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Cost-optimal CO_2 capture and transport infrastructure—A case study of Sweden

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ABSTRACT

This work applies a mixed integer cost-minimisation model to identify cost-optimal carbon capture and storage (CCS) infrastructure systems. The modelling applies two types of incentives for CCS implementation: carbon pricing, and binding emissions budgets. Both incentive schemes are applied with and without accounting for CO_2 capture from biogenic emissions sources. In the case of CO_2 pricing, biogenic CO_2 capture is implemented by letting each ton of biogenic CO_2 captured generate value for the model equivalent to the cost of emitting one ton of fossil CO_2. In the case of emissions budgets, biogenic CO_2 capture is included by allowing the model to use both biogenic and fossil CO_2 capture to stay within the budget. The main fossil and biogenic emissions sources in Swedish industry are used as a case study.

The results show that incentivising carbon removal has a significant impact on the design and development of the cost optimal system for CCS if there are suitable biogenic emission sources available for implementing biogenic CO_2 capture. The timing for investments in carbon capture is highly dependent on the discount rate - increasing the discount rate in the modelling from 5 % to 15 % delays the first investments in CO_2 capture by three years. To facilitate technology development and timely implementation of CCS on biogenic and fossil sources, it is important to consider that inclusion of carbon dioxide removal into the policy regime controlling fossil fuel emissions, might result in that the cost optimal strategy will be a delay in fossil fuel mitigation.

1. Introduction

To limit the global temperature increase to “well-below 2 °C”, near-term mitigation of large-scale fossil emissions and carbon dioxide removal (CDR) technologies are needed (Rogelj et al., 2018). Carbon capture and storage (CCS) and bio-energy carbon capture and storage (BECCS) are available technologies for large-scale emission reductions and for carbon dioxide removal (towards achieving negative emissions). Policies that motivate fossil CO_2 mitigation through carbon pricing and emissions trading schemes are implemented in many parts of the world, although, so far, they have yielded too-low carbon prices for the large-scale roll-out of CCS. The European Union (EU), via the European Green Deal, is committed to becoming the first climate-neutral continent by Year 2050, and to reduce emissions by 55 % (compared to Year 1990 levels) by Year 2030 (European Commission, 2022). In a national context, Sweden has the goals to reach net-zero GHG emissions by Year 2045 and to reach net-negative GHG emissions thereafter (Swedish Government, 2017). The Government of Sweden has also proposed the following explicit targets for carbon removal from BECCS: 1.8 $MtCO_2/y$ by Year 2030 and 3–10 $MtCO_2/y$ by Year 2045 (SOU, 2020). To motivate investments in BECCS technologies, a reverse auctioning system has been proposed with a budget of around 3.6 billion € for the period of 2026–2046.

The reverse auctioning system has attracted significant interest from several district heating companies, which typically operate biomass-fired combined heat and power (CHP) plants, with Stockholm Exergi having the most-advanced plans for implementing BECCS in one of their CHP plants in Stockholm (for more information, see BECCS Stockholm (Stockholm Exergi, 2022)). There are also many large pulp and paper plants in Sweden, which constitute the largest point sources of biogenic CO_2 emissions. In addition, a large cement manufacturer in Sweden (Cementa) has announced plans to implement CCS at their largest plant in Sweden, aiming to become a CO_2-neutral cement plant in Year 2030 (Cementa, 2023), and the Preem refinery has plans to implement CCS, at least in hydrogen processing units (HPU). The refinery will combine this with an increasing share of the biogenic feedstock (Preem, 2021). There are also several large point sources of emissions in the iron and steel industry, with the largest being blast furnaces. Nevertheless, at present,

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CCS is not the main mitigation option for these plants, instead, hydrogen-based steel-making via the HYBRIT route is preferred (HYBRIT, 2022).

Many of the techno-economic conditions for CO_2 capture implementation at large industrial sites are well-researched. Previous work in our research group, Johnsson et al. (2020) and Garðarsdóttir et al. (2018), have investigated the cost of CO_2 capture in large Swedish process industries, and have presented costs in the range of around 40–100 €/tCO_2. Biermann et al. (2019) have concluded that partial capture could be a cost-effective "stepping stone" towards full mitigation, and Eliasson et al. (2022) have shown that the utilisation of excess heat is important for reducing the operating costs for industrial CO_2 capture. For the Swedish heat and power sector, Beiron et al. (2022) have concluded that there is a large potential for BECCS from waste-fired and bio-fired CHP plants, with around 10 MtCO_2/y being available for capture in the Swedish system at a cost <100 €/tCO_2. These costs are in a similar range as the CO_2 capture costs for industry found in literature and reported by Leeson et al. of 20-120 USD/tCO_2 (Leeson et al., 2017) With respect to the CO_2 transportation infrastructure, Kjärstad et al. (2016) have investigated the conditions for CO_2 transport in the Nordic region, comparing ship and pipeline transportation from coastal transport hubs to potential storage sites. They conclude that ship transportation is a low-cost option, especially during the ramp-up phase. Roussanaly et al. (2014) performed techno-economic analyses for different transport modes over varying transport distances and CO_2 flows and found that pipeline transportation is favourable for high volumes and short distances, and ship transportation becomes favourable for longer transportation distances. In addition, some previous studies have considered the development of large pan-European CO_2 transportation networks. Kjärstad et al. (2013) have considered capture in the European power-producing sector and large pipeline networks, applying a modelling framework developed by Morbee et al. (2012) to determine the cost-optimal transportation infrastructure. D'Amore et al. (2021) present an optimization modelling framework for CCS supply chains, including capture, transport, and sequestration for European emissions sources in industry and power generation. The lowest system cost achieved entailed total specific costs of 52 €/tCO_2 with capture making up around 80 % of the costs. The work also identified that a few large power plants (particularly coal fired) could act as key players for establishing the supply chain infrastructure. If power generation sites were excluded from the modelling, the total cost increased by 9 % and if offshore storage was enforced, the supply chain costs increased by roughly 40 %.

Additionally, several works have been carried out looking at national CCS supply chains using optimization modelling approaches in the European context. In our previous work (Karlsson et al., 2023), we presented a cost-minimising model to aid decision-making regarding investments in CO_2 capture technologies and transportation infrastructure, depending on the cost structure of the CCS system. Our work indicates that a CO_2 price of around 80 €/tCO_2, excluding the cost of permanent storage, motivates the implementation of CCS at scale, considering the costs for both capture and transportation, which is in line with recent price levels within the EU-ETS (Ember 2022). Additionally, we found that most of the supply chain costs consists of the costs for capture and conditioning of CO_2. Kalyanarengan Ravi et al. (2017) presents a total supply chain cost minimizing MILP model and applies it to capture 54 MtCO_2/year in the Netherlands for 25 years of operation. The costs reported are between approximately 35–39 €/tCO_2, with the capture and compression stage making up most of the cost for the supply chain. The work also compares different capture technologies and indicates that pressure swing adsorption was the preferred capture technology and that the difference in cost compared to absorption technology was significant. Becattini et al. (2022) developed a CCS supply chain cost minimizing MILP model and applied it to study different emissions reductions pathways, linear reduction or cumulative reduction, for waste-to-energy plants in Switzerland. Two storage sites are considered, one in Norway (corresponding to the Northern Lights project) and a hypothetical storage site in Switzerland assumed to be available for use later in time. They present supply chain costs of up to 174 €/tCO_2, with transportation making up most of the system costs, when captured CO_2 was transported all the way from Switzerland to Norway. However, with access to the hypothetical Swiss storage site, the cost of transportation was reduced drastically.

In the UK context, Elahi et al. (2014) present a present value minimizing MILP optimization model considering the whole CCS chain applied to emissions sources in the UK and in a later work (Elahi et al., 2017) build upon the previous model to investigate the impact of uncertainty in carbon price development. In addition to looking at supply chains where permanent storage of CO_2 is the only considered end-use, some works using similar optimization modelling approaches include options for carbon capture and utilization (CCU). Klokk et al. (2010) included the possibility of using captured CO_2 for enhanced oil recovery (EOR) and applied it to a case in Norway and Ağralı et al. (2018) also included EOR as a utilization option, and applied it to a case in Turkey. Leonzio et al. (2019) considered the option of utilizing CO_2 to produce methanol in Germany as an alternative to permanent storage.

Generally, the economic conditions for CCS supply chains have been well researched, and the literature shows that in most cases, the majority of the costs for CO_2 supply chains are due to the capture and conditioning of CO_2, with the total supply chain costs varying widely, between around 35–174 €/tCO_2. However, apart from the economic performance of CCS supply chains, the incentive structures used to motivate their deployment are important for determining the timing and scale of implementation, and at present, there are no mechanisms designed to motivate carbon removal. On the EU level, discussions regarding carbon negative credits and certification of carbon removal are ongoing (European Parliament, 2022). Rickels et al. (2021) have discussed the economic and regulatory considerations for integrating carbon removal into the EU ETS and have stated that integrating CO_2 removal credits into the EU ETS would provide an option for achieving more-ambitious net emissions reduction targets at a given price for emissions allowances, and that the initial focus of such an effort should be placed on BECCS and direct air carbon capture and storage (DACCS). Zetterberg et al. (2021) have highlighted four policy models for incentivising BECCS: (i) quota obligations imposed on sectors with hard-to-abate emissions; (ii) the inclusion of carbon removal in emissions trading schemes (for instance, in the EU ETS, as discussed also by Rickels et al. (2021)); (iii) voluntary compensation; and (iv) (other) states as buyers. The planned reverse auctioning system in Sweden is an example of the latter policy model, as it involves the state as a buyer of BECCS outcomes. Jenkins et al. (2021) have presented an alternative policy structure, the carbon take-back obligation (CTBO), as a means to achieve net-zero emissions by Year 2050. Under this policy framework, producers and importers of fossil carbon would be mandated to store an increasing fraction of the carbon within the products, eventually reaching 100 % when net-zero emissions are to be achieved. This transfers the burden to the producer of high-carbon products, and means that any residual emissions would have to be compensated using CDR technologies.

In this work, we attempt to build upon the learnings from previous techno-economic studies of CO_2 capture and transportation, and the studies looking at the optimal design off CCUS chains, and add to the ongoing discussions on incentivising CCS and CDR. This work applies our previously developed optimisation model to investigate the influences of incentive structures for motivating CCS and BECCS on the development and cost of a CCS system, using Swedish industry as a case study. The chosen incentive structures include a cost for emitting fossil CO_2 (corresponding to the EU-ETS system), applying the projections of carbon cost given in the literature. We compare this with alternatively applying a carbon emissions budget for the entire modelled period. For the biogenic emissions, the investigated scenarios assess the effects on the system by including carbon removal as a complement to fossil emissions mitigation, i.e., incentivising BECCS.

2. Method

2.1. Model formulation

This work applies a mixed integer linear programming (MILP) optimisation model that determines the optimal investments in a CO_2 capture system in which the associated CO_2 transportation infrastructure is based on capturing CO_2 from the existing emissions in Sweden. The model has been presented in detail by Karlsson et al. (2023), and is only briefly described here. The model is a cost minimising model that includes capital expenditures (CAPEX) and operational expenditures (OPEX) for CO_2 capture, liquefaction, intermediate storage, and truck transportation on land and ship transport offshore. Costs for geological storage are not included, since only one storage location and one cost are considered regardless of the CCS system configuration. The main constraints governing the model are the CO_2 mass balances over the sites

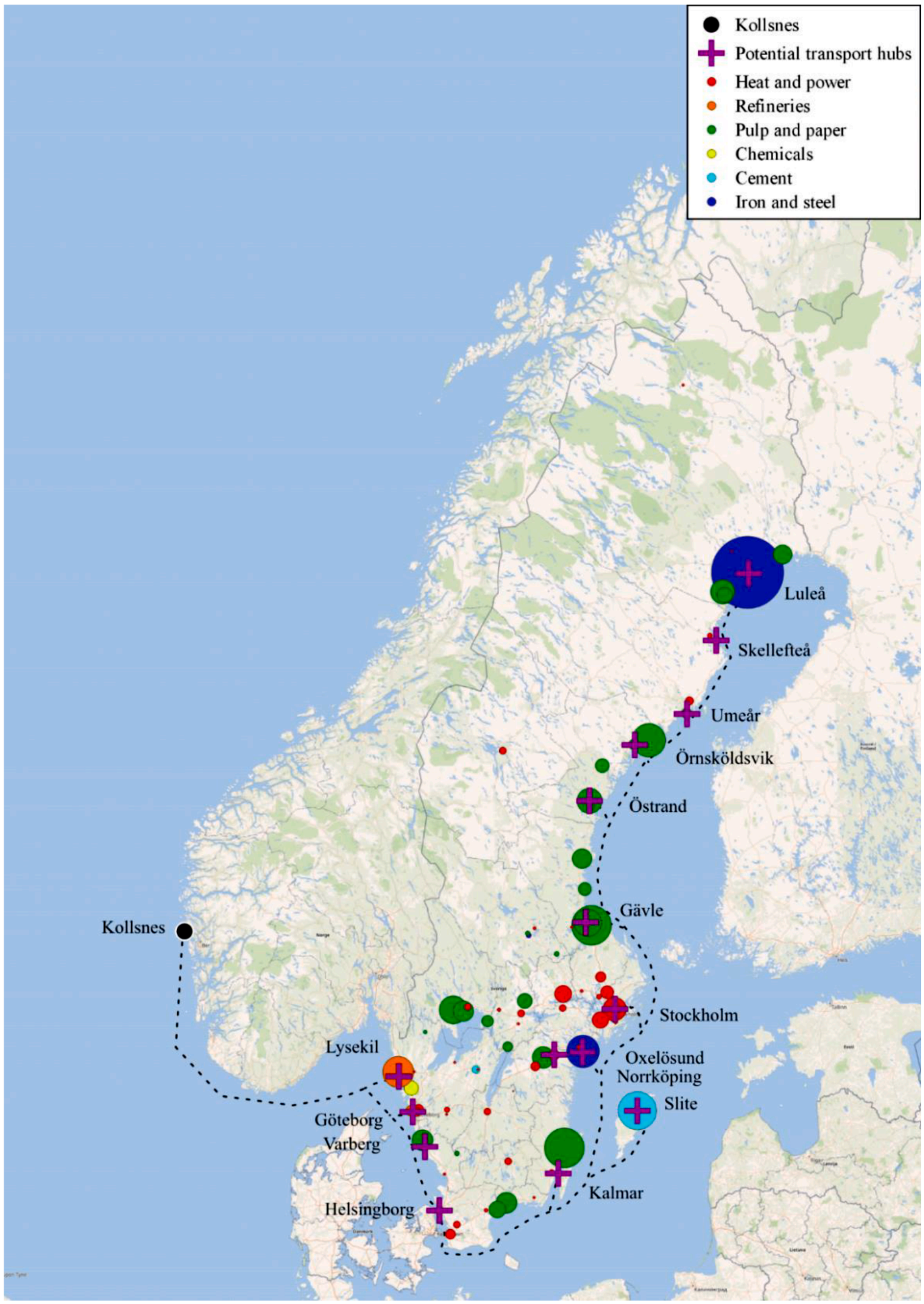

Fig. 1. A map of the studied system that includes: Swedish industrial sites with emissions of >100 ktCO_2/y divided into sectors and with the sizes of the sites related to the emissions levels (0.1–3.3 MtCO_2/y); harbours that can be used as transport hubs for CO_2; and the related ship routes included in the model. Kollsnes in Norway is the considered to be the end-point in the model. Figure from Karlsson et al. (2023).

and transport hubs, and the emissions budgets, in addition to the emissions prices to motivate the installation of capture equipment and transportation infrastructure. The model is written in the general algebraic modelling system (GAMS) and solved using the GAMS Cplex solver, which uses a branch and cut approach to solve a series of linear programming (LP) subproblems. The model contains a total of 335,328 equations and 3216,024 variables, out of which 1170 are non-continuous. The solution times are around 25 min on an Intel Core i5 processor with 16 GB of installed physical memory and a relative error tolerance, the proportional difference between the solution found by the solver and the best theoretical objective function, of 1 %.

The objective function is to minimise the net present value (NPV) of the total cost of the system, $c_{tot,NPV}$, according to Eq. (1).

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

where c_y^{annual} is the annual CCS system cost calculated according to Eq. (2), y is the year, y_0 is the reference year (start of modelled period), and r is the discount rate.

$$\begin{aligned} c_y^{annual} \geq\ & \sum_{i\in I}\sum_{j\in J}\left(c_{i,j,y}^{CAP,\ capture\&liq} + c_{i,j,y}^{OP,\ capture}\right) \\ & + \sum_{i\in I}\left(c_{i,y}^{OP,\ liq} + c_{i,y}^{CAP,storage,\ site} + c_{i,y}^{OP,storage,\ site}\right) \\ & + \sum_{i\in I}\sum_{l\in L}\left(c_{i,l,y}^{CAP,truck} + c_{i,l,y}^{OP,truck}\right) \\ & + \sum_{l\in L}\left(c_{l,y}^{CAP,storage,\ hub} + c_{l,y}^{OP,storage,\ hub}\right) \\ & + \sum_{l\in L}\left(c_{l,y}^{CAP,ship} + c_{l,y}^{OP,ship}\right) \\ & + \sum_{et\in ET}\sum_{et\in ET} c_{et,y}^{emission}\ \forall\, y \in Y \end{aligned} \tag{2}$$

where $c_y^{CAP,}$ and $c_y^{OP,}$ are the annualised CAPEX and OPEX for year y for any part of the CCS chain described by the indices: Capture equipment (*capture*) installed to capture CO_2 from stack type j at site i; Liquefaction (*liq*) and on-site storage (*storage,site)* at site i; Truck transportation (*truck*) between site i and transport hub l; Storage tanks (*storage,hub*) at transport hub l; and ship transportation (*ship*) to the storage location from transport hub l. The term $c_{et,y}^{emission}$ is the yearly cost of emitting CO_2 (of either biogenic or fossil origin, denoted by *et*) in year y, which is relevant for carbon pricing.

2.2. System description

Fig. 1 describes the industrial sites, potential transport hubs and ship transportation routes included in the modelling. Table 1 lists the yearly fossil and biogenic CO_2 emissions and the amounts that would be captured with a 90 % capture rate (some stacks are not considered for capture due to a low flow or concentration of CO_2).

The considered system includes Swedish industries that emit more than 100 $ktCO_2$/y, including both fossil and biogenic emissions. The pulp and paper, cement, chemical, refinery, steel and heat and power sectors are represented in the system. While CCS is not the only mitigation route for some sectors of the Swedish industrial system (for example, the iron and steel industry), the system serves as a representation of a distributed CCS system. Since the Swedish system is special in that a large majority of the emissions are of biogenic origin (mainly from the pulp and paper industry), one case is modelled in which the pulp and paper industry is excluded, to illustrate the influence on the results of not having as large biogenic emissions within the system. In this work, we define BECCS as CO_2 capture on any biogenic source of emissions, in contrast to only including CCS on bio-to-energy plants. This expands the definition of BECCS to include capture on biogenic CO_2 sources in other industries than heat and power, e.g., pulp and paper mills.

The modelled period is 2025–2050 with yearly time-steps. It is assumed that the industrial system, including existing plants, production, and, thus, emission levels, are maintained throughout the modelling period.

The model considers CO_2 capture at stack-level; the sites included in the model have 1–3 stacks, depending on the industry sector. After capture, the CO_2 is liquefied in preparation for intermediate storage and transportation. Trucks transport the CO_2 from the liquefaction plant to a transport hub, and ships transport the CO_2 from the transport hub to Kollsnes in Norway. In the model, ships are purchased in integer steps of a fixed size, in contrast to truck capacity, which is purchased linearly.

Table 2 lists the parameters included in the modelling to determine the site-specific costs for capture, liquefaction, storage tanks, and ship and truck transportation. Since the model may choose to incur costs in the future we need to account for the value of money over time. The discount rate used in the modelling is set to 5 % for the base case, whereas it is varied between 0 % and 15 % in the sensitivity analysis. The 5 % discount rate in the base case represents a social planner perspective, and not necessarily the investment conditions by the industry. However, a sensitivity analysis on the discount rate is performed since this parameter will have a large impact on the time-evolution of the CCS system.

The CO_2 capture performance (in terms of capture rate and specific heat demand) are based on the absorption process using an MEA-based

Table 1
Total emissions (in Mt/y) from the sites included in the system and the amounts of emissions that it is possible to capture with a capture rate of 90 % and excluding stacks that are unsuitable for capture implementation.

	Biogenic CO_2 [Mt/y]	Fossil CO_2 [Mt/y]
Total emissions	35	12
Capture potential	31	9
Capture potential, excluding the pulp and paper industry	11	9

Table 2
Input data and assumptions for capture, liquefaction, and truck and ship transportation used as parameter values in the model.

Parameter	Value	Unit
Capture		
Lifetime	25	years
Specific reboiler heat demand	3600	kJ/kg
Steam cost	30	€/MWh
Operation and maintenance cost	5	% of CAPEX yearly
Liquefaction		
Lifetime	25	years
Operating cost	9	€/tCO_2 liquefied
Intermediate storage tanks		
Lifetime	25	years
Investment cost	5	k€/tCO_2 storage capacity
Operation and maintenance cost	4	% of CAPEX yearly
Truck transportation		
Lifetime	10	years
Average truck speed	50	km/h
Distance adjustment factor	1.3	
Fuel consumption	0.5	l/km
Loading/unloading time	0.5	h
Driver salary	90	k€/(driver*year)
Fuel cost	1.4	€/l
CAPEX	320	k€/truck
Maintenance cost	5	% of CAPEX yearly
CO_2 carrying capacity	38	tCO_2/truck
Ship transportation		
Lifetime	25	years
Average ship speed	26	km/h
Distance adjustment factor	1.1	
Fuel consumption	0.835	t/h
Loading time	8	h
Unloading time	15	h
Fuel cost	420	€/t

solvent. The distances between the sites, hubs and storage location are measured in a GIS software and adjusted with the distance adjustment factors for trucks and ship shown in Table 2. Intermediate storage tanks are needed at each site, due to the use of trucks for land transportation, and at the transport hubs along the coasts, i.e., to be able to hold the CO_2 before ship transportation. On-site storage is designed to hold 24-hours of captured CO_2. Storage tanks at the transport hubs are assumed to hold 120 % of the capacity of a ship (20 % margin above the theoretically needed capacity).

Table 3 shows the CO_2 concentrations and the biogenic shares of the total emissions for the stacks considered in the modelling. The data are taken from Chalmers Industrial Case Study Portfolio (see Svensson et al. (2019), Garðarsdóttir et al. (2018) and Beiron et al. (2022)). For process industries, it is assumed that yearly production and emissions levels are evenly distributed over 8000 h. The CAPEX values for capture and liquefaction at process industries are calculated based on modelling work of Eliasson et al. (2022), and they depend on the volume of the captured CO_2 flow and its concentration. For CHP plants, the CAPEX values for capture and liquefaction are taken from Beiron et al. (2022), and are dependent upon the peak flow of CO_2, varying depending on how the plant is operated.

2.3. Scenarios and cases

Table 4 lists the six modelling setups investigated in this work. Two main "*Scenarios*" for incentivising CCS on fossil fuels are evaluated: CO_2 pricing; and a fixed emissions budget for the investigated period. Both scenarios are implemented for a series of "*BECCS Cases*" with and without the possibility for the model to account for captured biogenic CO_2 as negative emissions. In this work, it is assumed that biogenic CO_2 emissions (originating mainly from the pulp and paper and heat and power industries) included in the modelling are climate neutral and thus, that captured biogenic emissions from these CO_2 sources leads to negative emissions. The Swedish pulp and paper and heat and power industries source their biomass from forestry and the biomass used for energy purposes are waste streams. In the pulp and paper industry most of the steam generation stem from combustion of black liquor, burned primarily for the purpose of chemical recovery, and to some extent from combustion of bark generated from de-barking of trees. In the bio-fired heat and power plants, mainly wood chips produced from forestry residues in the form of branches and tops are used. Thus, no biomass is directly grown and harvested for energy purposes which could lead to potential land use conflicts that in turn could lead to reduced emissions performance of the biomass. Rather, in the Swedish forestry industry the harvested wood is used according to a cascading principle, where the primary products are construction materials, followed by pulp for paper manufacturing and in a final step, the rest products are combusted to generate heat and power.

Table 3
CO_2 concentrations and biogenic shares of the total emissions for the stack types used in the model.

Stack type	CO_2 concentration [%]	Biogenic share of total emissions [%]
Pulp and paper, recovery boiler	13	100
Pulp and paper, lime kiln	20	100
Pulp and paper, other	13	100
Cement, combined stack	20	10
Refinery, hydrogen production unit	24	0
Refinery, other	13	0
Iron and steel, power plant	30	0
Iron and steel, other	20	0
Chemicals, cracker furnace	5	0
Heat and power, waste	13	65
Heat and power, bio-based	13	100

Table 4
Scenarios investigated in this work. The scenario description presents the incentives that are implemented to motivate investments in CCS equipment. The BECCS case description details how BECCS is handled for the cases, and the sensitivity case shows for which Scenarios and BECCS cases the limits on capacity growth and exclusion of the pulp and paper industry are modelled. For the CO_2 pricing scenario, the cost of emitting fossil CO_2 starts at 60 €/tCO_2 and increases according to the Net Zero Emissions by 2050 (NZE) scenario in the World Energy Outlook (WEO) (International Energy Agency 2021).

Scenario	Scenario description	BECCS case	BECCS case description	Sensitivity case
CO_2 pricing	60–220 €/tCO_2. Increasing throughout the period according to WEO NZE scenario.	A	BECCS generates no value	Base case, Capacity growth limit
		B	BECCS generates value equal to cost of emitting fossil CO_2; unlimited.	Base case, Capacity growth limit
		C	BECCS generates value equal to cost of emitting fossil CO_2. Limited to not exceed yearly fossil CO_2 capture.	Base case, Capacity growth limit
		D	BECCS generates value equal to cost of emitting fossil CO_2. Limited to not exceed cumulative fossil CO_2 capture.	Base case, Capacity growth limit
Emissions budget (whole period up to 2050)	Allowed emissions of 25, 50, 75, 100, 150, and 200 Mt of mitigatable CO_2 over the modelled period	A	BECCS does not count towards emissions budget	Base case, Capacity growth limit, pulp and paper industry excluded
		B	BECCS counts towards emissions budget	Base case, Capacity growth limit, pulp and paper industry excluded

For BECCS cases B–D in the CO_2 pricing scenario, it is assumed that each tonne of biogenic CO_2 generates a value equivalent to the cost of emitting one tonne of fossil CO_2. Two limitations regarding the amount of BECCS (BECCS cases C and D) are considered in the CO_2 pricing scenario. In BECCS case B, all the captured biogenic CO_2 will generate value for the model without any requirement for mitigating fossil fuel emissions, in addition to whatever is the optimal solution considering the price of CO_2 emissions. BECCS cases C and D require that for each tonne of biogenic CO_2 that is captured, there needs to be at least one tonne of fossil CO_2 captured. This limitation is put in place so as to divert the model away from an over-reliance on BECCS. In BECCS case C, for every time-step, the amount of BECCS must be lower than or equal to the amount of fossil CO_2 captured in the system. In BECCS case D, the amount of BECCS for the period 2025–2050 cannot be higher than the accumulated level of capture of fossil emissions during the period 2025–2050.

The emissions budget scenario limits the accumulated fossil emissions from the system during 2025–2050, and considers six emissions budgets (i.e., allowed emissions) of 25, 50, 75, 100, 150 and 200 MtCO_2. The rationale for modelling a wide range of emissions budget sizes is to identify trends in the systems development trajectories when moving from stricter to less-strict emissions budgets, or having a larger or smaller share of the mitigation performed by CCS. The emissions budget encompasses all fossil emissions from the modelled industrial sites that could be mitigated using CCS. In BECCS case A, only fossil CCS can be used as mitigation to fulfil the carbon budget, whereas in BECCS case B, BECCS can be used in addition to CCS on fossil emissions.

Two cases are included in the sensitivity analysis: one with limitations as to the installation rate of capture capacity; and one without the dominating biogenic emissions from the pulp and paper industry in Sweden. The growth rate of the installed capacity is limited so that full capture from the entire industry system cannot be achieved before Year 2045 if implementation is started in Year 2025. This results in the installed capture capacity for each year (y) being limited to 112 % of the capacity in the previous year (*y-1*) plus 0.5 Mt, according to Eq. (3):

$$CaptureCapacity_y = CaptureCapacity_{y-1} * 1.12 + 0.5[\mathrm{MtCO_2}\ \text{installed capture capacity}] \quad (3)$$

This capacity growth limit scenario is modelled for both the CO_2 pricing scenario and the emissions budget scenario. The second sensitivity case excludes the pulp and paper industry from the analysis, so as to evaluate the system build-up when the emissions from the system are not dominated by biogenic CO_2, this is only modelled for the emissions budget scenario.

3. Results and discussion

3.1. CO_2 pricing scenario

Fig. 2 shows the annual levels of CO_2 captured for the base case and BECCS cases A-D (Fig. 2, a–d) in the CO_2 pricing scenario. In BECCS case A, mainly fossil CO_2 is captured, as there are no incentives for BECCS. However, some biogenic emissions are captured (albeit at levels that are too low to be visible in Fig. 2a), as the cement plants where capture is implemented emit a small fraction of biogenic CO_2. In BECCS case B, which includes BECCS at a value equivalent to the cost of emitting fossil CO_2, there is extensive implementation of capture in the large Swedish biomass-using sectors, i.e., the pulp and paper industry and waste- and bio-fired CHP plants. In the absence of any limits on the amount of BECCS, there is significant generation of negative CO_2 emissions from the Swedish industrial system, which then requires external (from outside the modelled system) financing, for example, from other sectors or countries. BECCS case C results in the implementation of capture from all large fossil emitters, several waste-fired CHP plants, and eight large pulp and paper mills. Most of the fossil CO_2 emissions from the included sites are captured. BECCS case D results in early implementation of capture from large fossil emitters, with biogenic capture being delayed slightly. This is because carbon removals via BECCS can be calculated cumulatively over the period, which leads to later implementation of

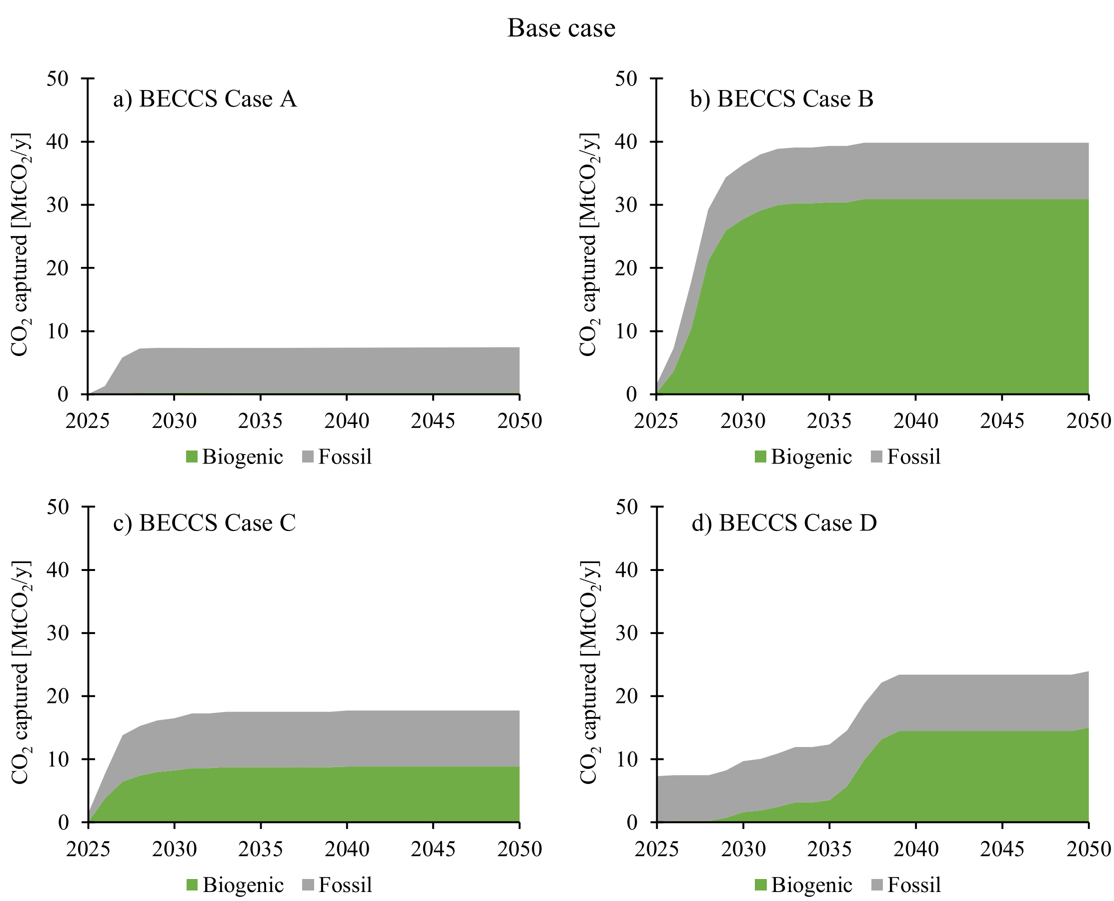

Fig. 2. Levels of CO_2 captured over time in the CO_2 pricing scenario for the base sensitivity case and BECCS cases A–D.

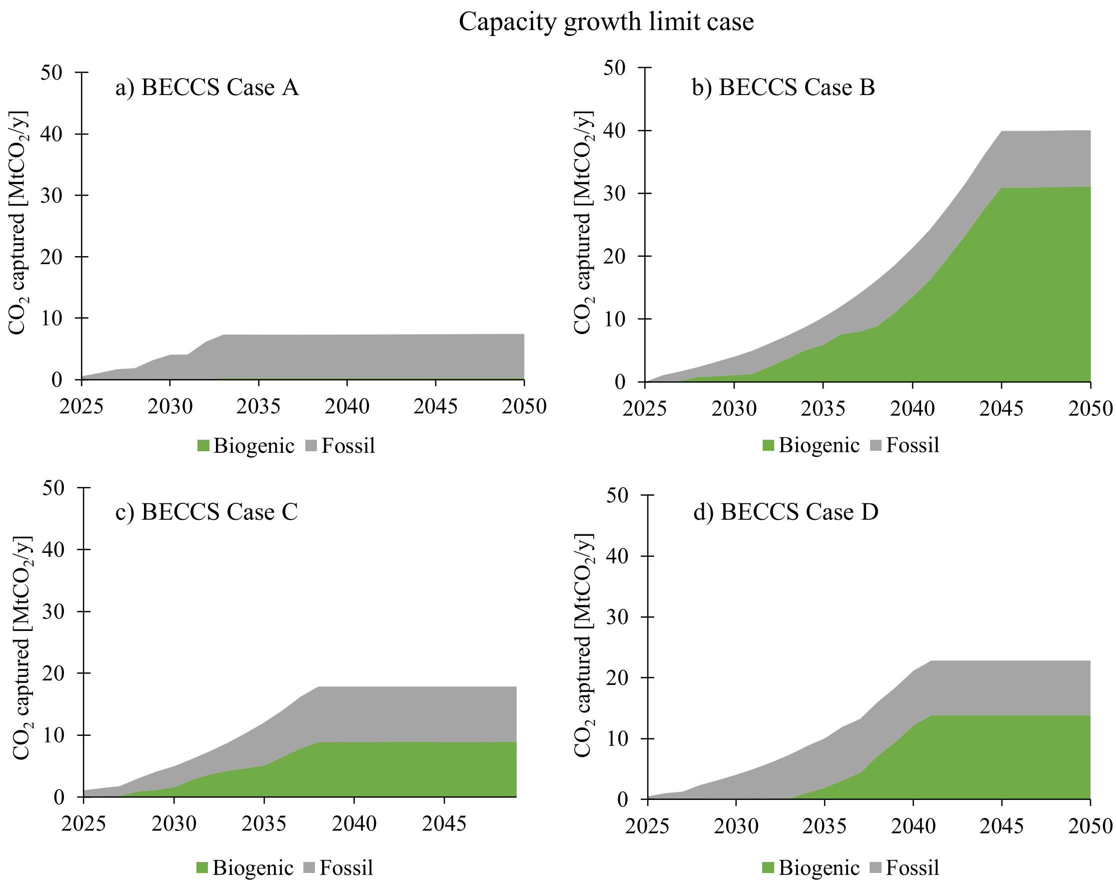

Fig. 3. Levels of CO_2 capture over time in the CO_2 pricing scenario for the capacity growth limit sensitivity case and for BECCS cases A–D.

BECCS, which in turn leads to a lower net present cost.

Fig. 3 shows the annual levels of CO_2 capture for the capacity growth limit case and BECCS cases A–D (Fig. 3, a–d). In contrast to the base case, for which deployment of capture is very rapid, the limit imposed on capture capacity growth becomes the determining constraint for how fast the system develops, rather than the cost of emitting CO_2 reaching threshold values at which large investments are made. In reality, there will be some ramp-up time for a technological development of this scale. These results, where an arguably fast maximum ramp-up rate is imposed on the system and determines the development of the system over time, indicate that deployment of CCS technologies should be started in the near term, so as to end up with a system that exerts cost-efficient mitigation.

Fig. 4 compares the timing of the implementation of transport hubs in the CO_2 pricing scenario and the base case between BECCS cases C and D. Although BECCS case C and BECCS case D are similar in principle (fossil capture must be greater than or equal to biogenic capture), the timing of the implementation, especially that of biogenic capture, differs greatly and this has serious implications for which transport hubs are used and at which point in time they will be utilized. The transport hubs that are implemented on the east coast during the period 2036–2038 in BECCS case D are located in close proximity to large pulp and paper mills that are used for the capture of biogenic CO_2 later in the period.

3.2. Emission budget scenario

Fig. 5 shows the levels of fossil and biogenic CO_2 that are captured in the base case for the emissions budget scenario in BECCS case A (fossil only) and B (BECCS is included in the emissions budget) and the emissions budget sizes (25–200 MtCO_2) investigated. In BECCS case A, in which BECCS is not accounted for in the emissions budget, there is cost inefficiency in that the biogenic CO_2 is captured as a result of full capture from waste-fired CHP plants and cement plants, especially when applying a strict emissions budget. The biogenic CO_2 is captured because it is mixed with the fossil CO_2 captured from waste-fired CHP plants and cement plants which are using a fraction of bio-based fuels. Biermann et al. (2020) have highlighted the importance of allocating green carbon atoms in industrial plants that are co-processing biogenic and fossil feedstocks, and they have recommended that policies should have some leeway in the allocation of emissions savings to low-carbon products. The reasoning behind this is that such allocation schemes would facilitate the implementation of low-carbon technologies by creating market opportunities. An analogy can be made to carbon captured from waste-fired CHP plants and cement plants that are emitting a mixture of biogenic and fossil CO_2. If industries were allowed to allocate freely the fossil carbon to the captured CO_2, the cost would be lowered because the system could be dimensioned after the fossil share in case A. In case B, when allowing for BECCS in the emissions budget, the cost efficiency is increased because all the captured CO_2 has a “value” for the system, given that both biogenic CO_2 and fossil CO_2 contribute to fulfilling the carbon budget.

Fig. 6 shows the system net present cost with and without allowing for BECCS in the emissions budget. It is clear that allowing for carbon removal with BECCS reduces the cost for all carbon budgets; however, the possibility to compensate with BECCS pushes the system towards less fossil mitigation and postpones investments in the carbon capture equipment and transportation infrastructure. The inclusion of BECCS in emissions budgets may, therefore, create a reliance on carbon removal that is reasonable from a system cost perspective but is sub-optimal from a resource utilisation perspective. In addition, in the modelling, allowing for BECCS in the emissions budgets pushes the mitigation of fossil fuel emissions into the future, which is undesirable and would need to be

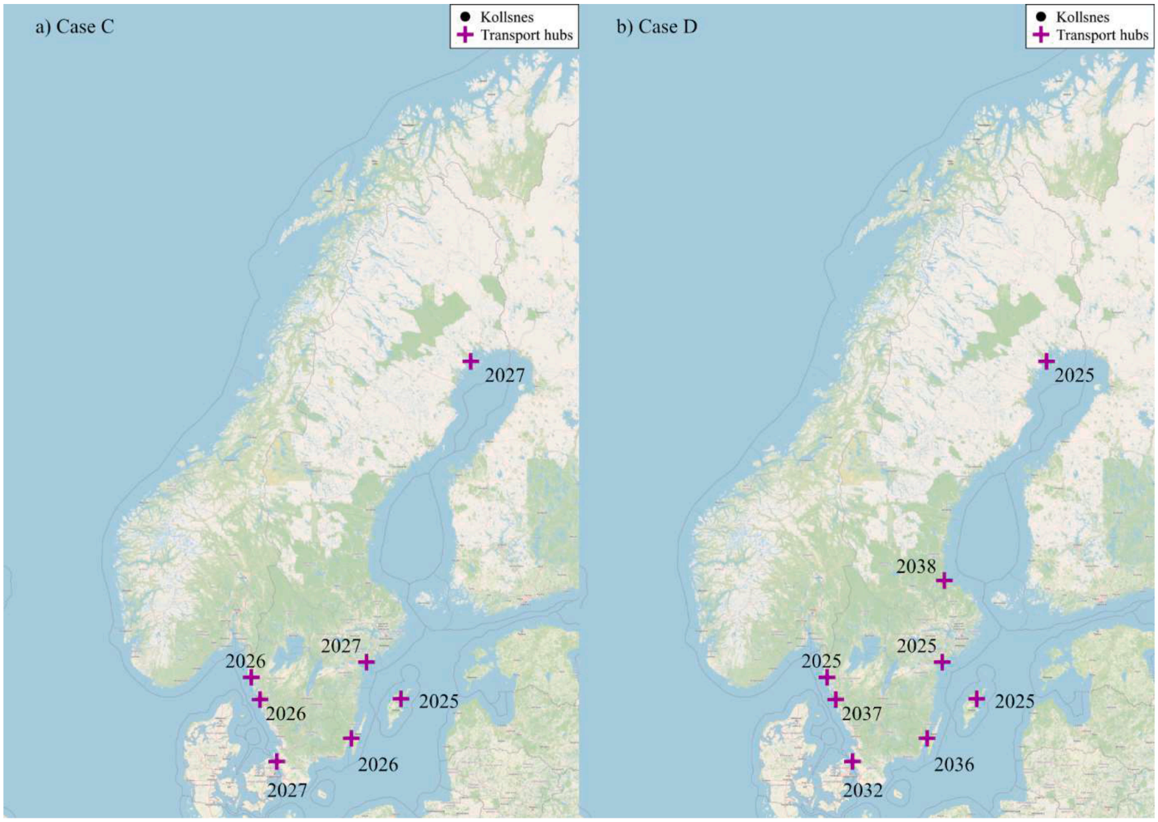

Fig. 4. Locations of the transport hubs and the year from which they are used in the CO_2 pricing scenario in the base case and in: a) BECCS case C; and b) BECCS case D.

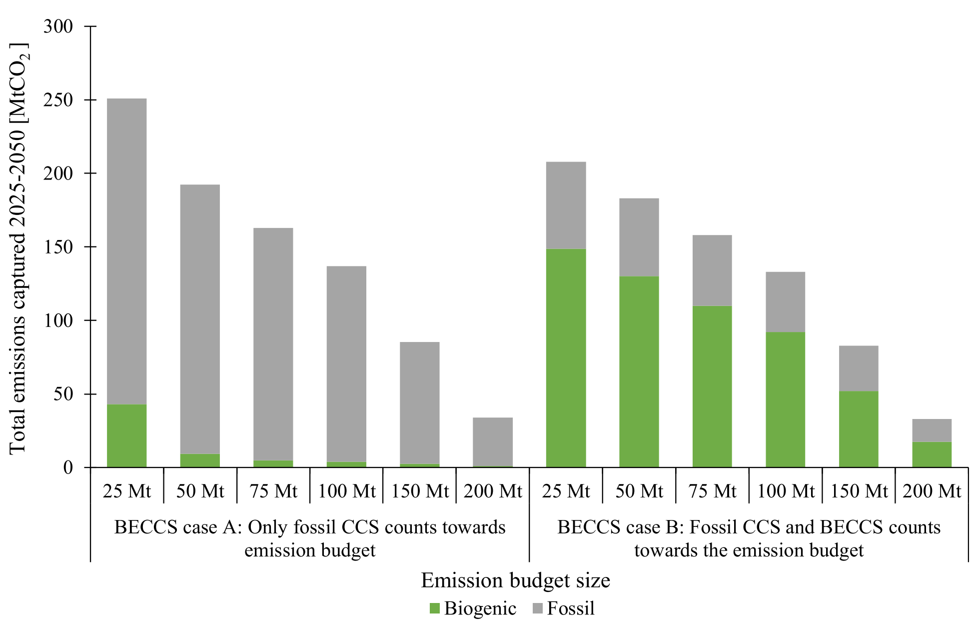

Fig. 5. Total amounts of fossil and biogenic CO_2 captured over the modelled period (2025–2050) in the emissions budget scenario for the different budget sizes (25–200 $MtCO_2$), with and without BECCS being included in the budget. Total emissions from the system for the studied period are around 1200 $MtCO_2$, out of which around 300 $MtCO_2$ are of fossil origin.

countered by specific policy measures. In Sweden, the planned policy structure for incentivising BECCS is for the state to procure BECCS outcomes via a reverse auctioning system. Such a policy would overcome the risk of delaying fossil fuel mitigation shown in this work, although there are other potential challenges with such a system. For instance, it entails a direct cost for the taxpayer which might be untenable in the long term, and creates a limited demand for BECCS in contrast to what could be achieved if CDR was integrated in a broader policy regime for CO_2 mitigation (Zetterberg et al., 2021). As shown in Fig. 6, the difference in net present cost between the case with and

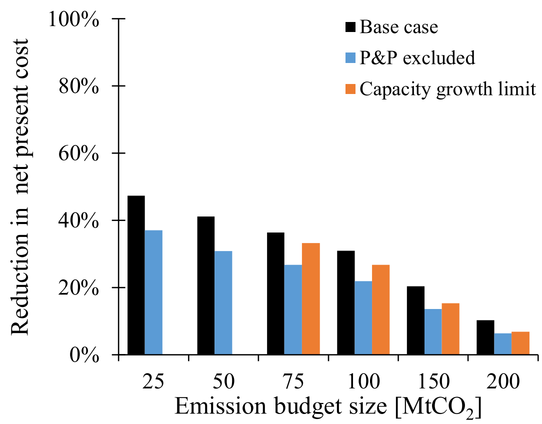

Fig. 6. Reductions in the net present cost of the system if allowing for carbon removal through the application of BECCS for closing the carbon budget for carbon budgets of 25–50 Mt for the period 2025–2050. The capacity growth limit case is not included for emissions budgets of <75 Mt, since these budgets cannot be fulfilled with the chosen growth rate.

without BECCS decreases with the size of the carbon emissions budget. The more carbon emissions that are allowed, the lower becomes the value of including BECCS. This is mainly due to two reasons:1) the stricter the budget, the more capture is needed, meaning that smaller emissions sources need to be included to meet the budget, while conversely a less-strict budget allows the focusing of capture on larger sources with a lower specific cost; and 2) a less-strict budget allows the model to postpone investments further, such that combining this with the inclusion of BECCS (more point sources to choose from) means that the model can take more investments later in the period and, thereby, achieve a lower system net present cost.

Fig. 7a–d show the levels of CO_2 captured over the modelled period in the emissions budget scenario for BECCS cases A and B in the base case (Fig. 7, a and b), as well as the sensitivity cases concerning limited capture capacity growth rate (Fig. 7c) and exclusion of the pulp and paper industry (Fig. 7d). The results are shown for an emissions budget size of 100 $MtCO_2$. Comparing panels a and b in Fig. 7, the magnitudes of the investments (see the yearly CO_2 capture) differ by a factor of about four. This is mainly due to the extensive and rapid implementation of BECCS in the pulp and paper and heat and power industries (Fig. 7b). Although such a late and rapid ramping up might be logical from a cost perspective, there is a clear issue with pushing the problem of mitigating emissions forward in time and creating such a heavy reliance on carbon removal. This is especially the case given that the likelihood of being able to ramp up to the required extent is low, as we see that the allowed growth rate becomes the limiting factor for implementation in Fig. 7c. Imposing a limit on the growth rate of the capture equipment in the system (Fig. 7c) makes the ramping up less dramatic, although the same trend is noted as in Fig. 7a. Investments are made as late as possible, and large amounts of BECCS are used to compensate for earlier fossil emissions. The implementation of large-scale CCS systems is likely to be associated with ramping up, and the type of "just in time" implementation seen in Fig. 7b will not be possible even with an arguably rapid growth rate, as seen in Fig. 7c. To ensure that investments are made to initiate the construction of a CCS system in time to meet emissions targets, specific targeted policy measures, could be used. When the pulp and paper industry is excluded (Fig. 7d), more capture equipment is installed in the waste-fired heat and power sector to capture both fossil and biogenic CO_2. These sites are typically smaller than the pulp and paper mills in the system, and as such, represent a slightly higher cost for the system. Although both sensitivity cases reduce the

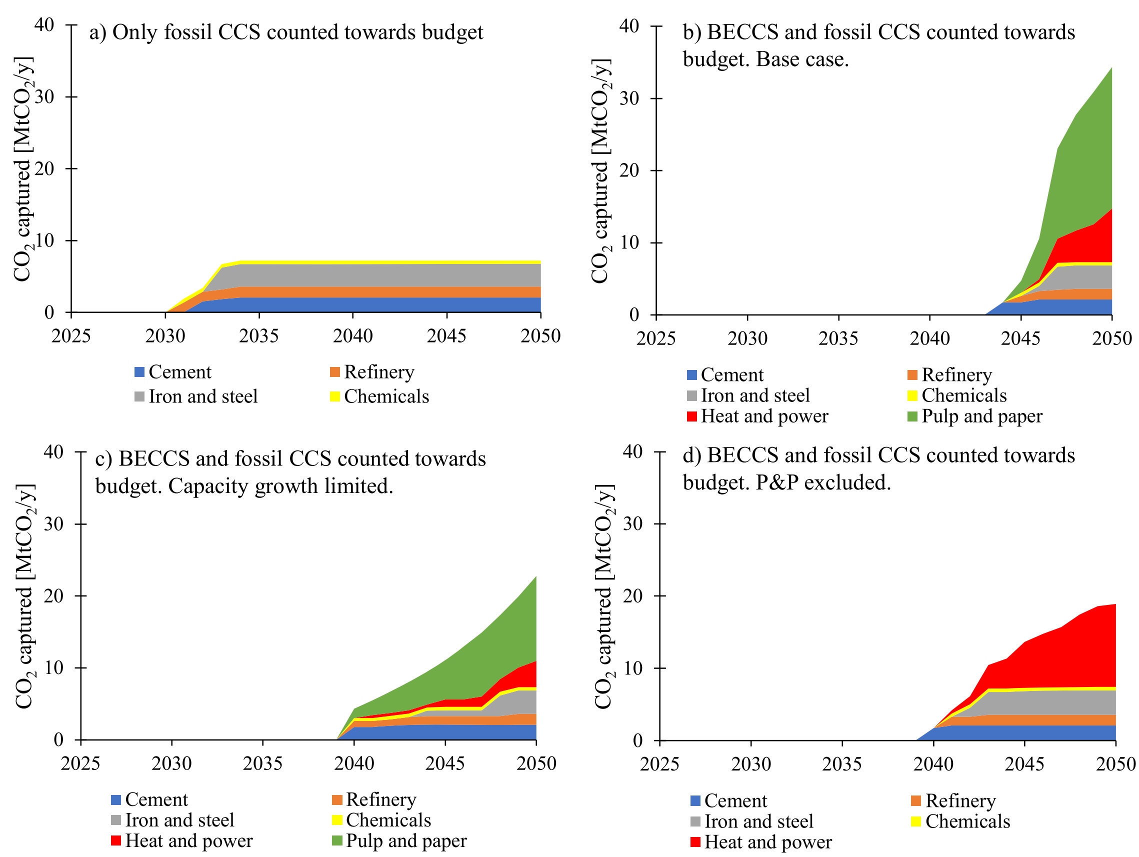

Fig. 7. Levels of CO_2 capture over time in different sectors comparing: a) BECCS case A; b) BECCS case B; c) BECCS case B with limits on capacity growth; and d) BECCS case B with the pulp and paper industry (P&P) excluded, in the emissions budget scenario with a 100 Mt emissions budget.

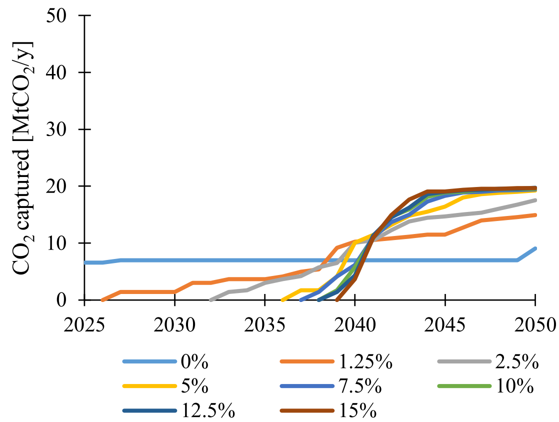

Fig. 8. Levels of CO_2 captured over the modelled period for an emissions budget size of 50 Mt and different discount rates.

reliance of the system on BECCS to compensate for early emissions, excluding the pulp and paper industry is the least-reliant on BECCS, which is reflected by the lowest cost reduction for this case (Fig. 6).

3.3. Sensitivity to discount rate

Fig. 8 shows the levels of CO_2 capture over time for an emissions budget of 50 Mt, including BECCS in the base case, for discount rates in the range of 0 %–15 %. The results show that the extent to which the investments are postponed depends largely on the discount rate, since this strongly influences the net present cost of the system, the minimisation of which is the objective of the model [see Eq. (1)]. In essence, this shows that economic assumptions made has a strong impact on the timing of cost-optimal CCS implementation. Another perspective is that many industrial actors perform investment calculations with relatively high discount rates (8 %–15 %), due to the technological uncertainties and financial risks faced when considering CCS as an alternative for emissions reduction. This could in turn could lead to CCS investments appearing to be economically unfavourable and postponing investment appearing to be preferential. In the modelling we observe that using a discount rate of 15 % instead of 5 % postpones the investments in CCS technology by about three years. The effect of discount rate on the timing of investments is limited for discount rates above 5 % since investments must happen at a certain point for the system to be able to stay within the emissions budget. Fig. 9 shows the reduction in system net present cost from including BECCS in accordance with the base case, for a 50 Mt emissions budget for discount rates in the range of 0–15 %. The higher the discount rate, the higher the value associated with including carbon removal in the emissions budget, since the model is more inclined to postpone investments in mitigation measures and compensate later with BECCS. The cost reduction does however decrease slightly as the discount rate is increased, as the investments cannot be postponed beyond a certain limit while staying within the emissions budget.

4. Conclusion

This work applies a cost-optimisation model to investigate the influences of policy design for CO_2 mitigation on the development, size, and configuration of CCS systems, using the Swedish industry as a case study. The results show that when implementing CO_2 pricing, without limiting the rate at which the installed capture capacity can be expanded, the deployment of capture occurs rapidly once the price of emissions reaches a threshold level. When limiting the potential deployment rate of the capture equipment, this limit becomes the determining constraint for how rapidly the system expands. This shows that cost-optimality alone is not enough for efficient implementation but that other mechanisms are required to incentivise and initiate timely deployment.

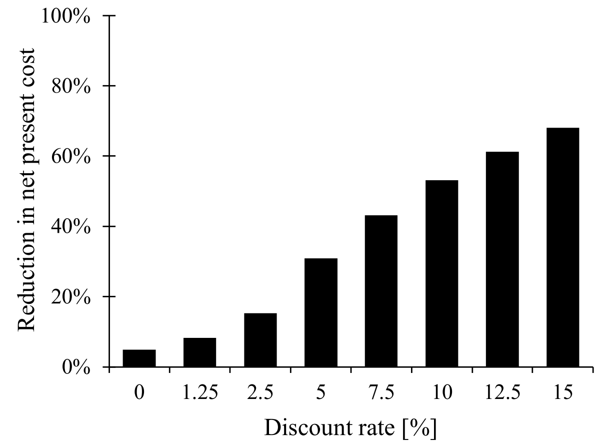

Fig. 9. Reduction in net present cost of the system derived from including BECCS in the modelling of a 50-Mt emission budget and discount rates in the range of 0 %–10 %.

In an industrial system with considerable biogenic emissions, such as Sweden, accounting for BECCS (i.e., CDR) in emissions budgets reduces the net present cost of the system by 5 %–50 %, depending on the size of the emissions budget. The reduced cost is caused by 1) including more sites (i.e., with biogenic emissions) with relatively low investment costs for CCS, and 2) postponing investments in fossil mitigation by compensating with BECCS at a later point in time, which reduces the net present cost. Excluding the pulp and paper industry from the analysis reduces the value of accounting for BECCS in emissions budgets by around 20–40 % compared to the base case. The net present cost and, thus, the value of postponing investments is largely dependent upon the discount rate. Varying the discount rate from 5 % to 15 % delays capture implementation by three years.

CRediT authorship contribution statement

Sebastian Karlsson: Methodology, Writing – original draft, Visualization. **Fredrik Normann:** Conceptualization, Writing – review & editing. **Filip Johnsson:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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