cost of CO_2 for bioenergy with carbon capture and utilization (BECCU) subsystem.

To achieve these objectives, a techno-economic analysis is conducted, integrating various factors such as BECCU requirements and fossil emissions price.

The findings reveal that the choice of policy to promote BECCS significantly influences the amount of CO_2 captured, while required amounts of CO_2 for utilization and fossil CO_2 price predominantly affect the levelized cost of CO_2. The CCUS system demonstrates levelized costs of CO_2 ranging from 92 to 115 €/tCO_2, with the capture and conditioning component constituting the largest share of system costs.

Two policy scenarios, BECCS credits and BECCS subsidies, are evaluated. In the BECCS credits scenario, a high demand for biogenic CO_2 in BECCS leads to an increased $LCCO_2$ for BECCU, reaching nearly 100 €/tCO_2. Shared transport infrastructure benefits the fossil carbon capture and storage (CCS) subsystem. In the BECCS subsidies scenario, biogenic CO_2 is less attractive for BECCS compared to BECCU, resulting in a decrease in the $LCCO_2$ for BECCU to almost 80 €/tCO_2.

The study also highlights the potential for creating a market for negative emissions in Sweden. The BECCS credits scenario indicates a market worth approximately 13,700 M€. Moreover, implementing a differentiated financing system for negative emissions to address hard-to-abate sectors could generate profit without significantly increasing the overall costs of the CCUS system.

In conclusion, this master's thesis contributes to the understanding of the interplay between CDR policies and CO_2 utilization in the development of the CCUS system for the Swedish industry. The findings have implications for designing effective policies and strategies to address carbon emissions and promote sustainable development in the region.

***Keywords**: CCUS, BECCU, CCS, industry, BECCS credits, BECCS subsidies.*

Acknowledgements

I would like to thank my supervisor Sebastian Karlsson for his guidance throughout this work. His willingness to help has been instrumental in overcoming challenges and progressing with my work. The constant availability of his guidance have been invaluable. I am also thankful to my examiner, Fredrik Normann for the weekly meetings, they have been instrumental in shaping the direction of this work and reaching the conclusions presented in this thesis. His expertise and constructive feedback have greatly enriched my work. Thank you to the Energy division for hosting me this entire semester, I had the pleasure to meet amazing people here.

Thanks to “tha office” group for making this semester a truly remarkable experience, full of laughs, fika breaks. You motivate me to come to the office every day. Thanks to all the friends I met during the last two years. Your friendship have made this journey truly memorable. Hannah, thanks for your support over these last months. Sergio, gracias por estos dos años que estuviste bancándome.

Belén y Lourdes gracias por apoyarme y acompañarme siempre cerca y a la distancia. Caro y Rudy gracias por darme la oportunidad de vivir esta experiencia, todo lo que soy es gracias a ustedes dos.

Gustavo Ezequiel Martínez, Gothenburg, June 2023

Table of Contents

List of Tables

List of Figures

Nomenclature

Abbreviations

BECCS	Bioenergy with Carbon Capture and Storage
BECCU	Bioenergy with Carbon Capture and Utilization
CAPEX	Capital Expenditures
CCS	fossil Carbon Capture and Storage
CCU	fossil Carbon Capture and Utilization
CCUS	Carbon Capture, Utilization and Storage
CDR	Carbon Dioxide Removal
CHP	Combined Heat and Power
DAC	Direct Air Capture
DMEA	Dimethylethanolamine
EU ETS	European Union Emissions Trading System
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate
$LCCO_2$	Levelized cost of carbon dioxide
LCOE	Levelized cost of electricity
MEA	Monoethanolamine
MIP	Mixed Integer Programming
NPV	Net Present Value
OPEX	Operational Expenditure
PSA	Pressure Swing Adsorption

1. Introduction

The implications of climate change can already be observed all over the world; rising sea levels, changing patterns in weather, and regularity of extreme weather events are some of the effects of climate change [1]. To mitigate these, and other consequences, action needs to be taken. In 2015, 197 countries signed the Paris Agreement, an international treaty with the goal of limiting global mean temperature increase to well below 2ºC above pre-industrial levels, while pursuing efforts to limit the increase to 1.5ºC [2]. The agreement aims to achieve this through countries pledging to reduce their greenhouse gas emissions and regularly reporting on their progress. The scientific consensus is clear that human activities, particularly the burning of fossil fuels, are the primary cause of climate change, and urgent action is needed to reduce emissions and limit its impacts.

Global mean temperature increase can be linked to cumulative CO_2 emissions; thus, mitigation needs can be quantified using a global carbon budget. To stay within the remaining budget, the Intergovernmental Panel on Climate Change (IPCC) suggest that carbon neutrality needs to be reached in less than 30 years (temperature increase below 2°C) or 20 years (temperature increase limited to 1.5°C) [3]. To achieve this goal, countries have set emissions reduction targets and implemented policies to transition to a low-carbon economy. The European Union has committed to reducing greenhouse gas emissions by 55 % in 2030 compared to the emissions in 1990, including both emissions reductions and removals [4]. In the case of Sweden, the objective is to reach net zero emissions by 2045, with emissions levels 63% lower than 1990 by 2030 [5]. On the other hand, China the world's largest emitter, aims to peak its carbon emissions by 2030 and achieve carbon neutrality by 2060 [6].

IPCC provided different pathways limiting temperature raise to 1.5 °C, and all of them require a reduction on fossil feedstock as well as carbon dioxide removal (CDR) to some extent [7]. Even though CDR has not been proven at scale, this is the only alternative to neutralize emissions from hard to abate sources. In addition, bioenergy with carbon capture and storage (BECCS) plays a crucial role to decarbonize energy use in some of the pathways provided [3]. According to the International Energy Agency (IEA), carbon capture, utilization and storage (CCUS) will need to play a significant role in limiting global warming to 1.5ºC above pre-industrial levels, the target set by the Paris Agreement [8]. Carbon capture, utilization and storage (CCUS) is a set of technologies and practices aimed at reducing carbon dioxide (CO_2) emissions from industrial processes. CCUS involves capturing CO_2 emissions from industrial facilities and either utilizing it to create value-added products or storing the CO_2 deep underground, where it can remain trapped for thousands of years. The upward trend in price levels in the European Union Emissions Trading System (EU ETS) has arisen the concern about CO_2 emissions reductions not only from industrial actors, but also on a national level. Carbon capture and storage related to fossil fuels (CCS) has been proposed as a potential method to decrease CO_2 emissions [9]. In contrast to CCS that can achieve zero emissions in the best case, BECCS has the potential to remove CO_2 from the atmosphere, resulting in net negative emissions [10]. Incentives promoting CDR have set BECCS into the spotlight, while bioenergy with carbon capture and utilization (BECCU) has emerged as a promising alternative to reduce fossil emissions, utilizing only bio-CO_2 as feedstock. Figure 1 presents a schematic diagram of the CCUS system and subsystems (CCS, BECCS and BECCU) considered for this report. This work intends to evaluate potential synergies and competitions between BECCS and BECCU for a bio-CO_2 restricted future and their effect in the CCUS system development.

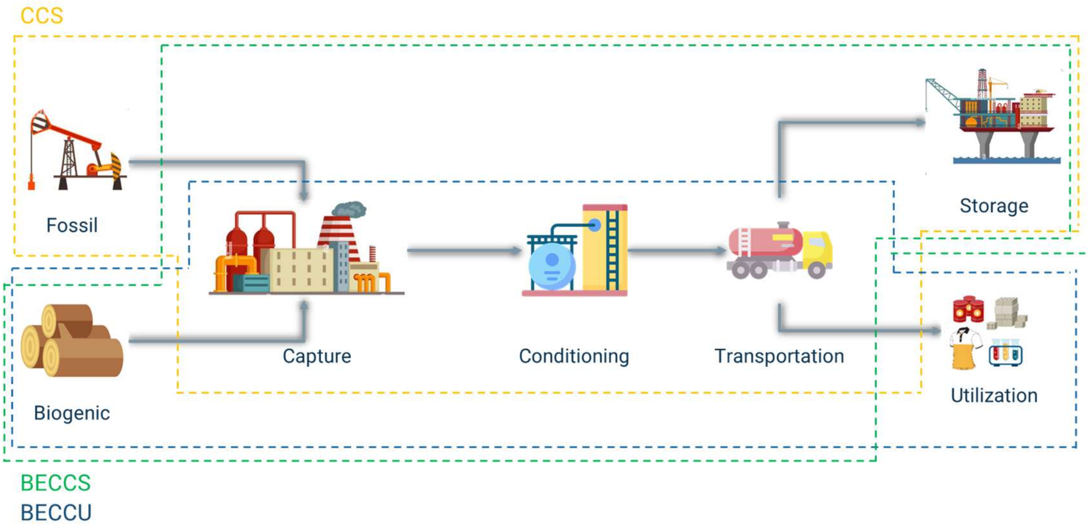

Figure 1: CCUS system considered in this work. Yellow dashed line represents the fossil carbon capture and storage (CCS) subsystem, blue dashed line represents the bioenergy carbon capture and utilization (BECCU) subsystem and green dashed line represents the bioenergy carbon capture and storage (BECCS) subsystem.

1.1. Aim

This master's thesis aims to determine the impact of carbon dioxide removal policies on the evolution of a carbon capture, utilization, and storage systems for Swedish industry. Emission pricing for fossil emissions, revenue from storing biogenic CO_2 and monetary subsidies to promote bio-energy carbon capture and storage are studied along with projected demands for biogenic CO_2 as a renewable feedstock in Swedish refineries and chemical manufacturing.

This thesis work focuses on the national system level and highlights compatibilities or conflicts in the system when bio-CO_2 captured is a potential resource for utilization in industry. The impacts of fossil emissions pricing and carbon utilization demand on the system development are also analyzed. The following research questions are addressed in this thesis:

i. How do different incentives for bioenergy with carbon capture and storage affect the carbon capture utilization and storage system development and cost?
ii. How will CO_2 utilization requirements influence the carbon capture utilization and storage system evolution and cost?
iii. Are cost related parameters the only barrier for carbon capture utilization and storage system or is infrastructure build-up time a major limitation?

2. Background

2.1. Emissions

Global emissions have quickly increased back to the levels before COVID-19, and emissions in 2022 were slightly above the pre-pandemic levels of 2019. Total anthropogenic CO_2 emissions were about 40.5 $GtCO_2$/y by 2022, shrinking the remaining budget proposed in 2019 in the IPCC AR6 Working Group 1 assessment by 131 $GtCO_2$. The remaining carbon budget to keep temperature under 1.5 ºC, with a 50% likelihood is 380 $GtCO_2$, and with 2022 emissions levels, that is equivalent to slightly more than 9 years, and even though emissions are being reduced in some regions, the global effort is not strong enough to reach the targets set in the Paris Agreement [11].

Figure 2, shows that more than 50% of the global anthropogenic CO_2 emissions were produced in the industry sector (22.4 $GtonCO_2$), being one of the sectors where emissions reductions need to focus.

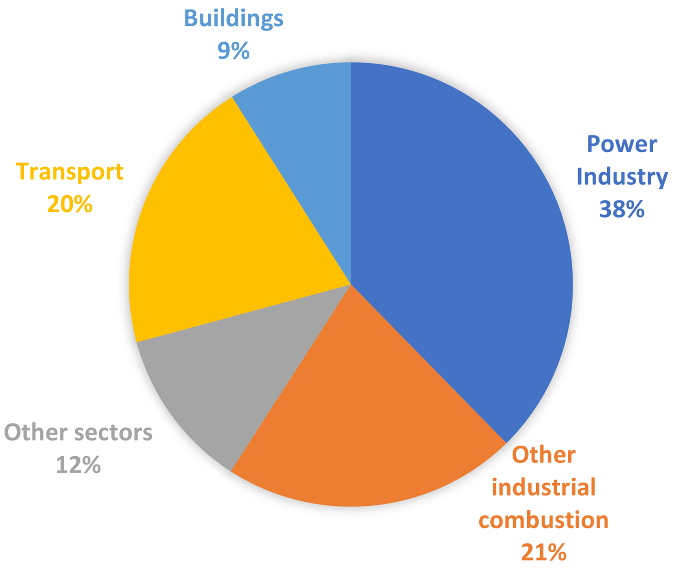

Figure 2: Global carbon dioxide emissions by sector for year 2021. Total greenhouse emissions were 37.8 $GtonCO_2$ [12].

In 2021, EU27 was the third largest CO_2 emitting economy globally, releasing 2.78 $GtonCO_2$ to the atmosphere corresponding to 7.3% of global emissions. In 2014, EU Member States agreed on long-term goals, to cut emissions by 40% in 2030 compared to 1990 levels [13], [14]. The targets set in 2014 resulted in a decreasing trend in the EU27 emissions over the last decade, but the pace has not been fast enough to achieve the goals set by 2030 [12]. In 2021, the European Union had produced a new set of rules, the so-called "Fit for 55" package, tightening the climate policies agreed upon previously, aiming to align EU with the 2030 goal to cut emissions by at least 55% compared to 1990 levels [15].

2.2. CCUS

Carbon capture, utilization and/or storage (CCUS), comprise a group of technologies used to capture, transport, utilize to produce goods, and/or store CO_2. These technologies have been in development for several decades, and some are already in commercial use. For example, the Sleipner project in Norway has been injecting CO_2 into an offshore aquifer since 1996 [16], while the Petra Nova project in Texas captures CO_2 from a coal-fired power plant and uses it for enhanced oil recovery [17]. However, the deployment of CCUS remains limited, and significant technological, economic, and regulatory challenges must be overcome to scale up these technologies. Despite the challenges, the potential benefits of CCUS are significant. In addition to reducing emissions, CCUS can help maintain energy security, create jobs, and facilitate the transition to a low-carbon economy.

The first step in the CCUS chain is CO_2 capture. The set of technologies that have been developed to capture CO_2 can be divided into four main groups: atmospheric capture, pre-combustion capture, post-combustion capture and oxy-fuel combustion.

Atmospheric capture, as the name states, consists of capturing CO_2 directly from the atmospheric air, either in natural processes, e.g., in forests, oceans and soil participate, or by circulating air through regenerative filters to separate CO_2 from ambient air, known as direct air capture (DAC) [18]. The major drawback observed with DAC is the large energy requirement due to the low concentration of CO_2 in the atmospheric air (400 ppm), with specific demands up to 10 GJ/tonCO_2 to produce CO_2 at the same concentration as other solutions where CO_2 is captured from a concentrated source like flue gases [19]. On the other hand, this technology has gained interest in the last few years because it can be used where conditions for energy supply are good or close to the end storage location. The European Commission communication, Sustainable Carbon Cycles [20], and the Net Zero by 2050 scenario proposed by the International Energy Agency [21], recommend that by 2050, DAC shall play a key role to reduce CO_2 concentration in the atmospheric air.

Pre-combustion capture refers to a set of technologies that transform carbon-based fuels into carbon-free fuel, for example, natural gas conversion into hydrogen through steam reforming. This is the most mature method to produce hydrogen in refineries and typically, CO_2 can later be removed by pressure-swing adsorption (PSA) [22]. In an integrated gasification combined cycle (IGCC), solid fossil fuels like coal and biomass are partially oxidized with pure O_2 and steam, producing syngas for power generation in a gas turbine. CO present in the syngas can be converted into CO_2 using the water-gas shift reaction before injecting the gas in the turbine. Acid gases and CO_2 are removed all together using the Selexol process [18].This process uses dimethyl ether of polyethylene glycol as a solvent, reducing CO_2 concentration in the gas by almost 85% [23].

Post-combustion capture is relatively easy to implement in any pre-existing combustion process, therefore it is the most studied pathway to capture CO_2. This technique refers to CO_2 capture from the flue gas emitted after combustion of carbon-based fuels. Removal of CO_2 from the exhaust gas can be carried out by chemical or physical absorption, adsorption, cryogenic or membrane separation. Chemical absorption using amine solutions like monoethanolamine (MEA) or dimethylethanolamine (DMEA) as sorbents is one of the best fitting technology for post-combustion with a low CO_2 partial pressure, and has been present in commercial scale for more than 50 years [24]. In chemical absorption, the flue gas from the stack is set in contact with the amine solution in an absorber. The solution rich in CO_2 is pumped into a second unit (regenerator), where CO_2 is removed from the solution, and the lean solution is recirculated to the absorber. Conventional capture rate for this technology is 90%, with CO_2 purity of up to 95%, and the major energy consumption takes place in the MEA solution recovery unit (regenerator), requiring up to 4 MJ/kgCO_2 of heat [25]. Physical adsorption, and membrane separation are promising technologies and might offer reduced capture cost, but they are still in the development stage [18].

Oxy-fuel combustion include also chemical looping combustion and for these technologies, the combustion reaction takes place in absence of nitrogen, therefore, the flue gas contains mostly carbon dioxide and steam. High purity CO_2 can easily be achieved by water condensation, and there is no thermal formation of NO_x. However, these technologies require major modifications to existing processes and thus, require large investments compared to other technologies [26].

CO_2 conditioning and transportation are critical aspects of the CCUS chain, as they ensure that the captured CO_2 is of sufficient quality for storage and that it can be safely transported to its final destination. Large volumes of CO_2 can be carried either by pipelines or ships. According to the Global CCS institute, to support the capture facilities required to reach climate targets, more than 200,000 km of pipeline are needed by 2050 [27]. By year 2022, there are over 8,000 km of CO_2 pipelines in operation only in the US [27]. In Europe, CO_2 pipelines have been operating since 1996 (Sleipner, Norway) transporting CO_2 to underground storage, and various projects are undergoing like Northern Lights, that aims to transport up to 1.5 $MtCO_2/y$ to a storage in the North Sea in 2024, with expansion potential as demand grows in Europe [28]. Another ambitious project involves a 1000 km pipeline from Belgium to the Norwegian North Sea, aiming to transport up to 40 $MtCO_2/y$ [29]. Ships emerged as a flexible transportation alternative for locations without close access to storage. Land transport of CO_2 can be done by trucks or railways, with trucks being the most flexible solution. However, these methods are frequently used to transport small volumes over short distances. Unlike pipelines, ships, trucks, and railways transportation require a previous liquefaction stage, that can be done either on-site after capture or collecting small volumes in a single plant using pipelines to decrease system costs. Liquefaction conditions depend on the requirements established by the final destination. In addition, ship, railway and truck transportation requires intermediate storage to balance the round-trip time and the time needed for CO_2 loading.

Permanent CO_2 storage in geological formations is the last step in the carbon capture and storage chain. It involves CO_2 injection deep underground, trapping CO_2 in empty spaces of the rocks, preventing it from being released to the atmosphere. The Nordic region have a large potential storage capacity, with sedimentary basins south of Sweden, on- and offshore in Denmark and the Norwegian continental shelf [30]. Geological storage has been demonstrated technically feasible, and safe to reduce CO_2 emissions, but potential leakages and long-term storage security have caused insecurity in some political sectors.

To decrease fossil emissions, some industrial sectors, such as refineries and chemical manufacturing, also plan to move from fossil feedstock to other sources. This transition requires a significant amount of carbon units; and here is where carbon capture and utilization can become interesting. Carbon capture and utilization focuses on finding productive uses for the captured CO_2. This promotes a circular economy by transforming greenhouse gases into a valuable resource. Some common examples of carbon capture and utilization are the production of synthetic liquid fuels by Fischer-Tropsch method (Power-to-Fuel) and chemical organic synthesis to produce diverse polycarbonates [31], [32]. Compared to carbon capture and permanent storage that reduce CO_2 emissions to the atmosphere, carbon capture and utilization only delays the emission of the captured carbon. The major environmental advantage of this alternative is the reduction of fossil resource extraction, and the potential emissions reduction that comes with this substitution.

CCUS can be categorized into four subsystems based on the nature of the CO_2 source and the end-use of the captured carbon dioxide. CCS and CCU (carbon capture and utilization related to fossil fuels) both include the capture of CO_2 from fossil feedstocks, with storage and utilization as end use respectively. BECCS and BECCU are in principle the same as CCS and

CCU, with the only difference being that the combusted fuel is of biogenic origin (biomass or bio-based waste) rather than fossil-based.

The idea behind BECCS as a CDR alternative, is that carbon dioxide emissions from biomass-based energy production are offset by the CO_2 absorbed during biomass growth, resulting in a net removal of CO_2 from the atmosphere when the CO_2 is captured and stored underground. BECCS has the potential to offset CO_2 emissions from hard-to-abate sectors, and eventually contribute to reaching net-negative emissions, but other challenges arise with this technology. Some of the major challenges and concerns associated with BECCS are the competition with food production for land use, and the environmental impact from large-scale biomass production for energy purposes. It is well known that biomass is not an unlimited resource, and an efficient use is mandatory, therefore it can be argued that this solution shall only be used as a supplementary measure to offset emissions from hard-to-abate sectors, whereas other sectors should improve their efficiency or develop new technologies to reduce emissions. The accounting method used to estimate emissions is another major challenge for BECCS. Moreover for slow growth biomass such as forestry, the time boundary to grow biomass can influence drastically in the emissions balance, while in the carbon dioxide removal scheme, emissions and removal are assumed to be instantaneous, the growing process is longer [33]. BECCU appears as an interesting alternative to BECCS and CCU from an economic and environmental perspective, since not only reduction of resources is achieved, but also the potential emissions from the process utilizing biogenic CO_2 becomes biogenic (until date, excluded from EU ETS system) [34].

2.3. Sweden´s perspective

Fossil CO_2 emissions in Sweden accounted for 41.7 $MtCO_2$ in 2021, which is less than 1.4% of the EU27 fossil CO_2 emissions. Sweden’s fossil emissions from the industrial and energy sectors are about 46% of total fossil emissions, and those emissions are mainly located in the iron and steel sector (see Figure 3). Sweden is a unique case, with the main sources for electricity generation being hydro and nuclear power with a steadily increasing share of wind, and a large use of bioenergy and waste incineration for district heat production [35].

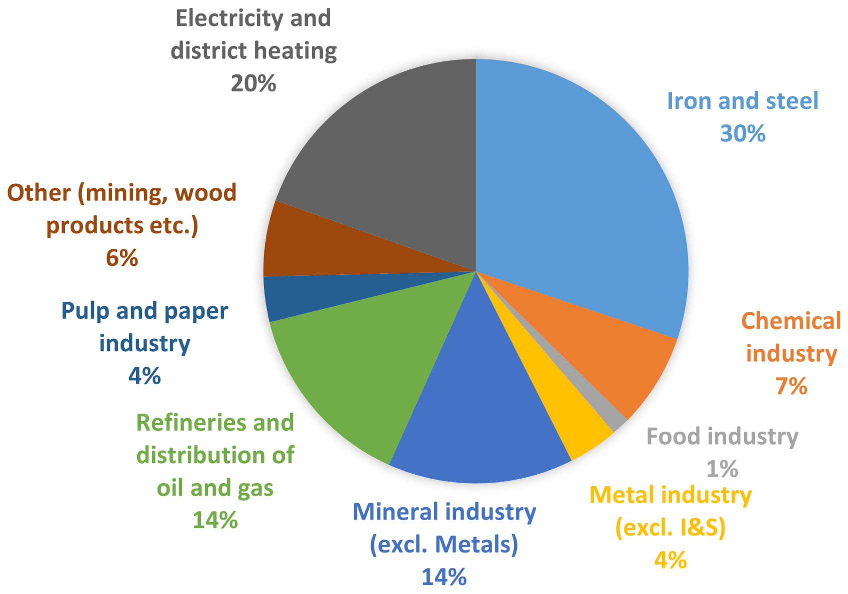

Figure 3: Fossil CO_2 emissions in Sweden by industrial sector in year 2021. Total emissions from industries were 19.2 $MtCO_2$ [36], [37].

Compared to most of the EU member states, Sweden has set more ambitious long-term targets, aiming to have net zero emissions by 2045 latest. This means in practice that GHG (greenhouse gas) emissions shall be at least 85% lower in 2045 than in 1990. The remaining 15% could be reduced by supplementary measures (i.e., carbon removals), like bio-energy carbon capture and storage (BECCS) [5]. Reducing GHG emissions in line with the target will require intensive fossil emitting industries to either reduce their emissions by CCS or replace fossil feedstock with renewable alternatives. The iron and steel industry has ongoing demonstrations to produce fossil-free steel (e.g., the HYBRIT project [38]), replacing coal for reduction of iron ore with fossil-free hydrogen. The project aims to produce fossil-free steel by 2026, avoiding 14.3 $MtCO_2$ to be emitted over the first 10 operational years [38]. Preem, the largest refinery operator in Sweden plans to produce up to 5 Mm^3 renewable fuels by 2030, which requires large amounts of carbon atoms from biogenic sources [39]. To keep a balance on the carbon cycle, it is possible that Sweden's biomass is not enough to supply the carbon units required by industries. Following the current biomass consumption trend and industrial forecasts, more than 40 TWh/y of additional biomass will be required by 2030 and 55 TWh/y by 2050 [40]. Using CO_2 from biogenic sources as feedstock, could also be an alternative for these industries, reducing their net emissions while some part of the CO_2 can be temporally stored as products.

2.4. Policy context

To address CO_2 emissions, policies are essential as they provide a regulatory framework, drive climate change mitigation efforts, fulfill international commitments, stimulate investment, and facilitate the transition towards a sustainable future [41]. Some alternatives to promote emissions mitigation generally, and carbon capture specifically, include policies with a price for fossil emissions, a credits system for capturing and storing biogenic emissions, and subsidies, i.e., public funding, for capturing and storing biogenic emissions.

2.4.1. Carbon Pricing

This method refers to the implementation of financial mechanisms that put a price on CO_2 emissions from a fossil source, applying a "polluter pays" principle to ensure that environmental risk is included in commercial activities. The strategy aims to incentivize industries to reduce their GHG emissions, adopting cleaner and more sustainable practices. Carbon pricing can take various forms, including carbon taxes and cap-and-trade systems.

Carbon taxes are an easy to implement strategy to decrease GHG emissions. This solution imposes a direct price on each unit of CO_2 emitted (e.g., €/tonCO_2), levied on fossil emissions. The price per ton of CO_2 emitted can be fixed or gradually increased over time, with local governments often in charge of this taxation scheme and enforcing it. This method provides a higher level of certainty about the cost for emitting, however the level of emissions reduction to be achieved present more uncertainties [42].

In a cap-and trade system, a cap is set on the total amount of GHG emissions allowed within the system. The European Union has been at the forefront of international efforts to reduce CO_2 emissions, with the European Union Emissions Trading System (EU ETS) as cornerstone policy to address emissions. Set up in 2005, the system operates on a cap-and-trade principle, whereby a cap is set on the total amount of GHG emissions allowed in the system [43], [44]. Emission allowances are allocated to installations (e.g., power plants and industries) that are covered by the system. One allowance represents the right to emit one metric ton of CO_2 or equivalent of other powerful GHG. The allowances can be traded between participants, allowing for flexibility in emissions reductions. The cap is gradually reduced over time to achieve emission reduction targets [45]. In 2021, EU ETS entered into the phase 4, increasing the pace of the emissions cuts at an annual rate of 2.2% compared to 1.74% reduction rate in the period 2013-2020 [46].

2.4.2. Carbon offsets (BECCS credits)

In a carbon market, also known as carbon trading system, a market-based approach is taken to address GHG emissions, trading both carbon credits or emissions allowances and carbon offset simultaneously. Compared to emissions allowances that are regulated by entities in a cap-and-trade system, carbon offsets participate in a voluntary market, where businesses buy credits to offset their own emissions. Nonetheless, the basic unit traded is the same for both (CO_{2eq}) [47]. BECCS has emerged as a compelling option to produce carbon offsets, based on the amount of CO_2 that is captured and stored. In Europe, a BECCS credits system could lead to economic and environmental benefits, incentivizing sectors that were not considered under the regulated market for emissions (EU ETS) to decrease their emissions. However, creating a carbon market that includes both carbon credits and offset credit could present challenges and potential drawbacks from an environmental perspective because the system could rely on negative emissions rather than decreasing fossil emissions, thus offset credits should be prioritized for hard-to-abate sectors [48]. Another potential trade-off is the competition for biogenic CO_2, which can serve as a substitute for fossil feedstock and contribute to a lower carbon footprint for certain industrial sectors. If a significant portion of the available biogenic CO_2 is used for carbon offsets, it could limit the availability of this resource for substitution in other sectors. This limitation could hinder the development of carbon-neutral or low-carbon innovations in industries that rely on biogenic CO_2 as a substitute for fossil feedstock.

2.4.3. Subsidies for negative emissions (BECCS subsidies)

Governments or other entities can provide financial assistance in the form of subsidies to support the development of CDR-related technologies and practices. These subsidies are aimed at accelerating the adoption of negative emissions technologies. State aid can help with deploying negative emissions technologies at scale, closing the cost gap between conventional technologies and negative emissions alternatives, or offsetting the large investment required. To promote CDR technologies, different subsidies schemes can be presented. A flat subsidy, in which a fixed price (i.e., €/tonCO_2) is set for BECCS and the volume fluctuates, is a simple way to fund BECCS with a quick reaction. In this system, all actors receive the same subsidy, resulting in overcompensation for some. Furthermore, in practice, a volume cap is more logical. A second alternative to support BECCS is by implementing a reverse auction system with a fixed volume. In this system, actors propose a bid on how much CO_2 they can capture and the associated cost. The winning bid is the solution that captures at the lowest cost. This alternative is frequently combined with a financial budget cap [49]. In Sweden, a reversed auctioning was proposed as a support system for BECCS, that plans to cover costs for capture, transport and storage during a period of 15 years. According to the Swedish government, the goal is to capture and store up to 2 MtCO_2/y by 2030, with potential to increase the BECCS level to 10 MtCO_2/y in 2045 with a budget cap of SEK 36 billon [50], [51], [52].

3. Method

The work studies the development of a CCUS system for Swedish industries. Primary elements of the system are CO_2 capture, transportation infrastructure and end-use. Site emissions are based on industrial databases, characterized as biogenic or fossil based on the feedstock and assumed constant over the period considered. Transportation infrastructure includes land transportation by trucks, CO_2 storage hubs and sea transport by ships. Possible CO_2 end-uses are geological storage or utilization for the chemical and refining industries. For the sake of this work, centralized utilization at a single location, and one permanent CO_2 storage location are considered. In this report, the CCUS system is divided into three subsystems to determine potential synergies or competitions between them, based on the CO_2 source and end-use: 1) CCS includes components of the CCUS system that capture and store CO_2 from fossil sources; 2) BECCS, same as CCS but focuses on biogenic CO_2; 3) BECCU, consisting of those components of the CCUS system that capture and utilize CO_2 from biogenic sources. No utilization of fossil CO_2 is considered. BECCS and CCS are promoted through existing and proposed policies (EU ETS or Carbon price, BECCS credits and BECCS subsidies) while BECCU requirements are set to fulfil part of the future industrial need for circular carbon units. This work includes possible limitations on the transport infrastructure build up. A techno-economic assessment is performed in an optimization model to determine the CCUS system development. The CO_2 utilization process itself, and subsequent implications on the CCUS system are outside the scope of this research. The main characteristics considered to evaluate the cases and compare them are the levelized cost of CO_2 (€/tonCO_2), net present value (M€), capture levels (MtCO_2/y), total capture (MtCO_2) and system evolution over time.

3.1. Model

This work is based on a cost optimization model using Mixed Integer Programing (MIP), where the objective is to find the cheapest, i.e., the lowest system cost, solution for a complete Swedish CCUS system. The model is based on the cost-minimizing of optimization model proposed by Karlsson et al., [53]. In this work, the model is adapted to include CO_2 utilization based on projected future demands for renewable carbon atoms in industry and time limitations to build the infrastructure required. On-site capture and liquefaction costs are studied together with the CO_2 transportation infrastructure required and costs related to permanent storage of CO_2. In the model both investment (CAPEX) and operational costs (OPEX) are considered. Figure 4 shows an overview of the model and where the system boundaries are set in the study.

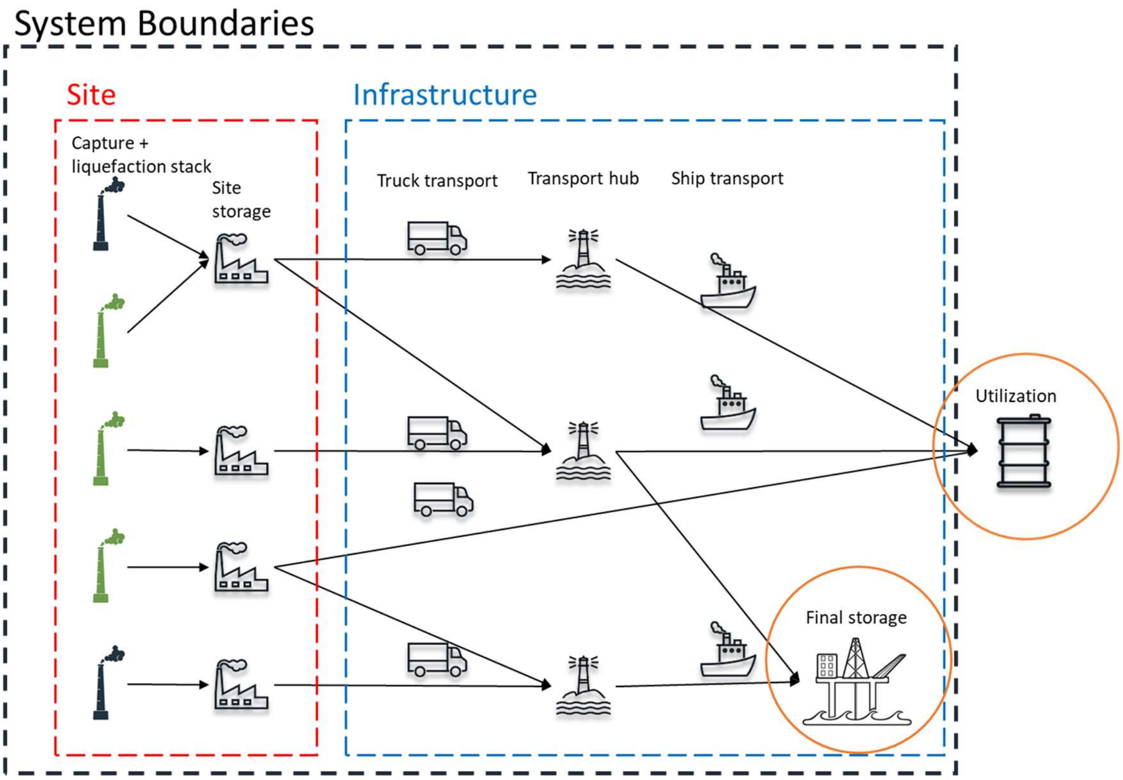

Figure 4: Model flowsheet. Black dashed box indicates the parts included in the optimization problem with related costs. Red dashed line indicates component of the site (individual stack capture and liquefaction and intermediate storage). Blue dashed line indicates infrastructure (land transport, hubs, and sea transport). Orange circles encompass possible end-use alternatives. Black chimneys represent fossil CO_2 captured, while green chimneys are biogenic CO_2 captured.

The model objective function is to minimize the net present value (NPV) of the CCUS system according to Equation 1. Where ${C_y}^{total}$ are the total annual costs for year y, including on-site partial or full capture for individual stacks at a plant, liquefaction of captured CO_2, intermediate on-site storage, land transport by truck, a second intermediate storage at the coastal transport hub, transportation by ship to the end-use (when required), and final storage. Profit made from selling CO_2 for utilization is not included in this study, instead the work evaluates the cost to deliver the CO_2 to the utilization location. The time period studied is 26 years discretized as yearly time-steps, starting in 2025.

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

Total annual costs ${C_y}^{total}$, are calculated as follows:

$$\begin{aligned}{C_y}^{total} \geq{} & \sum_{j\,\in\,J}\Big(\sum_{i\,\in I}\big({c_{i,j,y}}^{CAP,capture\,\&\,liq}\big) + {c_{j,y}}^{OP,capture} + {c_{j,y}}^{OP,liq} + {c_{j,y}}^{CAP,storage} + \\ & {c_{j,y}}^{OP,storage}\Big) + \sum_{j\,\in J}\big({c_{j,y}}^{CAP,truck} + \sum_{k\,\in K} {c_{j,k,y}}^{OP,truck}\big) + \sum_{k\,\in K}\big({c_{k,y}}^{CAP,hub} + \\ & {c_{k,y}}^{OP,hub}\big) + \big({c_y}^{CAP,ship} + \sum_{k\,\in K}\sum_{l\,\in L} {c_{k,l,y}}^{OP,ship}\big) + {c_y}^{final\ storage} + {c_y}^{emissions}\ \forall\ y \in Y \end{aligned}$$
(2)

Where ${C_y}^{CAP}$ and ${C_y}^{OP}$ are annualized CAPEX and OPEX respectively in year y for each component of the CCUS chain. Indices used in Equation 2 are as follows: stack type i, located at site j, transport hub k and end-use l. Final storage costs $c_y^{\text{final storage}}$ only depends on the CO_2 volume that is stored; thus, it can be considered as OPEX.

CO_2 mass flow is limited by installed capacity in year y for each component of the system, Equation 3 present this with the stack capacity as an example.

$$x^1_{i,j,y} \leq s_{i,j,y}\ \forall\ i \in I, j \in J, y \in Y \qquad (3)$$

Where $x^1_{i,j,y}$ is the CO_2 capture from stack i on site j for year y and $s_{i,j,y}$is the installed capture capacity for that stack in year y. Equation 4 represents the flow between components of the CCUS chain, using CO_2 flow from site j to hub k as an example.

$$\sum_{j \in J} x^2_{j,k,y} = \sum_{l \in L} x^3_{k,l,y}\ \forall\ k \in K, y \in Y \ (4)$$

Where $x^2_{j,k,y}$ is the CO_2 flow on land from site j to hub k and $x^3_{k,l,y}$ the CO_2 transported by ship from hub k to end-use l. Infrastructure is constrained to build-up only one hub every five years using Equation 5, except the year utilization starts to take place (2035), where two hubs can be opened. Equation 6 is an additional constraint to avoid hub relocation, this means that once a hub starts operating, it continues operating until the modelled period is over.

$$\sum_{k \in K} h_{k,y} \leq H_y\ \forall y \in Y \qquad (5)$$

Where $h_{k,y}$ is a binary variable to indicate whether a hub is operational or not and H_y is the total hubs that can operate in year y.

$$h_{k,y} \geq h_{k,y-1} \forall\ y\ \in Y, k \in K \qquad (6)$$

CO_2 utilization requirements are modeled according to Equation 7.

$$\sum_{k \in K} x^3_{k,utilization,y} \geq U^{demand}{}_y\ \forall\ y \in Y \ (7)$$

Where end-use in $x^3_{k,utilization,y}$ is fixed to utilization and $U^{demand}{}_y$ is the annual biogenic CO_2 demand for utilization. Annual emissions and capture-storage for biogenic and fossil CO_2 are calculated according to Equation 8, 9 and 10 respectively.

$$e_y \geq \sum_{j \in J} E_j - \dot{g}_{fossil,y}\ \forall\ y \in Y \ (8)$$

$$\dot{g}_{biogenic,y} \leq \sum_{i \in I, j \in J} x^1_{i,j,y} * b_j - \sum_{k \in K} x^3_{k,utilization,y}\ \ \forall\ y \in Y \ (9)$$

$$\dot{g}_{fossil,y} \leq \sum_{i \in I, j \in J} x^1_{i,j,y} * (1 - b_j) \ (10)$$

In this work emissions from biogenic CO_2 are not penalized when released into the atmosphere. E_j are the fossil emissions from site j, $\dot{g}_{et,y}$refers to the CO_2 stored annually from source et (biogenic or fossil), and $b_j$is the biogenic shareon emissions from site j.

When BECCS credits are modelled, the total credits are naturally limited by the biogenic CO_2 available to capture, but more tight constraints are reasonable since the majority of emissions come from biogenic sources in the Swedish industry. In this work, the total credits available are assumed to have a limitation set by the total fossil capture according to Equation 11. Otherwise the model will tend to rely on unrealistic levels of BECCS instead of reducing fossil emissions. This is only required in specific cases like Sweden, where most of the emissions are biogenic. Credits are accounted for according to Equation 12.

$$\sum_{y \in Y} Credits_y \leq \sum_{y \in Y} \dot{g}_{fossil,y} \ (11)$$

$$Credits_y \leq \dot{g}_{biogenic,y} \forall \ y \in Y \ (12)$$

Where $Credits_y$ are the credits used in year y. To include BECCS credits in the model, Equation 8 is restructured to include the effect that BECCS credits have in the system (see Equation 13. Notice that it is possible that emissions e_y could reach negative values i.e., negative emissions are achieved for year y.

$$e_y \geq \sum_{j \in J} E_j - \left(\dot{g}_{fossil,y} + Credits_{,y}\right) \forall \ y \in Y \ (13)$$

The net present value (NPV) is calculated according to Equation 1. Equation 14 represents the total capture of CO_2, also defined as the cumulative CO_2 captured in the entire period. The levelized cost of CO_2 ($LCCO_2$) in Equation 15 is based on the levelized cost of electricity (LCOE), as an average of the net present cost of the CO_2 for capture, transportation and storage/utilization over the project lifetime. The levelized cost of CO_2 is calculated as the ratio between discounted costs over the project duration divided by discounted CO_2 captured (see Equation 15). These parameters are studied for the entire CCUS system, and when required, for subsystems characterized by source and end-use (BECCS, BECCU and CCS) or by system components (site/plant, infrastructure and end-use).

$$Total\ capture = \sum_{i \in I, j \in J, y \in Y} {x^1}_{i,j,y} \ (14)$$

$$LCCO_2 = \frac{\sum_{y \in Y} \frac{\left({c_y}^{CAPEX} + {c_y}^{OPEX}\right)}{(1+r)^{y-y_0}}}{\sum_{y \in Y} \frac{\left(\sum_{i \in I, j \in J} {x^1}_{i,j,y}\right)}{(1+r)^{y-y_0}}} \ (15)$$

3.2. System description

Large plants in the pulp & paper, cement, iron & steel, refinery, chemical sector along with heat and power plants (CHP) operating in Sweden in 2021 were included in this work. Emissions data of industrial sites are taken from Chalmers Industrial Case Study Portfolio (ChICaSP), which includes most industrial sites from Sweden with CO_2 emissions over 100 $ktCO_2/y$ [54]. Site location and individual stacks CO_2 flow data are extracted from ChICaSP. The biogenic share of CO_2 emissions and CO_2 concentration in the flue gas are extracted from the work done by Karlsson et al. [53]. Total emissions and upper limit on CO_2 capture are presented in Table 1. Plants are assumed to operate 8000 h a year, and yearly emissions are distributed uniformly. The model used assumes that emissions are constant all over the period and the only technology available to reduce them is carbon capture (i.e., other decarbonization alternatives, like electrification and biomass use are not included). Additionally, for all stacks, CO_2 capture is based on chemical absorption using MEA as solvent, with a capture rate up to 90% and heat demand of 1 $MWh/tonCO_2$ captured. The work considers 15 potential transport hubs located over the Swedish coast, without limitations on the volume that can be transported from each hub. CO_2 storage takes place in the location established by the Northern Lights project (in the Norwegian North Sea off the coast of Øygarden, Norway) and utilization is assumed to take place in Lysekil, Sweden [55]. Sites, potential hubs, and CO_2 end point included in this model are shown in Figure 5.

Table 1: Total system CO_2 emissions considered in the work.

Emissions		Year [$MtCO_2/y$]	Total [$MtCO_2$]
All site emissions	Bio	34.8	904
	Fossil	12.0	312
Possible to capture	Bio	31.3	814
	Fossil	9.0	233

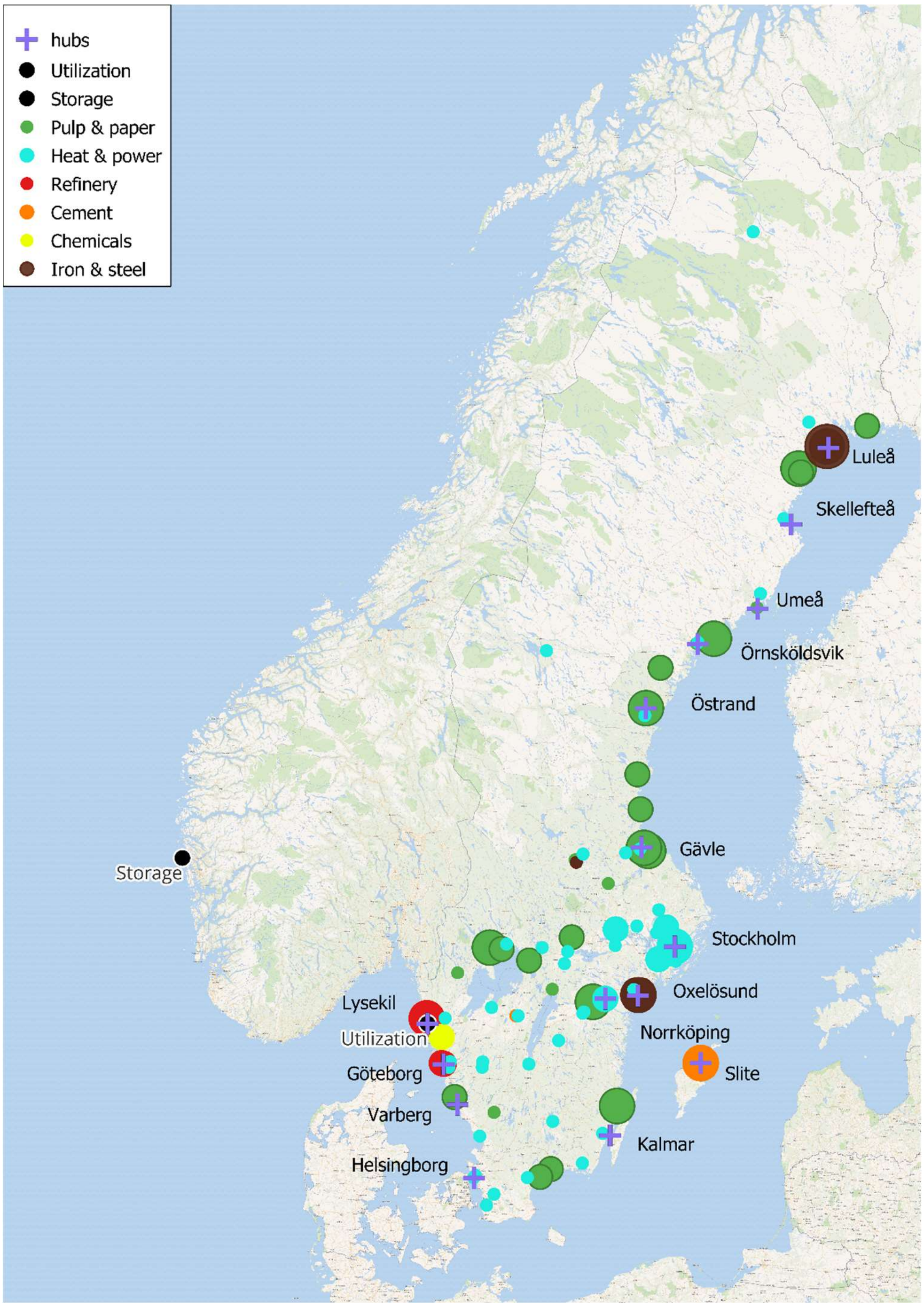

Figure 5: Industrial sites, transportation hubs and ship routes included in the model. Size on the industrial sites correspond to the level of emissions, with the smallest emitting around 100 $ktCO_2/y$ and the largest 3300 $ktCO_2/y$.

Table 2 shows the parameters for the components of the CCUS system included in the model. In this work, the discount rate is set to 5%. Investment cost for capture and liquefaction are based on the correlation proposed by Eliasson et al. [56]. In this correlation, CAPEX depends on the CO_2 mass flow ($\dot{m}_{CO_2}$) and parameters related to CO_2 concentration in the stack (α, β) as follows:

$$CAPEX_{capture\,\&\,liq} = \alpha * 10^4 * \dot{m}_{CO_2}{}^{\beta} (16)$$

Land transport from site to hub and sea transportation from hub to end-use distances are determined using the same procedure presented by Karlsson et al. [53], using terrain adjustment factor of 1.3 and 1.1 for trucks and ships respectively. Operational costs for trucks include fuel and labor costs, assuming 3 drivers required for each truck daily (8 h shift). Costs associated with the underground storage, including compression and pipeline transport from reception terminal to injection site and later underground injection were assumed 29 €/tonCO_2 [57].

Table 2: Input data and assumptions used as parameter values in this work.

Parameter	Value	Unit
Capture & liquefaction		
Lifetime	25	Years
OPEX capture	5	% of CAPEX yearly
OPEX liquefaction	9	€/tonCO_2 liquefied
Specific reboiler duty	3600	kJ/kgCO_2 captured
Intermediate storage		
Lifetime	25	Years
CAPEX	5	k€/tonCO_2
OPEX	4	% of CAPEX yearly
Land transport (trucks)		
Lifetime	10	Years
CAPEX	320	k€/truck
Maintenance costs	5	% of CAPEX yearly
CO_2 carrying capacity	38	tonCO_2/truck
Truck speed	50	km/h
Fuel consumption	0.5	l/km
Fuel cost	1.4	€/l
Driver salary	90	€/driver yearly
Loading/unloading time	0.5	H
Sea transport (ships)		
Lifetime	25	Years
CAPEX	44.3	M€/ship
Labor and maintenance costs	1760	k€/ship
Ship size	8625	T
Fuel cost	4.2	€/t
Fuel consumption	0.835	t/h
Ship speed	26	km/h
Loading time	8	H
Unloading time	15	H
Harbor costs	20	k€/ship
End-use (storage)		
OPEX storage	29	€/tonCO_2 stored

3.3. Scenarios and cases

Two main policy scenarios to promote BECCS are investigated in this work to evaluate the impact in a CCUS system development: BECCS credits, and subsidies for BECCS. Figure 6 presents a scheme containing all cases modelled in this work. A sensitivity analysis was also performed for the cases in the green boxes. Detailed explanation of the policy scenarios, respective cases and sensitivity analysis are presented in the following subsections. Fossil emissions costs are extrapolated from the work by Karlsson et al. [53] based on the Net Zero Emissions by 2050 scenario in the World Energy Outlook [58]. Fossil emissions prices vary almost linearly in the range of 80-220 €/tCO_2 for the period 2025-2050.

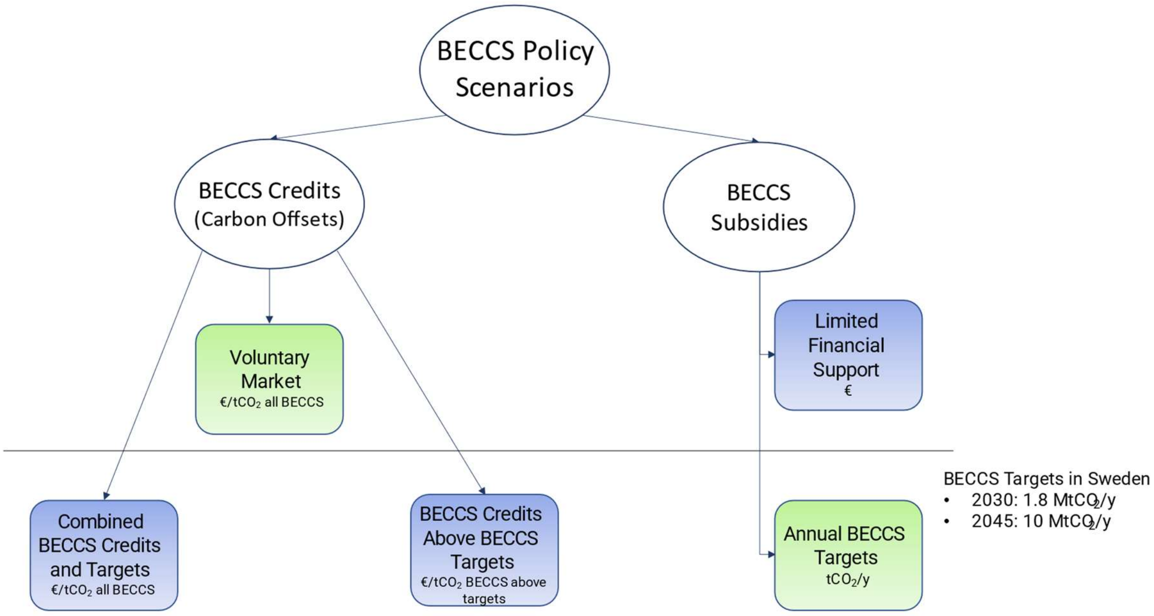

Figure 6: Policy scenarios to promote BECCS investigated in this work. Cases investigated in both scenarios are studied for the period 2025-2050, with same fossil price range and BECCU requirements.

In this work, policy scenarios to promote BECCS are coupled with CO_2 demands for utilization calculated from the future carbon requirements stated by companies in Sweden. In this work, BECCU is assumed to supply 25% of the carbon feedstock required for refineries by 2035 and 50% of the feedstock required for chemical industry by 2040 [39], [59], [60]. BECCU requirements are presented in .

Table 3.

Table 3: Annual BECCU requirements in the Refinery and Chemical sectors.

CO_2 flow for BECCU ($MtCO_2$/y)	Period		
	2025-2035	2035-2040	2040-2050
Refineries [39], [59]	0	6.42	6.42
Chemical [60]	0	0	1.83
Total	0	6.42	8.25

3.3.1. BECCS credits

The BECCS credits scenario models a carbon market, selling BECCS credits as carbon offsets to counteract the effect of emitting fossil CO_2. In essence, each unit of BECCS generates a value equivalent to the cost of emitting one unit of fossil CO_2. For this policy scenario, not only the actors included in the system can buy BECCS credits but also external entities, increasing the limits on the annual revenue. The first case introduced, called *"Voluntary Market"*, is a base case for the BECCS credits policy scenario and no additional constraints are included. In this case, the value of BECCS credits is assumed to be equal to the projected price of emitting fossil CO_2 used in the modelling in this work, even though buyers in certain voluntary carbon markets may currently be willing to pay a higher price for offsets compared to the price of fossil emissions, such as in the EU-ETS. The other two cases modelled in the BECCS credits policy scenario, incorporate additional constraints to include the targets for BECCS proposed by Swedish government in years 2030 (1.8 $MtCO_2/y$) and 2045 (10 $MtCO_2/y$) as lower boundary in the model (see Equation 17) [52]. For the second case, *"Combined BECCS Credits and Targets"*, the targets are enforced as a minimum limit on the BECCS levels from 2030 onwards. In the third case *"BECCS Credits Above BECCS Targets"*, only the BECCS units exceeding the specified targets are eligible for participation in the BECCS credits system. This implies that the BECCS below the targets cannot be sold as negative emissions credits and, as a result, do not contribute to cost reduction within the model. To emulate this case, Equation 18 replaces Equation 12. The last two cases are included to understand whether it is more efficient to include hard-to-abate sectors in the same voluntary market for carbon offsets with other sectors or whether to prioritize them, excluding a portion of BECCS from the voluntary market. The excluded BECCS could then participate in another financing system (e.g., subsidies).

$$\dot{g}_{biogenic,y} \geq targets_y \ \ \forall\, y \in Y \ (17)$$

$$Credits_y \leq \dot{g}_{biogenic,y} - targets_y \ \forall\, y \in Y \ (18)$$

3.3.2. BECCS subsidies

The policy scenario for BECCS subsidies simulates the reverse auctioning system proposed in Sweden. In the model, the winning bid is the one that presents the lowest capture, conditioning, transport and storage costs for BECCS, but keeping as objective function the cost minimization for the entire CCUS system. The binding period is not fixed to 15 years, but optimal periods are estimated based on the lowest system cost. Compared to the BECCS credits scenario, the subsidies do not generate profit by capturing and storing biogenic CO_2, instead the same targets for BECCS in 2030 (1.8 $MtCO_2/y$) and 2045 (10 $MtCO_2/y$) are set as the main constraint and monetary support is used to achieve them.

In the base case *"Annual BECCS Targets"*, the only constraints are the targets for BECCS and the monetary budget to promote them has no limits. The second case, so-called *"Limited Financial Support",* includes additional constraints to demonstrate the effect of a limited monetary budget to support BECCS. For this work, the monetary budget was set to 3600 M€ to simulate the total budget proposed by the Swedish Government to promote BECCS [50]. In this case, a monetary budget ($\mathrm{Budget}^{\mathrm{BECCS}}$) and annual distribution over the period ($\mathrm{budget}^{\mathrm{BECCS}}{}_{\mathrm{y}}$) are the main limitation (see Equation 19). The monetary budget annual distribution $\mathrm{budget}^{\mathrm{BECCS}}{}_{\mathrm{y}}$ is calculated in the same way as $C_y{}^{total}$in Equation 2, but in the right side of the equation only those costs related to biogenic CO_2 capture, transported to storage and underground stored are included. In addition, the objective function, Equation 1, need to be modified to include the system savings from the support budget for BECCS (see Equation 20.

$$Budget^{BECCS} \geq \sum_{y\,\in Y} \frac{budget^{BECCS}{}_y}{(1+r)^{y-y_0}} \ (19)$$

$$min: C_{tot,\ NPV} \geq \sum_{y\,\in Y} \frac{c_y{}^{total} - budget^{BECCS}{}_y}{(1+r)^{y-y_0}} \quad (20)$$

In the *"Annual BECCS Targets"* case, $Budget^{BECCS}$ is set to a large number to avoid restrictions in the monetary budget.

3.3.3. Sensitivity analysis

Sensitivity analysis is performed to evaluate the impact of some parameters on the system development and cost for both policy scenarios. The BECCS credits scenario *"Voluntary Market"* case and BECCS subsidies *"Annual BECCS Targets" case* are selected to demonstrate the effect in the system. Sensitivity analysis includes fossil emissions price (±50%) for the entire period, BECCU levels requirements for 2035 and 2040 presented in Table 3 (1%, 10%, 200%). The influence BECCS targets by 2045 have on the CCUS system evolution is analyzed for *"Annual BECCS Targets"* case (0, 3, 10 and 20 $MtCO_2/y$). A fourth sensitivity analysis is performed in the same case to evaluate the impact of the iron and steel sector (the major CO_2 fossil emitter industry in Sweden) in the CCUS system. For this case, it is assumed that clean technologies for the iron and steel sector are already well developed by 2030 and all iron and steel plants in Sweden include this technology. Therefore, from 2030 CO_2 emissions from iron and steel sector decrease to 0 $MtCO_2/y$

4. Results and discussion

This section presents the results from the cases modelled in this work. Figure 7 shows the cost distribution between components of the CCUS system. For all cases included in this report, the cost distribution between components of the CCUS system is similar. Results show that more than half of the total investment in the CCUS system corresponds to capture, liquefaction/conditioning and intermediate storage in-site, while transport infrastructure and end-use (underground storage) have a similar share.

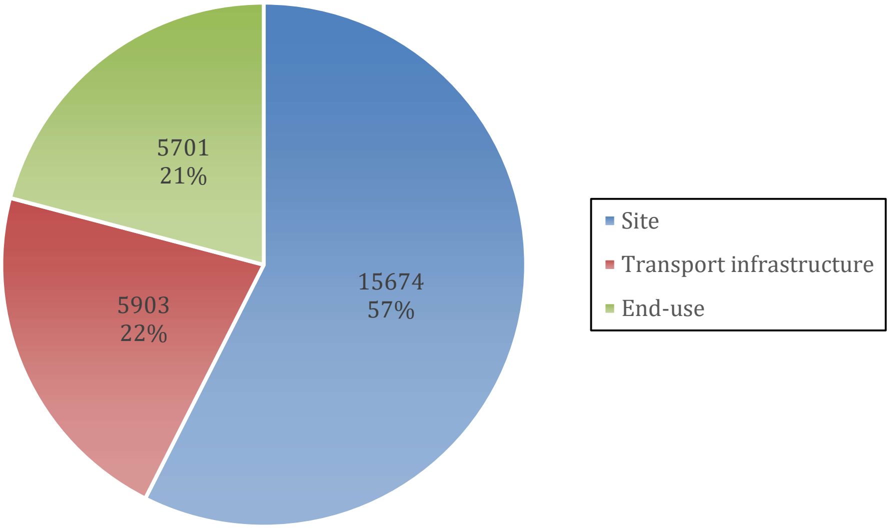

Figure 7: NPV (M€) for *Voluntary Market* case from BECCS credits policy scenario. Similar investment distribution is presented for all other cases in this work.

4.1. BECCS credits policy scenario

BECCS credits policy scenario results are presented in two individual subsections. The first one focuses exclusively on the *"Voluntary Market"* case and the second subsection called *Targets enforced* focuses on the *"Combined BECCS Credits and Targets"* and *"BECCS Credits Above BECCS Targets"* cases.

4.1.1. Voluntary Market case

Figure 8 presents the annual CO_2 capture for the sectors studied in this work and how it develops during the project lifetime. Before utilization takes place, waste-fired CHP plants are the only plants capturing biogenic CO_2, but this capture is only motivated by the reduction of fossil emissions. Figure 9 presents total capture per sector and end-use. Total fossil CCS serves as cap on the total BECCS credits available; therefore, BECCS and fossil CCS have the same volume. Most of the BECCS is provided by the pulp and paper sector (82%). BECCU distribution is more even, with almost 60% coming from the pulp and paper industry.

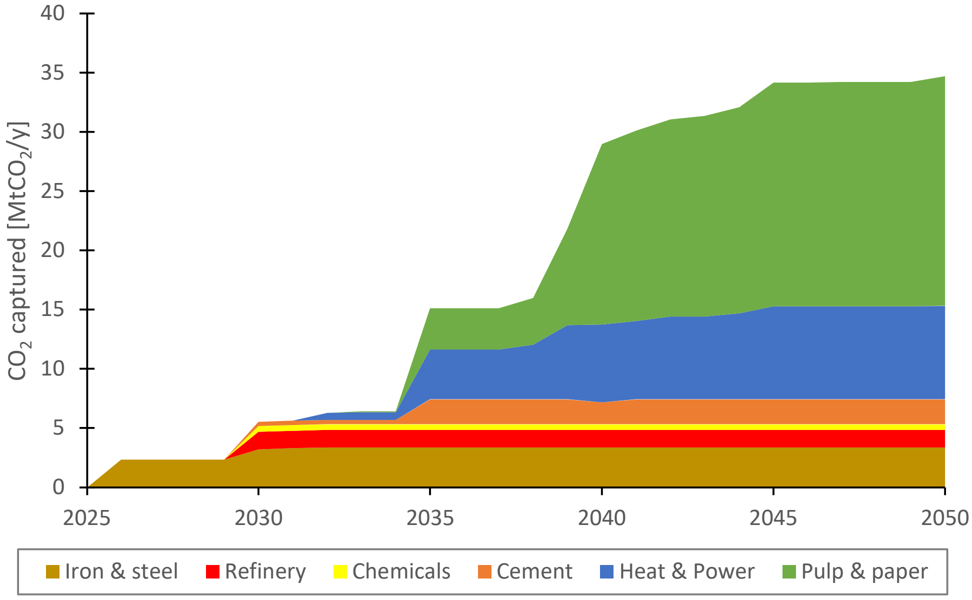

Figure 8: CO$_2$ capture evolution for industrial sectors in *Voluntary Market* case from BECCS credits policy scenario.

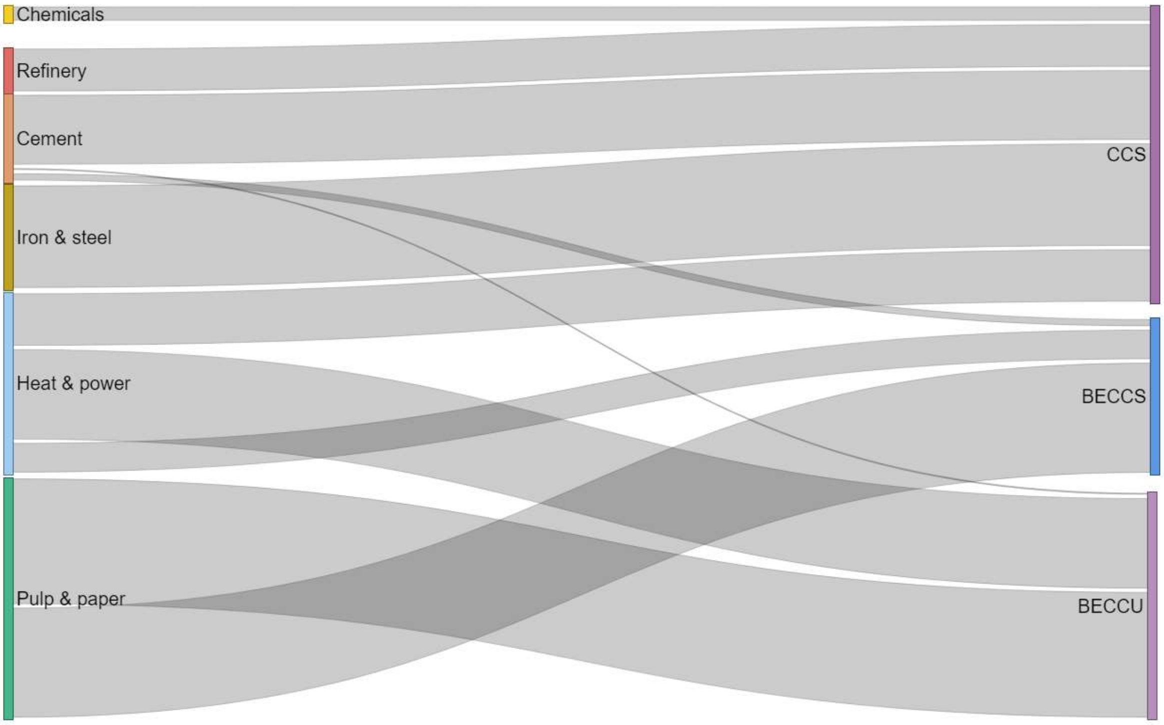

Figure 9: Total cumulative emissions captured per sector and end-use weighted in *Voluntary Market* case from BECCS credits policy scenario in the period 2025-2050.

Figure 10 shows the system evolution including capture sites, transport hubs and sea transport for three different years. Large fossil emissions from a single iron and steel plant located in northern Sweden is the main driver to open a hub in northern Sweden in 2025. In 2030 the second hub is installed closer to the storage location to minimize sea transportation costs. Early inclusion of fossil CO$_2$ capture in the system increases the number of BECCS credits available that can be sold in the future when emissions are more expensive. After 2030, small CHP plants burning waste located near the recently opened hub start capturing CO$_2$. Introduction of the first BECCU target in 2035 generates a significant increase in capture from the heat and power and pulp and paper industries, while capture from fossil emissions have reached almost complete maturity (8.6 $MtCO_2/y$). Over the next 15 years, the limitation of opening new hubs is not the main barrier to enlarge capture from the system, but the possibility to sell BECCS credits with an increased price promotes additional capture. The primary source of biogenic CO_2, the pulp and paper industry, is included in 2035, but there is a bigger increase in capture from this sector in 2040 reaching 95% of the sector's potential capture level by the end of the project's lifespan (19.4 $MtCO_2/y$). After 2040 the largest emitters are already included in the capture system, and the opening of new hubs mainly helps to reduce land transport costs, while promoting the inclusion of smaller emitters in the system. By 2050, CHP is the least developed sector, capturing only 63% of their emissions (7.9 $MtCO_2/y$). Total BECCS included in the credits system ($MtCO_2$), BECCS size by 2050 ($MtCO_2/y$), CCUS system cost (M€) and levelized cost of capturing CO_2 (€/tonCO_2) and total CO_2 captured ($MtCO_2$) are presented in Table 4.

Table 4: CO_2 capture and system costs for the *Voluntary Market* case.

BECCS credits [$MtCO_2$]	BECCS level in 2050 [$MtCO_2/y$]	CCUS system [M€]	$LCCO_{2,CCUS}$ [€/tonCO2 captured]	Total CO_2 captured [$MtCO_2$]
179	17.5	22585	107	482

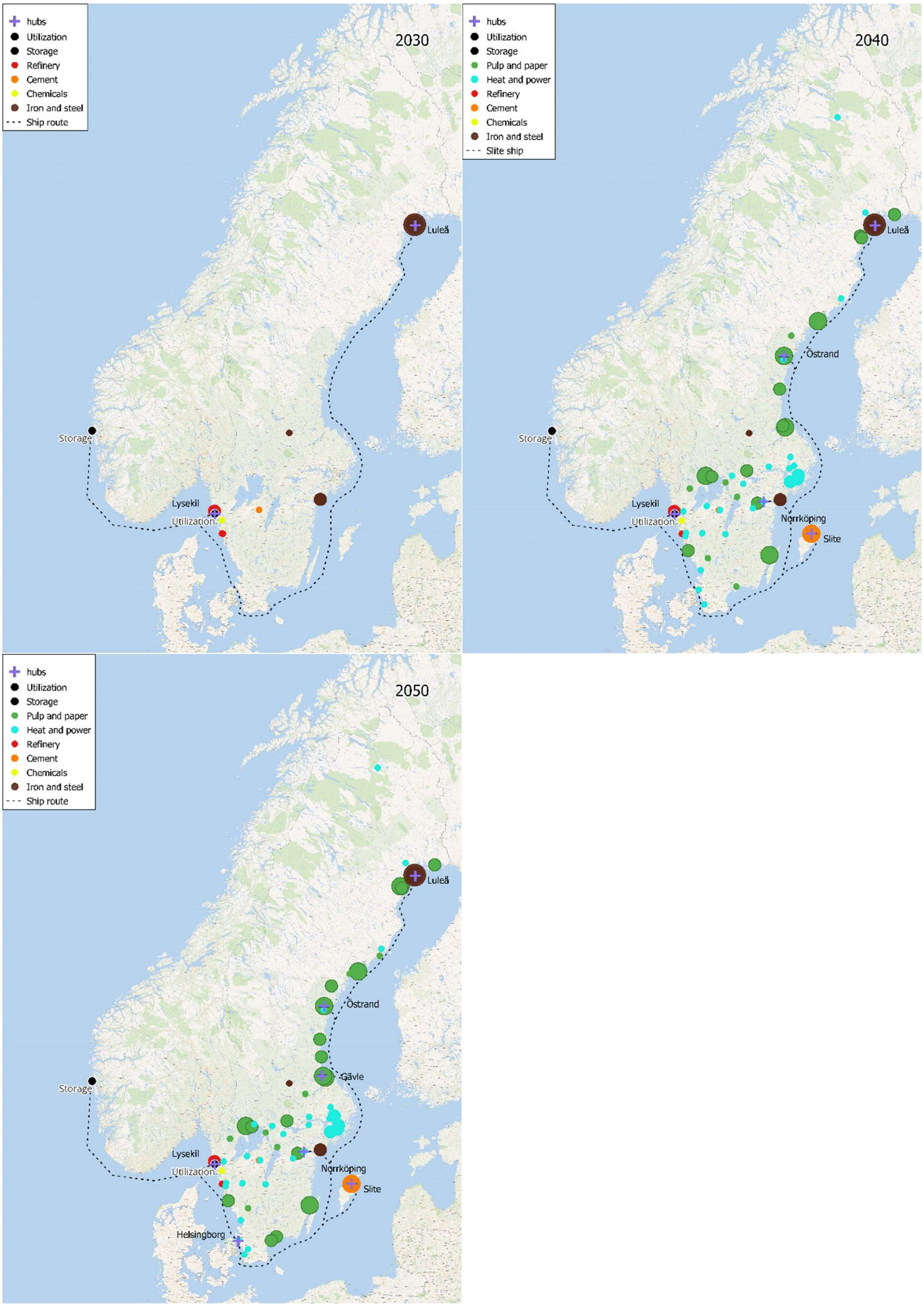

Figure 10: System evolution over periods of 10 years a) 2030, b) 2040 and c) 2050, including capture sites, transportation hubs, sea transport and end-use for *Voluntary Market* case in BECCS credits policy scenario.

4.1.2. Targets enforced

Enforcing targets for BECCS in 2030 and 2045 in the *"Combined BECCS Credits and Targets"* and *"BECCS Credits Above BECCS Targets"* cases have no influence in the total fossil CO_2 captured. For both cases fossil capture achieves almost full potential (99.5%) by 2050, while biogenic capture reaches less than 85%. Figure 11 shows the fossil and biogenic CO_2 emissions captured and stored in the period between 2025 and 2050 for the *"Combined BECCS Credits and Targets"* and *"BECCS Credits Above BECCS Targets"* cases. In the BECCS credits policy scenario, an earlier and larger scale inclusion of fossil capture was expected for the *"BECCS Credits Above BECCS Targets"* case, to increase the number of BECCS credits available. Nonetheless, a similar trend is seen in the CO_2 capture levels for both cases. Over the period 2035-2040, an exponential increase in BECCS is presented and in both cases the system configuration develops in an equivalent way until 2045. In the *"Combined BECCS Credits and Targets"* case most of the new CO_2 capture units installed have larger capture volume and are located near the new hub opened in Östrand, while for *"BECCS Credits Above BECCS Targets"* case, the new CO_2 capture units have a smaller size and are spread out over Sweden as shown in Figure 12, thus no large investment in new ships is required.

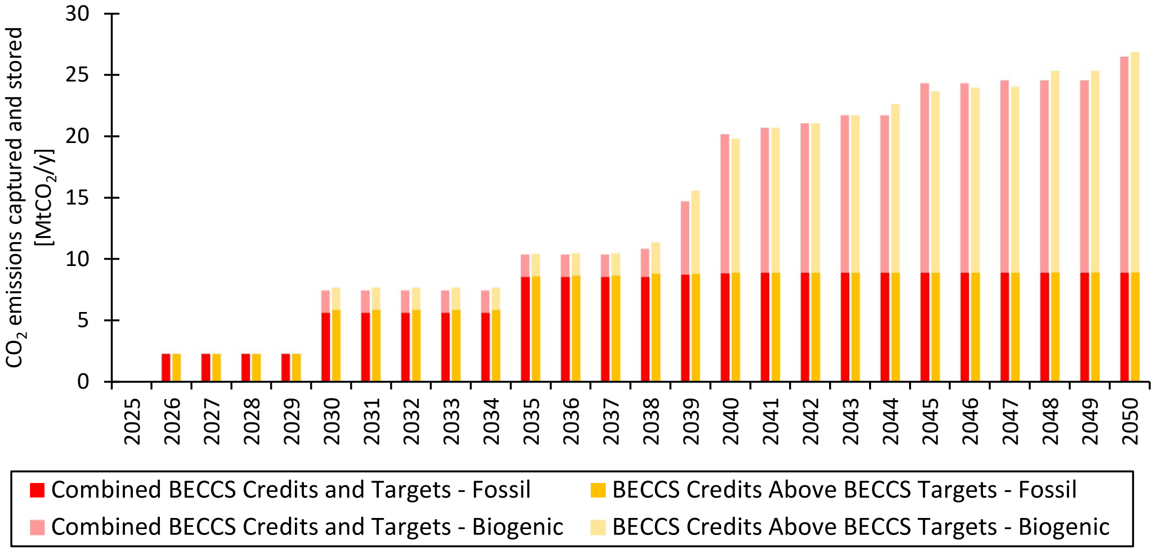

Figure 11: Fossil and biogenic CO_2 emissions captured and stored yearly in the period 2025-2050 in the BECCS credits system scenario for *BECCS Credits Above BECCS Targets* and *Combined BECCS Credits and Targets* cases. Fossil and biogenic potential emissions to capture annually are 9 $MtCO_2$ and 31.3 $MtCO_2$ respectively.

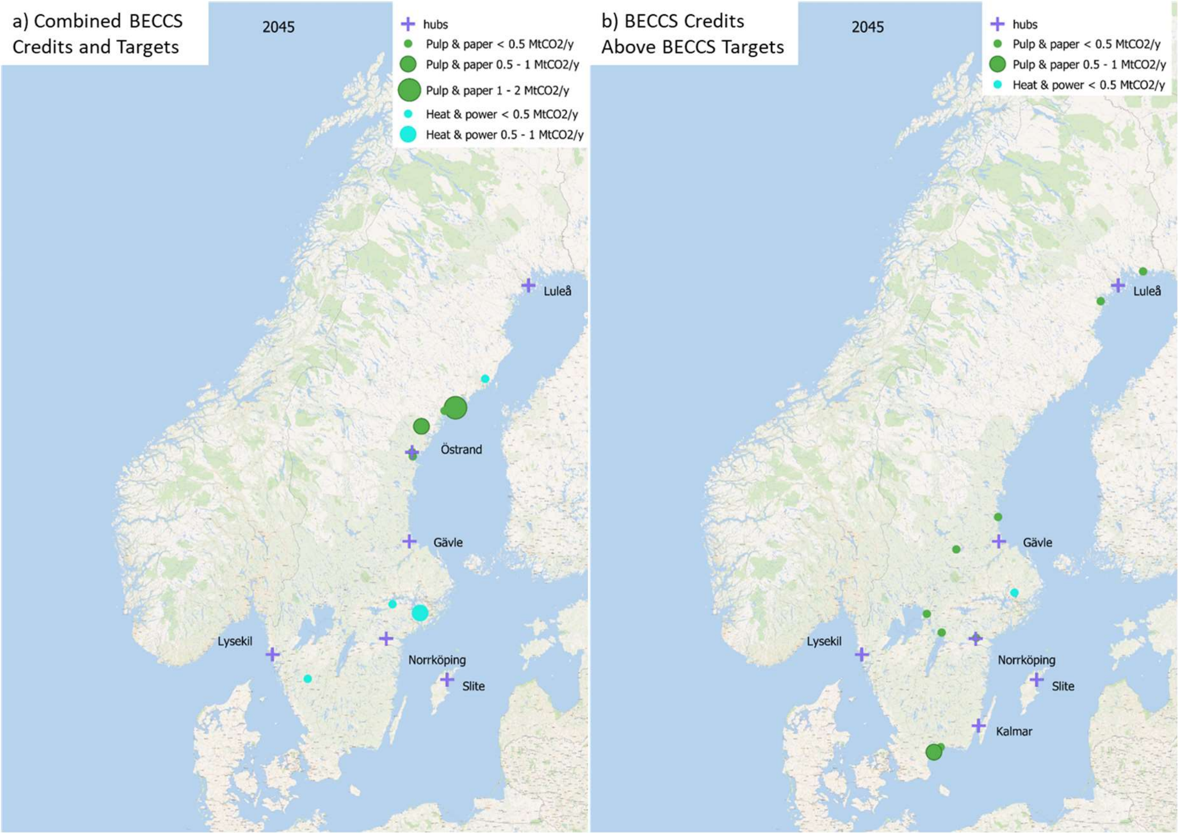

Figure 12: Hubs opened in 2045 and industrial sites capturing CO_2 that are unique for cases: a) *Combined BECCS Credits and Targets* and b) *BECCS Credits Above BECCS Targets* in BECCS Credits scenario.

Table 5 presents the total system cost, profit generated from selling credits, levelized cost of CO_2 and total CO_2 capture for the entire period. The total system cost for the "*BECCS Credits Above BECCS Targets*" case is 1.3% higher than "*Combined BECCS Credits and Targets*". The increase in total capture is only 4 $MtCO_2$ and the levelized cost of CO_2 for the system rises by only 0.8%. In addition, the potential profit from selling BECCS credits is almost double for "*Combined BECCS Credits and Targets*" case compared to "*BECCS Credits Above BECCS Targets*".

Table 5: Economic parameters and CO_2 capture considered to compare *Combined BECCS Credits and Targets* and *BECCS Credits Above BECCS Targets* cases in the BECCS credits system scenario.

	Total system cost [M€]	Credits profit [M€]	$LCCO_{2,CCUS}$ [€/tonCO_2 captured]	Total CO_2 capture [$MtCO_2$]
Combined BECCS Credits and Targets	22744	13680	106	480
BECCS Credits Above BECCS Targets	23043	7251	107	484

4.1.3. Sensitivity analysis

This section presents the results for the sensitivity analysis performed for the "*Voluntary Market*" case. The results show that increasing the CO_2 volumes required for utilization does not drastically affect the fossil emissions abatement but leads to cheaper levelized costs of the CCUS system (€/tonCO_2 captured). Figure 13 shows that the levelized cost of CO_2 for the entire CCUS system decreases while increasing the utilization volume, and this is mainly because of larger volumes of CO_2 are captured, while infrastructure and end-use costs are almost the same. In addition, in Figure 13 the levelized cost of CO_2 only considering the BECCU component of the CCUS system shows a decreasing trend with the utilization volume requirements until 100% BECCU demand. Despite the decrease in the levelized cost of CCUS, the size increase in the utilization demand could be counter effective from the utilization cost perspective, since it means that there is major competition for the same biogenic CO_2 with BECCS. For small volumes the biogenic CO_2 for utilization could instead be considered a residual fraction that is captured, and thus avoids making big investments for sea transport to storage. Notice that sites selected, transport infrastructure, as well as transportation hubs are also affected by the utilization volume. Figure 14 presents the plants capturing biogenic CO_2 by the end of the project and the capture size distribution for the different utilization volumes. The results show that increasing the utilization demand increases the number of smaller plants (0-0.5 $MtCO_2/y$ and 0.5-1 $MtCO_2/y$), while larger size plants (1.5-2 $MtCO_2/y$) are included in all cases.

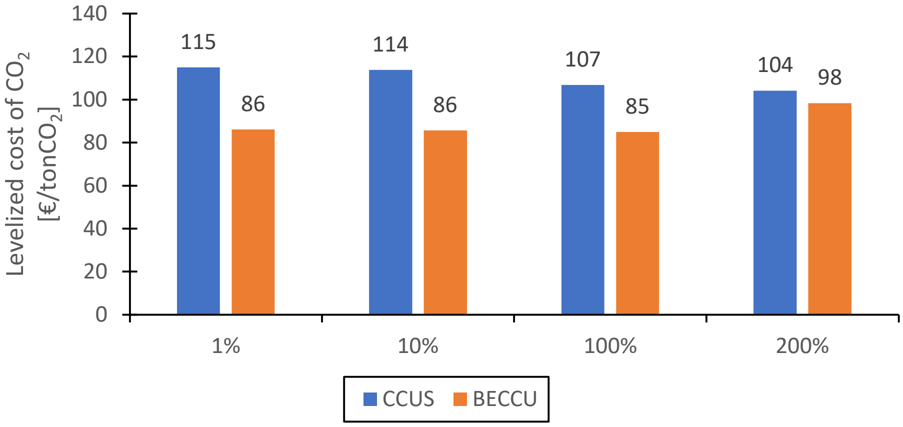

Figure 13: Levelized cost of CO_2 for the complete CCUS chain and BECCU component for the *Voluntary Market* case in BECCS credits scenario at different utilization volumes required. Base case (100%) requires 6.42 $MtCO_2/y$ in 2035 and 8.25 $MtCO_2/y$ in 2040.

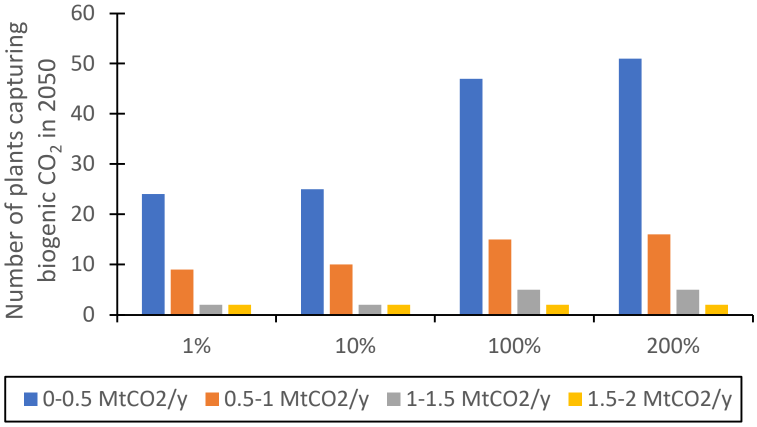

Figure 14: Number of industrial sites capturing biogenic CO_2 by 2050 for the *Voluntary Market* case in BECCS credits scenario at different utilization volumes required. Base case (100%) requires 6.42 $MtCO_2/y$ in 2035 and 8.25 $MtCO_2/y$ in 2040. Plants are grouped according to capture level by 2050 in the range of 0-0.5 $MtCO_2/y$, 0.5-1 $MtCO_2/y$, 1-1.5 $MtCO_2/y$ and 1.5-2 $MtCO_2/y$.

Figure 15 shows the cumulative biogenic capture and storage for the period 2025-2050. The results show that BECCS implementation is more sensitive to decrease in the price of fossil fuels than raising them in the BECCS credits policy scenario. Decreasing fossil price by 50% leads to almost no biogenic capture, and the biogenic capture system is driven by utilization requirements, leading to higher prices for CCU. On the other hand, increasing the fossil emissions price by 50% produces a small increase in the total BECCS participating in the credits system, with an earlier inclusion of biogenic CO_2 capture in large scale. In addition, Figure 16 shows that increasing fossil price trend helps enable a smoother transition for BECCS in 5 years periods. For the base case, between the 3rd and the 4th periods, there is an increase of almost 1000% in BECCS levels (1.5 $MtCO_2/y$ to 13.6 $MtCO_2/y$), while the most intense increase for the 150% case is observed between the 1st and 2nd period, increasing from 0.5 $MtCO_2/y$ to 2.9 MtCO2/y.

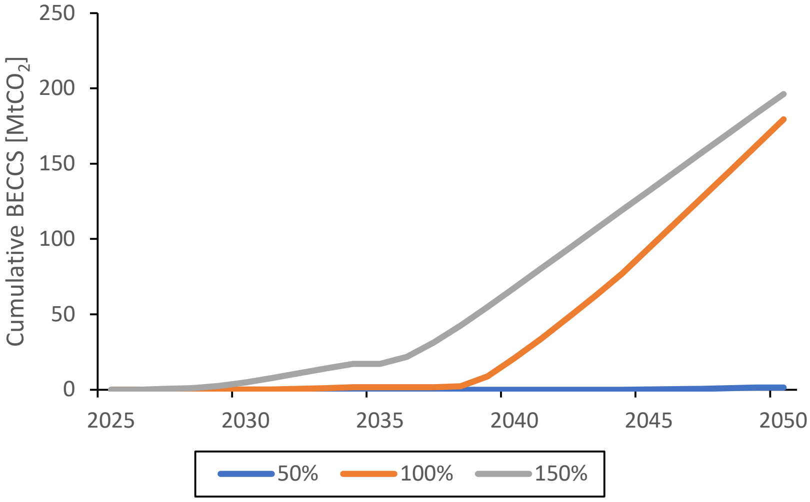

Figure 15: Cumulative BECCS over the period modelled for *Voluntary Market* case in BECCS credits scenario for different fossil price trends. Base case (100%) fossil emissions price is in the range 80-220 €/tonCO_2.

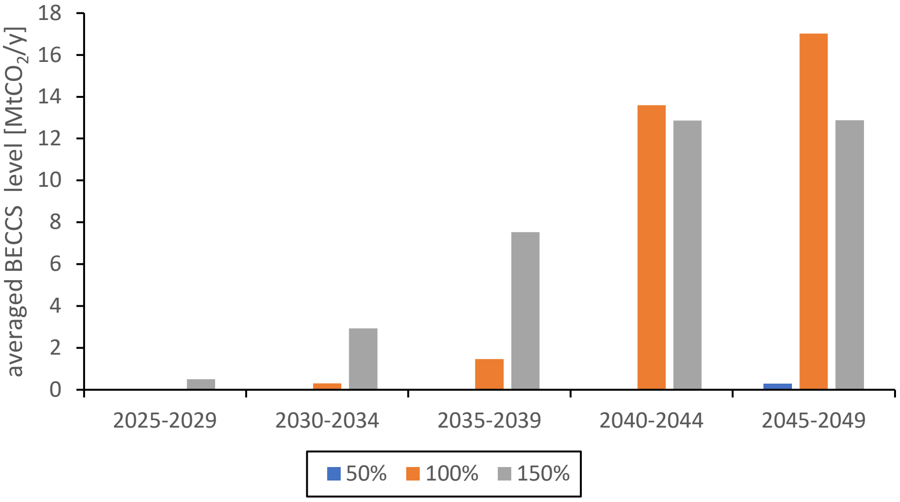

Figure 16: Averaged BECCS levels in 5 years periods for the entire period modelled in the *Voluntary Market* case at BECCS credits scenario for different fossil price trends. Base case (100%) fossil emissions price is in the range 80-220 €/tonCO_2.

4.2. BECCS subsidies policy scenario

Results from the BECCS subsidies policy scenario are presented in this subsection. Figure 17 shows a similar evolution in the capture and storage of CO_2 from fossil sources after 2035 for the "*Annual BECCS Targets*" and "*Limited Financial Support*" cases. Opening of the hub in Lysekil for the *Annual BECCS Targets* case in 2030, promotes an earlier inclusion of refineries and chemical industries into the CCUS system, while in the "*Limited Financial Support*" case a large increase in fossil CO_2 capture is presented in 2035 when BECCU forces the opening of the hub located in Lysekil. In both cases, fossil CO_2 capture reaches almost full capacity in 2035. The results also show that for the "*Limited Financial Support*" case, the pulp and paper and heat and power industries share similar levels in the biogenic CO_2 capture until 2045 and the demand created from CO_2 utilization is fulfilled evenly from both sectors, with most of the capture plants opened near Lysekil. In 2045, there is a large increase in the biogenic CO_2 required that is fulfilled by medium and large pulp and paper plants located in coastal areas, promoting the opening of hubs in middle Sweden. Figure 18 shows the system layout for two years in the period considered for this work. In the *Annual BECCS Targets* case, the system layout includes plants capturing biogenic CO_2 primarily on the west coast. This approach allows for the sharing of infrastructure with other fossil emitters located near the hub on the west coast. By doing so, the cost of emitting fossil CO_2 is reduced while still achieving the required targets. For the *Limited Financial Support* case, the plants capturing CO_2 are located near the east coast. Since there is no need to reach a specific BECCS level, there is more flexibility in designing the transport infrastructure to provide CO_2 for BECCU, which is the major consumer of biogenic CO_2 during the period 2035-2044. The emphasis here is on transporting biogenic CO_2 for utilization efficiently rather than meeting specific BECCS targets. In the period 2035-2044, BECCU is the main driver for biogenic CO_2 capture, leading to a similar layout for both cases.

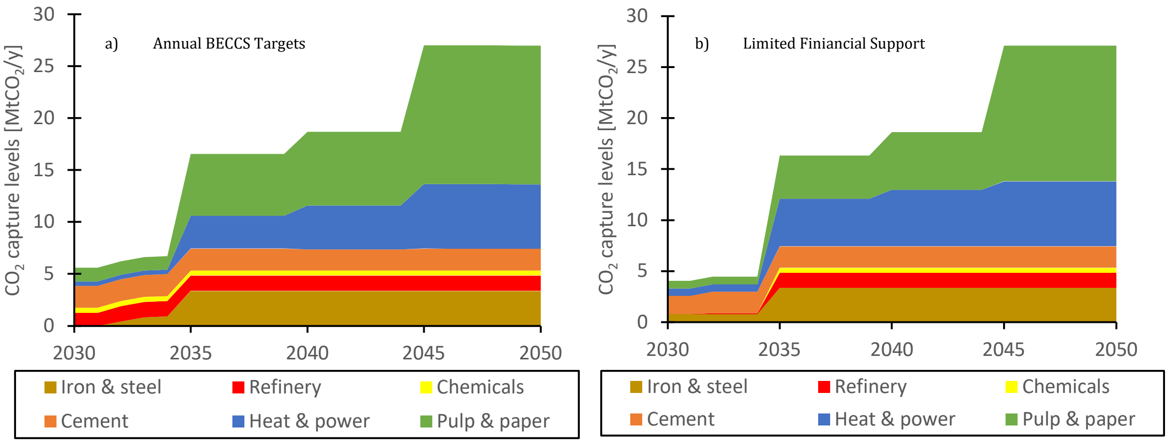

Figure 17: CO_2 capture levels for industrial sites included in this work in the period modelled for a) *Annual BECCS Targets* and b) *Limited Financial Support* cases in the BECCS subsidies scenario.

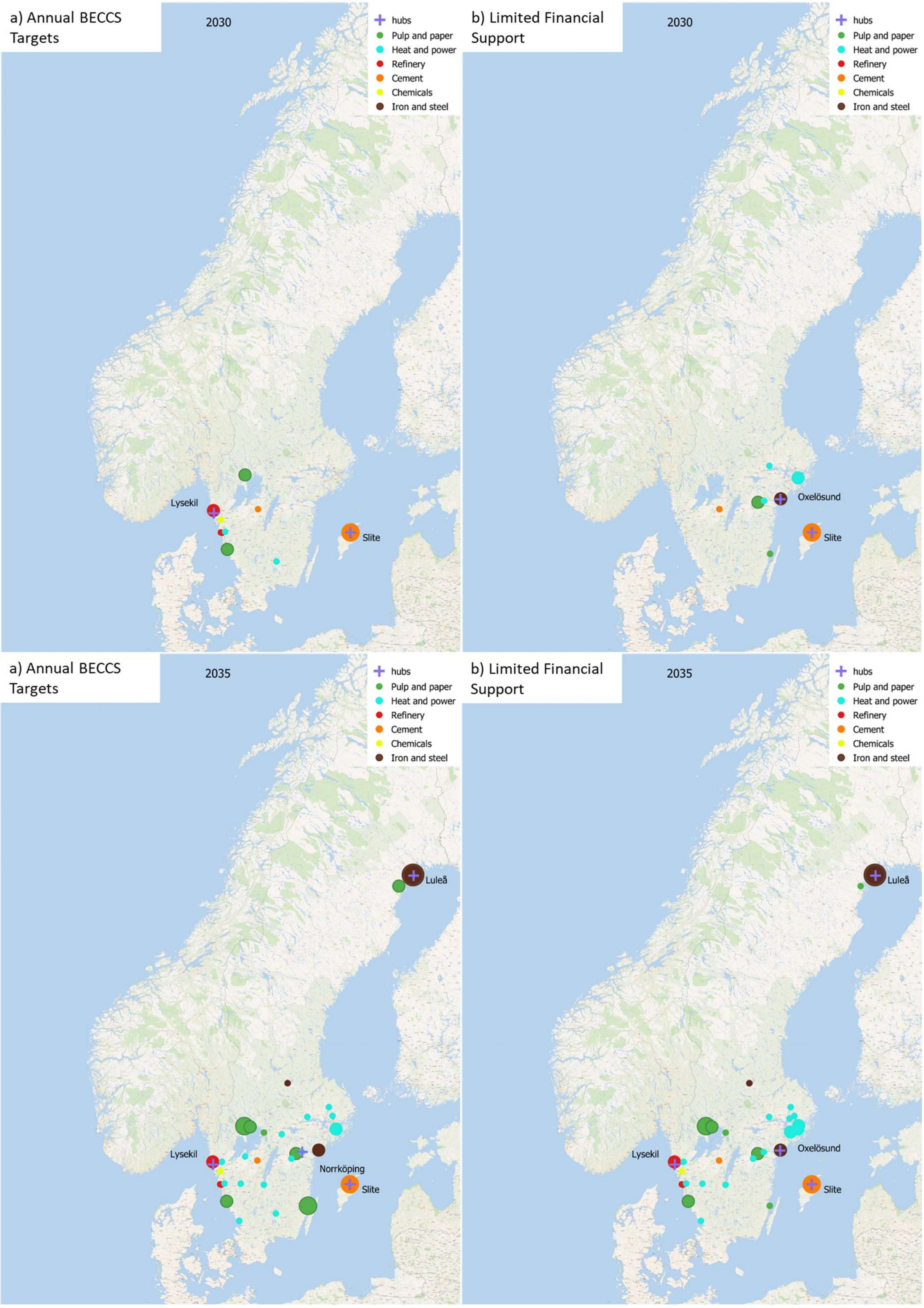

Figure 18: Plants and hubs operating in the CCUS system for years 2030 and 2035 for the a) *Annual BECCS Targets* and b) *Limited Financial Support* cases for BECCS subsidies scenario.

Table 6 presents the NPV, levelized cost of CO_2 and total CO_2 captured for both cases considering total CCUS system and only BECCS subsystem. From the results, it is possible to decrease the budget required for BECCS in the second case by almost 10% while total system capture ($MtCO_2$) differs by less than 3% in the 25 years. Nevertheless, levelized costs for the total CCUS chain and only BECCS subsystem are at the same level.

Table 6: Net present value (NPV), levelized cost of CO_2 ($LCCO_2$) and total CO_2 captured over the period 2025-2050 for the *Annual BECCS Targets* and *Limited Financial Support* cases in BECCS subsidies scenario.

	Annual BECCS Targets		Limited Financial Support	
	System	BECCS	System	BECCS
Net present value [M€]	16468	3983	16017	3600
Levelized cost of CO_2 [€/tonCO_2]	101	112	101	111
Total CO_2 captured [$MtCO_2$]	368	87	358	82

Figure 19 shows the levelized cost of CO_2 for the *"Limited Financial Support"* case in the entire period modelled. BECCU transport infrastructure costs are at least 50% smaller than for other subsystems considered because land transport is the main transportation option, and only small volumes are transported by ship from other hubs. To decrease CCUS system costs, BECCS relies on the cheapest solutions to capture biogenic CO_2, while BECCU relies on more expensive solutions. Nevertheless, overall $LCCO_2$ for BECCU is lower than for BECCS. Figure 20 presents CCS, BECCU, BECCS and CCUS costs averaged over periods of 5 years for the "*Limited Financial Support*" case. In 2030, CHP and pulp and paper plants located near Stockholm are the first sites included in the CCUS system that participates in the BECCS subsidy scheme. Waste fired CHP plants benefit not only by getting subsidies for BECCS, but also by decreasing their fossil emissions. In 2035, BECCU forces the opening of a hub in Lysekil, and the large requirements of CO_2 for utilization is fulfilled by industries located near the hub where utilization takes place. Fossil CCS also benefits from this, with refineries and chemical industries located on the west coast implementing capture with shared investments for transportation infrastructure. In the period 2035-2039, BECCU only requires land transportation, since all BECCS is delivered from the east coast, leading to lower costs for the utilization infrastructure. Before 2045, BECCU is the major consumer of bio-CO_2, and increases in requirements promote the opening of hubs in southern Sweden, leading to a small increase of BECCS in the system with no large modification in the costs for the subsystems. In 2045, the large increase in the BECCS requirements and the vast budget still available promotes the inclusion of large pulp and paper industries on the east coast. Even though the BECCS level is increased more than 5 times in the period 2045-2049, the location of the hub opened in 2045 and the relatively cheap capture and liquefaction costs for large pulp and paper plants, helps to keep the $LCCO_2$ for BECCS in the same order as previous periods. Figure 21 presents the hubs that were used for BECCS, and the volume transported to storage from the hub in the CCUS system. Before 2045, Oxelösund is the most important hub in the BECCS infrastructure, while after 2045, there is an even distribution between Oxelösund, Gävle and Kalmar; all of them located on the east coast.

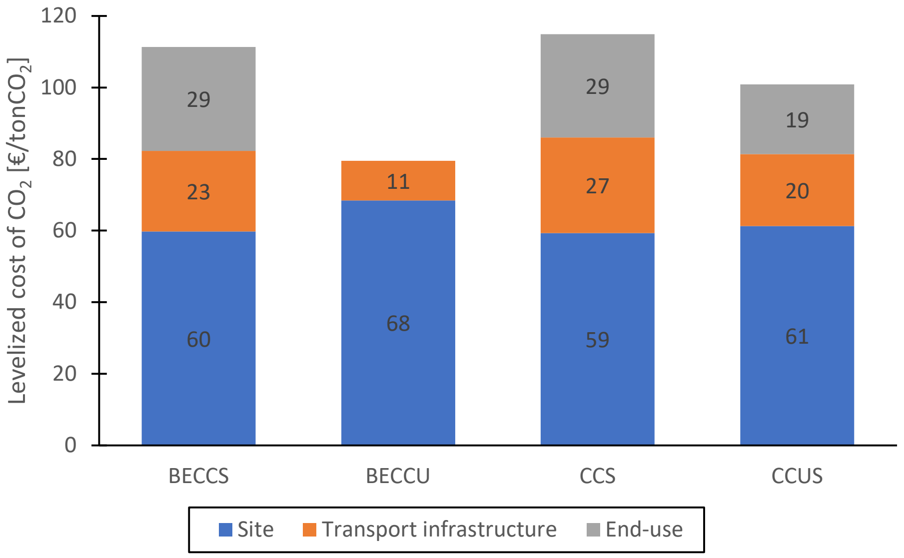

Figure 19: Levelized cost of CO_2 for BECCS, BECCU, CCS subsystems and entire CCUS system in *Limited Financial Support* case for BECCS subsidies scenario.

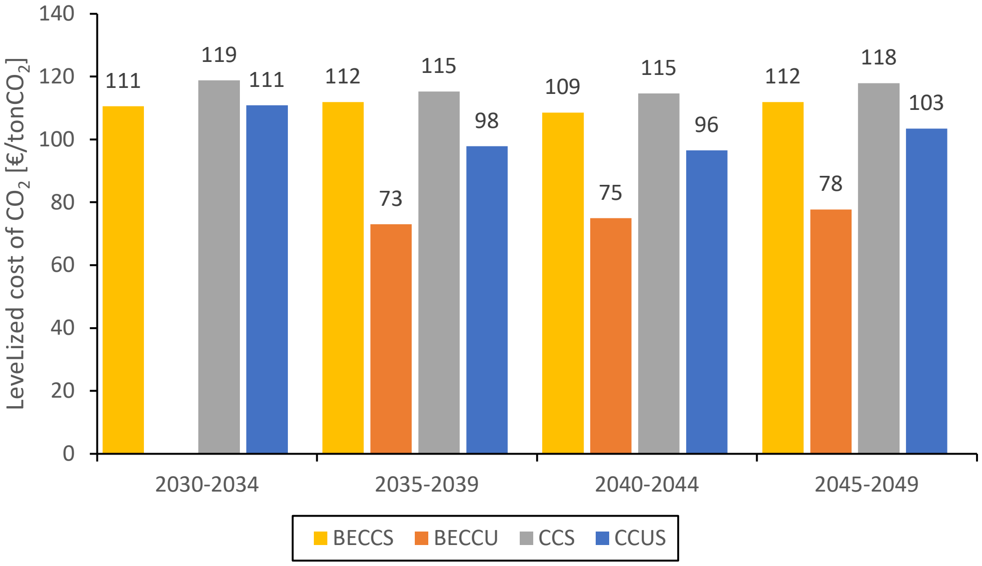

Figure 20: Cost of CO_2 [€/tonCO_2] for subsystem in the CCUS chain for the *Limited Financial Support* case, averaged over period of 5 years in the BECCS subsidies scenario.

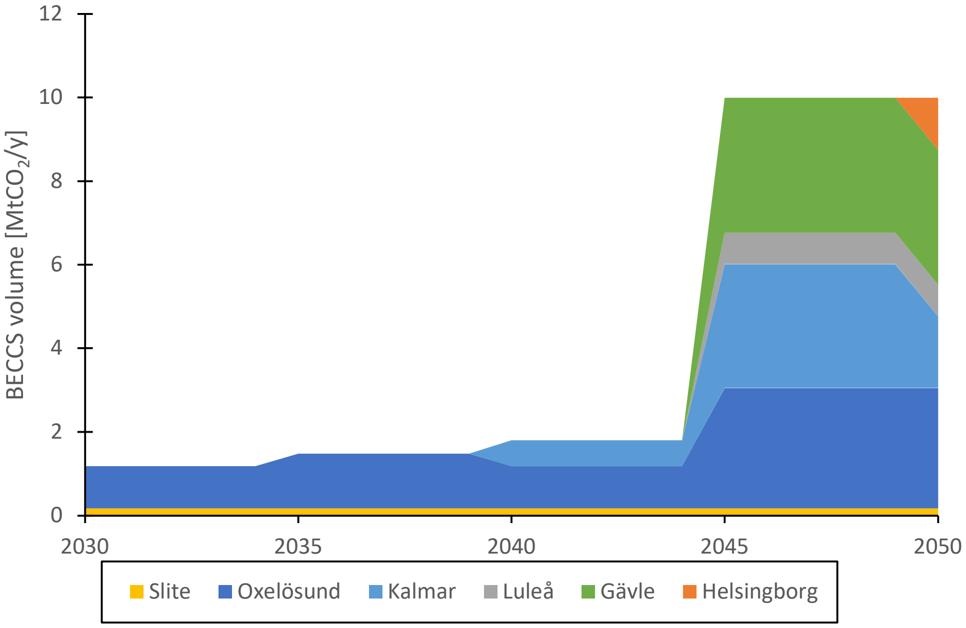

Figure 21: BECCS volume collected in hub and transported to storage in Norwegian North Sea for the *Limited Financial Support* case in the BECCS subsidies scenario.

Figure 22 presents the levelized costs of CO_2 for the transport infrastructure in the CCUS system for the "*Limited Financial Support"* case. It shows that plants located on the west coast require less investing in infrastructure, with values under 20 €/tonCO_2, while for most of the plants located in the east coast, infrastructure costs could rise to 30 €/tonCO_2 despite larger CO_2 volume transported from them. Some plants located in southern Sweden present larger infrastructure costs (25-36 €/tonCO_2), mainly because those are included late in the system to increase the BECCS volume with the remaining financial budget. In addition, the results also show that land transportation could increase infrastructure costs significantly for plants far away from transport hubs.

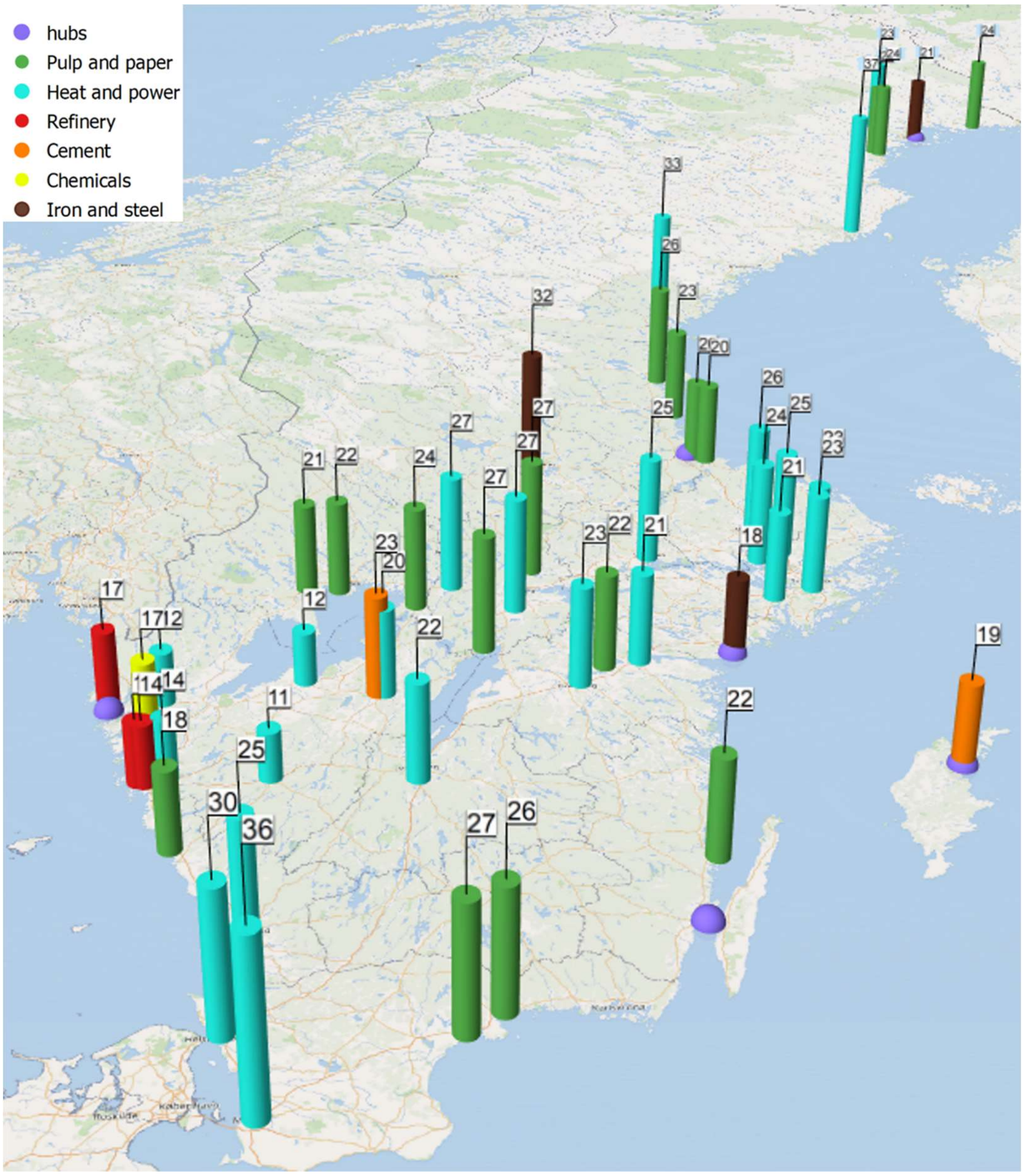

Figure 22: Levelized cost of CO_2 for the infrastructure component in the CCUS system for the *Limited Financial Support* case in the BECCS subsidies scenario. In this work, infrastructure cost includes CAPEX and OPEX for land transport by trucks, intermediate storage in transport hubs and sea transport by ships.

4.2.1. Sensitivity analysis

Results from the sensitivity analysis of the "*Annual BECCS Targets*" case in the BECCS subsidies policy scenario are presented in this section. Figure 23 shows the impact of CO_2 utilization requirements on fossil CCS evolution over time in the period modelled. For all the utilization requirements included in the sensitivity analysis, BECCS promotes fossil capture to start in 2030. Results show that large CO_2 utilization requirements foster an earlier inclusion of the remaining fossil emitting industries, reaching 95% of fossil capture capacity for the 100% and 200% cases in 2040 and 2035 respectively. Smaller utilization requirements also reach previously mentioned fossil CO_2 capture levels but in 2045, supported by large CO_2 requirements for BECCS that can only be provided by remaining heat and power plants.

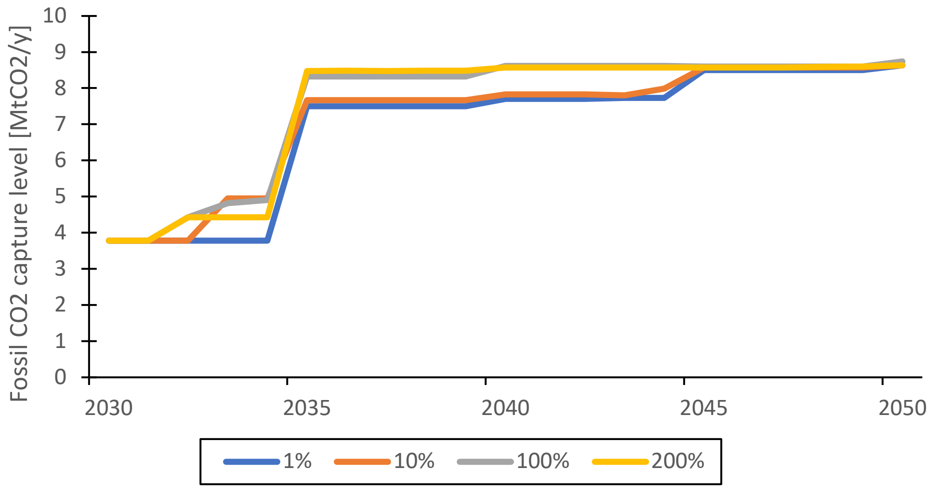

Figure 23: Fossil CO_2 capture level in the period 2030-2050 for *Annual BECCS Targets* case in the BECCS subsidies scenario. The base case (100%) requires 6.42 $MtCO_2/y$ in 2035 and 8.25 $MtCO_2/y$ in 2040.

Figure *24* presents the levelized cost of CO_2 and NPV for the CCUS system and respective subsystems. The results demonstrate that increasing the CO_2 utilization requirements decrease the levelized cost of CO_2 for the entire CCUS system because CO_2 capture volume increases, but total CO_2 stored is almost invariable, thus expenditures for underground storage as end-use and sea transport OPEX after Lysekil remains the same. The levelized cost of CO_2 for BECCS is not largely affected by utilization requirements. For the base case (100%), BECCU is the most expensive solution, since small CHP plants are included. However, fossil CCS costs decrease from this since capture and land transport expenses are shared with biogenic CO_2 that is then utilized. For the 200% case, the BECCU level decreases because heat and power plants are installed earlier, and investment are more evenly distributed in the period modelled.

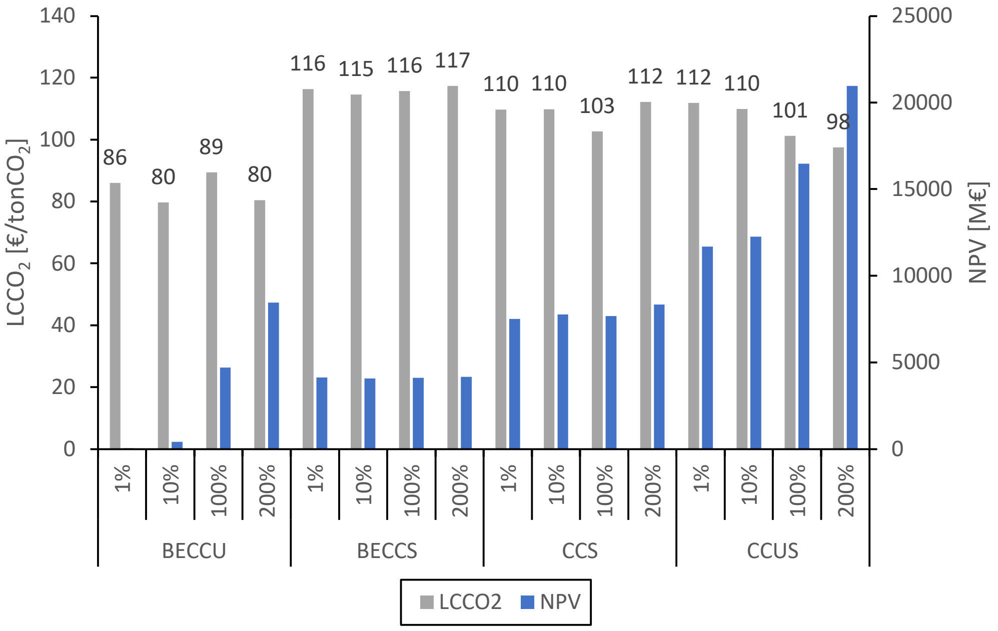

Figure 24: Levelized cost of CO_2 and NPV for subsystems BECCU, BECCS, CCS and complete CCUS chain in the period modelled for the *Annual BECCS Targets* case in the BECCS subsidies scenario. The base case (100%) requires 6.42 $MtCO_2/y$ in 2035 and 8.25 $MtCO_2/y$ in 2040.

Figure 25 shows the annual fossil CO_2 captured in the period modelled for three fossil emissions price trends for the "*Annual BECCS Targets*" case. Results shows that increasing fossil price by 50% leads to an earlier inclusion of fossil emitters in the CCUS system while for the base case (100%), fossil capture is included in 2030, driven not only by the price but also because the system is forced to reach the BECCS targets proposed for that year, sharing the investment for transport infrastructure between BECCS and CCS. In the period 2030-2034, 150% capture levels remain the same and BECCU requirements in 2035 motivates the inclusion of heat and power plants burning waste, increasing fossil capture by more than 3 $MtCO_2$/y. After 2035, small increases in fossil CO_2 capture produced by additional CHP plants implementing capture. For the base case, the fossil price is large enough in the period 2030-2034 to be the main driver to increase the fossil CO_2 capture. After 2035 a similar trend is presented for the 100% and 150% cases. On the other hand, when decreasing the emissions price by 50%, less than 1 $MtCO_2$/y is captured from fossil emitters before 2045. In 2045 the biogenic capture is large enough to give cheap transportation costs for fossil CO_2.

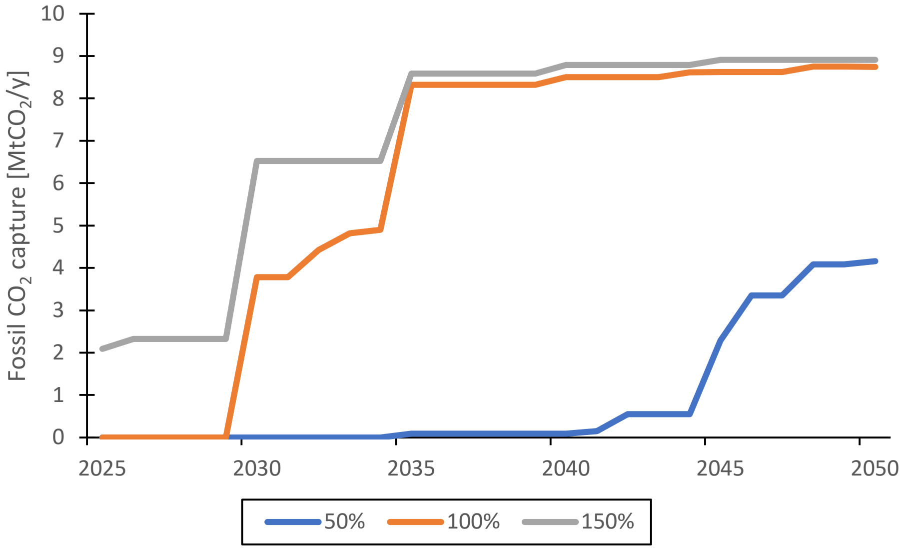

Figure 25: Fossil CO_2 capture for the *Annual BECCS Targets* case in the BECCS subsidies scenario. For three fossil price trends. Fossil price for the base case (100%) is in the range 80-220 €/tonCO_2.

Figure 26 presents snapshots of the plants and hubs operating in 2050 for the *Annual BECCS Targets* case with 50%, 100% and 150% fossil price trends. Results shows that when the fossil emissions price is 50% lower than the base case, biogenic CO_2 capture requirements are not enough to motive the opening of hubs in northern Sweden, and most of the biogenic CO_2 is provided by the pulp and paper sector and only few CHP's are included in the CCUS system. Increasing the fossil price by 50% is sufficient for CHP plants to become important actors in the CCUS chain, even promoting the inclusion of small plants distant from transportation hubs.

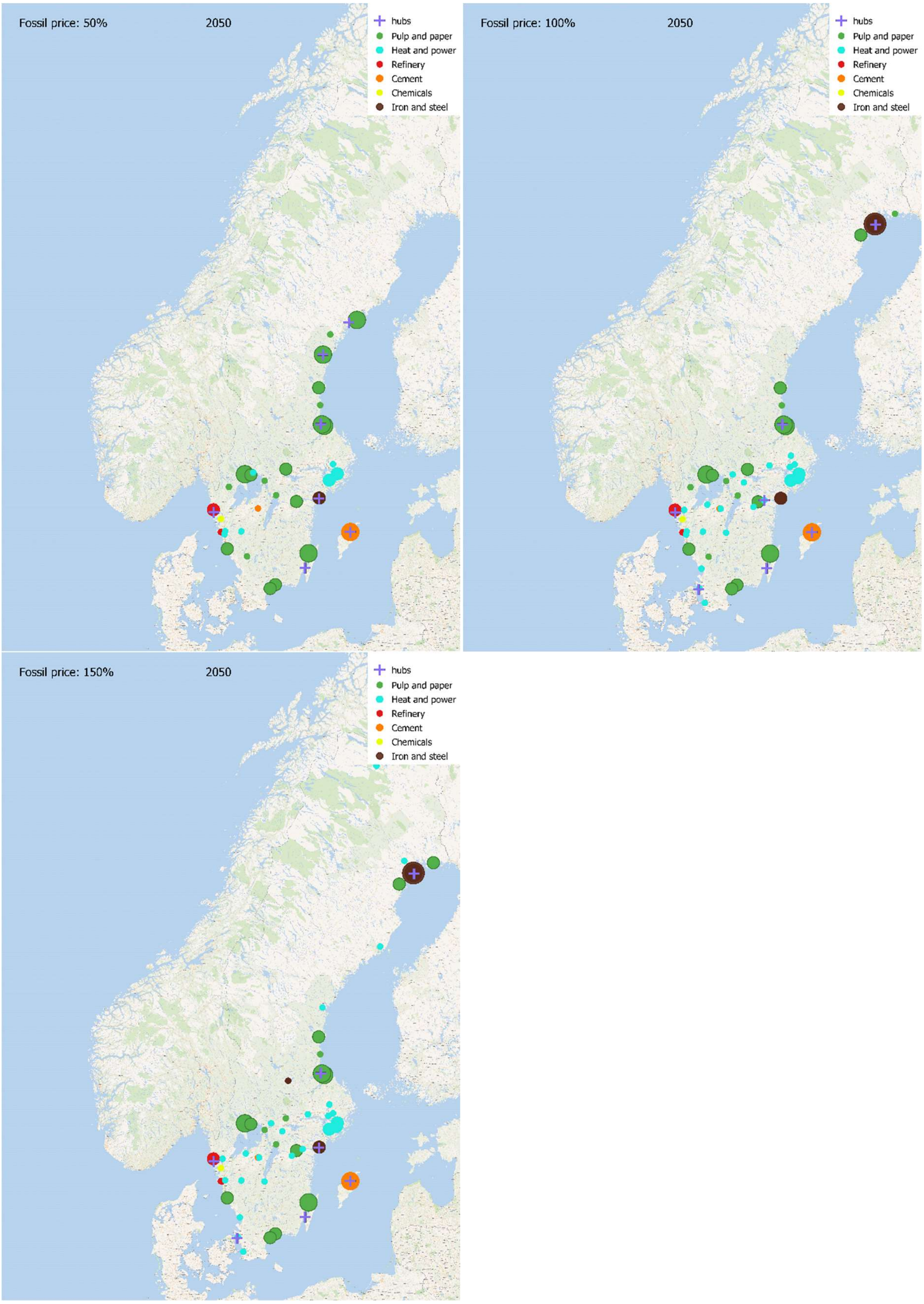

Figure 26: Plants and hubs operating in the CCUS system in 2050 for the *Annual BECCS Targets* case part of the BECCS subsidies scenario. Fossil price for the base case (100%) is in the range 80-220 €/tonCO_2.

Figure 27 presents the NPV and levelized cost of CO_2 for complete CCUS system and respective subsystems when fossil emissions price trend changes. Increasing the CO_2 emissions price increases the $LCCO_2$ for BECCS and the entire CCUS system, since more fossil emissions are being captured from CHP plants and thus, infrastructure costs are shared by BECCS and CCS. On the other hand, BECCU benefits from this by having the infrastructure installed beforehand. For CCS the lowest $LCCO_2$ is presented for the base case because large fossil emitters have lower capture and liquefaction unitary cost, without being the major actor carrying the cost for transportation infrastructure development.

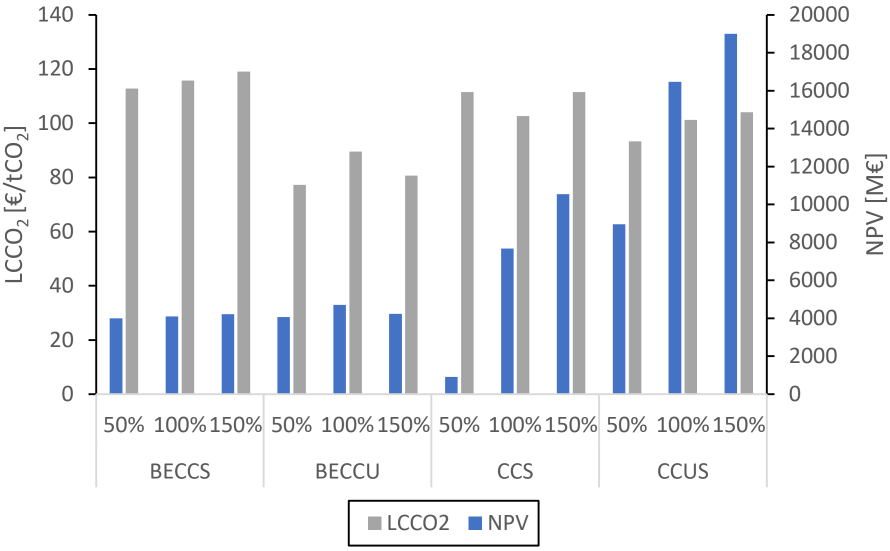

Figure 27: Levelized cost of CO_2 and NPV for subsystems BECCU, BECCS, CCS and complete CCUS chain in the period modelled for the *Annual BECCS Targets* case in the BECCS subsidies scenario. Fossil price for the base case (100%) is in the range 80-220 €/tonCO_2.

Figure 28 presents the influence of BECCS targets in 2045 for the CCUS system development for the "*Annual BECCS Targets*" case. Results show that targets for BECCS in 2045 have a great impact on the $LCCO_2$ for the BECCU and CCS subsystems. If targets are not set, a small portion of biogenic CO_2 coming from cement industry is captured before utilization takes place, and since utilization is always the cheaper end-use (due to lower transportation cost and no storage cost), these bio-CO_2 units go to utilization. Small targets (3 $MtCO_2$/y) could decrease costs for CO_2 utilization including mostly pulp and paper industries in the system with lower capture costs than CHP plants. However, this target level could increase $LCCO_2$ for CCS by almost 50% because the CCS system has to take a larger share in the investment for sea transportation to storage. A similar behavior is presented when targets are large (20 $MtCO_2$/y), and almost all biogenic CO_2 in the system is captured leading to competition for the resource. The levelized cost of CO_2 for CCS increases because model decides to use CHP's as the main source of biogenic CO_2 to reach the 1.8 $MtCO_2$/y BECCS target by 2030 and the 8.25 $MtCO_2$/y utilization requirements by 2040. This leads to a more distributed system before 2045, without a large impact on the total fossil CO_2 captured in the entire period simulated. Table 7 shows the capture level of bio-CO_2 for the pulp and paper and CHP sectors in 2040 and 2045, with a similar CO_2 capture level for both sectors when BECCS targets in 2045 are 3 and 20 $MtCO_2$/y.

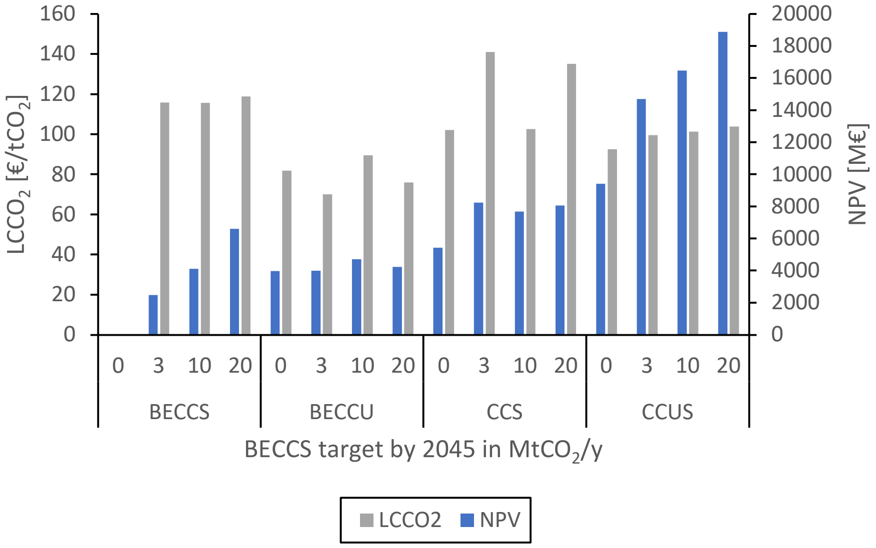

Figure 28: Levelized cost of CO_2 and NPV for subsystems BECCU, BECCS, CCS and complete CCUS chain for the *Annual BECCS Targets* case in the BECCS subsidies scenario.

Table 7: Capture level of bio-CO_2 for pulp and paper (P&P) and heat and power (CHP) industries in the *Annual BECCS Targets* case in the BECCS subsidies scenario in 2040 and 2045 for four targets level in 2045.

	Annual CO_2 capture [$MtCO_2$/y]			
	2040		2045	
BECCS target level by 2045[$MtCO_2$/y]	P&P	CHP	P&P	CHP
0	5.3	4.1	5.3	4.1
3	5.7	5.6	6.4	6.2
10	7.1	4.2	13.4	6.2
20	5.4	5.8	20.2	9.4

Removing the iron and steel sector from the modelling (to represent a case where Swedish steel industry electrifies their operations) in the "*Annual BECCS Targets*" case, presents a positive effect for the CCUS system from economic and CO_2 emissions perspectives. Excluding the iron and steel industry decreases transportation costs and possible emissions from sea transport (that are not accounted in this work), since the major emitter in the iron and steel sector is in northern Sweden. However, removing the iron and steel sector decreases the levelized cost of CO_2 for the CCUS chain and subsystems by less than 3% (see Table 8) while also decreasing the economically motivated potential to capture fossil CO_2 from CHP plants in the system. Excluding a major player such as the iron and steel sector from the CCUS system results in significant rises in investments required for transport infrastructure for smaller plants, thereby reducing the appeal of these plants to capture fossil CO_2. Figure 29 shows the fossil capture from the CHP sector when the iron and steel industry is included and excluded from the modelling, and the potential decrease in fossil capture for the CHP sector when the iron and steel industry is removed from the model. If fossil emissions from iron and steel industry are left in the system to be captured, CHP plants capture 45 $MtCO_2$ more fossil emissions, while removing the iron and steel sector saves 70 $MtCO_2$ of fossil emissions from the iron and steel plant itself.

Table 8: Levelized cost of CO_2 for BECCS, BECCU, CCS and CCUS in the *Annual BECCS Targets* case, BECCS subsidies scenario for the base case and iron and steel removed case.

	LCCO₂ [€/tCO₂]			
	BECCS	BECCU	CCS	CCUS
Annual BECCS Targets with Iron and steel removed	114	86	99	98
Annual BECCS Targets	116	89	103	101

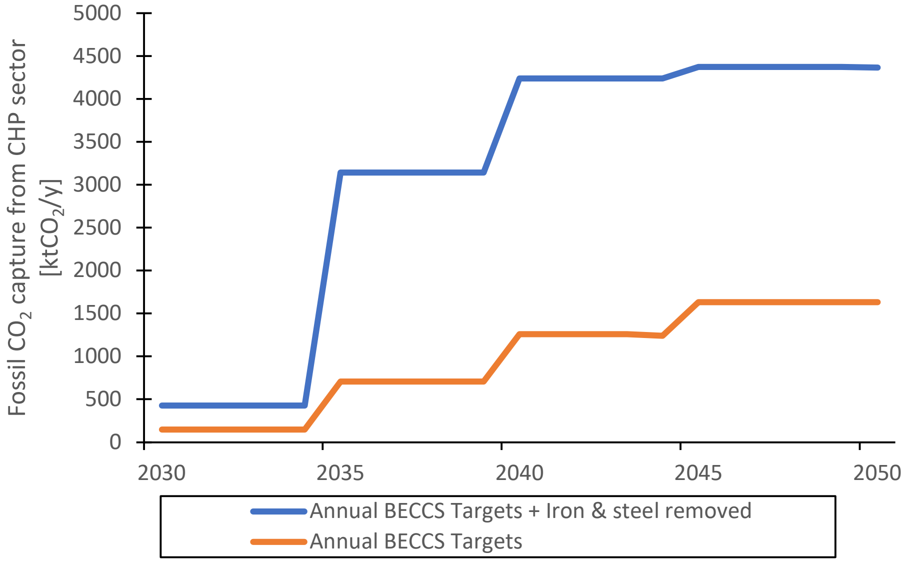

Figure 29: Fossil CO_2 capture from CHP plants for the *Annual BECCS Targets* case and iron and steel removed case in the BECCS subsidies scenario.

Figure 30 presents the CHP and pulp and paper plants operational in 2050. Including iron and steel is beneficial for pulp and paper plants in northern Sweden, decreasing transportation costs per ton of CO_2 and ramping up CHP capture in southern Sweden.

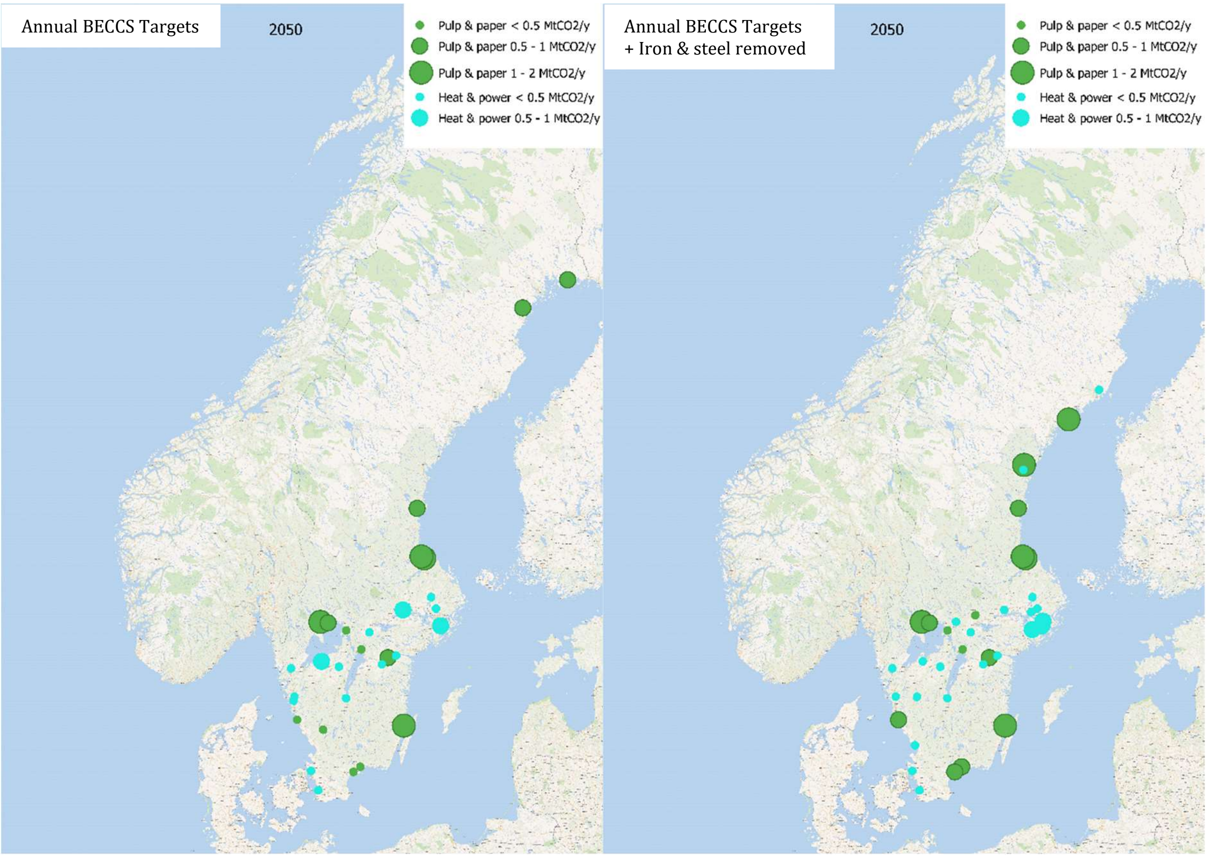

Figure 30: CHP and pulp and paper plants operating in the CCUS system in 2050 for the *Annual BECCS Targets* case in the BECCS subsidies scenario with and without the iron and steel industry.

5. Conclusion

This work studies the impact of carbon dioxide removal (CDR) policies and CO_2 utilization on the development of the carbon capture, utilization, and storage CCUS system for Swedish industry. The findings reveal that the combination of policies promoting bioenergy with carbon capture and storage (BECCS) and utilization requirements, along with the price of fossil emissions, led to distinct evolutions in the CCUS system, affecting both the total amount of CO_2 captured and the levelized cost of CO_2 ($LCCO_2$).

The $LCCO_2$ for the CCUS system ranged from 92 to 115 €/tCO_2, with the capture and conditioning component constituting the largest portion of the system costs. The choice of policy to promote BECCS has a significant influence on the quantity of CO_2 captured, while utilization requirements and fossil price primarily impacts the $LCCO_2$ for the CCUS system. Meanwhile, the BECCU (bioenergy with carbon capture and utilization) subsystem presented a $LCCO_2$ ranging from 79 to 98 €/tCO_2.

Implementing BECCS credits, as an incentive structure to motivate BECCS, the inclusion of fossil emitters into the CCUS system occurred earlier, constrained mainly by the limitations on infrastructure build-up. The *"Voluntary Market"* case within the BECCS credits scenario delayed large-scale bio-CO_2 capture until utilization opportunities arose, resulting in the highest capture levels toward the end of the modelled period. Moreover, substantial utilization requirements necessitate the involvement of small combined heat and power (CHP) plants, leading to higher levelized costs for the BECCU subsystem. The price of fossil emissions demonstrated a pronounced influence on the total BECCS for the *"Voluntary Market"* case, showing greater sensitivity to a decreasing price trend than to an increasing one.

In the BECCS subsidies scenario, a fossil price level around 105 €/tCO_2 proved sufficient to incentivize the capture and storage of fossil CO_2. The waste-fired CHP plants and pulp and paper industries exhibited greater sensitivity to the BECCS targets. The iron and steel sector has the potential to significantly reshape the entire system layout, where plants located in northern Sweden emerged as attractive options only when the iron and steel sector was included in the CCUS system. With a limited financial budget, plants capable of providing BECCS were situated on the east coast, while utilization requirements were fulfilled by plants in proximity to the utilization location in Lysekil, resulting in a substantial decrease in infrastructure costs for BECCU.

The BECCS credits scenario demonstrated the potential to establish a market for negative emissions in Sweden, estimated to be worth approximately 13,700 M€. Even when a small portion of the BECCS was excluded from the credit system to meet the Swedish Government's targets for hard-to-abate sectors of 1.8 MtCO_2/y by 2030 and 10 MtCO_2/y by 2045 [52], the required investment for the entire CCUS system increased by a mere 200 M€, leaving room for a market worth 7,250 M€. The monetary subsidies for BECCS set by the Swedish Government (36 billon SEK, approx. 3.6 B€) [50] appear to be sizable enough to potentially achieve their targets when there is no potential to create profit by selling carbon offsets in a voluntary market.

In the BECCS credits scenario, where there is a high demand of biogenic CO_2 for BECCS, the CCS subsystem benefits from the shared sea infrastructure, resulting in a decrease in the $LCCO_2$ for CCS. However, meeting the large demand for biogenic CO_2 requires the inclusion of small plants, which have larger capture costs. This increases the $LCCO_2$ for BECCU to nearly 100 €/tCO_2. In the BECCS subsidies scenario biogenic CO_2 is not as attractive for

BECCS as for BECCU. Consequently, there is less competition for carbon units with BECCU, leading to a decrease in the $LCCO_2$ for BECCU to almost 80 €/tCO_2. Nonetheless, in this scenario, a larger portion of the infrastructure costs for the CCUS systems falls on the CCS subsystem. This increased burden on the CCS subsystem causes an increase in the $LCCO_2$ for CCS.

In summary, this study sheds light on the interplay between CDR policies, CO_2 utilization, and the development of the CCUS system for the Swedish industry. The findings provide valuable insights for policymakers and industry stakeholders in their pursuit of efficient and economically viable strategies to address carbon emissions and promote sustainable development.

References

[1] ‘Climate Change Evidence: How Do We Know?’, *Climate Change: Vital Signs of the Planet*. https://climate.nasa.gov/evidence (accessed Mar. 20, 2023).

[2] ‘Global Warming of 1.5 ºC —’. https://www.ipcc.ch/sr15/ (accessed Mar. 30, 2023).

[3] IPCC, ‘Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development’, in *Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, Cambridge: Cambridge University Press, 2022, pp. 93–174. doi: 10.1017/9781009157940.004.

[4] *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Stepping up Europe’s 2030 climate ambition Investing in a climate-neutral future for the benefit of our people*. 2020. Accessed: Mar. 30, 2023. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52020DC0562

[5] ‘Sweden’s Climate Act and Climate Policy Framework’. https://www.naturvardsverket.se/en/topics/climate-transition/sveriges-klimatarbete/swedens-climate-act-and-climate-policy-framework/ (accessed Jan. 27, 2023).

[6] IEA, ‘An energy sector roadmap to carbon neutrality in China’, IEA, Paris, 2021. [Online]. Available: https://www.iea.org/reports/an-energy-sector-roadmap-to-carbon-neutrality-in-china

[7] ‘Summary for Policymakers — Global Warming of 1.5 ºC’. https://www.ipcc.ch/sr15/chapter/spm/ (accessed Mar. 30, 2023).

[8] IEA, ‘CCUS in Clean Energy Transitions’, IEA, Paris, 2020. [Online]. Available: https://www.iea.org/reports/ccus-in-clean-energy-transitions

[9] M. E. Boot-Handford *et al.*, ‘Carbon capture and storage update’, *Energy & Environmental Science*, vol. 7, no. 1, pp. 130–189, 2014, doi: 10.1039/C3EE42350F.

[10] ‘Workshop on applicable Bio-CC(U)S concepts for member states 2030 – 2050’. https://task41project5.ieabioenergy.com/publications/workshop-on-applicable-bio-ccus-concepts-for-member-states-2030-2050/ (accessed May 24, 2023).

[11] P. Friedlingstein *et al.*, ‘Global Carbon Budget 2022’, *Earth System Science Data*, vol. 14, no. 11, pp. 4811–4900, Nov. 2022, doi: 10.5194/essd-14-4811-2022.

[12] European Commission. Joint Research Centre., *CO2 emissions of all world countries :JRC/IEA/PBL 2022 report.* LU: Publications Office, 2022. Accessed: Apr. 03, 2023. [Online]. Available: https://data.europa.eu/doi/10.2760/730164

[13] ‘Climate change: what the EU is doing’, Feb. 07, 2023. https://www.consilium.europa.eu/en/policies/climate-change/ (accessed May 25, 2023).

[14] S. Fischer, *The EU’s new energy and climate policy framework for 2030: implications for the German energy transition*, vol. 55/2014. in SWP Comment, vol. 55/2014. Berlin: Stiftung Wissenschaft und Politik -SWP- Deutsches Institut für Internationale Politik und Sicherheit, 2014.

[15] ‘Fit for 55’, Mar. 29, 2023. https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/ (accessed Apr. 03, 2023).

[16] ‘Sleipner carbon capture and storage project’, *Institution of Civil Engineers (ICE)*, May 25, 2023. https://www.ice.org.uk/engineering-resources/case-studies/sleipner-carbon-capture-and-storage-project/ (accessed May 25, 2023).

[17] ‘The ill-fated Petra Nova CCS project: NRG Energy throws in the towel’. https://ieefa.org/resources/ill-fated-petra-nova-ccs-project-nrg-energy-throws-towel (accessed May 25, 2023).

[18] J. A. Garcia, M. Villen-Guzman, J. M. Rodriguez-Maroto, and J. M. Paz-Garcia, ‘Technical analysis of CO2 capture pathways and technologies’, *Journal of Environmental Chemical Engineering*, vol. 10, no. 5, p. 108470, Oct. 2022, doi: 10.1016/j.jece.2022.108470.

[19] M. Erans, E. S. Sanz-Pérez, D. P. Hanak, Z. Clulow, D. M. Reiner, and G. A. Mutch, ‘Direct air capture: process technology, techno-economic and socio-political challenges’, *Energy Environ. Sci.*, vol. 15, no. 4, pp. 1360–1405, Apr. 2022, doi: 10.1039/D1EE03523A.

[20] ‘Register of Commission Documents - COM(2021)800’. https://ec.europa.eu/transparency/documents-register/detail?ref=COM(2021)800&lang=en (accessed Apr. 04, 2023).

[21] ‘Net Zero by 2050 – Analysis’, *IEA*. https://www.iea.org/reports/net-zero-by-2050 (accessed Apr. 04, 2023).

[22] J. W. Andrews, ‘Hydrogen production and carbon sequestration by steam methane reforming and fracking with carbon dioxide’, *International Journal of Hydrogen Energy*, vol. 45, no. 16, pp. 9279–9284, Mar. 2020, doi: 10.1016/j.ijhydene.2020.01.231.

[23] M. I. Stewart, ‘Chapter Nine - Gas Sweetening’, in *Surface Production Operations (Third Edition)*, M. I. Stewart, Ed., Boston: Gulf Professional Publishing, 2014, pp. 433–539. doi: 10.1016/B978-0-12-382207-9.00009-3.

[24] T. Kuramochi, A. Ramírez, W. Turkenburg, and A. Faaij, ‘Comparative assessment of CO2 capture technologies for carbon-intensive industrial processes’, *Progress in Energy and Combustion Science*, vol. 38, no. 1, pp. 87–112, Feb. 2012, doi: 10.1016/j.pecs.2011.05.001.

[25] M. Biermann, C. Langner, S. Roussanaly, F. Normann, and S. Harvey, ‘The role of energy supply in abatement cost curves for CO2 capture from process industry – A case study of a Swedish refinery’, *Applied Energy*, vol. 319, p. 119273, Aug. 2022, doi: 10.1016/j.apenergy.2022.119273.

[26] M. Songolzadeh, M. Soleimani, M. Takht Ravanchi, and R. Songolzadeh, ‘Carbon Dioxide Separation from Flue Gases: A Technological Review Emphasizing Reduction in Greenhouse Gas Emissions’, *The Scientific World Journal*, vol. 2014, p. e828131, Feb. 2014, doi: 10.1155/2014/828131.

[27] ‘CCS Explained: Transport’, *Global CCS Institute*. https://www.globalccsinstitute.com/ccs-explained-transport/ (accessed May 25, 2023).

[28] ‘Global Carbon’. https://status22.globalccsinstitute.com/ (accessed Apr. 04, 2023).

[29] ‘Equinor and Fluxys unveil plans for CO2 pipeline from Belgium to Norwegian offshore CCS’, *Upstream Online | Latest oil and gas news*, Jun. 29, 2022. https://www.upstreamonline.com/energy-transition/equinor-and-fluxys-unveil-plans-for-co2-pipeline-from-belgium-to-norwegian-offshore-ccs/2-1-1247604 (accessed May 25, 2023).

[30] K. L. Anthonsen *et al.*, ‘Characterisation and Selection of the Most Prospective CO2 Storage Sites in the Nordic Region’, *Energy Procedia*, vol. 63, pp. 4884–4896, Jan. 2014, doi: 10.1016/j.egypro.2014.11.519.

[31] ‘Carbon dioxide Fischer-Tropsch synthesis: A new path to carbon-neutral fuels | Elsevier Enhanced Reader’. https://reader.elsevier.com/reader/sd/pii/S0926337316307603?token=5F72849008B85836B05335CF47867F14404A4CD1C6BCFFF858B259471EC235C611CF6A1AFED79F

702B54C5B8434B79A9&originRegion=eu-west-1&originCreation=20230227101933 (accessed Feb. 27, 2023).

[32] Q. Liu, L. Wu, R. Jackstell, and M. Beller, ‘Using carbon dioxide as a building block in organic synthesis’, *Nature Communications*, vol. 6, no. 1, p. 5933, Jan. 2015, doi: 10.1038/ncomms6933.

[33] S. E. Tanzer and A. Ramírez, ‘When are negative emissions negative emissions?’, *Energy Environ. Sci.*, vol. 12, no. 4, pp. 1210–1218, Apr. 2019, doi: 10.1039/C8EE03338B.

[34] W. Rickels, A. Proelß, O. Geden, J. Burhenne, and M. Fridahl, ‘The future of (negative) emissions trading in the European Union’, Kiel Working Paper, Working Paper 2164, 2020. Accessed: May 25, 2023. [Online]. Available: https://www.econstor.eu/handle/10419/224064

[35] ‘Swedish Energy Agency’. https://www.energimyndigheten.se/en/ (accessed Apr. 03, 2023).

[36] Statistics Sweden. (n.d.)., ‘Total air emissions by greenhouse gas, sector and year’. Accessed: May 25, 2023. [Online]. Available: https://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__MI__MI0107/TotaltUtslappN/table/tableViewLayout1/

[37] Statistics Sweden, ‘Emissions of greenhouse gases from industry by greenhouse gas, industry and year.’ Accessed: May 25, 2023. [Online]. Available: https://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__MI__MI0107/MI0107IndustriN/table/tableViewLayout1/

[38] ‘HYBRIT Demonstration’, *Hybrit*. https://www.hybritdevelopment.se/en/hybrit-demonstration/ (accessed Mar. 02, 2023).

[39] ‘preem_sustainability-report-2021_01_juni.pdf’. Accessed: Feb. 27, 2023. [Online]. Available: https://www.preem.se/globalassets/om-preem/hallbarhet/hallbarhetsredovisning/preem_sustainability-report-2021_01_juni.pdf

[40] P. Börjesson, *Potential för ökad tillförsel av inhemsk biomassa i en växande svensk bioekonomi – en uppdatering*. Lunds universitet. Avdelningen för miljö- och energisystem, 2021. Accessed: May 25, 2023. [Online]. Available: http://lup.lub.lu.se/record/29600a2a-724e-4e06-b407-2f5681040fec

[41] R. och Regeringskansliet, ‘Sweden’s carbon tax’, *Regeringskansliet*, Feb. 26, 2018. https://www.government.se/government-policy/swedens-carbon-tax/swedens-carbon-tax/ (accessed May 25, 2023).

[42] ‘Carbon Tax Basics’, *Center for Climate and Energy Solutions*. https://www.c2es.org/content/carbon-tax-basics/ (accessed May 25, 2023).

[43] ‘EU Emissions Trading System (EU ETS)’. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en (accessed May 25, 2023).

[44] ‘Development of EU ETS (2005-2020)’. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/development-eu-ets-2005-2020_en (accessed May 25, 2023).

[45] ‘Emissions cap and allowances’. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/emissions-cap-and-allowances_en (accessed May 25, 2023).

[46] ‘Revision for phase 4 (2021-2030)’. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/revision-phase-4-2021-2030_en (accessed May 25, 2023).

[47] C. Credits, ‘The Ultimate Guide to Understanding Carbon Credits’, *Carbon Credits*, Jan. 26, 2022. https://carboncredits.com/the-ultimate-guide-to-understanding-carbon-credits/ (accessed May 26, 2023).

[48] L. Zetterberg, F. Johnsson, and K. Möllersten, ‘Incentivizing BECCS—A Swedish Case Study’, *Frontiers in Climate*, vol. 3, 2021, Accessed: May 26, 2023. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fclim.2021.685227

[49] M. Fridahl and L. Lundberg, *Aktörspreferenser i design av ett stödsystem för bio-CCS*. Linköpings universitet, 2021. Accessed: May 26, 2023. [Online]. Available: https://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-175381

[50] R. och Regeringskansliet, 'Stor satsning görs på infångning av biogen koldioxid', *Regeringskansliet*, Nov. 04, 2022. https://www.regeringen.se/pressmeddelanden/2022/11/stor-satsning-gors-pa-infangning-av-biogen-koldioxid/ (accessed Mar. 01, 2023).

[51] 'Energimyndigheten föreslår omvända auktioner som stöd för bio-CCS'. https://www.energimyndigheten.se/nyhetsarkiv/2021/energimyndigheten-foreslar-omvanda-auktioner-som-stod-for-bio-ccs/ (accessed May 26, 2023).

[52] 'State aid for BECCS'. https://www.energimyndigheten.se/en/sustainability/carbon-capture-and-storage/state-aid-for-beccs/ (accessed May 16, 2023).

[53] S. Karlsson, F. Normann, M. Odenberger, and F. Johnsson, 'Modeling the development of a carbon capture and transportation infrastructure for Swedish industry', *International Journal of Greenhouse Gas Control*, vol. 124, p. 103840, Mar. 2023, doi: 10.1016/j.ijggc.2023.103840.

[54] E. Svensson, P. Bokinge, S. Harvey, and F. Normann, 'Chalmers Industrial Case Study Portfolio - Contents, Structure and Example Applications', 2019, Accessed: Apr. 08, 2023. [Online]. Available: https://research.chalmers.se/en/publication/507813

[55] 'Northern Lights – What we do'. https://norlights.com/what-we-do/ (accessed Apr. 08, 2023).

[56] Å. Eliasson, E. Fahrman, M. Biermann, F. Normann, and S. Harvey, 'Efficient heat integration of industrial CO2 capture and district heating supply', *International Journal of Greenhouse Gas Control*, vol. 118, p. 103689, Jul. 2022, doi: 10.1016/j.ijggc.2022.103689.

[57] 'Samverkan kring infrastruktur för transport och lagring av koldioxid 2022-838'. https://energiforsk.se/program/bio-ccs-i-fjarrvarmesektorn/rapporter/samverkan-kring-infrastruktur-for-transport-och-lagring-av-koldioxid-2022-838/ (accessed May 28, 2023).

[58] International Energy Agency, 'World Energy Model Documentation', *2021*.

[59] 'SCA and St1 enter joint venture to produce and develop liquid biofuels'. https://www.st1.com/sca-and-st1-enter-joint-venture-to-produce-and-develop-liquid-biofuels (accessed Apr. 08, 2023).

[60] 'Transformativa omställningen av industrin skapar nya möjligheter för fjärrvärmesektorn'. https://energiforsk.se/konferenser/genomforda/transformativa-omstallningen-av-industrin-skapar-nya-mojligheter-for-fjarrvarmesektorn/ (accessed May 27, 2023).

Department of Space, Earth and Environment
Division of Energy Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
www.chalmers.se