Influence of Policy Decisions on CCS-System Development in Swedish Industries

Master's thesis in Sustainable Energy Systems

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Abstract

This report uses an optimization model that minimizes the net present value of a carbon capture and storage system for Swedish industry. The systems include the capture units at the industrial site, liquefaction process, transport by truck and ship and both intermediate storage and permanent storage under the seabed. The optimization model invests in carbon capture at large industrial sites for pulp and paper, cement, refinery, iron and steel, chemicals and heat and power production. The implementation of policies for carbon reduction in the model and how these impact the development of CCS is investigated.

The choice of policy affects the amount of CO_2 captured and from which sites the emissions are captured. The Swedish industry is dominated by pulp and paper and the total amount of captured CO_2 is higher for policies incentivizing capture on biogenic emissions. Carbon pricing, gives a threshold effect as CCS becomes cost effective. The system invests in fossil carbon captured at a carbon price at about 80-85 €/tCO_2. An emission budget for the entire period incentivizes carbon captured at the sites with lower investment cost early in the period. The timing of the early investments depend on the size of the budget. A continuously decreasing annual emission budget gives a linear increase on investment of carbon capture equipment.

CCS in Swedish industry will require clear goals and policies. In order for CCS to be involved in achieving net zero emissions in 2045, the investment must begin in the coming years to avoid large annual investments in the years just before 2045. Investing in certain industries within a couple of years can lead to low costs for the system while capturing much carbon dioxide throughout the period.

Keywords: CCS, BECCS, Policies, Swedish industry, Carbon Pricing, Emission Budget.

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Sara Eriksson, Gothenburg, May 2022

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Introduction

In 2015 when the Paris agreement was signed, the leaders of the world decided to decrease the greenhouse gas emissions due to the rising global average temperature and climate change. The 196 Parties attending agreed on limiting global warming to below 2°C but preferably below 1.5°C[55]. The Intergovernmental Panel on Climate Change (IPCC) have reported scenarios for the future climate with different assumptions on future GHG emissions. In the reports the global average temperature is compared to pre-industrial levels. Between 2011 and 2020 the global surface temperature was 1.09°C higher than the period of 1850-1900[36]. The increase of temperature has resulted in rising global sea levels due to ice loss and thermal expansion. Thermal expansion stood for 50% of the rising sea levels between 1971 and 2018. Since 2006 the biggest contributors have been ice sheet and glacier mass loss[36]. The largest contribution of the rising greenhouse gases in the atmosphere is carbon dioxide and it is considered to be the primary driver of global warming. Scientists suggest global warming will stop if a net zero global anthropogenic carbon dioxide emission is reached[27]. When anthropogenic carbon dioxide emissions are stopped the global average temperature will continue to rise due to inertia in the climate system[29]. The global temperature change is roughly proportional to cumulative emissions of carbon dioxide. Therefore, there is an emission budget for the different temperature targets. Because of climate sensitivity it is hard to determine how small the budgets need to be. IPCC's best estimation shows a doubling of carbon dioxide concentration resulting in an increase of 3°C[36]. For the different 1.5°C scenarios presented in IPCC's report[27], all the scenarios depend on a decreasing use of fossil fuel and for most scenarios Carbon Capture and Storage (CCS) and Bio Energy Carbon Capture and Storage (BECCS) are included in the plans.

1.1 Aim

The aim of this master's thesis is to determine the effects of policy decisions and incentives on the development and cost of a system for capture and storage of carbon dioxide in Swedish industry. The work investigates whether there are synergies in implementing several policy decisions or whether certain policies counteract each other. The goal is also to investigate differences in targeting biogenic and fossil carbon.

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Theory

The policies for carbon capture and storage in Sweden are affected by the climate laws in both Sweden and the European Union. Some technical and legal limitations in development of carbon capture are described in the following chapters as well as the most promising policies to increase the speed of development.

2.1 European Union

The European Union's climate law has a target for all the member states 2050. By then all states should achieve net zero GHG emission. The law also includes a target of reducing the net GHG emission in 2030 by at least 55% compared to 1990[11]. The European Union can see the benefits of using carbon capture technologies in process and power industries and how these can contribute to mitigating climate change. There is a European Union directive on the geological storage of carbon dioxide, this directive says that geological storage sites require a storage permit. The permits are given to the sites that meet the requirements of the directive and are therefore managed in an environmentally safe way[13]. The directive urges the member states to strengthen the research and development of carbon capture and storage. The geological storage of carbon dioxide within research and testing of new products and processes are not included in the directive. Neither are storages with less than 100 kilotons required to have permits to store carbon dioxide. Development of carbon capture and storage have been a focus in some member states in the European Union. These countries have expressed positive reactions to the directive. Other member states have been critical of the proposal[37]. They suggest that developing carbon capture technologies will benefit the countries with oil and gas production and carbon capture and storage will not help in the quest of reaching the goals in the Paris accords. In the directive on the geological storage of carbon dioxide the European Union has addressed these concerns and written that the development of carbon dioxide storage should not lead to an end of the efforts to reduce emissions nor a reduction in the support for renewable energy and sustainable technologies[13].

The first London protocol was signed in 1972 and the purpose was to protect the marine environment from human activities. This was one of the first international agreements of this kind. The protocol includes prevention of uncontrolled disposal of wastes into the ocean. Sweden signed the first protocol and the first rewritten protocol from 1996 but they have not agreed on the suggestions from 2006 and 2013. In 2006 an alteration was made regarding carbon dioxide storage. The suggestion was to allow storage of carbon dioxide under the seabed. According to the London protocol it is allowed to store carbon dioxide under the seabed, but only when it is safe to store[26],[24]. According to the latest approved London protocol it is however not allowed to export carbon dioxide for geological storage purposes[29] and some members of the London convention think it should be an exception. To make it possible for Sweden to export carbon dioxide for permanent geological storage, Sweden ought to ratify the proposed change. In addition to Sweden's approval, there is a requirement that two thirds of the parties must ratify the changes[39],[26]. Only six out of 53 parties have approved the changes from 2006. As of 2019 it is possible to export carbon dioxide intended for storage under the seabed provided that the exporting and importing countries enter a bilateral treaty.

2.2 Sweden

In 2017, it was decided to acquire a new climate law in Sweden with the aim of reducing carbon dioxide emissions[38]. This includes both preserving and creating new functions to counteract climate change and working towards the long-term goal to have zero net GHG emissions by 2045. The emissions in 2030 must also be at least 85% lower than in 1990 according to the Climate Policy Council[31]. Emissions in the trading sector in 2045 must be at least 85 percent lower than emissions in 1990[42]. To achieve net zero emissions, negative emissions are needed in other areas. After 2045 GHG emission must be net negative in Sweden, meaning that complementary measures need to capture more GHG than emitted.

Of the total emissions in Sweden, heat and power plants and industrial processes accounted for around a third of the emissions in 2018. Industries which emit high amounts of fossil carbon dioxide are iron, steel, minerals, cement, refinery, and chemical industry. Heat and power emit about one tenth of the total emissions in Sweden. Sweden does not have any specific regulations for carbon capture and storage and the technology is not used at any industrial sites. In a regulation on state support for measures that contribute to reduced industrial climate change from 2017, the Swedish Energy Agency may provide state aid for measures that contribute to negative emissions through capture and geological storage of GHG of biogenic origin or gases captured from the atmosphere if there is money in the budget[38].

2.2.1 Emission Intensive Industries in Sweden

The cement industry is one of the largest fossil CO_2 emitters in Sweden. The calcination process, when limestone is heated to produce calcium oxide, accounts for about two thirds of the production's emissions, the rest of the emission comes from the fuel used to heat up the cement kiln. The cement industry has a mixture of fossil and biogenic emissions and it is possible to reduce the emission by using alternative fuels for the cement kiln and using fly ash in the cement. However, there will still be carbon dioxide emissions from the calcination process. Cementa (the largest cement manufacturer in Sweden) has started a carbon capture and storage project at their site in Slite on Gotland and their plan is to be climate neutral in 2030. Slite produces three fourths of the cement in Sweden and has been the second largest single site emitter in Sweden in recent years[57],[**?**]. The plan is to take inspiration from Norcem's cement production in Brevik, Norway and capture and store carbon dioxide under the seabed. Norcem has started to build the first carbon capture site applied to a cement plant in the world, and the facility is planned to be in operation by 2024 and achieve net zero emissions by 2030. The emission from the facility is about 800 000 ton CO_2 annually[44]. In the European Union the cement industry does not pay much for their carbon dioxide emissions, this is because they receive large amounts of free allocation in the emissions trade system (EU ETS). In Sweden, Cementa has received more free allocations than released emissions. This means that Cementa could sell the surplus allowances to other companies[34].

The metal industry stands for another large part of the carbon dioxide emissions in Sweden. For every ton of steel produced, twice as much carbon dioxide is emitted[19]. One option to reduce the carbon dioxide emission in iron and steel production is to use hydrogen made from renewable electricity in the direct reduced iron production[49]. The byproduct would then be water instead of fossil-based carbon dioxide. CCS would be another option to reduce the carbon dioxide emissions from the steel production.

Pulp and paper industry is energy-intensive and has high levels of biogenic GHG emissions. In Sweden most of the fossil fuels used in the processes have been replaced with biofuel, which have resulted in a large reduction of carbon dioxide emissions[40],[20]. The emissions are mostly biogenic and therefore would investing in carbon capture technology result in net negative emissions.

Fossil fuels are used as raw materials in both refineries and chemical industries. It is difficult to replace fossil fuels in these processes, but with funding is it possible to develop substitutes which are bio-based[40]. Both refinery and chemical industries are candidates for carbon capture and storage.

The heat and power sector is important in a northern country like Sweden. GHG emissions from district heating and electricity production accounted for 9% of the total fossil emission in Sweden in 2018. Since 1990, emissions from this sector have decreased significantly, mainly due to the transition from fossil fuel to biofuel and waste in electricity and district heating production[40]. Today, almost all use of fossil fuel has been phased out and the electricity production in Sweden is mainly hydro, nuclear and wind power. In combined heat and power plants, bioenergy is most commonly used. The heat and power sector's emissions are mainly biogenic and therefore the potential for BECCS is great.

2.3 Carbon Capture and Storage

Carbon capture and storage is a technology that includes several steps. The first part is when carbon is separated from other gases. This can be done in several ways. Collection from the air is called direct air capture. The advantage with direct air capture is that it can be done everywhere. The low concentration of carbon dioxide in the air complicates the process and makes it expensive due to energy consumption and equipment requirement[54].

Another, more cost-effective option, is to capture the carbon from a point source, such as industrial sites with large CO_2 emissions. The carbon can be separated before the combustion by removing carbon from fossil fuels. Gasification of the fuel at elevated pressure with low oxygen levels produces syngas, which consist mainly of carbon monoxide and hydrogen[17]. Water is added to the syngas and the CO_2 can easily be captured. Left is a fuel gas rich with hydrogen which can be used in the combustion. This is an efficient but expensive technology.

The carbon dioxide can also be collected after the combustion before the gas is vented to the atmosphere. This is done by separating the carbon dioxide from the flue gases. There are relatively low CO_2 concentrations in the flue gas which is a challenge when the separation is done. This is not as efficient as pre-combustion carbon capture, but the investment cost is lower and post-combustion can be used at all types of industrial sites and without any rebuilding of the process only an extension for capturing the CO_2 from the stacks[48]. There are various methods that can be used to capture CO_2. It can be done with cryogenic distillation, membrane separation, adsorption, and absorption[47],[48]. The most mature technology is absorption[35]. In the CO_2 absorption process with monoethanolamine (MEA), two sub-processes take place. The first is an absorber and stripper section and the second is a compression or liquefaction process, depending on the transport conditions of the CO_2. After combustion, the flue gases are fed into a direct-contact cooler to reduce the temperature[15]. The water used in the direct-contact cooler is sent to a water treatment after use. In the absorber, the flue gases are mixed with an MEA solution which the carbon dioxide is absorbed in. The flue gases are purified before being released from a stack. There is a requirement of larger compressors and increased cooling with an increase of CO_2 volume flow[15]. Depending on whether the CO_2 is going to be transported by trucks and ships or pipelines, it is either compressed to high pressures (approximately 100 bar) or liquefied (at e.g., 15 barg and -26 $\circ$C)[4]. This process consumes a large amount of energy.

In oxy-combustion the fossil fuels are combusted in nearly pure oxygen, rather than air. This means the flue gases contain mostly carbon dioxide and water. The CO_2 can easily be separated by condensing the water[47],[48]. This technology is not cost-competitive due to high capital cost, energy consumption and challenges in the oxygen separation[41].

There are a few options for permanent storage and the most talked about is geological storage. The goal of CO_2 storage is to isolate CO_2 from the atmosphere. It is injected in the bedrock and the geological storage retains the CO_2 in the rocks deep in the ground. The Norwegians have been researching and developing carbon capture and storage systems for many years. The leading storage project is called Northern Lights. The CO_2 will be transported by ships to a terminal on Norway's west coast where the CO_2 is pumped offshore via pipeline to a structure at the seabed. The CO_2 is then injected in a permanent storage about 2600 meters below the seabed[45].

Large scale carbon dioxide transportation can be done via ship or pipeline. For short distances and small volumes, the CO_2 can be transported by truck or rail. It is important that the transportation is safe and reliable. Ships and pipelines are the cheapest options, but they have some limitations. Pipelines are of course the cheapest transportation option onshore. It is sometimes also the cheapest option offshore, depending on the distance and volume. Shipping through pipelines has been used for many years. Pipelines need regular maintenance to maintain a safe operation both for environmental and health reasons. Land pipelines are monitored from the air by aircraft and by patrols on foot. Pipelines underwater are inspected with the help of small unmanned submersibles[5].

For transportation by ships, truck, or rail there is a need to liquefy the CO_2. Ship transportation includes a temporary storage on land. The size of the storage depends on the number of ships, the capacity of the ships, the time one trip takes and the capture rate. The CO_2 is unloaded from the ships at the delivery point and left at temporary storage tanks. Geological storage site under the seabed requires a floating storage facility where the ship can unload the CO_2. There are various kinds of tank structures for transportation of liquid gas on ships. A combination of high pressure and low temperature is a requirement for CO_2 to remain in the liquid state[23]. Trucks are adaptable but the operation cost of transported CO_2 is high. Sweden does not have a permanent storage site for CO_2, so it needs to be transported to Norway. In the long run, pipelines will be cheaper, provided that CCS is implemented at scale, but then a substantial investment is required[18].

2.3.1 Bioenergi with Carbon Capture and Storage

Similar to carbon capture and storage is CO_2 capture and permanently stored in a geological storage. The difference is that the carbon comes from biomass and CO_2 storage creates negative emissions of CO_2. The combustion part of the process can be considered carbon neutral. The process is considered net negative when the carbon emitted has been captured and permanently stored. In Sweden, the forest is not logged to burn biomass. The trees are mainly used for timber and paper[28]. The biomass most used for biofuel is forestry litter, almost 85 percent[32]. The rest of the fuel is waste, peat and residues from arable land. Some people argue that bioenergy with carbon capture might give a false sense of security. The actions to reduce climate change and fossil fuel use might be delayed when there is hope for negative emissions. The potential for negative emission with BECCS is unlikely to meet the climate targets on its own. In none of the 2°C scenarios made by the IPCC is bioenergy with carbon capture and storage the only solution. The use of fossil fuels must be reduced. Another concern is that the green carbons from bioenergy combustion are stored and not used to replace fossil carbon in the refinery and chemical industries[14].

2.3.2 Carbon Capture and Utilisation

The captured CO_2 can be applied in other processes. This means the CO_2 will be recycled and industrial processes can benefit through the reuse of the CO_2. Permanent geological storage is not the result nor aim in carbon capture and utilisation. However, the aim to reduce the amount of CO_2 in the atmosphere is similar to the one for carbon capture and storage. The CO_2 can convert materials into more valuable materials or products while the production process remains carbon neutral. Carbon dioxide can be used in various sectors, such as fuels, chemicals, building materials, yield boosting, solvent, and heat transfer fluid[25]. Other commercial uses of carbon dioxide include welding, medical use, food, and beverage. CO_2 can be used when converting hydrogen into a synthetic fuel. CO_2 can also replace fossil fuels when some chemicals are produced. It can be used to enhance oil recovery. The CO_2 is then injected into existing oil fields, this will make the oil thinner and collecting of oil becomes easier[25]. One advantage compared to carbon capture and storage is that the CO_2 dioxide can be sold. One disadvantage with carbon capture and utilisation is that CO_2 is a stable and relatively inert molecule which makes chemical reactions challenging[2].

3

Policies

A policy provides guidance for decisions and is applied to achieve certain goals. Not managing to follow a policy might lead to punishment but comparatively less severe penalties for non-compliance with the law. Policies for carbon capture can be regulated with a price for emitting carbon, credits for capturing biogenic emissions, a carbon budget, an emission trading system and carbon contracts for difference.

3.1 Carbon Pricing

Carbon pricing is a strategy for reducing climate change by having the responsible emitters pay for the carbon emitted. Carbon pricing ensures that climate risks are included in the cost of doing business. The responsible emitters are given an opportunity to either reduce emissions by transforming their activities and not have to pay the carbon tax or continue to emit CO_2 but pay for the emissions[56]. The revenue from the carbon pricing can be used to help communities in vulnerable areas adapt to the effects of climate change[56]. The revenues can also be used for research and development into green technology and the transition to a low-carbon economy. Carbon pricing is a low-cost and effective method[56] and an advantage of CO_2 pricing is that it tries to change people's behaviour. It is beneficial for companies that use renewable technology and processes with low climate impact. Unfortunately, it is uncertain to predict the environmental performance of carbon dioxide pricing. There may be many who choose to emit CO_2 rather than change their processes, especially if the price is low. Some experts suggest carbon pricing should be combined with complementary energy and environment policies in order to exploit the full potential of carbon pricing[56].

3.2 BECCS Credits

Biomass energy with carbon capture and storage offers added value compared to avoiding emissions. This is one of the few options for reducing the levels of carbon in the atmosphere. Other options are afforestation, reforestation, ocean fertilization and direct air capture. BECCS credits are the carbon that counts as negative emissions as the carbon has been captured from the atmosphere and before they are released again it is captured and stored. The efficiency of the separation process, the transport and the global carbon cycle feedback leads to those credits of negative emissions being reduced compared to how much carbon is combusted[52].

3.3 Emission Budget

Emission budgets for GHG are set to limit global warming. Countries or companies are not allowed to emit more CO_2 than the cap specified in the emission budget. The emitters can choose when the CO_2 is emitted, but the total emissions must not exceed the budget. The budgets are usually in line with scenarios for limiting global warming to 1.5 or 2°C above pre-industrial levels. The European Union and Sweden both have emission targets for 2030 to reduce the emission to 55% and 85% of the emissions in 1990, respectively[11],[31]. There are also zero emission targets by 2050 and 2045, respectively. This system provides clarity about the environmental impact of the emissions because it is known in advance how much emissions will be allowed.

3.4 Emission Trading System

In an emission trading system there is a budget for how much may be emitted and the activities included in the system must have emission allowances that correspond to their carbon emissions. The emission allowances are partly distributed free of charge, partly auctioned. The motivation behind the free allowances is to counteract the risk of carbon leakage. Some facilities are given free allowances, but most buy them on the market.

Each company must at the end of each year hand in enough allowances to cover all emissions. During the year those who have less allowances can either reduce their emissions or buy more emission allowances. Too many allowances enables the owner to either save the spare allowances for the future or sell them to a company which is short of allowances. The facilities included in an ETS do not pay carbon tax but pay for the emission allowances. The system is designed to decrease the emission cap (i.e., the amount of total allowances in the system) each year and enable companies to slowly adapt to more ambitious emission targets. This method offers flexibility for companies since the actors can decide whether they want to buy allowances or take action and reduce emissions. In industries where the allowance price is higher than reduction costs, companies are encouraged to take action. For emitters who have higher reduction costs, the actions are postponed.

The price for emission allowances is decided by the market and affected by how many allowances are available in the system. Excess allowances leads to low prices which in turn may lead to participants in an emission trading system not taking measures to reduce emissions. This has been the case in the EU Emissions Trading Scheme (EU ETS). To provide price stability the Market Stability Reserve (MSR) was introduced in 2019[12]. The MSR enables the availability of emission allowances to respond to changes in demand. The aim of the reserve is to provide a long-term solution to the growing surplus of emission allowances and thus maintain the balance in the system[**?**]. Between 2019 and 2023, the percentage of allowances in circulation invested in the reserve is planned to go from 12% to 24% in the European Union. After 2024, the share that will be placed in the reserve will return to 12%[9]. From 2023, the emission allowances in the reserve that exceed the previous year's auction amount will no longer be legitimate[12].

This system is used within the European Union and is one of the main strategies for reducing emissions within the union[**?**]. It was implemented in 2005 to ensure that the emission target GHG would be achieved in a cost-effective manner. The total reduction in the emission cap was 21 percent in the years between 2005 and 2020[3],[6]. Of Sweden's national fossil emissions, the facilities included in the EU-ETS account for 37 percent. It is primarily industry and energy production that are included in the system. The carbon price in Sweden is higher than the allowances in the EU-ETS. The emission allowances cost were only about 50-60€ in 2020, but in the year or 2022 were the cost between 80 and 100€, compared with the Swedish carbon dioxide tax of 115 euro per ton[53],[50]. In order to cut GHG emissions by at least 40% in 2030 compared to the levels in 1990 the allowances need to keep the reduction rate[10]. The annual reduction rate in the period of 2013-2020 was 1.74% and from 2021 onwards is the annual rate 2.2% in order to meet the goal for 2030[12]. In 2021 the European Commission published a proposal to amend the Emission Trading System Directive. The new proposed reduction factor is 4.2[8]. Most of the reduction is done by investing in more efficient technology and reducing the production. The CCS system is still a long way from being the solution in Europe. According to an analysis made by the International Energy Agency (IEA) the development of carbon capture will be slow in the beginning and most emission reduction will be an effect of changes to renewables in the electricity generation and improvement of technology performance[1].

3.5 Carbon Contract for Difference

One way to minimize the carbon price uncertainty is Carbon Contracts for Difference (CCFD)[16]. An agent (e.g., an industrial plant owner) and a government agree on a fixed carbon price, the strike price, over a period. The difference between the market price and the strike price will be paid by either the government or the agent depending on whether the market price is lower or higher than the strike price. According to Gerres Linares[16], carbon contracts for difference are the most powerful option for reducing uncertainty about carbon prices. The regulatory risk can be reduced with perfect forecasts on reduction goals, but this does not reduce other risks, which are not controlled by national policies, according to the two authors. The authors argue that the regulatory uncertainty is not necessarily reduced if there are caps and floors on the carbon price, like those implemented by the EU ETS Market Stability Reserve, but the variability in carbon prices is only short-term[16].

4

Methods

The theoretical basis of this work is based on a literature study, using industrial databases, techno-economic evaluations and other literature containing information about policies. This information was used to construct policy scenarios which were evaluated in the optimization model.

4.1 Mathematical model

The Mixed Integer Program (MIP) optimization model used in this work finds the cheapest option for collecting CO_2 from the industrial sites included in the system. The reference GAMS simulations were made by Sebastian Karlsson[30]. Considers both investment cost and operating cost. An overview of the model and the parts of the CCS chain can be seen in Figure 4.1. The carbon is captured from stack type j∈J and then liquefied at liquefaction facility k∈K both these are located at a site i∈I. Each site is limited to one liquefaction facility but there can be more than one stack at each site where CO_2 can be captured. CO_2 is transported to a transport hub l∈L by truck and transported by ship from the transport hub to the final storage. The number of sites and stacks available for the CCS system is constant during the modelled period.

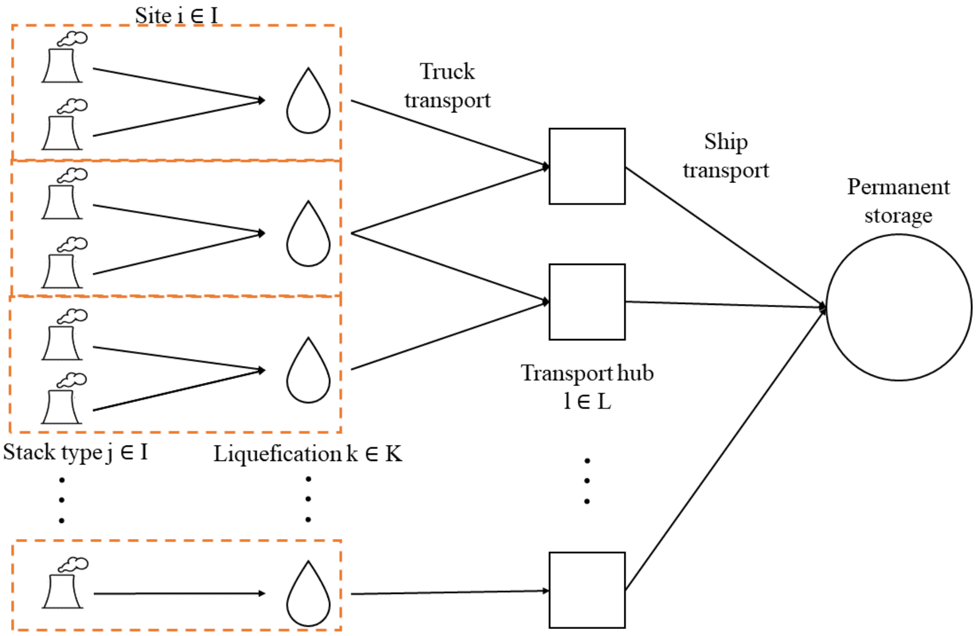

Figure 4.1: Simplified overview of the model in a flowchart. The dashed line surrounds the parts of the system that take place at site i∈I.

The objective function, Equation 4.1, is to minimise the net present value of the total cost for the studied period

$$min\ c_{tot} \geq \sum_{y \in Y} \frac{c_y^{annual}}{(1+r)^{y-2020}} \tag{4.1}$$

c_{tot} is the net present value, y is the years studied, r is the interest rate, r this is 5% and c_y^{annual} is the total annual cost. The annual cost is calculated by adding the annual investment and operation cost for all sites, liquefaction plants, transportation, and storage.

$$\begin{aligned} c_y^{annual} \geq & \sum_{i \in I}(c_{i,y}^{CAPEX,capture} + c_{i,y}^{OPEX,capture}) \\ & + \sum_{k \in K_i} (c_{j,y}^{CAPEX,liq} + c_{k,y}^{OPEX,liq} + c_{k,y}^{CAPEX,storage,liq} + c_{k,y}^{OPEX,storage,liq}) \\ & + \sum_{k \in K_i} \sum_{l \in L}(c_{k,l,y}^{CAPEX,truck} + c_{k,l,y}^{OPEX,truck}) + \sum_{l \in L}(c_{l,y}^{CAPEX,hub} + c_{l,y}^{OPEX,storage,hub}) \\ & + \sum_{l \in L}(c_{l,y}^{CAPEX,ship} + c_{l,y}^{OPEX,ship}) + \sum_{et \in ET} c_{et,y}^{emission} \quad \forall\ y \in Y \end{aligned} \tag{4.2}$$

Where c_y^{CAPEX} and c_y^{OPEX} is the annual investment and operation cost for each part of the CCS chain. The equation for each part is displayed in Appendix A.2. The investment cost is calculated with an annuity factor. The annuity factor method shows the profitability of an investment in terms of the lifetime of the technology.

$$\alpha = \frac{r}{(1-(1+r)^{(-LT)})} \tag{4.3}$$

Where r is the interest rate and LT is the lifetime of the equipment.

4.1.1 Sensitivity analysis

Sensitivity analysis was done in order to see how stable the result was. The first check was how the interest rate changed the result. This was done by changing the parameter r in the total cost and annuity factor equation 4.1 and 4.3.

The second sensitivity analysis was to check the growth rate of the system, meaning the annual size of investments in capture and liquefaction equipment is limited according to Equation 4.5.

$$b_{i,j,y}^{capture} = b_{i,j,(y-1)}^{capture} - a_{i,j,(y-LT)}^{capture} + a_{i,j,y}^{capture} \quad \forall\ i \in I,\ j \in J,\ y \in Y \tag{4.4}$$

$$\sum_{i \in I} \sum_{j \in J} a_{i,j,y}^{capture} \geq \sum_{i \in I} \sum_{j \in J} b_{i,j,(y-1)}^{capture} + g_y^{capture} \quad \forall\ i \in I,\ j \in J,\ y \in Y \tag{4.5}$$

Where $a_{i,j,y}^{capture}$ is the investment in capture capacity at stack j at site i and $b_{i,j,y}^{capture}$ is the installed capacity at stack type j at site i. $g_y^{capture}$ is the maximum allowed investment in year y.

The impact of transport investment cost on the development of the CCS system was investigated by changing Equation 4.6 in the model. By dividing the investment cost calculations for each hub could the investment cost for each hub easily be changed, see Equation 4.7-4.11. When all hubs have zero investment costs can this easily be done by setting $CAPEX^{ship}$ as zero in Equation 4.6.

$$c_{l,y}^{CAPEX,ship} \geq b_{l,y}^{ship} \cdot CAPEX^{ship} \cdot \alpha \quad \forall\ l \in L,\ y \in Y \tag{4.6}$$

When only one or a few hubs have free investment cost for transportation by sea were the investment cost for respective transport hubs set to zero.

$$c_{l,Ostrand,y}^{CAPEX,ship} \geq b_{l,Ostrand,y}^{ship} \cdot CAPEX^{ship} \cdot \alpha \ \ \forall \, l \in L, \ y \in Y \tag{4.7}$$

$$c_{l,Oxelsund,y}^{CAPEX,ship} \geq b_{l,Oxelsund,y}^{ship} \cdot CAPEX^{ship} \cdot \alpha \ \ \forall \, l \in L, \ y \in Y \tag{4.8}$$

$$c_{l,Lysekil,y}^{CAPEX,ship} \geq b_{l,Lysekil,y}^{ship} \cdot CAPEX^{ship} \cdot \alpha \ \ \forall \, l \in L, \ y \in Y \tag{4.9}$$

$$\vdots \tag{4.10}$$

$$c_{l,Skelleftea,y}^{CAPEX,ship} \geq b_{l,Skelleftea,y}^{ship} \cdot CAPEX^{ship} \cdot \alpha \ \ \forall \, l \in L, \ y \in Y \tag{4.11}$$

4.1.2 Equations for policies

In carbon pricing is the cost for emitting CO_2 was calculated with Equation 4.13.

$$e_{et,y}^{annual} \geq \sum_{i \in I} e_{i,et}^{CO_2} - e_{et,y}^{capture} \ \ \forall \, et \in ET, \ y \in Y \tag{4.12}$$

$$c_{et,y}^{emission} \geq e_{et,y}^{annual} \cdot c_{et,y}^{CO_2} \ \ \forall \, et \in ET, \ y \in Y \tag{4.13}$$

Where $e_{et,y}^{annual}$ is the annual emissions of $et \in ET$ given in tonCO_2, $e_{i,et}^{CO_2}$ is all emissions from site i of emission type et each year, $e_{et,y}^{capture}$ is the amount of CO_2 of respective emission type that has been captured in year y, $c_{et,y}^{emission}$ is the annual emission cost for respective emission type and $c_{et,y}^{CO_2}$ is the cost for emitting CO_2 in M€/tonCO_2 of respective emission type each year.

For BECCS credits, emitting fossil CO_2 results in a carbon tax, but capturing biogenic emissions counts as negative emissions and the companies capturing biogenic emissions were compromised with money. This was implemented by changing the equation for calculating the emission, Equation A.16 in Appedix A.3, for the biogenic emissions. For the annual biogenic emissions only the captured CO_2 accounted for, this because the emitted biogenic CO_2 is assumed to be net zero, see Equation 4.14.

$$e_{bio,y}^{em,annual} \geq -e_{bio,y}^{capture} \ \ \forall \, y \in Y \tag{4.14}$$

Where $e_{bio,y}^{capture}$ is the captured biogenic CO_2 of year y. The emission cost is calculated with equation 4.13 but $c_{bio,y}^{emission}$ will be equal to zero or negative.

A budget for the model period is implemented by using Equation 4.15. The budget was investigated but setting a budget for fossil and biogenic emissions separate, see equation 4.16.

$$e^{total} \geq e^{budget} \tag{4.15}$$

$$e_{et}^{total} \geq e_{et}^{budget} \tag{4.16}$$

Where e^{total} is the total emission and e_{et}^{total} is the total emissions during the period for emission type et. e^{budget} is the budget for the period and e_{et}^{budget} is the set budget emission type et.

The annual budget is implemented by setting a constraint on the annual emissions, e_{y}^{annual}

and like the total emission budget is the annual emission budget divided in emission type when there is a separate budget for respective emission type, $e_{et,y}^{annual}$.

$$s_{et,y}^{sum} = \sum_{i\in I}\sum_{j\in J} s_{i,j}^{CO_2} \cdot m_j^{bio} \;\; \forall\, y \in Y,\; et = bio \tag{4.17}$$

$$s_{et,y}^{sum} = \sum_{i\in I}\sum_{j\in J} s_{i,j}^{CO_2} \cdot (1 - m_j^{bio}) \;\; \forall\, y \in Y,\; et = fossil \tag{4.18}$$

$$e^{annual} \geq \sum_{i\in I}\sum_{et\in ET} e_{i,et}^{CO_2} - \sum_{et\in ET} s_{et,y}^{sum} \cdot (y - 2019) \cdot z_{reduction} \tag{4.19}$$

$$e_{et,y}^{annual} \geq \sum_{i\in I} e_{i,et}^{CO_2} - s_{et,y}^{sum} \cdot (y - 2019) \cdot z_{reduction} \tag{4.20}$$

Where $s_{et,y}^{sum}$ is the sum of the supply of the available CO_2 for capture of emission type et year y, $s_{i,j}^{CO_2}$ is the supply of the available CO_2 for capture at site i and stack type j, m_j^{bio} is the share of biogenic emissions from stack type j. $e_{i,et}^{CO_2}$ is the total emissions emitted at site i and $z_{reduction}$ is the reduction rate for the budget.

The policy carbon contract for difference needs some changes in the equations. CCfD requires that the annual emission costs are different depending on which industry sector the sites are part of. Implementing CCfC was done by changing the equations for annual capture (equation A.13), annual emissions (equation A.16) and annual emission cost (equation 4.13) so that this is dependent on the site i, and not by only emission type and years. So, the amount of annual capture changed from $e_{et,y}^{capture}$ to $e_{i,et,y}^{capture}$ the same changes were done for the other two equations. The cost for emitting CO_2 is then calculated with a carbon price for each industry sector.

$$e_{i,et,y}^{capture} = \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} x_{i,j,k,y}^{1} \cdot m_j^{bio} \forall y \in Y and et = biogenic \tag{4.21}$$

$$e_{i,et,y}^{annual} \geq e_{i,et}^{CO_2} - e_{i,et,y}^{capture} \forall i \in I, et \in ET, y \in Y \tag{4.22}$$

$$c_{i,et,y}^{emission} \geq e_{i,et,y}^{annual} \cdot c_{i,et,y}^{CO_2} \forall i \in I, et \in ET, y \in Y \tag{4.23}$$

$$c_y^{annual} \geq \sum_{x\in X} c_{x,y}^{CAPEX} + \sum_{x\in X} c_{x,y}^{OPEX} + \sum_{i\in I}\sum_{et\in ET} c_{i,et,y}^{emission} \forall i \in I, et \in ET, y \in Y, x \in X \tag{4.24}$$

4.2 Input data

The data used in this study was collected from other case studies. The data for the industrial sites included in this study were gathered from case studies made by Svensson[51]. From these the location of the site and emissions from each site, as well as the distribution of emissions and CO_2 concentration from the different stacks were found. For the sites that lack information on the CO_2 concentration and distribution of emission between stacks, it was assumed to be the same as other sites in the same industrial sector. In Table 4.1 is the CO_2 concentration and the biogenic fraction for each stack type presented. For the pulp and paper sites and the heat and power sites with bio-based fuel is all the emission biogenic carbon. The cement industry has mostly fossil emissions but there are some biogenic emissions. In the heat and power plants with waste as fuel, two thirds of the waste that is burned is assumed to be non-fossil products[46]. This master's thesis will only cover the largest industrial sites in Sweden, with 100 kilotons of emissions per year and the reference system is the Swedish industry in 2019. It is assumed that the production from the sites is unchanged during the period and therefore the emission from the stacks is constant each year and the emissions will only be reduced if CCS were implemented at the stacks. The industrial sites included in this study are all part of the emission trading system in 2020[43], even the biogenic emission sites. The period studied is 2020 to 2045.

Table 4.1: CO_2 concentration and share of biogenic emission from the stacks included in the carbon capture system

Sector	Stack	CO_2 concentration [%]	Percent biogenic emissions [%]
Pulp and paper	Recovery Boiler	13	100
Pulp and paper	Lime Kiln	20	100
Pulp and paper	Other stacks	13	100
Cement	Combine stack	20	10
Refinery	Hydrogen production unit	24	0
Refinery	Other stacks	13	0
Iron and steel	Power plant	30	0
Iron and steel	Other stacks	20	0
Chemicals	Cracker furnace	5	0
Heat and power	Waste	13	65
Heat and power	Bio-based	13	100
Heat and power	Fossil-based	13	0

The lifetime for trucks is assumed to be 10 years and for the rest of the equipment is the lifetime 25 years. The sites are mostly located in the south of Sweden but there are some facilities on the east coast in northern Sweden, see Figure 4.2. In the figure are the sites categorised by which industry they are a part of. The amount of emission from all the sites is shown in table 4.2, here is both the total emissions and the emissions from the stacks J presented.

Table 4.2: Emissions from system without carbon capture

Emissions		One year [tonCO_2/year]	26 years [tonCO_2]
Availible for capture	Bio	31 358 891	815 331 169
	Fossil	9 288 151	241 491 918
All emissions from sites	Bio	34 529 589	897 769 314
	Fossil	12 895 674	335 287 524

The distance from the hubs to the Norwegian permanent storage were assumed and the values used in the model can be found in table 4.3. The distance between the site and the hubs were measured in a GIS-software, these distances are presented in Appendix A.4.

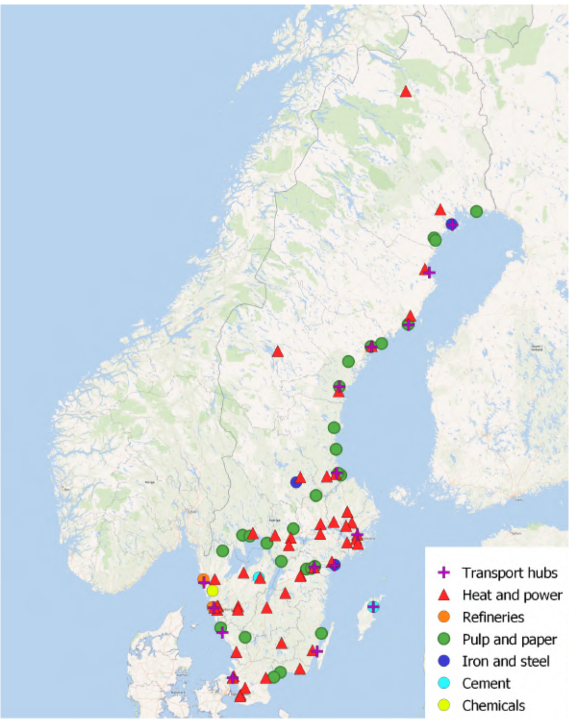

Figure 4.2: Map with sites included in the model

Table 4.3: Distance from the hubs to the permanent storage

Hub	Distance to storage [km]	Hub	Distance to storage [km]
Östrand	2 200	Varberg	840
Oxelösund	1 650	Kalmar	1 350
Lysekil	685	Gävle	2 040
Göteborg	770	Norrköping	1 650
Helsingborg	960	Örnsköldsvik	2 350
Stockholm	1 850	Umeå	2 450
Luleå	2 700	Skellefteå	2 580
Slite	1 520		

The investment cost for the capture and liquefaction equipment was calculated using the equation below. These calculations are based on the work by Eliasson[7]. The investment cost is dependent on the CO_2 massflow and the value of two variables, these changes depending on the CO_2 concentration. The variables for the closest concentration are used.

$$CAPEX^A = \alpha \cdot 10000 \cdot \dot{m}_{CO_2}^{\beta} \ [k€] \tag{4.25}$$

Where $\dot{m}_{CO_2}$ is the mass flow of the captured CO_2 out from the stacks. The values for α and β are chosen depending on the CO_2 share in the flue gas, see Table 4.4.

Table 4.4: Variables for absolute investment cost

Share CO_2	α	β
9%	1.174	0.6017
13%	1.552	0.6339
25%	1.183	0.6326

The specific investment cost was then calculated using the following equation.

$$CAPEX^{S} = \frac{CAPEX^{A}}{\eta^{capture} \cdot \dot{m}_{CO_2}^{stack}} \quad [M€/tonCO_2] \tag{4.26}$$

Where $CAPEX^{A}$ is the absolute investment cost in M€, $\eta^{capture}$ is the capture rate which is assumed to be 90% in this model and $\dot{m}_{CO_2}^{stack}$ is the CO_2 supply from the stack in $tonCO_2$.

4.3 Policy scenarios

The scenarios investigated in this work are shown in Appendix A.5, based on the findings in the literature study. A more detailed explanation on the data used in each policy model can be found in 4.3.1 - 4.3.5.

4.3.1 Carbon pricing

The emission cost was tested for three scenarios, 0, 50 and 100 €/ton in 2020 and each year the cost was increased by 5 €/ton, see Table 4.5. In the first case Carbon pricing A, there were only one cost to emit fossil CO_2. In the second policy case, Carbon pricing B, there was an emission cost for both fossil and biogenic emissions. The emission cost followed the same increase as the previous scenarios but both the fossil and biogenic emissions need to be paid for, see Table 4.5.

Table 4.5: Emission cost, €/$tonCO_2$, each year for the three scenarios

Scenario	Emission Cost [€/ton]						
	2020	2021	2022	2023	...	2044	2045
1	0	5	10	15		120	125
2	50	55	60	65		170	175
3	100	105	110	115		220	225

4.3.2 BECCS credits

The first policy case, BECCS credits A, where the money gained for capturing one ton CO_2 is the same price as for emitting fossil emissions each year. The second policy case, BECCS credits B, is when two ton captured biogenic emissions compensate for the emissions of one tonne of fossil emissions.

Table 4.6: Emission cost for each year for BECCS credits

Case	Scenario	Emission Cost [€/ton]								
		2020		2021		...	2044		2045	
		Fossil	Bio	Fossil	Bio		Fossil	Bio	Fossil	Bio
A	1	0	0	5	5		120	120	125	125
	2	50	50	55	55		170	170	175	175
B	1	0	0	5	2.5		120	60	125	62.5
	2	50	25	55	27.2		170	85	175	87.5
	3	100	50	105	52.5		220	110	225	112.5

4.3.3 Emission budget

The first emission budget case, Emission budget A, considers a fossil emission budget for the entire modelled period. The total fossil emissions from all sites must be lower than 100, 125 and 150 Mton. The second emission budget model, Emission budget B, considers a total emission budget including both fossil and biogenic emissions. The system could either capture fossil or biogenic emissions or both. The size of the emission budget studied is 200, 300 and 400 $MtCO_2$. Emission budget C has a separate budget for biogenic and fossil carbon emissions. The three scenarios have a budget of 100, 150, 200 Mton for respective emission types.

4.3.4 Annual emission budget

Annual emission budget A, scenario 1, reduces the fossil emissions budget by 2.2% each year similar to the reduction of emission allowances in the EU ETS. Annual emission budget A, scenario 2, considers a reduction of the fossil emission budgets by 3.8% each year. By 2045 almost all emissions available to capture from the stacks will be captured. The EU ETS system does not only depend on CCS to reduce all the emissions and annual emission budget A, scenario 3, would be a more reasonable scenario with a yearly reduction rate of 0.44%. The annual emission budget B, scenario 1 to 3 are with the same reduction rate as for annual emission budget A, but there is an annual budget on the total emissions. Annual emission budget C have the same reduction rates but here have fossil and biogenic emissions separate budget.

4.3.5 Carbon Contract for Difference

This policy is modelled with 2 different prices decided in the contract for the cement industry. All other fossil emissions follow the emission cost of 50 €/ton in 2020 and an increase with 5 €/ton each year, see table 4.7.

Table 4.7: Emission cost, €/$tonCO_2$, for the cement industry and for each year for the two scenarios

Scenarios	Cement emission cost [€/ton]	Emission cost [€/ton]						
		2020	2021	2022	2023		2044	2045
1	80	50	55	60	65	. . .	170	175
2	90	50	55	60	65		170	175

4.4 Sensitivity Analysis

The sensitivity to interest rate was performed with an emission cost of 50 €/$tonCO_2$ in 2020 with an annual increase of 5€/$tonCO_2$. The interest rates investigated are presented in Tabel 4.8.

Table 4.8: Interest rate used in the 5 models

Test	Interest rate
1	1%
2	3%
3	5%
4	7%
5	9%

The sensitivity case on the growth rate of the system, were done for carbon pricing

A with scenario 2, see Table 4.9. The cases were simulated with different amounts of maximum annual installing capacity.

Table 4.9: The maximum allowed investment and the emission cost, €/tonCO_2, each year for the three scenarios and reference scenario

Scenario	Max investment per year [ton]	Emission Cost, €/ton								
		2020		2021			2044		2045	
		Fossil	Bio	Fossil	Bio		Fossil	Bio	Fossil	Bio
1	5 000	50	0	55	0	…	170	0	175	0
2	50 000	50	0	55	0		170	0	175	0
3	500 000	50	0	55	0		170	0	175	0
Ref	unlimited	50	0	55	0		170	0	175	0

The sensitivity analysis of the effect of the investment cost for transportation was done with four tests, the investment cost for ship transportation was set to zero according to Table 4.10. All tests had an emission cost of 50€/tonCO_2 in 2020, like carbon pricing A scenario 2, see Table 4.5.

Table 4.10: Where the investment for ships is free and the emission cost, €/tonCO_2, each year for the four scenarios and reference scenario

Test	Free ship investment cost	Emission Cost [€/ton]					
		2020	2021	2022		2044	2045
1	Lulea	50	55	60		170	175
2	Lulea and Slite	50	55	60		170	175
3	Lulea and Gothenburg	50	55	60	…	170	175
4	All hubs	50	55	60		170	175
Ref	No free investment cost	50	55	60		170	175

5

Results and Discussion

This section presents and discusses the results from the modelling performed in this work. System cost is defined as the investment and operation cost for all parts of the CCS-system. The model minimise the net present value of the system cost.

The lowest average investment cost is at the cement and chemical sites, followed by pulp and paper, and iron and steel. The highest average investment cost is at the heat and power sites. The average investment cost is almost over 7 times higher than the cement sites, but the fossil heat and power sites do not have as high investment cost as the other heat and power sites, this is more than half of the other heat and power sites. The investment cost will be divided and paid over the 25 years of the equipment's lifetime.

Table 5.1: The average investment cost for the stacks in each industry sector

Sector	Average investment cost [€/tonCO_2]
Cement	126
Chemical	197
Pulp and paper	380
Iron and steel	382
Refineries	474
Heat and power	945

5.1 Carbon Pricing A

The annual system costs for the three scenarios are presented in Figure 5.1. Scenario 2 starts to capture carbon in the year of 2027 when the fossil emission price is 85 €/ton. In scenario 1 the price is 80 €/ton 2036 when the system starts collecting carbon dioxide. This is because the optimization model finds the lowest net present value in 2020. In 2036 the investing cost is considered to be lower in 2020 than investing in the same amount in 2027. Scenarios 1 and 2 follows a similar trend when the fossil emission price is over 85 €/ton. The same investments are done in scenario 2 in the years between 2027 and 2031 as for the years 2037 to 2041 in scenario 1.

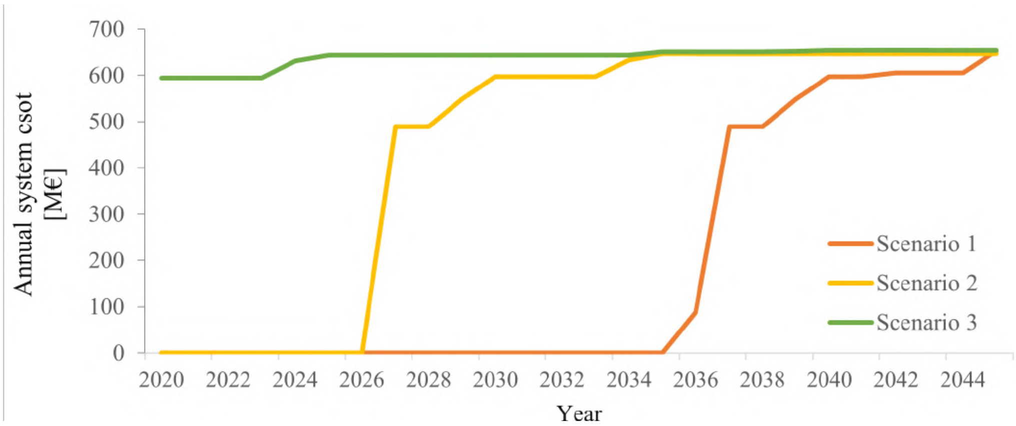

Figure 5.1: System cost when fossil emission cost for the period 2020-2045 are 0-125, 50-175 and 100-225 €/ton

The captured emissions each year in Carbon pricing A scenario 1-3 over the period are presented in Figure 5.2. The emissions are captured from five of the six sectors. After the year of 2034 is the captured amount almost the same for scenario 2 as for scenario 3. The emission cost is 125 €/ton in scenario 2 in 2035. This means that perfect foresight has a big effect on the result because other wise would not scenario 2 and 3, with a 50€/tonCO$_2$ difference, have the same annual capture amount after 2034.

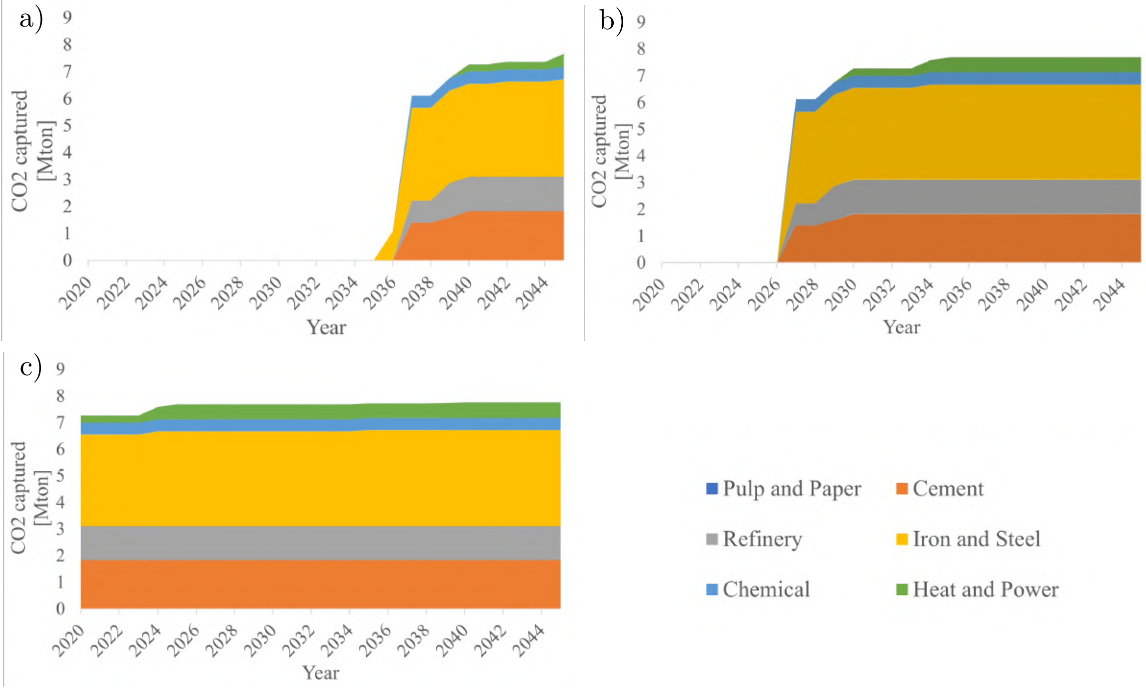

Figure 5.2: Captured emissions when the fossil emission cost for the period 2020-2045 are a) Scenario 1 0-125, b) Scenario 2 50-175 and c) Scenario 3 100-225 €/ton

The total emissions, total system cost and specific system cost is presented in Table 5.2 for scenario 1, 2 and 3. The amount of captured biogenic emissions is low for all three cases. The biggest difference between the Carbon pricing A scenarios is the amount of captured fossil emissions. The higher the capture amount the higher will the specific system cost be. This is because the sites with low cost will be included in the system when the carbon price is low but with a higher carbon price the system will be bigger and stacks with higher cost will also be included in the carbon capture system. The cost for each captured ton CO_2 will therefore be higher for scenario 2 and 3 compared to scenario 1. The sites captured from in scenario 1 are also captured from in scenario 2. The same transportation hubs are also used, see Figure 5.3. Scenario 3 has the same hubs and sites included but there is one additional heat and power site in Gothenburg where carbon is being captured from starting in 2040.

Table 5.2: Total emissions and total system costs for Scenarios 1, 2 and 3 over the entire modelled period.

Scenario	Total fossil emissions [MtonCO_2]	Total biogenic emissions [MtonCO_2]	Total system cost [M€]	Specific system cost [€$_{2020}$/tonCO_2]
1	272	896	5 280	70.5
2	198	894	11 657	72.5
3	141	893	16 623	74.8

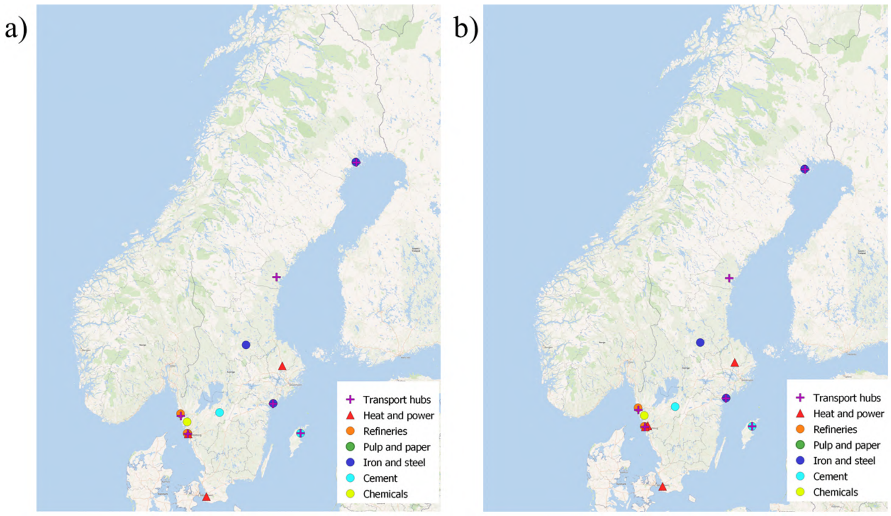

Figure 5.3: Location of the transportation hubs used and sites captured from in a) scenario 1 and 2, and b) scenario 3 with one more heat and power plant in Gothenburg

5.2 Carbon Pricing B

Adding a cost for emitting biogenic CO_2 results in an increase of invested carbon capture technology in the pulp and paper industry and heat and power industry. The captured emissions each year over the period presented in Figure 5.4 for the three scenarios. In scenario 1 is the cement industry included in the system 2035 and the following year is one pulp and paper site investing in carbon capture technology. The fossil emission cost affects the system at first but the second year there are more biogenic emissions captured. This is because both cement and pulp and paper have low investment cost for capture equipment and the pulp and paper site only have biogenic emissions, and at cement sites the biogenic fraction is 10%. 2037 is half of the emissions captured from the pulp and paper industry and in 2039 heat and power have the second highest amount of carbon captured. The reason for this is because the emissions from pulp and paper, and heat and power are much higher than the emissions from other sectors and the emission cost will therefore be much higher for these sectors when there is both an emission price on all emissions.

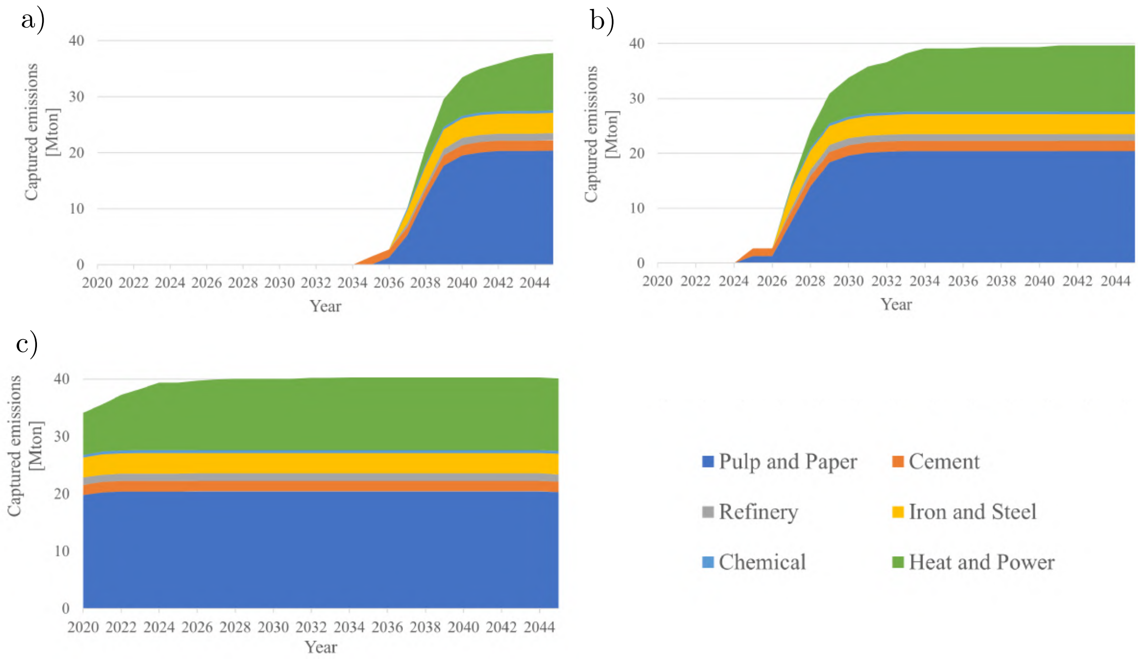

Figure 5.4: Captured emissions when the emission cost for the period 2020-2045 are a) scenario 1, 0-125, b) scenario 2, 50-175 and c) scenario 3, 100-225 €/ton

Table 5.3: Total emissions, system costs and specific cost for Scenarios 1, 2 and 3 over the entire modelled period.

Scenario	Total fossil emissions [MtonCO_2]	Total biogenic emissions [MtonCO_2]	Total system cost [M€]	Specific system cost [€2020/tonCO_2]
1	262	690	24 305	74.2
2	166	375	61 146	77.0
3	97	109	92 492	80.4

In scenario 3 is carbon dioxide captured from all sites but there are four transportation hubs that are not used: Oxelosund, Varberg, Umeå and Skellefteå. These hubs are not used in scenario 1 either. In scenario 2 however, is the transport hub in Varberg used. There is some other difference between the usage of the hubs. The number of ships invested in 2045 in their hubs are presented in Table 5.4. For all scenarios there are seven ships in Lysekil. In scenario 2 is the amount of carbon transported to the Lysekil hub the same amount as for the other two scenarios. The big difference between scenario 2 and 3 is the changes of ships going from Gothenburg, Helsingborg and Varberg, see Table 5.5.

Table 5.4: The amount of invested ships for the hubs in Lysekil, Gothenburg, Helsingborg, Varberg and the total number of ships for the system for the three scenarios.

Scenario	Ships				
	Lysekil	Gothenburg	Helsingborg	Varberg	Total number of ships
1	7	5	5	0	109
2	7	4	5	2	114
3	7	7	6	0	114

Table 5.5: The hubs used to transport carbon for the sites where there are changes in transport hubs between the scenarios.

Scenario	Hubs used to transport carbon from sites						
	PP10	PP25	R2	HP14	HP18	HP25	HP47
1	Gothenburg Lysekil	Gothenburg Helsingborg	Gothenburg	Lysekil	Lysekil Norrkoping	Helsingborg	-
2	Gothenburg Varberg	Helsingborg Varberg	Gothenburg Lysekil	Gothenburg Lysekil	Gothenburg Lysekil	Helsingborg Varberg	Lysekil
3	Gothenburg	Gothenburg Helsingborg	Gothenburg	Gothenburg	Gothenburg	Helsingborg	Gothenburg Lysekil

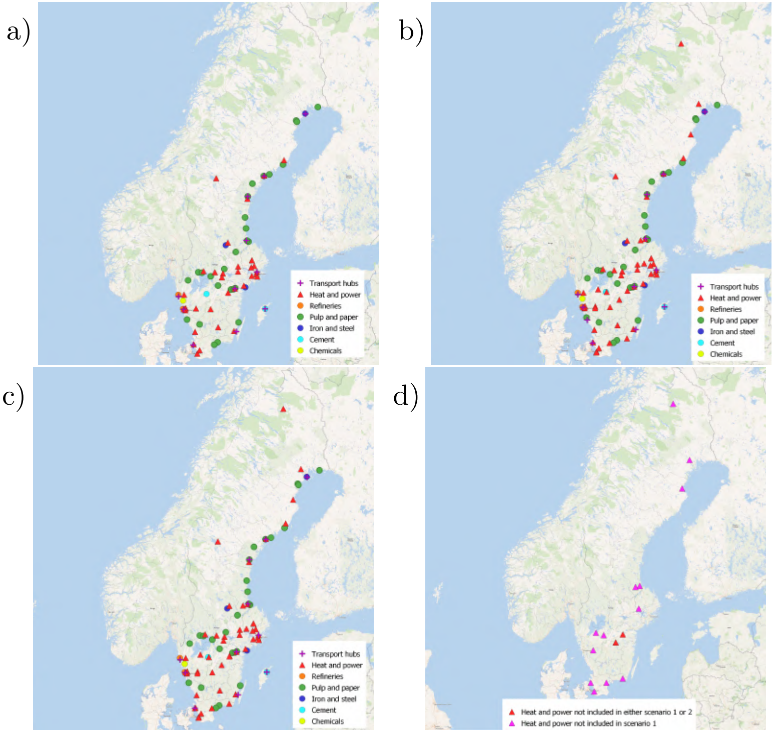

Figure 5.5: Location of the transportation hubs used and sites captured from in. a) scenario 1 and 2. b) scenario 3. Figure d) shows the location of the heat and power plants not included in scenario 1 and 2.

5.3 BECCS credit

The results from the BECCS credit A, scenario 1 and 2, are presented in Table 5.6 together with the result of BECCS credit B. The captured emissions are very similar to the policy carbon pricing when there is the same emission cost for biogenic and fossil emission, carbon pricing B. The two scenarios 2 had no difference in fossil carbon emissions and only a difference of 5 MtonCO_2 during the whole period. The specific cost for scenarios 1 and 2 in carbon pricing B is a little bit lower compared to the specific system cost in this policy case, because there are lower emissions than these results. The case BECCS credits B had a lower system cost, however the biogenic emissions was higher.

Table 5.6: Total emissions and system costs for policy BECCS credits A and B over the entire modelled period.

Case	Scenario	Total fossil emissions [MtonCO_2]	Total biogenic emissions [MtonCO_2]	Total system cost [M€]	Specific system cost [€$_{2020}$/tonCO_2]
A	1	259	676	25 860	74.4
	2	166	370	61 708	77.2
B	1	271	895	5 470	70.0
	2	187	843	17 051	72.5
	3	114	584	46 167	75.5

In scenario 1 when the carbon price is low is carbon capture only invested at site which emits fossil emissions or both fossil and biogenic emissions, see Table 5.7. It is only when the carbon price increases that it is profitable to invest in carbon capture techniques in the pulp and paper industry and heat and power plants with biogenic fuel.

Table 5.7: The amount of emissions and share of the captured carbon from site with only fossil emission, biogenic emissions, or both for case BECCS credits A

Scenario	Capture at sites with both biogenic and fossil emissions		Capture at sites with fossil emissions		Capture at sites with biogenic emissions	
	[MtonCO_2]	[%]	[MtonCO_2]	[%]	[MtonCO_2]	[%]
1	18.7	27.9	48.4	72.1	0	0.0
2	68.7	33.7	105.0	51.5	30.2	14.8
3	128.2	24.0	151.0	28.2	255.6	47.8

5.4 Emission budget

The emissions, system cost and specific system cost for Emission budget A-C is presented in Table 5.8. Comparing emission budget B and C more fossil emission are captured if the system can choose if capturing biogenic or fossil emissions, like in emission budget B.

Table 5.8: Total emissions, system costs and specific system cost for emission budget A, B and C scenarios 1, 2 and 3 over the entire modelled period.

Case	Scenario	Total fossil emissions [MtonCO_2]	Total biogenic emissions [MtonCO_2]	Total system cost [M€]	Specific system cost [$€_{2020}$/tonCO_2]
A	1	100	821	28 107	80.1
	2	125	866	20 979	77.1
	3	150	890	16 207	74.4
B	1	96	104	94 006	81.3
	2	111	189	83 680	79.4
	3	134	266	74 357	78.4
C	1	100	100	93 456	80.8
	2	150	150	84 265	80.1
	3	200	200	75 192	79.5

For Emission budget (EB) A the capture is mostly done at sites with only fossil emission and cement industry (90% fossil emissions), however there are some biogenic emissions captured from waste heat and power plants as well, see Figure 5.6.

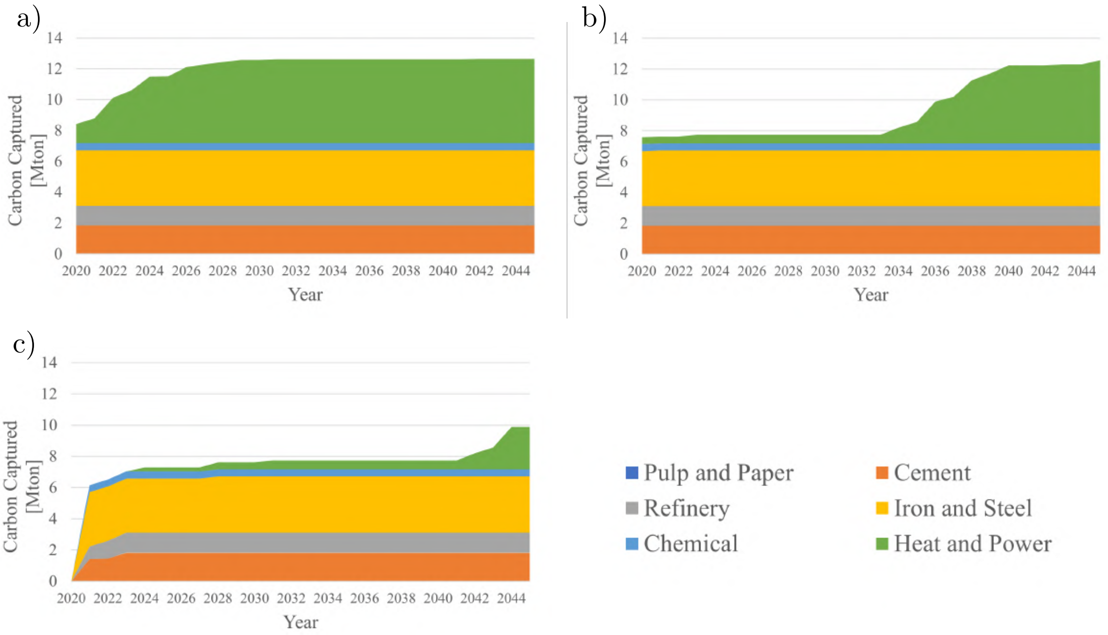

Figure 5.6: Captured emissions for Emission Budget A a) scenario 1, b) scenario 2 and c) scenario 3.

The capture from waste heat and power plants is higher in EB A scenario 1 and 2 compared to EB A scenario 3. In EB B there are more biogenic emissions captured. Of the total biogenic emissions is 88% of the emissions captured in scenario 1 and 78% of the fossil emissions is captured. When the system can choose fossil or biogenic emissions, Emission budget B, is more cost efficient compared when the budget is divided for the emission types. In emission budget B scenario 3 is 33.5% of the emissions from fossil based carbon and 66.5% are from biogenic carbon but there is much more biogenic emissions captured compared to fossil emissions, see Figure 5.6. Of the total fossil emissions is 40% captured and for the biogenic is 30% captured in emission budget B scenario 3, so despite capturing more biogenic emissions is there a lower share of the emissions captured.

5.5 Annual emission budget

In annual emission budget (AEB) A and C the capture of fossil emissions is the same because in AEB C is the fossil budget the same as for AEB A, see Table 5.9. This means that all additional biogenic carbon capture when there is an annual budget on the biogenic emissions is captured from pulp and paper industry and heat and power plants with biogenic fuel.

Table 5.9: Total emissions, system cost and specific cost for annual emission budget A, B and C Scenarios 1, 2 and 3 over the entire modelled period.

Case	Scenario	Total fossil emissions [tonCO_2]	Total biogenic emissions [tonCO_2]	Total system cost [M€]	Specific system cost [$€_{2020}$/tonCO_2]
A	1	264	898	5 976	72.8
	2	211	887	11 418	74.0
	3	321	898	1 304	79.8
B	1	205	715	25 813	71.9
	2	170	521	46 174	74.4
	3	305	865	4 928	68.6
C	1	264	656	25 955	72.3
	2	211	480	46 539	75.0
	3	321	849	5 056	70.5

The amount of carbon capture in each sector in scenario 1 for all three types of annual emission budget cases is presented in Figure 5.7.

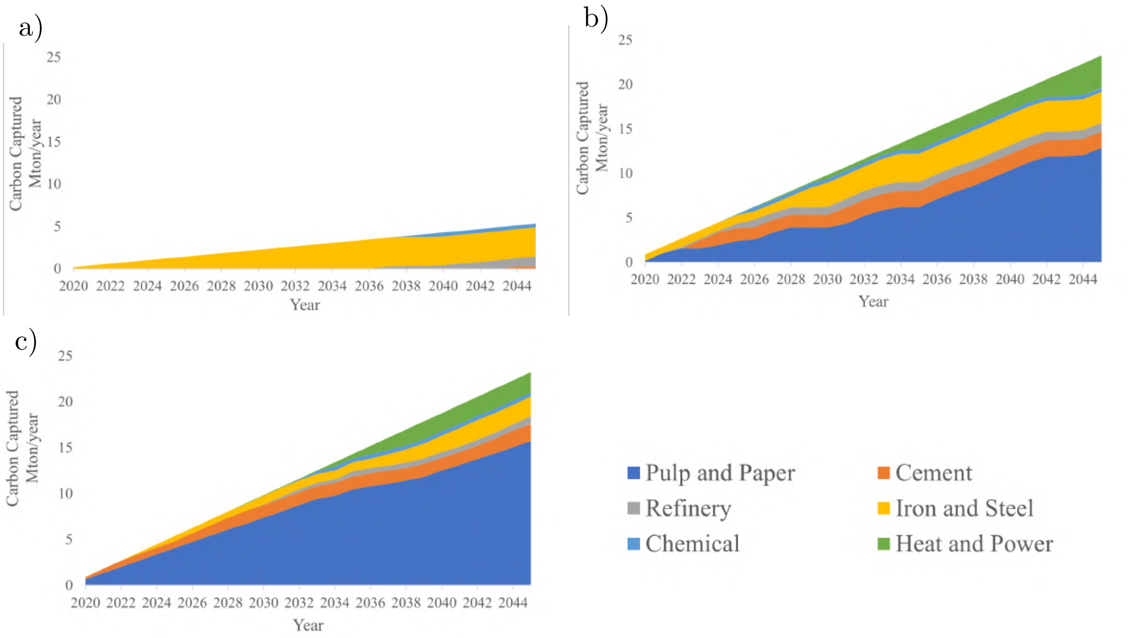

Figure 5.7: Captured emissions for a) Annual emission Budget A scenario 1, b) Annual emission Budget B scenario 1 and c) Annual emission Budget C scenario 1.

An interesting observation is that the specific system cost in scenario 1 is higher for AEB A compared to AEB C in the same scenario, but the AEB A has a lower specific system cost in scenario 2. This is because the capture of biogenic emission is lower for some parts of the sites, but when almost everything needs to be captured there are a couple of small sites that have to be included in the system and the cost for capture at these is higher compared to the large iron and steel facilities.

When comparing Annual emission budget B and C both the total system cost and specific system cost are lower when the system can choose how much emissions of the respective emission type is captured. In AEB B the amount of fossil emission captured is higher for all three scenarios compared to AEB C.

5.6 Carbon Contract for Difference

In scenario 1 when the carbon price for cement was 80 €/ton no CO_2 from the cement industry was captured, no biogenic emissions were captured either. In scenario 2 the only biogenic emission captured came from the cement site at Gotland, and this was low because the share of biogenic emission is only 10%. There is perfect foresight in the modelling and therefore is it easy to know when to invest and not. The tricky part of this policy is that it is not known how high the emission cost will be in the future. The contract is written with some prediction on how the future carbon pricing will be but the exact number is unknown.

Table 5.10: Total emissions, system cost and specific cost for carbon contract scenarios 1 and 2 over the entire modelled period.

Scenario	Total fossil emissions [MtonCO_2]	Total biogenic emissions [MtonCO_2]	Total system cost [M€]	Specific system cost [€$_{2020}$/tonCO_2]
1	230	898	8 937	73.8
2	198	894	11 564	71.8

The total system cost is lower for scenario 1 when the carbon strike price is low enough for the system not to invest in carbon capture at Gotland, however is the specific system cost higher. This is because the specific cost of capturing carbon from the cement sites is low compared to most other sites. Looking at the specific cost would scenario 2 be the best option for the system but usually every company pays for their respective costs and for the companies in the cement industry, in Sweden Cementa, would scenario 1 be better.

The investment of carbon capture is made at the same sites in the two scenarios, the only difference is the cement facility on Gotland, see Figure 5.9. The carbon capture from the cement industry is also the largest difference in how much carbon that is captured at each site. The iron and steel industry in Luleå and chemical industry in Stenungsund has the same amount of carbon captured in both scenarios. The other seven sites were a total of 1 ton additional carbon captured in scenario 1, see Figure 5.8.

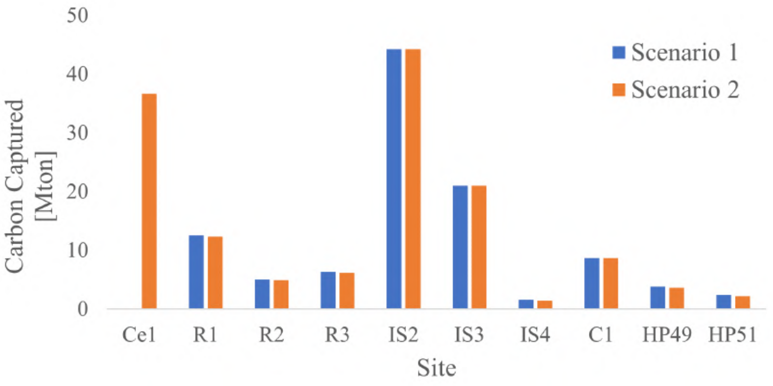

Figure 5.8: Amount of carbon captured at each site during the period for scenario 1 and 2.

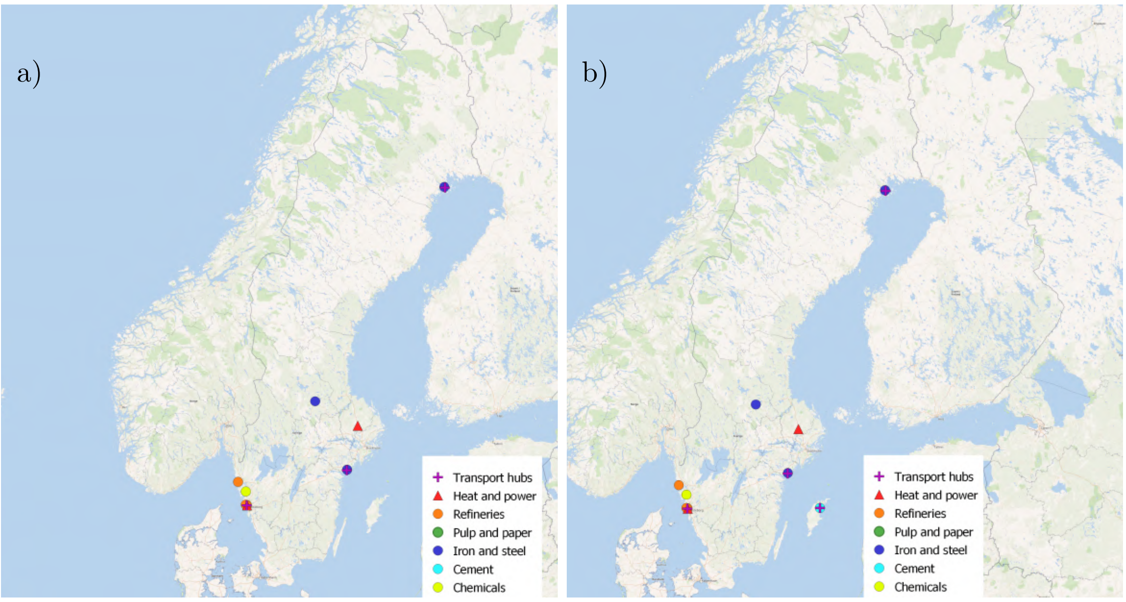

Figure 5.9: Location on the transportation hubs used and sites captured from. a) scenario 1 and b) scenario 2 with one additional hub and site on Gotland.

5.7 Sensitivity analysis

The result of the three sensitivity analysis is divided into three chapters.

5.7.1 Interest rate

The result of this analysis is presented in Table 5.11. The interest rate, looking at policy Carbon pricing A scenario 2, has a large effect on how much fossil emission is captured and also the cost. For this period it is unlikely for the system to have a 7% and 9% interest rate. Somewhere between 1% and 3% is more reasonable. In this system an interest rate of 5% used and change in interest rate will have effects on the results.

Table 5.11: Total emissions, system cost and specific cost for Scenarios 1-5 over the entire modelled period.

	Total fossil emissions [MtonCO_2]	Total biogenic emissions [MtonCO_2]	Total system cost [M€]	Specific system cost [$€_{2020}$/tonCO_2]
1%	185	894	11 481	74.7
3%	191	894	11 698	79.0
5%	198	894	11 656	83.1
7%	206	895	11 582	87.4
9%	213	895	11 604	92.6

Which sites that are included in the system are not affected by the interest rate for Carbon pricing A scenario 2 but which hubs are used are. For 1% and 3% are the transport hub in Gothenburg used. For 5% interest rate is both the hub in Gothenburg and Lysekil used for transport and in the case of 7% or 9% is the Lysekil hub used but not the one in Gothenburg, see Figure 5.10.

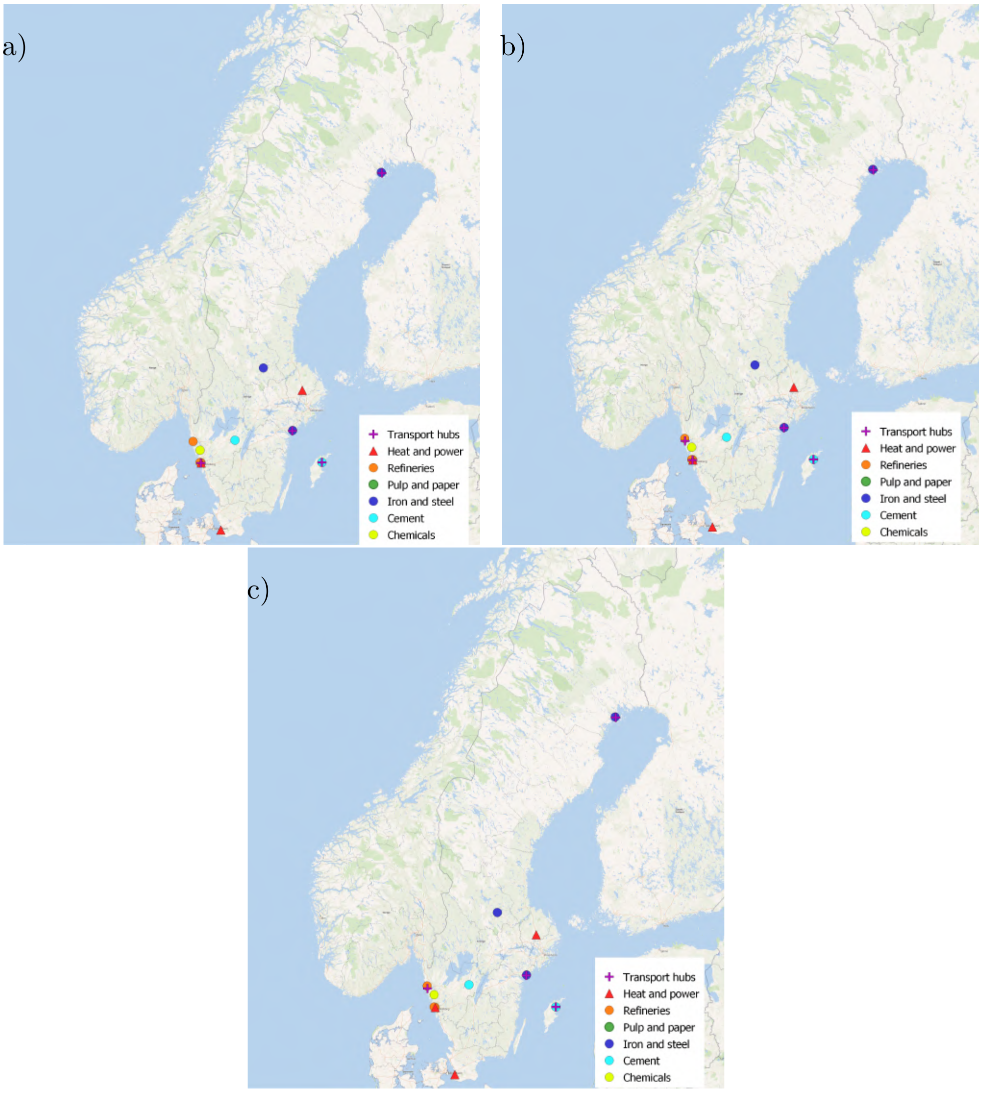

Figure 5.10: Location on the transportation hubs used and sites captured from. a) interest rate 1% and 3%, b) interest rate 5% and c) interest rate 7% and 9%.

5.7.2 Growth limitations

The limitations on how much capacity that is possible to invest every year have effects, Table 5.12. Comparing the limitation by 5 000 ktonCO$_2$/year and when the investment is limitless it is clear that the system does not capture as much emissions but the specific cost for these two scenarios is almost the same. There is not much different between the cases when the limit are 50 000 and 500 000 and the reference case.

Table 5.12: Total emissions, system cost and specific cost for Scenarios 1, 2, 3 and reference scenario over the entire modelled period.

Limitation	Total fossil emissions [MtonCO$_2$]	Total biogenic emissions [MtonCO$_2$]	Total system cost [M€]/[M€2020]	Specific system cost [€$_{2020}$/tonCO$_2$]
5 000	210	895	10 685	72.3
50 000	199.038	894	11 575	72.3
500 000	198.523	894	11 663	72.6
Ref	198	894	11 657	72.5

5.7.3 Investment cost for ships

In all scenarios with free ship investment and the reference case the number of ships is 22 in 2045. The difference is where the ships retrieve the carbon. Case 1, 2 and 3 when the investment was free for Luleå and Gothenburg or Slite were four hubs used. When all ships have a free investment cost and the reference case when no ships were free were five hubs used, with an additional hub used in Lysekil, see Figure 5.11.

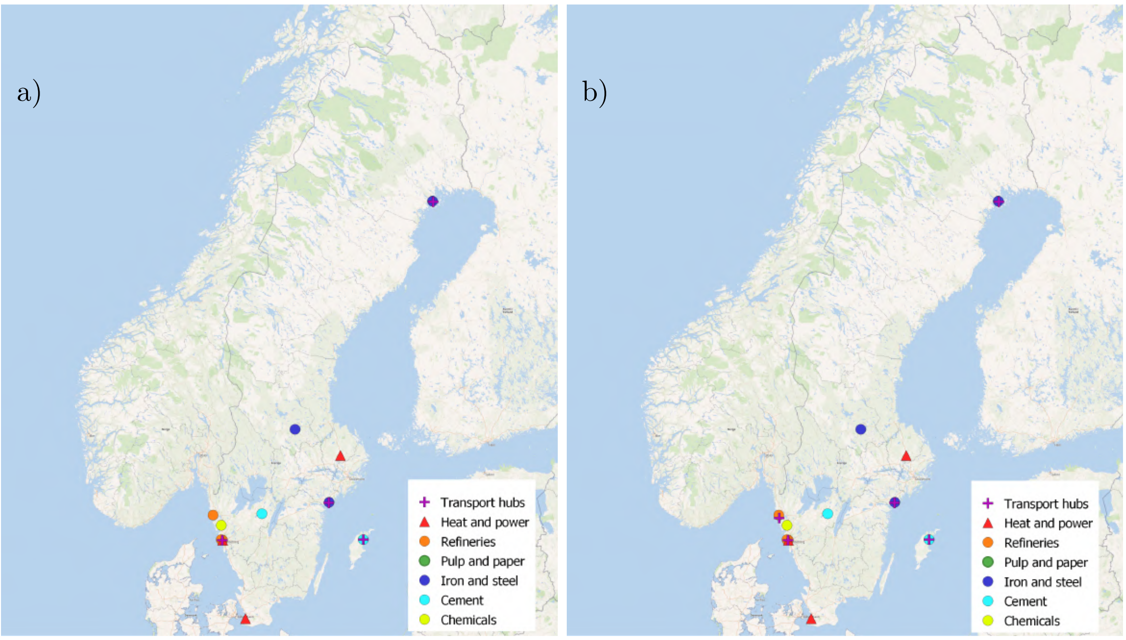

Figure 5.11: Location on the transportation hubs used and sites captured from. a) case 1-3 and b) case 4 and reference case.

The development of CCS starts 2024 for case 1-4, see Figure 5.12. For all four cases the system captures carbon from the steel industry in Luleå in 2024. The next site to invest in carbon capture technology depends on which hubs have free investments. The system invest in carbon capture in the cement industry in 2025 when the ships from Gotland are free. When the ships are free from Gothenburg is carbon from two refineries and one chemical site close to Gothenburg being captured starting at 2026. When all hubs have free ships is two iron and steel sites and the cement site on Gotland part of the CCS-system from 2024 and the refinery closest to Lysekil is included in the system from 2025.

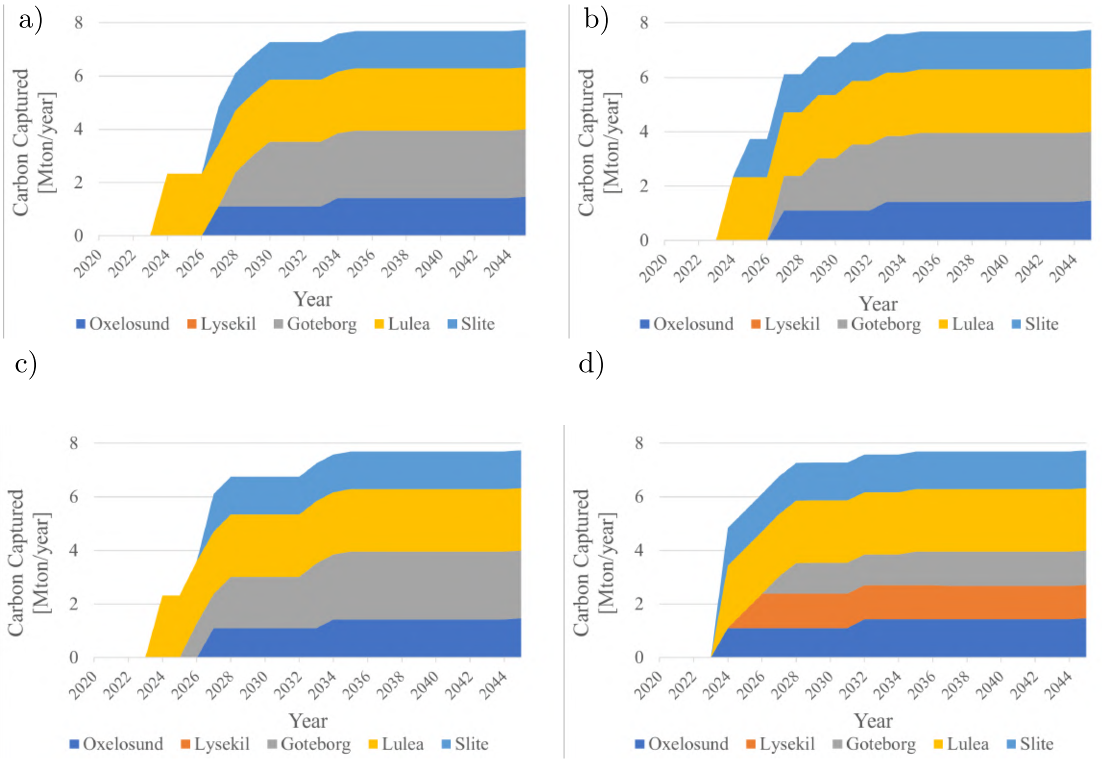

Figure 5.12: Carbon capture development with the captured carbon divided in from which of the transport hubs it is transported from a) scenario 1 when the investment of ships from Luleå is free, b) scenario 2 when Luleå and Slite is free, c) scenario 3 when Luleå and Gothenburg is free and d) scenario 4 when all ships are free

The cheapest specific system cost is when all investment cost for ships is free and this scenario capture also most emissions. The interesting result from this is the comparison between scenario 2 and 3. There is more emission captured and transported via Gothenburg than Slite in both cases, 47.97 Mton and 29.59 Mton for 2 and 44.85 Mton and 26.77 Mton from 3. But there are more emissions captured in scenario 2 when the ships from Slite is free. The specific system cost is also lower for case 2.

The investment of transportation by ship is high compared to the investments of the trucks needed. The investments are affecting the development of the CCS system but there is a large cost for the government if they were to finance the cost of ships.

Table 5.13: Total emissions, system cost and specific system cost for Scenarios 1-4 and reference scenario over the entire modelled period.

Case	Total fossil emissions [MtonCO_2]	Total biogenic emissions [MtonCO_2]	Total system cost [M€] [M€2020]	Specific system cost [$€_{2020}$/tonCO_2]
1	193	894	11 398	68.3
2	189	894	11 441	66.8
3	191	894	11 302	67.0
4	180	894	11 407	62.7
Ref	198	984	11 657	72.5

5.8 Comparison

In Appendix A.7 is a table with most of the results from the policy models. For the models with carbon pricing and BECCS credits are the specific cost increase between the three cases with the same rate. The same is true for emission budget A but the specific cost difference between the scenarios in emission budget B is smaller. The annual emission budget B scenarios has an increased specific cost when the annual budget reduction increases. In the annual emission A model is this not the case. Here is scenario 1 with a reduction rate 2.2% lower than scenario 3 with 0.44%. This can be explained by looking at which sites that are included in the system for the two scenarios. In scenario 1 is sites for cement, refinery, iron and steel, and chemical industry included, but in scenario 3 is only one site in the iron and steel industry included. There are only 3 ships bought and most of the years these are not filled, this is one reason for the high specific cost together with lower investment cost for cement and chemical industry compared to iron and steel industry.

The different policies show potential but there are both advantages and disadvantages with each policy. Carbon pricing is a good cost-efficient way to reduce emissions and as can been seen in the results of carbon pricing A and B. If the price increases, will more polluters prevent emissions, but this policy does not set a cap and it will be hard to limit to a specific emission budget with carbon pricing. Carbon pricing is a good solution both for the environment and economy at the moment, but it might not be the solution to the problem. As long as the big polluters can afford to pay for the emissions will the emissions not decrease. Including biogenic emissions in policies will in most situations reduce the total emissions. In some circumstances will the specific system cost decrease but this was not the case for the scenarios in carbon pricing B.

A disadvantage of BECCS credit A and B is that it entails a cost for the state. Money used to pay for the captured CO_2 is money that could be used for something else that would benefit the country's population or be used for other environmental improvements. This policy may be very expensive in the future with much biogenic emissions being captured and may not be the best policy in the long run without large changes. The benefits with BECCS credits are good but the results are similar to carbon pricing B. It is also difficult to determine how much money should be reworded for capturing biogenic emissions. Too high a price will result in a lot of companies investing in capturing equipment in facilities with biogenic emission and a high cost for the government and with too low reward money will the policy not have any effect. Comparing BECCS credits B scenario 1 and carbon pricing A scenario 1 is the amount of emissions about the same but the specific system cost is 0.5€/ton lower for BECCS. For the same cases but scenario 2 is the specific cost the same but here is the BECCS credits option also better for the system, there is 62 Mton more emissions captured.

One way to ensure that not too many emissions are emitted is by setting a budget. The good thing with emissions budget is that the companies can choose when and where the emissions are emitted. The result of emission budget A-C and annual emission budget A-C may be the best policies models when regarding the foresight. In all models there is perfect foresight but is policies would be implemented in the Swedish industry would not the system have any foresight on how the situation will be in the future. With a budget is the amount of emissions already decided, but the problem with the model for the budget policies is that the production and therefore emissions will change over the years. It is unknown if the production will increase in 2030 or if some of the processes will be electrified. In the system modelled is the budget for the whole system. This requires good communication between every industry sector and sites. If the emission budget were to be implemented in the Swedish industry, would it be a good idea to divide the budget between the sectors or sites. When there is a plan on how emissions will be reduced, and a policy has been chosen is it important that a clear long-term plan is communicated to all actors so that the plan is followed.

Depending on the goals set for Swedish industry, the emission budget would be a good option. The carbon pricing cannot be limited by a budget but will be affected by how much the companies are willing to pay. The positive aspect of carbon pricing is that it can easily be changed over the years. This is also easier to change the annual emission budget compared to a total budget over a period.

The highest carbon price on fossil emissions, staring at 100€/ton in 2020, results in 141 Mton fossil emissions and 893 Mton biogenic emissions and the specific cost for this policy is 74.8 €/ton, see **??**. This can be compared to two other policy scenarios. Emission budget of 150 for fossil emissions, with 150 Mton and 890 Mton emissions and a specific cost of 74.4 and total annual emission with 2.2% reduction rate with 211 Mton fossil emissions and 887 Mton biogenic emissions. The specific cost with annual emission budget is 74.0 €/ton. The difference in emission between carbon price and emission budget is not much, only 6 Mton, but the specific cost in lower for emission budget. The specific cost is lowest for annual emission budget but there is 58 Mton more emissions compared to the emission budget.

Comparing carbon pricing and emission budget when the policies includes both fossil and biogenic emissions shows that carbon pricing is the better option for the modelled period when the emissions is about 200 Mton. Carbon pricing with 100 €/ton for all emissions result in 97 fossil emissions and 109 biogenic and a specific cost of 80.4 €/ton. Emission budget B scenario 1 have a specific cost of 81.3 €/ton, 96 fossil emissions and 104 biogenic emissions. There is 6 Mton more emissions for carbon pricing scenario but the total system cost resulting in a lower specific cost for the carbon pricing scenario.

Depending on the policy, different sites are included in the CCS system. The annual emission budget for fossil emission is a higher amount of carbon captured from iron and steel sites. Both with carbon pricing and emission budget is high amount emissions captured from iron and steel, but the cement sites and chemical industry is included earlier and more emissions is captured from these sites. Looking at the same policies but including biogenic emission is the emissions captured from iron and steel sites higher for annual emission budget B compared to carbon pricing B and emission budget B. But for all three policies is the highest amount of emissions captured from the pulp and paper industry. The reason for higher percent of the carbon captured from iron and steel industry in annual emission budget is that these are big sites with many emissions. In this policy is the increase each year small and there is not a bigger investment any year. Therefore, is there system focusing on some sites with high emissions instead of investing in more sites.

Sweden is country with a lot of pulp and paper industry and therefore there are great opportunities to capture biogenic emissions. Including biogenic emissions in the policies do affect the system greatly. The difference between the policies for fossil emissions and the policies for all emissions is that there are much more emissions to take into account and therefore it is difficult to compare the different policies. The cheapest investments are to only capture from a few fossil emissions sites but with large amounts of emission captured will it be cheaper to capture both fossil and biogenic emissions. There is a synergy between the two emission types. Cement industry emits both biogenic and fossil but there are much more fossil emissions. The heat and power sites with waste as fuel have however a more even distribution of biogenic and fossil emissions. By capturing emissions from waste heat and power sites will both the fossil and biogenic emissions be reduced. But it will be cheaper for the system to capture from cement or chemical sites and the pulp and paper industry to capture both types of emissions.

Reaching net zero emissions by 2045 will be tough without CCS in the biggest industries, but CCS will not be the only solution in reducing the amount of carbon dioxide being released in the atmosphere. There has to be an increase in efficiency in all processes, reduction in fossil fuel and reduction of production in most industries. There is a long way to go before CCS can be implemented in a large extent in the Swedish industry. CCS will not be the only thing that will get us to meet net zero emissions but maybe it can cover 10 or even 20% of today's emissions in the future. Reaching a net zero can be done by investing in some carbon capture technology each year or investing much in the ten years before 2045. CCS is a good option for reducing fossil emissions that are difficult to reduce by changing the production processes and it is a good option for negative emission by capturing and storing biogenic emission.

6

Conclusion

In this work, a mixed integer programming optimization model has been used to find the lowest net present value of carbon capture and storage system for Swedish industry. The implementation of policies resulted in various amounts of carbon captured and different annual system costs. The choice of policy affects how much CO2 are captured, and from which sites these are captured from.

Most of the policies investigated gave a specific capture cost of 69-81 €/tonCO_2. The most important differences between the policies are the amount of emissions captured and the total system cost. The implementation of the CCS system is greatly affected by the amount of CO2 captured.

Carbon capture with carbon pricing policies give a threshold effect, there is a large increase in carbon captured over a few years. The choice of carbon price increase has little effect on how much is captured in 2045, the carbon price rather affects how much emissions are captured during the period. The carbon price does not affect the share captured from each industry.

The carbon captured when there is an emission budget do also have some threshold effects, but the increase is not as large at the end of the period as for carbon pricing. With emission budget, the emission sources with low investment cost are included early in the period. The amount of carbon captured the following years is almost constant for these low-cost sources. The more expensive sources invest in carbon captured later, the year depends on how low the budget is, with a budget of 100 Mton fossil emissions is biogenic heat and power plants included from year one. In the Swedish industry is the sites with biogenic emissions more affected by the emission budget when there is a total budget for all emissions.

When there is a continuously decreased annual emission budget the increase of carbon captured linear. The investments are the same size each year. The annual investment size influence which sites are includes in the CCS system. Having an annual emission budget result in more emissions captured from the iron and steel industry. There is also less sites included in the CCS system and the share of emissions captured from the site is higher compared to other policies.

With total emission budget and total annual emission budget the system benefits from choosing between fossil and biogenic emissions. For these cases there are fewer fossil emissions but there are higher amounts of biogenic emissions captured. For the largest total emission budget tested, 400 Mton, which is about 32% of the emissions, 60% of the total fossil emissions captured and 70% of the biogenic emissions captured. A total annual emission budget with a reduction rate of 2.2% there is a higher share of the fossil emissions captured compared to the percent of the biogenic emissions. With a reduction rate of 2.2% is 39% of the fossil emissions are captured and 20% of the biogenic emissions. When more emissions are captured and when the reduction rate is 3.8% is the percentage 42% and 49% for fossil emissions captured respective biogenic emissions captured.

6.1 Future Work

Here is a list of suggestions that could be included in future work with studies like this.

- Not have perfect foresight.
- Have an increase or decrease on the production at the sites and therefore emissions.
- Divide the policies more by each sector or company, so budget can be set for respective company.
- Look at more policies were the policies for fossil emissions are stricter than for the biogenic emission policies.

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A

Appendix

A.1 Nomenclature for mathematical model

Table A.1: The decisions variable used in the GAMS model

Abbreviation	Unit	Definition
$x^{1}_{site,stack_type,liq,year}$	tonCO$_2$	Flow between site $i \in I$, stack type $j \in J$ and liquefaction plant $k \in K_i$
$x^{2}_{k,l,y}$	tonCO$_2$	Flow on land between liquefaction plant $k \in K_i$ and hub $l \in L$
$y^{3}_{l,y}$	$y^{3}_{l,y} \in 0, 1$	Hub use

Table A.2: Other variables from the GAMS model, table 1

Abbreviation	Unit	Definition
c_{tot}	M€	Total net present value of system
c^{annual}_{y}	M€/year	Annual cost of system in year $y \in Y$
$c^{CAPEX,capture}_{i,y}$	M€	CAPEX for capture installations at site $i \in I$ in year $y \in Y$
$c^{OPEX,capture}_{i,y}$	M€	OPEX for capture installations at site $i \in I$ in year $y \in Y$
$c^{CAPEX,liq}_{i,y}$	M€	CAPEX for capture installations at liquefaction plant $k \in K_i$ in year $y \in Y$
$c^{OPEX,liq}_{i,y}$	M€	OPEX for liquefaction at liquefaction plant $k \in K_i$ in year $y \in Y$
$c^{CAPEX,storage,liq}_{i,y}$	M€	CAPEX for capture installations at liquefaction plant $k \in K_i$ in year $y \in Y$
$c^{OPEX,storage,liq}_{i,y}$	M€	OPEX for storage at liquefaction plant $k \in K_i$ in year $y \in Y$
$c^{CAPEX,truck}_{i,y}$	M€	CAPEX for trucks transporting CO$_2$ between liquefaction plant and hub $l \in L$ in year $y \in Y$
$c^{OPEX,truck}_{i,y}$	M€	OPEX for trucks transporting CO2 between liquefaction plant $k \in K_i$ and hub $l \in L$ in year $y \in Y$
$c^{CAPEX,storage,hub}_{i,y}$	M€	CAPEX for storage at hub $l \in L$ in year $y \in Y$
$c^{OPEX,storage,hub}_{i,y}$	M€	OPEX for storage at hub $l \in L$ in year $y \in Y$
$c^{CAPEX,ship}_{i,y}$	M€	CAPEX for ships transporting CO$_2$ between hub $l \in L$ and the final storage location in year $y \in Y$
$c^{OPEX,ship}_{i,y}$	M€	OPEX for ships transporting CO2 between hub $l \in L$ and the final storage location in year $y \in Y$

Table A.3: Other variables from the GAMS model, table 2

Abbreviation	Unit	Definition
c_{tot}	M€	Total net present value of system
c_y^{annual}	M€/year	Annual cost of system in year $y \in Y$
$e_{et}^{captured}$	tonCO$_2$	Total CO2 of type $et \in ET$ captured
$e_{et,y}^{captured,annual}$	tonCO$_2$	CO2 of type $et \in ET$ captured in year $y \in Y$
$e_{et,y}^{em,annual}$	tonCO$_2$	CO$_2$ of type $et \in ET$ emitted by the system in year $y \in Y$
$e_{et,y}^{em,total}$	tonCO$_2$	Total CO$_2$ of type $et \in ET$ emitted by the system
$c_{et,y}^{emission}$	M€	Annual cost of emitting CO$_2$ of type $et \in ET$ in year $y \in Y$
$b_{i,j,y}^{capture}$	tonCO$_2$	Installed capture capacity at site $i \in I$ on stack of stack type $j \in J$ in year $y \in Y$
$b_{k,y}^{liq}$	tonCO$_2$	Installed treatment capacity at liquefaction plant $k \in K_i$ in year $y \in Y$
$b_{k,y}^{storage,liq}$	tonCO$_2$	Installed storage capacity at liquefaction plant $k \in K_i$ in year $y \in Y$
$b_{l,y}^{storage,liq}$	tonCO$_2$	Installed storage capacity at hub $l \in L$ in year $y \in Y$
$b_{k,l,y}^{truck}$	tonCO$_2$	Installed truck transport capacity between liquefaction plant $k \in K_i$ and hub $l \in L$ in year $y \in Y$
$b_{l,y}^{ship}$	$b_{l,y}^{ship} \in$	Number of ships installed to transport CO$_2$ from hub $l \in L$ in year $y \in Y$
$a_{i,j,y}^{capture}$	tonCO$_2$	Investment in CO$_2$ capture capacity at site $i \in I$ on stack of stack type $j \in J$ in year $y \in Y$
$a_{k,y}^{liq}$	tonCO$_2$	Investment in CO$_2$ treatment capacity at liquefacftion plant $k \in K_i$ in year $y \in Y$
$a_{k,y}^{storage,liq}$	tonCO$_2$	Investment in CO$_2$ storage capacity at liquefaction plant $k \in K_i$ in year $y \in Y$
$a_{l,y}^{storage,hub}$	tonCO$_2$	Investment in CO$_2$ storage capacity at hub $l \in L$ in year $y \in Y$
$a_{k,l,y}^{truck}$	tonCO$_2$	Investment in CO$_2$ truck transport capacity between liquefaction plant $k \in K_i$ and hub $l \in L$ in year $y \in Y$
$a_{l,y}^{ship}$	tonCO$_2$	Investment in CO$_2$ ship transport capacity at hub $l \in L$ in year $y \in Y$

Table A.4: The sets from the GAMS model

Abbreviation	Unit	Definition
Y	$Y \in [year_{start}, ..., year_{end}]$	Time steps in years
I	$I \in [site_1, ..., site_{n_i}]$	Sites included in the system
J	$J \in [stack\ type_1, ..., stack\ type_{n_j}]$	Stack types
K	$K_i \in [liq\ plant_1, ..., liq\ plant_{n_k}]$	Liquefaction plants at site i
L	$L \in [hub_1, ..., hub_{n_l}]$	Transport hubs
ET	$ET \in [biogenic, fossil]$	Carbon emission type

A.2 Equations for CAPEX and OPEX

The investment cost calculated for each part of the system is displayed in Equation A.1 - A.6.

$$c_{i,y}^{CAPEX,capture} \geq \sum_{j \in J} b_{i,j,y}^{capture} \cdot CAPEX_{i,j}^{capture} \cdot \alpha \forall i \in I, y \in Y \tag{A.1}$$

$$c_{j,y}^{CAPEX,liq} \geq b_{j,y}^{liq} \cdot CAPEX_{j}^{liq} \cdot \alpha \forall j \in J, y \in Y \tag{A.2}$$

$$c_{k,y}^{CAPEX,storage,liq} \geq b_{k,y}^{storage,liq} \cdot CAPEX^{storage} \cdot \alpha \forall k \in K, y \in Y \tag{A.3}$$

$$c_{k,l,y}^{CAPEX,truck} \geq b_{k,l,y}^{truck} \cdot CAPEX^{truck} \cdot \alpha_{truck} \forall k \in K, l \in L, y \in Y \tag{A.4}$$

$$c_{l,y}^{CAPEX,hub} \geq b_{l,y}^{hub} \cdot CAPEX^{storage} \cdot \alpha \forall l \in L, y \in Y \tag{A.5}$$

$$c_{l,y}^{CAPEX,ship} \geq b_{l,y}^{ship} \cdot CAPEX^{ship} \cdot \alpha \forall l \in L, y \in Y \tag{A.6}$$

Where $c_{i,y}^{CAPEX,capture}$ is the investment cost, in M€, for capturing the carbon dioxide for the stacks at site i, $b_{i,j,y}^{capture}$ is the installed capacity, tonCO$_2$, for the stack type j at site i, $CAPEX_{i,j}^{capture}$ is the investment cost for each stack in M€/tonCO$_2$ and α is the annuity factor. α_{truck} in Equation A.4 is the annuity factor for the trucks. The operation costs for capture are calculated using Equation A.7.

$$\begin{aligned} c_{i,y}^{OPEX,capture} \geq & \sum_{j \in J} b_{i,j,y}^{capture} \cdot CAPEX_{i,j}^{capture} \cdot c^{O\&M,capture} + \\ & \sum_{j \in J} \sum_{k \in K} x_{i,j,k,y}^{1} \cdot d^{reboiler} \cdot c^{steam} \forall i \in I, y \in Y \end{aligned} \tag{A.7}$$

Where $b_{i,j,y}^{capture}$ is the installed capacity, tonCO$_2$, for the stack type j at site i, $CAPEX_{i,j}^{capture}$ is the investment cost for each stack in M€/tonCO$_2$, $c^{OM,capture}$ is the percent of the investment cost that operation and maintenance for capturing cost, $x_{i,j,k,y}^{1}$ is the amount of carbon captured from the stacks and transported to the liquefaction plant, $d^{reboiler}$ is the heat demand, in MWh/tonCO$_2$, in the reboiler and c^{steam} is the stream cost in M€/MWh.

$$c_{k,y}^{OPEX,liq} \geq b_{k,y}^{liq} \cdot OPEX^{liq} \forall k \in K, y \in Y \tag{A.8}$$

where $c_{k,y}^{OPEX,liq}$ is the operation cost for the liquefying of the carbon dioxide. $b_{k,y}^{liq}$ is the installed liquefication capacity at liquefaction plant k in tonCO$_2$ and $OPEX^{liq}$ is the operation cost per installed liquefication capacity in M€/tonCO$_2$. The calculation for storage at liquefication site and hub operation cost is calculated with similar equations.

$$c_{k,y}^{OPEX,storage,liq} \geq b_{k,y}^{storage,liq} \cdot CAPEX^{storage} \cdot OM_{storage} \forall k \in K, y \in Y \tag{A.9}$$

$$c_{l,y}^{OPEX,storage,hub} \geq b_{l,y}^{storage,hub} \cdot CAPEX^{storage} \cdot OM_{storage} \forall l \in L, y \in Y \tag{A.10}$$

Where $b_{k,y}^{storage,liq}$ and $b_{l,y}^{storage,hub}$ is the storage capacity at respective location. $CAPEX^{storage}$ is the annual investment cost and $OM_{storage}$ is the percent operation of the investment cost that operation and maintenance for storage at liquefaction plant k and at transport hub l. The operation cost calculations for trucks and ships are a little bit more complicated. The truck operation costs are maintenance cost, fuel cost and labour cost. The total truck operation cost is calculated with Equation A.11.

$$\begin{aligned} c_{k,l,y}^{OPEX,truck} \geq & b_{k,l,y}^{truck} \cdot CAPEX^{truck} \cdot c^{O\&M,truck} + \frac{\frac{x_{k,l,y}}{t^{op}}}{\frac{p^{truck}}{t_{k,l}^{rt,truck}}} \cdot d_{k,l} \cdot 2 \cdot u_{fuel}^{truck} \cdot c_{fuel}^{truck} \cdot t^{op} + \\ & \frac{\frac{x_{k,l,y}}{t^{op}}}{\frac{p^{truck}}{t_{k,l}^{rt,truck}}} \cdot c_{labour}^{truck} \cdot n^{drivers} \forall k \in K_i, l \in L, y \in Y \end{aligned} \tag{A.11}$$

Where $b_{k,l,y}^{truck}$ is the installed truck capacity between respective liquefaction plant, k, and transport hub, l. $CAPEX^{truck}$ is the investment cost and $c^{OM,truck}$ is the operation and maintenance cost in percent of the truck investment cost. $x_{k,l,y}$ is the amount of carbon dioxide transported with truck between the liquefaction plant k and transport hub l, t^{op} is the annual operation time, p^{truck} is the capacity in one truck and $t_{k,l}^{rt,truck}$ is the time it takes for one truck to go round-trip between liquefaction plant, k, and transport hub, l. $d_{k,l}$ is the distance the truck travel, u_{fuel}^{truck} is the fuel use in l/km/truck, c_{fuel}^{truck} is the fuel cost for the trucks in M€/l, c_{labour}^{truck} is the annual labour cost in M€/driver and $n^{drivers}$ is the number of drivers per truck. The operation cost for transporting carbon dioxide with ships is calculated using Equation X. The ship operation costs are labour and maintenance cost, fuel cost and harbour cost.

$$c_{l,y}^{OPEX,ship} \geq b_{l,y}^{ship} \cdot c^{L\&M,ship} + b_{l,y}^{ship} \cdot \frac{t^{op}}{t_l^{rt,ship}} \cdot u_{fuel}^{ship} \cdot h_{day} \cdot c_{fuel}^{ship} + b_{l,y}^{ship} \cdot \frac{t^{op}}{t_l^{rt,ship}} \cdot c^{harbour} \tag{A.12}$$

Where $b_{l,y}^{ship}$ is the number of invested ships, $c^{LM,ship}$ is the yearly labour and maintenance cost in M€ for one ship, t^{op} is the yearly operation time, $t_l^{rt,ship}$ round trip time for one ship between hub, l, and storage, u_{fuel}^{ship} is the fuel consumption per hour, h_{day} is number of hours per day, c_{fuel} cost for one ton ship diesel and $c_{harbour}$ is the harbour cost for one stop in the harbour in Norway.

A.3 Equations for carbon capture

$$e_{et,y}^{capture,annual} = \sum_{i \in I} \sum_{j \in J} \sum_{k \in K_i} x_{i,j,k,y}^{1} \cdot m_{j}^{bio} \quad \forall\, y \in Y,\ et = biogenic \tag{A.13}$$

$$e_{et,y}^{capture,annual} = \sum_{i \in I} \sum_{j \in J} \sum_{k \in K_i} x_{i,j,k,y}^{1} \cdot (1 - m_{j}^{bio}) \quad \forall\, y \in Y,\ et = fossil \tag{A.14}$$

$$e_{et}^{capture,total} = \sum_{y \in Y} e_{et,y}^{capture,annual} \quad \forall\, et \in ET,\ y \in Y \tag{A.15}$$

$$e_{et,y}^{em,annual} = \sum_{i} e_{i,et}^{CO_2} - e_{et,y}^{capture,annual} \quad \forall\, et \in ET,\ y \in Y \tag{A.16}$$

$$e_{et}^{em,total} = \sum_{y} e_{et,y}^{em,annual} \quad \forall\, et \in ET \tag{A.17}$$

Where $e_{et}^{capture}$ is the amount of emissions captured of type et, $e_{et}^{em,annual}$ and $e_{et}^{em,total}$ is the amount of CO_2 emitted by the system annually and total. m_j^{bio} is the share of biogenic emissions from stack type j and $e_{i,et}^{CO_2}$ is the total emissions emitted at site i of type et.

A.4 Distance between sites and hubs

Site	Ostrand	Oxelosund	Lysekil	Goteborg	Helsingborg	Stockholm	Lulea
PP1	780	231	430	375	343	347	1283
PP2	265	287	555	591	756	194	776
PP3	172	689	910	964	1155	580	374
PP4	541	312	199	256	480	368	1083
PP5	259	292	552	589	757	202	774
PP6	551	738	795	992	455	542	697
PP7	486	1005	1223	1281	1475	890	59
PP8	572	92	340	333	446	199	1094
PP9	932	405	401	318	168	528	1453
PP10	846	432	162	72	178	546	1387
PP11	532	289	213	263	479	344	1074
PP12	122	430	635	686	875	339	654
PP13	609	1110	1347	1403	1591	992	72
PP14	953	431	400	315	144	554	1476
PP15	484	1000	1220	1279	1472	886	60
PP16	455	177	339	367	539	205	990
PP17	77	625	812	870	1069	525	468
PP18	186	365	593	638	819	274	710
PP19	528	230	242	275	467	292	1068
PP20	146	675	884	940	1134	568	397
PP21	264	762	1000	1053	1238	647	292
PP22	567	173	263	271	427	260	1101
PP23	12	540	730	786	982	443	551
PP24	335	231	456	492	664	180	864
PP25	845	383	230	146	147	503	1382
PP26	311	296	438	487	682	258	852
PP27	618	366	120	190	429	437	1159
PP28	568	76	356	349	457	185	1087
PP29	560	64	368	362	469	172	1076
Ce1	697	189	570	535	540	243	1157
Ce2	642	251	181	180	352	349	1181
R1	730	432	11	101	350	520	1271
R2	793	422	89	2	250	527	1335
R3	794	426	86	5	253	530	1336
IS2	542	1054	1280	1337	1529	938	3
IS3	549	2	433	425	516	122	1051
IS4	315	291	436	484	678	253	855
C1	747	409	40	57	305	506	1289
HP1	455	124	522	528	637	0	937
HP2	468	111	516	519	624	14	951
HP3	421	141	423	444	593	122	941
HP4	563	66	366	359	465	175	1080
HP5	596	114	320	309	418	226	1120
HP6	783	408	91	15	252	513	1325

Site	Ostrand	Oxelosund	Lysekil	Goteborg	Helsingborg	Stockholm	Lulea
HP7	1041	544	404	314	65	668	1574
HP8	415	149	517	530	654	42	905
HP9	380	177	516	535	672	79	877
HP10	285	786	1022	1075	1262	672	268
HP11	485	167	318	342	509	214	1019
HP12	453	111	410	425	565	119	972
HP13	831	314	331	259	209	438	1355
HP14	755	346	138	82	247	456	1296
HP15	766	351	144	81	236	463	1306
HP16	477	85	485	488	596	41	970
HP17	519	283	226	276	490	334	1061
HP18	727	264	225	178	268	381	1261
HP19	204	676	745	818	1044	604	584
HP20	149	677	887	943	1137	570	394
HP21	484	104	518	518	617	29	965
HP22	262	290	544	582	751	202	779
HP23	646	298	135	153	359	389	1188
HP24	986	507	334	245	7	630	1522
HP25	903	439	259	169	91	561	1440
HP26	795	415	100	13	241	521	1337
HP27	960	445	386	299	116	569	1487
HP28	405	919	1143	1200	1391	804	137
HP29	13	538	727	783	979	442	554
HP30	510	161	303	322	485	223	1044
HP31	785	410	90	13	252	515	1327
HP32	295	300	456	504	697	254	835
HP33	539	15	425	419	517	120	1044
HP34	558	1081	1292	1352	1549	967	51
HP35	599	117	318	306	415	229	1123
HP36	710	395	38	95	341	485	1252
HP37	664	186	272	244	341	303	1193
HP38	411	140	464	482	621	86	921
HP39	991	513	338	248	1	636	1528
HP40	271	283	518	558	732	207	797
HP41	909	368	438	361	238	488	1421
HP42	380	177	516	535	672	79	877
HP43	424	133	496	509	634	46	920
HP44	494	215	278	312	500	264	1033
HP45	796	1343	1496	1565	1781	1236	352
HP46	841	295	432	366	294	413	1348
HP47	640	247	186	184	353	345	1179
HP48	1013	515	386	296	56	639	1546
HP49	794	422	91	2	249	527	1336
HP50	1047	550	409	319	70	674	1580
HP51	380	177	517	535	672	79	877

Site	Slite	Varberg	Kalmar	Gavle	Norrkoping	Ornskoldsvik	Umea	Skelleftea
PP1	197	338	64	523	223	906	991	1145
PP2	437	639	581	14	304	389	483	637
PP3	812	1025	984	404	710	30	92	236
PP4	489	329	460	354	254	687	801	947
PP5	444	638	585	5	307	386	481	635
PP6	858	843	258	562	146	264	406	
PP7	1114	1344	1300	723	1029	342	245	93
PP8	255	352	280	320	26	705	800	954
PP9	390	243	147	680	374	1066	1160	1314
PP10	520	17	340	626	372	991	1099	1249
PP11	467	332	445	337	232	678	790	937
PP12	581	745	722	137	440	259	366	516
PP13	1207	1464	1403	836	1138	462	354	203
PP14	418	235	175	703	397	1088	1183	1337
PP15	1108	1341	1295	719	1025	339	240	87
PP16	366	415	415	221	141	595	699	851
PP17	765	934	918	332	638	78	199	333
PP18	516	693	657	72	377	317	418	571
PP19	408	331	398	312	172	672	780	930
PP20	803	1002	970	386	693	2	122	260
PP21	872	1111	1056	483	787	121	2	153
PP22	340	308	326	330	109	707	810	962
PP23	685	849	832	246	551	155	270	414
PP24	406	542	513	95	229	471	573	725
PP25	446	79	252	611	329	987	1091	1243
PP26	478	547	563	129	281	455	565	714
PP27	530	271	461	436	303	765	879	1024
PP28	242	366	280	314	10	700	793	947
PP29	236	379	286	304	3	690	783	937
Ce1	518	244	446	236	803	871	1021	
Ce2	393	221	318	415	185	785	891	1042
R1	572	190	454	543	366	876	991	1136
R2	535	90	382	585	358	939	1050	1198
R3	539	93	386	587	361	940	1052	1199
IS2	1158	1400	1349	776	1080	397	295	141
IS3	189	438	297	291	67	672	758	912
IS4	472	544	558	128	276	459	568	717
C1	539	144	409	547	344	893	1006	1152
HP1	243	551	411	204	175	567	645	799
HP2	230	540	397	216	164	581	660	813
HP3	321	482	423	167	141	553	648	802
HP4	236	376	284	308	1	693	786	940
HP5	263	325	263	345	52	730	826	980
HP6	521	91	371	573	344	929	1040	1188
HP7	549	225	308	799	502	1181	1281	1434

Site	Slite	Varberg	Kalmar	Gavle	Norrkoping	Ornskoldsvik	Umea	Skelleftea
HP8	284	559	442	163	188	531	613	766
HP9	321	570	472	125	207	498	583	737
HP10	897	1135	1081	507	812	139	26	128
HP11	354	387	389	249	122	625	728	880
HP12	296	459	391	198	109	584	678	832
HP13	335	205	126	581	276	966	1062	1215
HP14	454	104	310	532	283	899	1007	1157
HP15	455	94	306	542	290	910	1017	1168
HP16	229	510	377	221	133	595	678	831
HP17	463	344	448	323	227	664	777	924
HP18	358	172	228	487	207	867	969	1121
HP19	844	894	951	400	669	266	375	471
HP20	805	1005	972	389	696	3	119	257
HP21	214	537	385	232	161	596	674	826
HP22	444	631	582	5	303	390	486	640
HP23	445	213	363	433	232	791	901	1050
HP24	535	156	303	749	459	1127	1230	1382
HP25	491	82	279	669	387	1045	1149	1301
HP26	524	80	369	584	351	941	1051	1200
HP27	442	216	200	712	409	1097	1194	1347
HP28	1028	1262	1214	638	944	260	159	15
HP29	684	846	830	245	549	158	274	418
HP30	344	364	367	273	109	649	752	904
HP31	523	91	373	574	346	930	1041	1189
HP32	479	564	572	113	289	439	548	697
HP33	203	435	306	281	60	663	751	904
HP34	1190	1417	1376	799	1105	415	321	169
HP35	264	322	260	348	55	733	830	983
HP36	535	181	423	515	329	856	970	1116
HP37	298	250	226	418	128	801	900	1053
HP38	306	517	433	153	159	537	627	781
HP39	540	160	308	755	465	1133	1236	1388
HP40	446	609	573	32	291	405	505	657
HP41	328	295	84	653	346	1038	1128	1281
HP42	321	570	472	125	207	498	583	737
HP43	280	538	428	168	168	543	627	781
HP44	399	366	412	275	164	637	745	895
HP45	1468	1638	1637	1052	1358	669	602	462
HP46	254	315	17	584	279	968	1055	1209
HP47	389	223	315	413	181	783	889	1040
HP48	522	208	282	771	473	1153	1253	1406
HP49	534	88	381	585	358	940	1051	1199
HP50	554	230	312	805	508	1187	1287	1440
HP51	321	570	472	126	207	498	583	737

A.5 Policy cases and scenarios

Table A.5: The policies modelled in this study.

Case	Scenario 1	Scenario 2	Scenario 3	Policy for fossil emissions	Policy for biogenic emissions
Carbon pricing A	Fossil emission cost 2020:			Emission cost increases with 5€/ton each year.	No policy
	0 €/ton	50 €/ton	100 €/ton		
Carbon pricing B	Emission cost 2020:			Emission cost increases with 5€/ton each year.	Emission cost increases with 5€/ton each year.
	0 €/ton	50 €/ton	100 €/ton		
BECCS credits A	Emission cost 2020:			Emission cost increases with 5€/ton each year	One ton biogenic CO_2 captured equal to one ton fossil emissions
	0 €/ton	50 €/ton	100 €/ton		
BECCS credits B	Emission cost 2020:			Emission cost increases with 5€/ton each year	Two ton biogenic CO_2 captured equal to one ton fossil emissions
	0 €/ton	50 €/ton	100 €/ton		
Emission budget A	Fossil emission budget:			Fossil emission for 2020 to 2045 cannot be more than budget	No policy
	100 ton	125 ton	150 ton		
Emission budget B	Total emission budget:			Total emission for 2020 to 2045 cannot be more than budget	
	200 ton	300 ton	400 ton		
Emission budget C	Emission budget:			Fossil emission for 2020 to 2045 cannot be more than budget	Biogenic emission for 2020 to 2045 cannot be more than budget
	200 ton	300 ton	400 ton		
Annual emission budget A	Fossil emission budget reduction rate:			Annual fossil emission budget	No policy
	2.2%	3.8%	0.44%		
Annual emission budget B	Total emission budget reduction rate:			Annual total emission budget	
	2.2%	3.8%	0.44%		
Annual emission budget C	Emission budget reduction rate:			Annual fossil emission budget	Annual biogenic emission budget
	2.2%	3.8%	0.44%		
Carbon contract for difference B	Fossil emission cost cement & fossil emission cost 2020:			Fixed cost for cement and rest industries' CO_2 cost increases with 5€/ton.	No policy
	80 €/ton 50 €/ton	90 €/ton 50 €/ton			

A.6 The location of the sites and emissions at each site

Table A.6: The definition of the abbreviation of the stack types

Abbreviation	Stack type
RB	Recovery boiler
LK	Lime kiln
PP other	Pulp & paper other
Ce combined	Cement combined
HPU	HPU
R other	Refinery other

Abbreviation	Stack type
IS power	Iron and steel power plant
IS other	Iron and steel other
Cracker furnace	Cracker furnace
HP waste	Heat and Power waste
HP bio	Heat and Power bio
HP fossil	Heat and power fossil

Table A.7: The location of the sites, the stack types available for caption and the annual emissions from the stacks at each site.

Site ID	Name of site and location	Stacks	Biogenic emissions [ton/year]	Fossil Emissions [ton/year]
PP1	Södra Cell Mönsterås, Mönsterås	RB, LK	1 710 000	0
PP2	Stora Enso Skutskär, Älvkarleby	RB, LK	1 044 000	0
PP3	Metsä Board Husum, Örnsköndsvik	RB, LK	1 125 000	0
PP4	Billerud Korsnäs Gruvön, Grums	RB, LK	1 080 000	0
PP5	Billerud Korsnäs Gävle, Gävle	RB, LK	972 000	0
PP6	SCA Östrand, Timrå	RB, LK	1 764 000	0
PP7	Smurfit Kappa Kraftliner, Piteå	RB, LK	990 000	0
PP8	Billerud Krosnäs Skärblacka, Norrköping	RB, LK	909 000	0
PP9	Södra Cell Mörrum, Karlshamn	RB, LK	972 000	0
PP10	Södra Cell Värö, Varberg	RB, LK	1 548 000	0
PP11	Störa Enso Skoghall, Hammarö	RB, LK	927 000	0
PP12	Holmen Iggesund, Hudiksvall	RB, LK	819 000	0
PP13	Billerud Korsnäs Karlsborg, Kalix	RB, LK	774 900	0
PP14	Stora Enso Nymölla, Bromölla	RB, LK	709 200	0
PP15	SCA Munksund, Piteå	RB, LK	622 800	0
PP16	Billerud Korsnäs Frövi, Lindesberg	RB, LK	649 800	0
PP17	Mondi Dynäs, Kramfors	RB, LK	576 900	0

Table A.8: The location of the sites, the stack types available for caption and the annual emissions from the stacks at each site.

Site ID	Name of site and location	Stacks	Biogenic emissions [ton/year]	Fossil Emissions [ton/year]
PP18	Rottneros Vallviks Bruk, Söderhamn	RB, LK	589 500	0
PP19	Nordic Paper Bäckhammar, Kristinehamn	RB, LK	469 800	0
PP20	Domsjö Fabiker, Örnsköldsvik	RB, LK	470 700	0
PP21	SCA Obbola, Umeå	RB, LK	457 200	0
PP22	Munksjö Aspa Bruk, Askersund	RB, LK	415 800	0
PP23	SCA Ortviken, Sundsvall	PP other	0	0
PP24	Stora Enso Fors, Avesta	PP other	188 100	0
PP25	Stora Enso Hylte, Hylte	PP other	270 900	0
PP26	Stora Enso Kvarnsveden, Borlänge	PP other	0	0
PP27	Munksjö Paper Billingsfors, Bengtsfors	RB, LK	148 500	0
PP28	Fiskeby bruk, Norrköping	PP other	81 478	0
PP29	Holmen Braviken, Norrköping	PP other	138 600	0
Ce1	Cementa Slitefabriken, Gotland	Ce combined	140 910	1 268 190
Ce2	Cementa Skövdefabriken, Skövde	Ce combined	42 336	381 024
R1	Preemraff Lysekil, Lysekil	HPU, R other	0	666 015
R2	St1 Refinery, Göteborg	HPU, R other	0	273 979
R3	Preemraff Göteborg, Göteborg	HPU, R other	0	342 256
IS2	SSAB och Lulekraft LUKAB, Luleå	IS power, IS other	0	2 372 420
IS3	SSAB Oxelösund, Oxelösund	IS power, IS other	0	1 112 712
IS4	SSAB Borlänge, Borlänge	IS power, IS other	0	122 441
C1	Borealis Krackeranläggning, Stenungsund	Cracker furnace	0	454 751

Table A.9: Stack types available for caption and emissions for heat and power site

Site ID	Stacks	Biogenic emissions [ton/year]	Fossil Emissions [ton/year]
HP1	HP bio	967 740	0
HP2	HP waste	336 515	181 201
HP3	HP bio, HP waste	564 209	154 372
HP4	HP waste	292 737	157 628
HP5	HP waste	250 770	135 030
HP6	HP waste	277 564	149 457
HP7	HP waste	277 107	149 211
HP8	HP bio, HP waste	473 836	79 704
HP9	HP waste	114 893	61 866
HP10	HP bio, HP waste	294 922	55 686
HP11	HP bio	304 386	0
HP12	HP bio	294 192	0
HP13	HP bio	301 141	0
HP14	HP bio, HP waste	155 673	79 530
HP15	HP bio	110 526	0
HP16	HP bio	688 861	0
HP17	HP bio	286 118	0
HP18	HP bio, HP waste	240 834	54 895
HP19	HP bio	305 399	0
HP20	HP bio	282 415	0
HP21	HP bio	185 500	0
HP22	HP bio	125 144	0
HP23	HP waste	68 229	36 738
HP24	HP waste	91 498	49 268
HP25	HP waste	77 414	41 684
HP26	HP bio	181 072	0
HP27	HP bio	169 882	0
HP28	HP bio	213 831	0
HP29	HP waste	88 511	47 660
HP30	HP waste	79 778	42 958
HP31	HP bio	187 584	0
HP32	HP bio	145 178	0
HP33	HP bio	187 097	0
HP34	HP waste	68 706	36 995
HP35	HP bio	57 906	0
HP36	HP waste	67 925	36 575
HP37	HP bio	65 121	0
HP38	HP bio	139 104	0
HP39	HP bio	129 832	0
HP40	HP bio	123 806	0
HP41	HP bio	117 537	0
HP42	HP bio	438 622	0
HP43	HP waste	142 054	76 490
HP44	HP waste	102 207	55 034
HP45	HP waste	75 019	40 395
HP46	HP bio	199 725	0
HP47	HP bio, HP waste	107 026	15 425
HP48	HP bio	296 320	0
HP49	HP fossil	0	263 790
HP50	HP fossil	0	106 830
HP51	HP fossil	0	185 940

A.7 Comparison of the results

Table A.10: Total emissions, system cost and specific system cost for all policies cases over the entire modelled period.

Policy	Scenario	Total fossil emissions [MtonCO_2]	Total biogenic emissions [MtonCO_2]	Total system cost [M€]	Specific system cost [$€_{2020}$/tonCO_2]
Carbon pricing A	1	272	896	5 280	70.5
	2	198	894	11 657	72.5
	3	141	893	16 623	74.8
Carbon pricing B	1	262	690	24 305	74.2
	2	166	375	61 146	77.0
	3	97	109	92 492	80.4
BECCS credit B	1	271	895	5 470	70.0
	2	187	843	17 051	72.5
	3	114	584	46 167	75.5
Emission budget A	1	100	821	28 107	80.1
	2	125	866	20 979	77.1
	3	150	890	16 207	74.4
Emission budget B	1	96	104	94 006	81.3
	2	111	189	83 680	79.4
	3	134	266	74 357	78.4
Annual emission budget A	1	264	898	5 976	72.8
	2	211	887	11 418	74.0
	3	321	898	1 304	79.8
Annual emission budget B	1	205	715	25 813	71.9
	2	170	521	46 174	74.4
	3	305	865	4 928	68.6
Combination	1	100	821	27 861	79.4
	2	100	335	71 128	78.3
	3	97	103	93 976	81.3
Carbon contract	1	230	898	8 937	73.8
	2	198	894	11 564	71.8

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