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Modeling the development of a carbon capture and transportation infrastructure for Swedish industry

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ABSTRACT

This work presents and applies a mixed integer programming (MIP) optimization model that minimizes the net present costs for CO_2 capture and storage (CCS) systems for cases with defined emissions costs and/or capture targets. The model covers capture from existing large point sources of CO_2 emissions in Sweden, liquefaction, intermediate storage and transportation using trucks to hubs on the coast, followed by ship transport to a storage location (excluding storage cost). The results show that the capture and transportation infrastructure, in terms of both the sites chosen for capture and the associated transportation setup, differs depending on whether the system is incentivized to capture biogenic or fossil CO_2, or both. Waste-fired combined heat and power (CHP) plants are only chosen for capture at scale when biogenic capture targets and fossil emissions costs are combined, since the emissions from these sites comprise a combination of biogenic and fossil CO_2. The value for the system in mitigating the costs from fossil CO_2 emissions exceeds the increased cost of BECCS at waste-fired CHPs compared to larger pulp mills given the fossil emissions cost development assumed in this work. Although the cost for capture and liquefaction dominates the total cost of the CCS system, it is not the only factor determining the choice of sites for capture. Proximity to transport hubs with short offshore transportation distances to the final storage location is also an important factor. For the transportation infrastructure, it is shown that the cost for ships is the main cost driver.

1. Introduction

Carbon capture and storage (CCS) and bioenergy with carbon capture and storage (BECCS) have been identified as key technologies to achieve deep reductions in carbon emissions from the energy system and carbon-dependent industries. Scenarios considered by the intergovernmental panel on climate change (IPCC) that limit greenhouse gas (GHG) concentrations in the atmosphere in line with the Paris Agreement typically contain high levels of (BE)CCS (Rogelj et al., 2018). In the European Union (EU), it has been proposed that the EU should work towards climate neutrality by Year 2050 (European Comission, 2020). Sweden, which has a target of net-zero GHG emissions by Year 2045, has in a recent public inquiry (SOU, 2020) proposed negative emissions in the range of 3–10 Mt/year by Year 2045, as a so-called ‘supplementary measure’ for offsetting residual emissions from hard-to-abate sectors and to contribute to the target of net-negative emissions after Year 2045. Thus, BECCS is important in generating net-negative emissions and in offsetting hard-to-abate fossil emissions. CCS is, therefore, important for industrial sectors in which fossil emissions are difficult to abate using other technologies, for example in the cement, chemical and petroleum refining industries (IVA, 2019).

Techno-economic analyses of carbon capture facilities are usually carried out on the plant level, with detailed investment cost estimations based on the specific plant configuration and conditions (see for example Biermann et al., 2018; Garðarsdóttir et al., 2018; Johnsson et al., 2020; Martinez Castilla et al., 2019). The specific cost for capturing CO_2 in such studies usually lies in the range of 40–100 €/tCO_2 depending mainly on the size of the emission source, the CO_2 concentration in the flue gas, the potential for utilizing residual heat for the desorption process during post-combustion capture, and the yearly operating time. Kjärstad et al. (2016) investigated potential transportation solutions for CO_2 in the Nordic region and concluded that ship transport is the most-cost-efficient and feasible mode of transportation, especially during a ramp-up phase. Knoope et al. (2015) compared investments in the pipeline and ship transport of CO_2 under uncertainty, and concluded that ships are the preferable mode when transporting low volumes over large distances. Large-scale CO_2 capture and infrastructure developments that consider capture from large European CO_2 emissions

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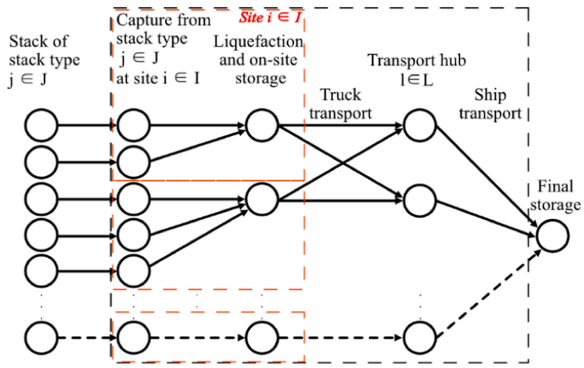

Fig. 1. Flowsheet overview of the model. The black dashed line indicates the parts of the CCS chain included in the cost minimization modeling. The red dashed lines include the parts of the CCS chain that are located at the site i∈I.

sources utilizing transnational pipelines for CO_2 transportation have been studied previously (see Kjärstad et al., 2013; Kjärstad et al., 2014; Morbee et al., 2012; d'Amore and Bezzo, 2017). Some of these works (Kjärstad et al., 2013; Kjärstad et al., 2014; Morbee et al., 2012) have considered capture from large electricity-generating plants and pipeline networks for (cross-border) transportation of CO_2 and potential storage sites on-shore and off-shore. d'Amore and Bezzo (2017) have investigated on-shore and off-shore pipelines, along with ships for CO_2 transportation, for large-scale CO_2 emitters in multiple sectors in Europe. d'Amore and Bezzo (2017) have reported costs in the range of 27–38 €/tCO_2 for a system that captures up to 70% of the total CO_2 emissions of the system over 20 years, and they have concluded that the capture cost dominates the total supply chain costs, with transport and sequestration costs never becoming more than 10% of the total system cost.

In the case of the EU, technological and cost developments in the electricity-generating sector and legal frameworks rendering cross-border transportation and land-based storage of CO_2 difficult have geared recent CCS developments more towards national systems, with capture primarily aimed at industrial sectors with hard-to-abate emissions, incentivized by national policy measures. Such emissions sources may be smaller than large power plants and, thus, the specific costs for capture, transport and storage may be higher, depending on the extent to which transport of CO_2 can be in the form of an integrated system for several capture projects.

This work builds upon previous techno-economic analyses of CCS systems, on both the plant and infrastructure levels, and presents an optimization model for studying the development of regional CCS systems. The model estimates the temporal and spatial distributions of optimal investments in capture technology at existing industrial sites and within the infrastructure. The proposed method is applied to study the impacts of, and relationships between, CCS and BECCS incentives, as well as the influence of the sensitivity to cost parameters in the CCS chain on the cost-optimal development of the CCS system. Since the main decarbonization strategy for the iron and steel industry is in the form of hydrogen-driven steelmaking, we also investigate how the exclusion of the iron and steel industry influences the results. Finally, we use the modeling to investigate how a presumed early implementer of BECCS influences the results.

2. Mathematical model

To study the development of a regional CCS system, we develop and apply a mixed integer linear programming (MILP) optimization model that minimizes the net present value (NPV) of costs for CO_2 capture and infrastructure systems. A complete model description that includes the equations for determining the investments, installed capacity, and costs for individual parts of the CCS chain are given in Appendix A, together with a complete nomenclature. The model is implemented in the general algebraic modeling 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 consists of 335,224 equations and 3215,998 variables and takes around 10 min to solve on an Intel Core i5 processor with 16 GB of installed physical memory and a relative error tolerance of 0.1% i.e., the proportional difference between the solution found by the solver and the best theoretical objective function. In the model, a binary variable is used to control which transport hubs are used (see Eq. (8), which exemplifies the use of this binary variable), and an integer variable is used to control how many ships are invested in to transport CO_2 between the transport hubs and the storage location. Fig. 1 gives an overview of the model. The costs consist of capital expenditures (CAPEX) and operating expenditures (OPEX) for the technologies in the investigated CCS chains, namely, capture, liquefaction, storage (on-site after liquefaction and at transport hubs), trucks and ships. The OPEX parameter consists of different cost items depending on which part of the CCS chain that is considered. For example, the OPEX for CO_2 capture and liquefaction consists of energy costs (dependent upon the captured CO_2 flow) and operation and maintenance costs (dependent upon the installed capacity), while the OPEX for transportation is additionally dependent upon the transportation distance.

The cost of the geologic storage is not included, since it will be the same for all cases (only one location for final storage is considered) and, thus, will only influence the total cost and not the system configuration. Site emissions are divided between multiple stacks located at the sites. Capture is performed on individual stacks and CO_2 liquefaction is performed at the site where it is captured. The system has a fixed number of point sources with the CO_2 available for capture being limited by the present emissions from the given stacks and the capture rate of the CCS technology. The boundary conditions governing the model are the mass balances, emission costs, and capture targets.

The objective function of the model is to minimize the net present value of the sum of all the annual costs for capture and liquefaction installations, transportation infrastructure and emissions costs. The objective function is described as:

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

where $c_{tot,NPV}$ is the net present value of the total cost associated with capture, transportation, and emissions of CO_2 for the entire period investigated, c_y^{annual} is the annual costs, y is the years investigated, and r is the discount rate. The annual costs c_y^{annual} are calculated as:

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

where $c_y^{CAP,}$ and $c_y^{OP,}$ are the annualized CAPEX and OPEX, respectively, in year y for a given part of the CCS chain according to the following 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; transport hubs (*storage,hub*) at, and ship transportation (*ship*) to, the final storage from transport hub l. $c_{et,y}^{emission}$ is the yearly cost of emitting CO_2 of type et (biogenic or fossil) in year y.

The flow of CO_2 in the model is controlled by Eqs. (3)–(6). The captured CO_2 cannot exceed the amount of CO_2 available for capture

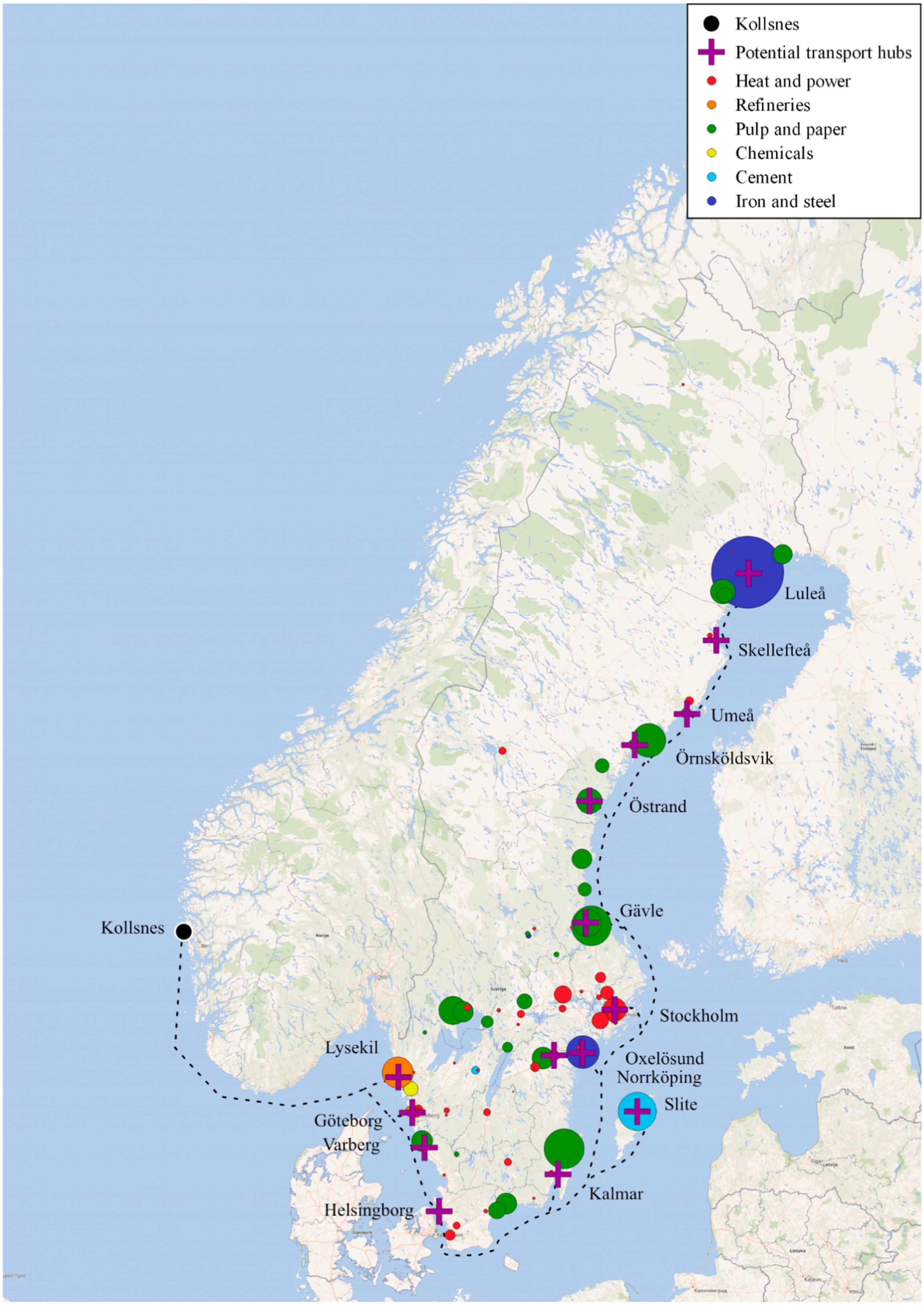

Fig. 2. Industrial sites, locations for transportation hubs and ship routes with investment possibilities for the model. The transport hub location names are given in the figure. The sizes of the industrial sites correspond to the total emissions from the sites, with the smallest site emitting around 100 $ktCO_2/y$ and the largest site emitting around 3300 $ktCO_2/y$.

Table 1
Shares of biogenic carbon, CO_2 concentrations, and values of α and β (according to Eq. (10)) for each stack considered in the model.

Stack	Share of total emissions counted as biogenic	CO_2 concentration [vol%]*	α / β
Pulp and paper, recovery boiler	1	13	1.552 / 0.6339
Pulp and paper, lime kiln	1	20	1.183 / 0.6326
Pulp and paper, other	1	13	1.552 / 0.6339
Cement, combined stack	0.1	20	1.183 / 0.6326
Refinery, hydrogen production unit	0	24	1.183 / 0.6326
Refinery, other	0	13	1.552 / 0.6339
Iron and steel, power plant	0	30	1.183 / 0.6326
Iron and steel, other	0	20	1.183 / 0.6326
Chemicals, cracker furnace	0	5	1.737 / 0.6017
Heat and power, waste#	0.65		
Heat and power, bio-based#	1		
Heat and power, fossil-based	0	13	1.552 / 0.6339

* Chalmers Industrial Case Study Portfolio (for more information, see Svensson et al. (2019)).
\# Cost estimates from Beiron et al. (2022).

Table 2
Economic assumptions made for the capture and liquefaction equipment.

Parameter	Value
Lifetime [years]	25
Operation and maintenance costs for capture [% of CAPEX yearly]	5
Specific reboiler heat demand [kJ/kgCO_2]	3600
Steam cost [€/MWh]	30
Operating expenditures for liquefaction [€/tCO_2]	9

Table 3
Economic assumptions made in relation to the storage tanks used in the modeling.

Parameter	Value
Lifetime [years]	25
Investment costs [k€/tCO_2]	5
Operation and maintenance costs [% of CAPEX yearly]	4

according to Eq. (3).

$$x_{i,j,y} \leq s_{i,j} \ \forall \ i \in I, \ j \in J, \ y \in Y, \tag{3}$$

where $x_{i,j,y}$ is the flow of CO_2 captured at site i from stack of type j and $s_{i,j}$ is the yearly CO_2 available for capture at site i from stack type j. The yearly flow of CO_2 captured at a given site relates to the flow out of the site according to Eq. (4).

$$\sum_{j\in J} x_{i,j,y} \geq \sum_{l\in L} z_{i,l,y} \ \forall \ k \in K, y \in Y \tag{4}$$

where $z_{i,l,y}$ is the flow of CO_2 from site i to transport hub l. The annual CO_2 captured by the system is calculated using Eq. (5).

$$e_{et,y}^{capture,annual} \leq \sum_{i\in I}\sum_{j\in J} x_{i,j,y} \cdot m_{j,et} \ \forall \ y, \ et \in ET, \tag{5}$$

Table 4
Input data and assumptions for the truck and ship transportation calculations performed in the modeling.

Parameter	Value
Truck transportation	
Average speed [km/h]	50
Terrain factor	1.3
Diesel consumption [l/100 km]	50
Loading/unloading time [h]	0.5
Driver salary [k€/(driver*year)]	90
Lifetime [years]	10
Diesel cost [€/l]	1.4
CAPEX [k€/truck]	320
Maintenance cost [% of CAPEX/year]	5
CO_2-carrying capacity [t/truck]	38
Diesel emissions [kgCO_2/l]*	2.7
Ship transportation	
Average speed [km/h]	26
Distance adjustment factor ("Terrain factor")	1.1
Fuel consumption [t/h]	0.835
Loading time [h]	8
Unloading time [h]	15
Lifetime [years]	25
Fuel cost [€/t]	420
CAPEX [M€/ship]	44.3
Operating and maintenance cost [% of CAPEX/year]	4
Ship capacity [t]	8625
Harbor cost [k€/stop]	20
Residual fuel oil emissions [kgCO_2/l]*	2.98

*Environmental Protection Agency (2014).

Table 5
Policy scenarios used for the modeling.

Scenario	Fossil CO_2 cost [€/tCO_2]	Biogenic CO_2 capture target 2030 / 2045 [MtCO_2/year]*	Sensitivity cases
1	According to Fig. 3	0	None
2	0	1.8 / 10	None
3	According to Fig. 3	1.8 / 10	Site CAPEX *1.5 Fuel cost*2.0 Heat integration Early mover I&S excluded

* Suggested levels from SOU (2020) (high level for Year 2045).

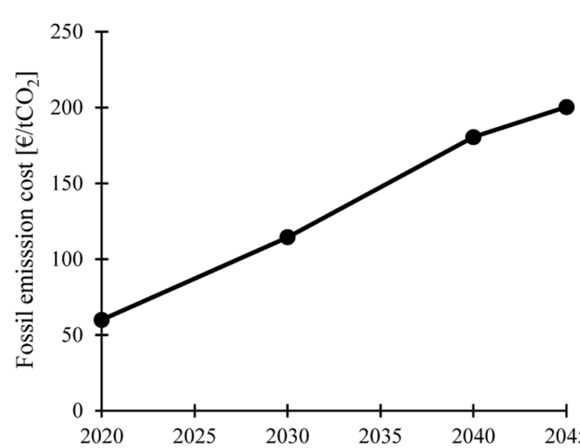

Fig. 3. The cost development trajectory for fossil CO_2 emissions, as given by the Net Zero Emissions by 2050 (NZE) scenario in the World Energy Outlook (International Energy Agency 2021) using a € to USD conversion factor of 0.88 €/USD and linear interpolation between decades.

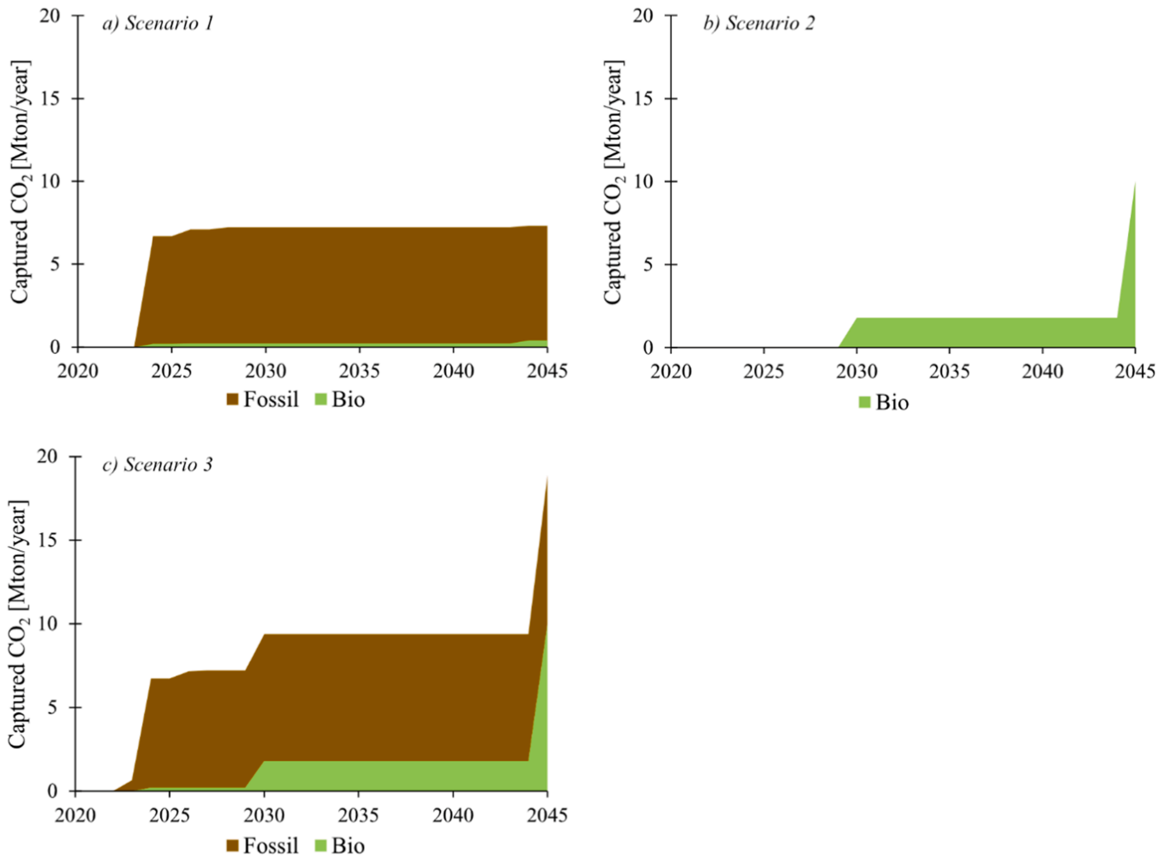

Fig. 4. Amounts of fossil and biogenic CO_2 captured, respectively in Scenarios 1 (a), Scenario 2 (b), and Scenario 3 (c). The sharp increase in the level of biogenic CO_2 captured in Year 2045 is due to the drastic increase in the modeled capture target for Year 2045 (if the time period of the study would have been extended beyond Year 2045, this would be a new plateau similar to the one seen between 2030 and 2044).

where $e_{et,y}^{capture,annual}$ is the annual CO_2 of emission type *et* (biogenic or fossil) captured by the system and $m_{j,et}$ is the share of emissions from stack type *j* that are biogenic or fossil in origin. The capture target for biogenic and fossil CO_2 must be satisfied according to Eq. (6).

$$e_{et,y}^{capture,annual} \geq e_{et,y}^{target} \; \forall \; et \in ET, \;\; y \in Y, \tag{6}$$

where $e_{et,y}^{target}$ is the capture target of CO_2 of type *et* in year *y*. Emissions costs are considered according to Eq. (7).

$$c_{et,y}^{emission} \geq e_{et,y}^{em,annual} \cdot c_{et,y}^{CO_2} \; \forall \; et \in ET, \;\; y \in Y, \tag{7}$$

where $e_{et,y}^{em,annual}$ is the CO_2 of type *et* emitted by the system in year *y* and $c_{et,y}^{CO_2}$ is the cost of emitting CO_2 of type *et* in year *y*. Eq. (8) describes the installed storage capacity at a given transport hub, and exemplifies the use of the binary variable $\gamma_{l,y}$ in the model.

$$b_{l,y}^{storage,hub} \geq u_{storage,hub} \cdot \gamma_{l,y} \; \forall \; l \in L, \;\; y \in Y \tag{8}$$

where $b_{l,y}^{storage,hub}$ is the installed storage capacity at transport hub *l* in year *y*, $u_{storage,hub}$ is the pre-determined size of storage at a transport hub, and $\gamma_{l,y}$ is the binary variable determining whether or not hub *l* is used in year *y*.

3. CCS system and scenario analysis

The development of the CO_2 capture and transportation infrastructure is determined by the mixed integer programming (MIP) optimization model described in the previous section. The model is used for studying the potential synergies between fossil CCS and BECCS implementation and the impacts of cost variations in the CCS chain.

3.1. System description

The modeling considers emissions from Swedish industries and energy plants and CO_2 transportation to storage in the Norwegian North Sea. The sites and potential transport hub locations included are shown in Fig. 2. Process-related industrial sites are included based on their emission of more than 100 ktCO_2/y and being included in the Chalmers Industrial Case Study Portfolio (for more information, see Svensson et al. (2019)). Heat and power plants are included in the modeling based on their emitting at least 100 ktCO_2/y and being included in the paper of Beiron et al. (2022). This results in 86 sites being included in the modeling: 48 heat and power plants, 29 pulp and paper mills, 3 refineries, 3 iron and steel mills, 2 cement plants, and 1 chemical plant. It should be noted that CCS might not be the only relevant mitigation option for the sites in the modeled sectors. For example, the iron and steel industry in Sweden is currently focusing on fossil-free steel production through direct reduction using hydrogen. Nevertheless, mitigation options other than CCS are not included in the model.

The captured CO_2 is transported by trucks on land and with ships offshore. The discount rate used in the modeling is set at 5%. In the modeling, capture can be implemented at individual stacks at a given site (see Fig. 1), and the investment cost for capture depends on the CO_2 flow and concentration from a given stack. The model is limited to yearly time-steps over the period of 2020–2045, with investments and operating costs for sites with industrial processes considered with the assumption that production, and therefore emissions, are evenly distributed over 8000 operating hours each year. For the heat and power sector (which is typically only operated for part of the year), investment

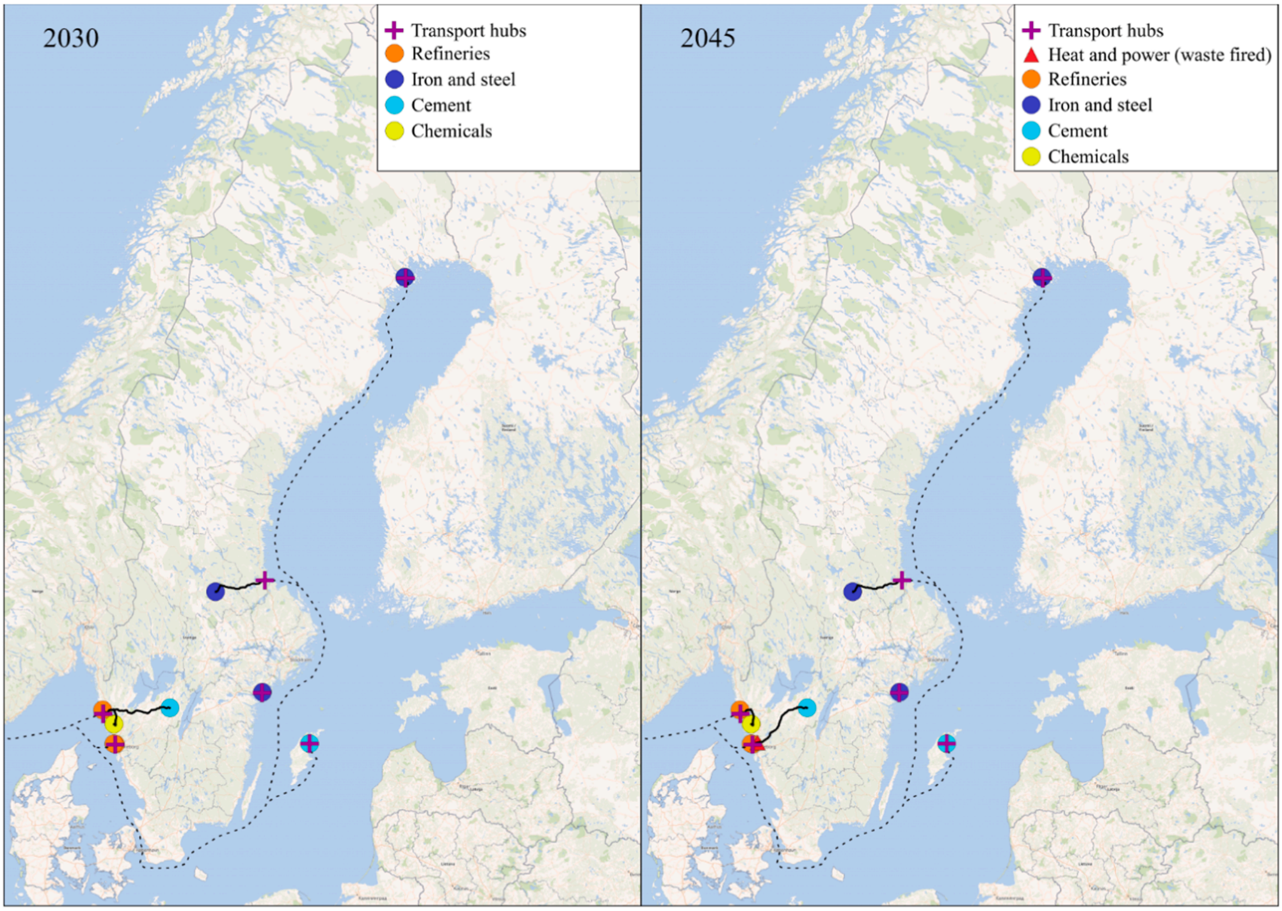

Fig. 5. CCS system in Years 2030 and 2045 for Scenario 1.

costs are related to the peak flow of CO_2 and are taken from Beiron et al. (2022). Yearly capture targets or costs for emitting CO_2 determine CCS implementation in the modeling. At each site, carbon capture may be installed to capture 0%–90% of the emissions from a given stack, and each site has 1–3 stacks from which capture can be performed. A complete list of all the included sites, the stacks at each site, and the site emissions is presented in Table A2 in Appendix A. The modeling considers the current Swedish industries, which are assumed to remain in place and be active until 2045 at the maintained production and emission levels.

It should be pointed out that the present work minimizes the societal cost based on the available cost data and is, therefore, not necessarily representative of the conditions faced by individual companies that implement CCS (e.g., the current *price* offered for transportation by one actor – Stockholm Exergi – seems to be significantly higher than what is obtained from the costs available in the literature).

3.1.1. CO_2 capture and liquefaction

The capture rate and specific heat demand of CO_2 capture are based on absorption in an aqueous monoethanolamine (MEA)-based solvent. The costs for capture and liquefaction equipment are based on Eliasson et al. (2022) for process industries and Beiron et al. (2022) for the heat and power sector. Other technologies for capturing carbon may be more efficient for certain applications, but the MEA-based capture process represents a mature technology and is considered a benchmark technology for carbon capture. In addition, absorption is relatively easy to implement as an end-of-pipe solution for emission mitigation at exiting sites. The CAPEX estimations for CO_2 capture and liquefaction at process industries are based on the above-mentioned work by Eliasson et al. (2022). The expression depends on the CO_2 mass flow, as well as on the CO_2 concentration and is written as follows:

$$CAPEX_{capture\&liquefaction} = \alpha \cdot 10^4 \cdot \dot{m}_{CO_2}^{\beta} [k \in] \quad (10)$$

where the values of α and β depend on the CO_2 concentration in the flue gas. The biogenic carbon shares, CO_2 concentrations, and values of α and β for each stack type in the model are presented in Table 1. The CO_2 concentrations, taken from the Chalmers Industrial Case Study Portfolio, have either been documented in case studies at relevant sites or reported as a general value for an industry of that type. The specific CAPEX (€/tCO_2) used for implementation in the model is calculated based on a CO_2 flow corresponding to a capture rate of 90%. Different policy measures are simulated by the modeling for biogenic and fossil CO_2 emissions. The model distributes emitted CO_2 as biogenic or fossil according to Eq. (5), i.e., it does not optimize the allocation between captured fossil CO_2 and captured biogenic CO_2.

Table 2 lists the general economic assumptions for the capture and liquefaction equipment (not site- or stack-specific). Operating costs for capture comprise the operational and maintenance costs and the cost for steam to regenerate the solvent in the reboiler. After separation, the CO_2 is liquefied onsite in preparation for truck and ship transportation.

3.1.2. Intermediate storage

Intermediate storage is installed at both the site where CO_2 is liquefied and the transport hubs. The cost parameters for storage tanks are listed in Table 3. Intermediate storage at the site is designed to hold the total amount of CO_2 captured in a 24-hour period, while intermediate storage at transportation hubs is designed to match 120% of the CO_2-carrying capacity of the ship, i.e., 20% more than the theoretically required storage capacity. The model chooses between 15 locations for

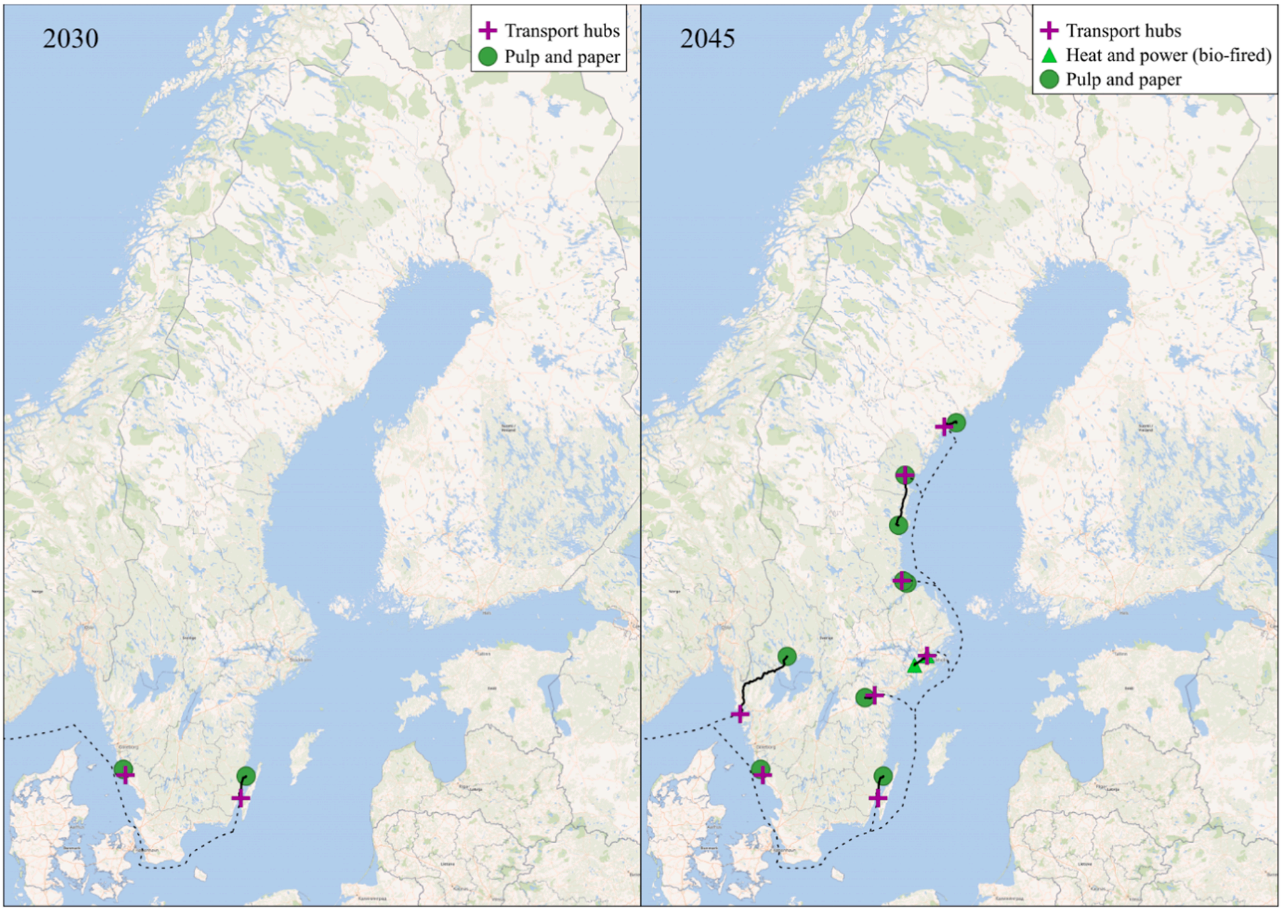

Fig. 6. CCS system in Years 2030 and 2045 for Scenario 2.

investment in transport hubs (the hubs are marked with crosses in Fig. 2).

3.1.3. Transportation

Trucks transport the liquefied CO_2 between the site and the transport hub and ships transport the liquefied CO_2 from the transport hub to Kollsnes, Norway. It should be noted that liquefied CO_2 is currently classified as dangerous goods (Swedish Civil Contingencies Agency 2022), and therefore, trucks carrying CO_2 might need to avoid some routes in urban areas, which could lead to longer transportation distances. At Kollsnes, there will be an intermediate storage unit from which a pipeline will transport the CO_2 to the final storage location beneath the North Sea. As mentioned above, the costs for the intermediate storage in Kollsnes and the storage cost (including the pipeline from Kollsnes to the injection hole) are not included. Ship transport is chosen over pipeline transport based on the studies conducted by Kjärstad et al. (2016), Knoope et al. (2015), and the Norwegian CCS-project Longship (CCS Norway 2021). Ships are purchased in integer steps of a pre-determined size. The assumptions and input data required to determine case-specific costs for truck and ship transportation are presented in Table 4. The assumed diesel cost of 1.4 €/l might seem optimistic at the moment, with prices currently in the range of 2–3 €/l. However, it is uncertain whether the current price levels of transportation fuels are the new normal, or if they will return to lower levels. A sensitivity analysis is therefore carried out on the cost of transportation fuels. The calculated distance between a given site and a transport hub is shown in Table A3 in Appendix A. The distance from each hub to Kollsnes was measured using the GIS software and a terrain factor of 1.1 was used. The transport of CO_2 by trucks and ships contributes to additional CO_2 emissions, and the emissions factors used in this work are presented in Table 4.

3.2. Scenarios

Table 5 presents the three scenarios for capture incentives, including fossil emissions costs and/or capture targets for BECCS, as investigated in this work. Scenario 1 considers only a cost for emitting fossil CO_2, without incentives for BECCS. The fossil emissions cost is shown in Fig. 3 and is based on the Net Zero Emissions by 2050 scenario in the World Energy Outlook (International Energy Agency 2021). Scenario 2 considers capture targets for biogenic CO_2 that are based on a Swedish public inquiry that proposed levels of negative emissions from different technologies, including BECCS (SOU 2020). Scenario 3 combines both of these incentives, i.e., a cost for emitting fossil CO_2 and capture targets for biogenic CO_2. It should be noted that for Scenarios 1 and 3, the model only includes two alternatives for the fossil CO_2 emissions, i.e., investment in CCS to mitigate the emissions or paying the CO_2 emission cost, whereas mitigation options such as electrification and fuel switching are not considered.

A sensitivity analysis for some the parameters given in the rightmost column in Table 3 is performed for Scenario 3. Scenario 3 is chosen because it involves incentives for both fossil and biogenic CCS, and this is likely to be the case for Sweden in the future (EU ETS for fossil CO_2 and proposed BECCS targets, incentivized by a reverse auctioning system, for biogenic CO_2). The sensitivity analysis includes the costs of investments in capture and liquefaction facilities (+50%) (*Site CAPEX*1.5*) and the cost for transportation fuel (+100%) (*Fuel cost*2*). The third (in addition to the *base* case) sensitivity case assumes that 50% of the reboiler steam demand can be covered by residual heat on-site, at no cost (*Heat integration*). The fourth sensitivity case investigates the

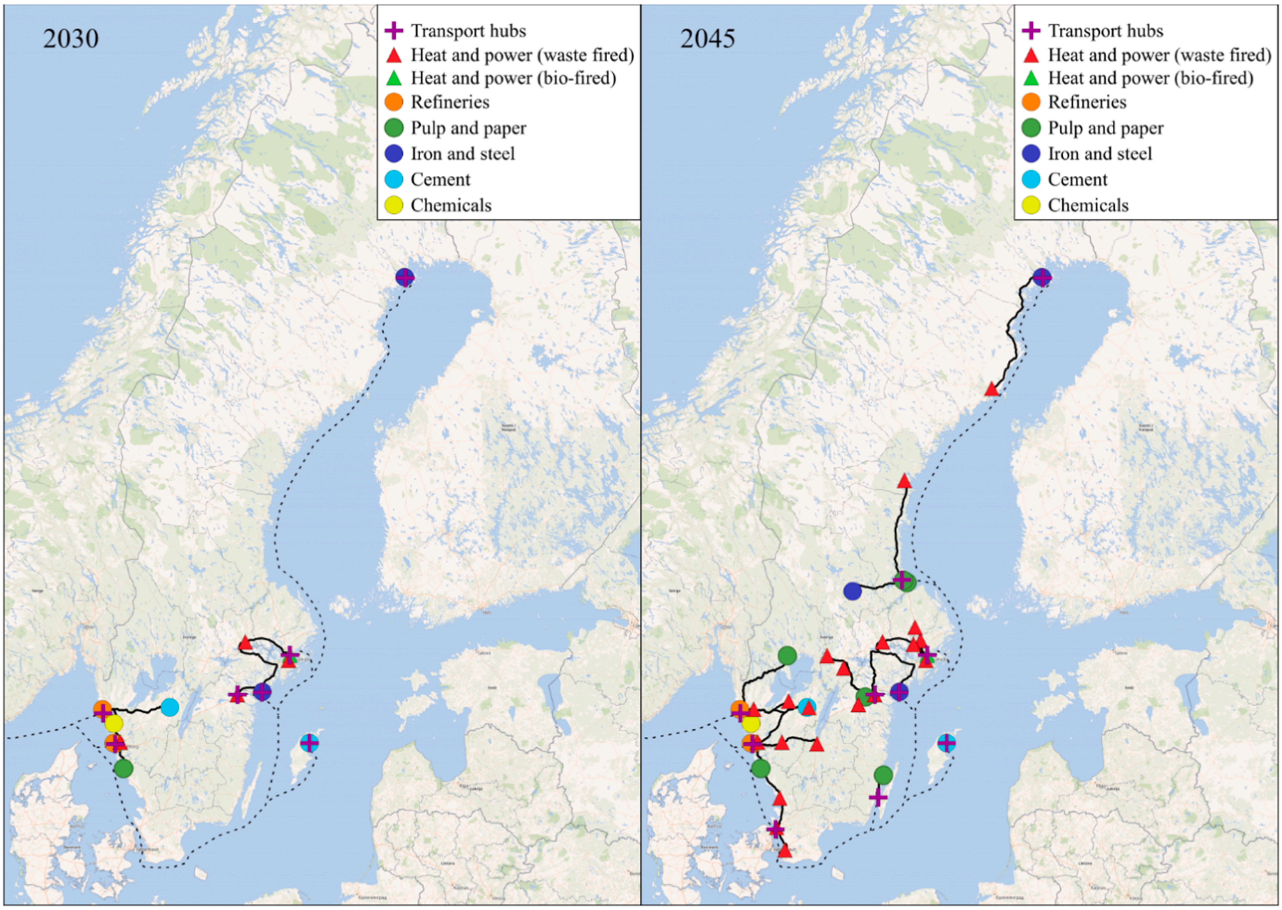

Fig. 7. CCS system in Years 2030 and 2045 for Scenario 3.

Table 6
Infrastructure costs for Scenarios 1, 2 and 3 over the entire modeled period. The specific system cost includes the cost for the entire CCS chain (capture, liquefaction, trucks and ships and intermediate storage) over the modeled period. The specific transport cost includes the costs for trucks, intermediate storage and ships over the modeled period.

Scenario	Specific system cost [€/tCO_2]	Specific transportation infrastructure cost [€/tCO_2]	Truck transport distance [1000*km/MtCO_2]	Ship transport distance [1000*km/ MtCO_2]
1	84	27	927	498
2	83	25	2384	370
3	82	24	1380	419

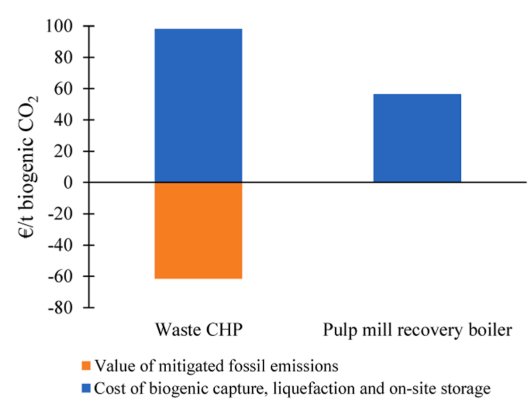

Fig. 8. Costs of biogenic capture and liquefaction, including on-site storage, for the largest waste-fired CHP plant (taken from Scenario 3) and pulp mill recovery boiler (taken from Scenario 2) in the modeling for Year 2030. The value of mitigated fossil emissions (set to the avoided cost for emitting fossil CO_2) is allocated to each ton of biogenic CO_2 captured.

influence on the cost of a so-called "early mover", by assuming that one actor, a bio-based heat and power plant in Stockholm, invests in the capture of 0.5 MtCO_2/year in Year 2022 and captures at least this amount of CO_2 during the period of 2022–2045. The final sensitivity case excludes capture implementation in the iron and steel industry, since the Swedish iron and steel industry is currently aiming to produce fossil-free steel using green hydrogen (*I&S excluded*).

The *Site CAPEX*1.5* is to reflect uncertainties in the investment costs for capture equipment, or conditions faced by industrial actors that use shorter economic lifetimes or higher discount rates for performing investment calculations. For instance, in the case of using the annuity factor method, using a discount rate of 5% and drastically reducing the economic lifetime from 25 to 12.5 years increase the annuity factor, and thus the yearly cost for CAPEX, by around 55%. The *I&S excluded case* is modelled since the Swedish iron and steel industry is currently envisioning a process where iron ore is reduced using direct reduction with hydrogen as a reduction agent. After the direct reduction, the produced sponge iron is melted using electric arc furnaces to produce steel. Thus, CCS is not the primary technological path considered in Swedish iron and steel manufacturing. For the *early mover* case, choosing Year 2022 for BECCS implementation, which is obviously unlikely, ensures that this actor is the first to implement capture, making it possible to judge if this has an impact on the subsequent development of the CCS infrastructure.

Table 7
Indicator values for the CCS system for Scenario 3 and the three studied cost cases. To enable comparison between cases, all values are divided by the amount of CO_2 captured in that case.

	Base case	Site CAPEX* 1.5	Fuel cost*2	Heat integration	Early mover	I&S excluded
Specific system cost [€/tCO_2]	82	94	83	69	84	86
Truck fuel intensity [1000*m^3/MtCO_2]	0.7	0.8	0.5	0.9	1.3	0.9
Ship fuel intensity [kt/MtCO_2]	2.6	2.8	2.6	2.7	2.8	3.1
Infrastructure emission intensity [ktCO_2/MtCO_2]	9.8	10.7	9.4	10.3	11.8	11.7
Capture installations [# of capture installations/MtCO_2]	0.2	0.2	0.3	0.2	0.2	0.3
Fossil CO_2 captured in period 2020–2045 [Mt]	164.1	152.9	156.8	187.5	159.5	99.6
Biogenic CO_2 captured in period 2020–2045 [Mt]	38.3	37.9	38.1	38.8	42.2	38.3
Total CO_2 captured in period 2020–2045 [Mt]	202.3	190.8	194.8	226.3	201.7	137.9

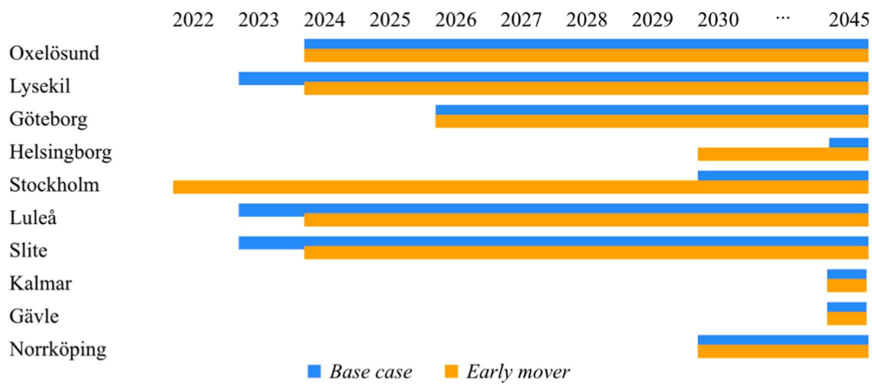

Fig. 9. Timeline of the use of transport hubs in Scenario 3 and the base case (blue), and the early mover case (orange) where a bio-fired CHP plant in Stockholm implements capture in Year 2022.

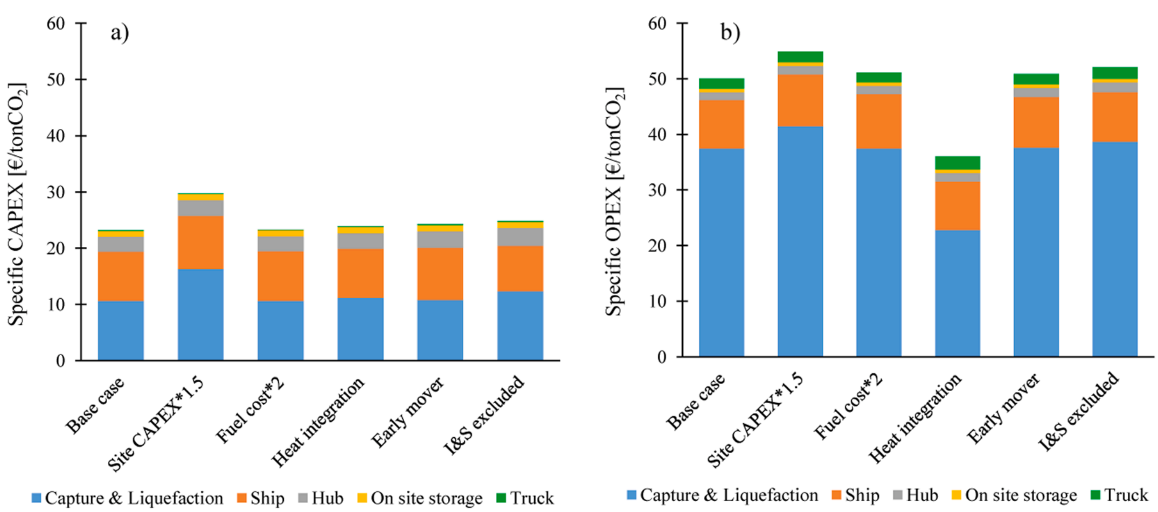

Fig. 10. Cost structure of specific CAPEX (a) and OPEX (b) for Scenario 3 including the sensitivity analysis.

4. Results and discussion

4.1. System development and synergies between fossil CCS and BECCS

Fig. 4 shows how the amounts of fossil and biogenic CO_2 captured develop over time, and Figs. 5–7 show the optimal system configurations in Years 2030 and 2045 for Scenarios 1–3. Table 6 gives the specific system cost (specific cost for the entire CCS chain over the modeled period in €/tCO_2), the specific cost for transportation infrastructure (specific cost for trucks, transport hubs and ships in €/tCO_2 over the modeled period), and the truck transportation distance and the ship transportation distance (1000*km/MtCO_2) for Scenarios 1–3.

In Scenario 1 (Figs. 4a and 5), capture of fossil emissions from the emission sources included in this work are driven by the emission cost from Year 2024 onwards. Additional investments are then made in Years 2026 and 2028, as well as later in the period, as the emissions cost keeps increasing. This indicates that with the modeled cost development, CCS at large industrial sites can become cost efficient in the near-term, and policies aimed at ramping up development might be motivated. The specific cost of the system over the entire modeled period in Scenario 1 is 84 €/tCO_2. The biogenic emissions captured in Scenario 1 represent the share of biogenic emissions in the combined stack from the cement plants and, in Years 2044 and 2045, also from a waste-fired CHP plant.

In Scenario 2 (Figs. 4b and 6), biogenic emissions are captured in line with the capture targets by implementing capture at large pulp and paper mills and at one bio-fired CHP plant. The specific cost of the

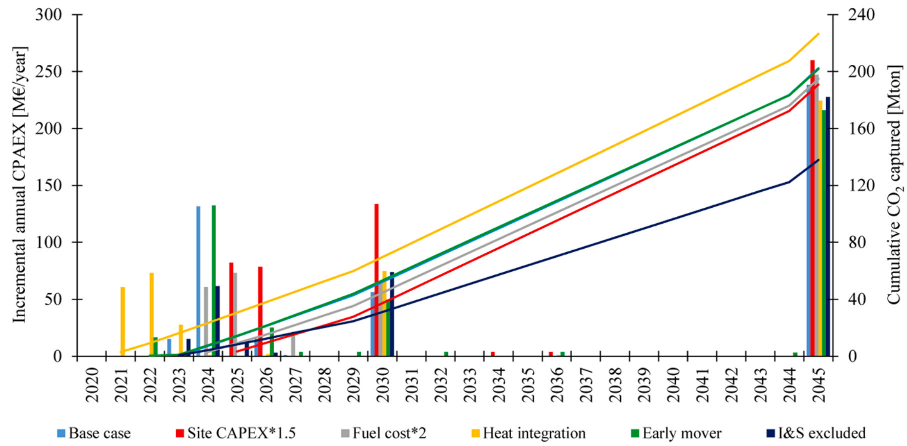

Fig. 11. Incremental annualized CAPEX (bars) and cumulative captured emissions (lines) over time for Scenario 3 and the studied cost cases from Year 2020–2045.

system in Scenario 2 is 83 €/tCO_2. Scenario 2 exemplifies well how the sites chosen for capture are not selected solely based on minimizing the investment costs for capture and liquefaction installations. In Year 2030, two pulp and paper mills are chosen for capture, one on the east coast, which is the largest, and one on the west coast, which is the tenth largest of the pulp mills in the model. Since the CAPEX for capture and liquefaction is related to the size of the emission source (see Eq. (10)), the implementation of capture at the pulp mill on the west coast is motivated in part by its proximity to a transport hub close to the ship destination in Kollsnes, Norway.

Comparing Figs. 5 and 6, there are considerable differences regarding which sites are chosen by the model for capture as well as the choice of transport hubs, since the biogenic and fossil emissions sources are differently distributed. However, there are similarities with respect to the build-up of the system in Scenarios 1 and 2, since in both cases these large investments are made over short time-spans. In Scenario 2, this is obvious due to the capture targets. In Scenario 1, this means that over a relatively narrow range of carbon prices, the capture and transportation of the majority of the CO_2 from the fossil point sources included in the model become economically preferable compared to the cost of emitting the CO_2.

In this work we minimize the NPV since the model may choose to incur costs in the future, and therefore we need to account for the value of money over time. It should be noted that when minimizing the NPV there is a risk that investments are postponed, in particular if the discount rate is overestimated. In this work we apply a discount rate of 5% to represent the social planner perspective. To avoid postponing investments to a point where the deployment of technology required to reach climate goals is no longer feasible, incentives could contain intermediate targets to initiate timely implementation. Such intermediate targets would make the ramp up of the biogenic CO_2 capture system for Year 2045 in Scenario 2 take place over a longer time period.

Scenario 3, which entails a combination of CO_2 prices for fossil fuel emissions and targets for captured biogenic CO_2 (Figs. 4c and 7), exposes important differences in the modeling results, as compared to Scenarios 1 and 2. In Year 2030, when the first biogenic capture target comes in to play, the model invests in capture on waste-to-energy plants in Scenario 3. In Scenario 1, on the other hand, only one waste-to-energy plant is chosen for capture implementation late in the modeled period and in Scenario 2 no waste-fired CHP plants are chosen for capture. This shows that for a case in which there is both a price placed on fossil CO_2 emissions and capture targets imposed on biogenic emissions, there is a synergy (low cost) for waste-to-energy plants, since the biogenic CO_2 captured from these sites is fulfilling the biogenic capture targets, while the fossil CO_2 captured reduces the overall system cost by mitigating the costs associated with fossil emissions. This effect is highlighted in Fig. 8, which shows the costs for biogenic capture, liquefaction, and on-site storage for the largest waste-fired CHP plant (all costs are allocated to the 65% of emissions that are biogenic) and pulp mill recovery boiler in the model, and the value of the mitigated fossil emissions in the case of the waste-to-energy plant. The costs are taken from Year 2030 when the first biogenic capture targets are implemented, and Scenario 3 for the waste-fired CHP, and Scenario 2 for the pulp mill. In Fig. 8, the value of mitigated fossil emissions (set to the avoided cost for emitting fossil CO_2) is allocated to each ton of biogenic CO_2 captured. The fossil emissions cost in 2030 makes the CHP plant roughly equivalent to the pulp mills recovery boiler, considering only the site-related costs (compare the blue bars with the orange bar in Fig. 8). For the system, this means that biogenic capture is shifted from large point sources to a larger number of smaller point sources that are emitting both biogenic and fossil CO_2 if the value of removing fossil CO_2 emissions offsets the cost difference in capturing biogenic CO_2 from the different point sources.

In Table 6, it is evident that the specific system cost for is lower if both biogenic and fossil CO_2 is captured (compare Scenario 3 with Scenarios 1 and 2). In addition, Scenario 3 gives the lowest specific cost for transportation infrastructure due to the combination of short ship transportation distance and truck transportation distance in relation to the amount of CO_2 captured (1,000 km per MtCO_2) (see rightmost column in Table 6). The specific transportation infrastructure cost is highest in Scenario 1 due to a larger share of the total CO_2 being transported long distances by ship from the northern-most transport hub, thereby requiring large investments in ship capacity. At the same time, the truck transportation distance is shortest in Scenario 1. This shows that the total ship transportation distance is more important than the truck transportation distance in determining the overall cost of the transportation infrastructure for the system, since the decreased costs resulting from shorter truck transportation distances are outweighed by the cost increase from longer ship transportation distances in Scenario 1. It is important to note that the results concerning transportation infrastructure costs would likely be different if pipeline transportation costs were to be included in the analysis.

4.2. Sensitivity analysis

Table 7 summarizes the results of the sensitivity analysis, i.e., applying the parameter variation given in the rightmost column in Table 5 for Scenario 3. The increased investment cost for capture (*Site CAPEX*1.5*) results in the largest increase in specific system cost and, thereby, a reduction of the total amount of CO_2 captured (less fossil carbon is captured, whereas the biogenic capture targets are still valid). The truck and ship fuel usage levels increase relative to the *base* case, so as to focus the capture installations to larger point sources and, thereby, lower the specific CAPEX for capture and liquefaction. Increasing fuel cost (*Fuel cost*2*) decreases the truck fuel use, as well as the emissions intensity from the truck and ship infrastructure relative to the *base* case. The lower level of truck fuel usage is achieved by implementing capture at slightly smaller stacks that are located closer to coastal transport hubs. The ship fuel usage level is not noticeably affected by increasing fuel costs, indicating that the use of ships in the system is not sensitive to their fuel-related costs. Heat integration significantly reduces the specific system cost (and increases the amount of CO_2 captured), although it results in higher truck fuel use due to the increased demand for CO_2 transportation when capture is implemented at additional sources. Excluding the iron and steel industry from the analysis (*I&S excluded*) while maintaining the fossil CO_2 cost and target on biogenic capture results in a system with a slightly higher specific cost than the *base* case, which is due to several factors. First, implementing capture at a large iron and steel plant entails a lower cost compared to implementation at the other plants in this study. Second, two of the iron and steel plants included in this work have good conditions for transportation infrastructure. These two plants, Luleå and Oxelösund (cf. Fig. 2), are located at potential transport hub locations, which are used in all the sensitivity cases, except for the *I&S excluded* case, which is reflected in the increased use of truck fuel for this case. The high level of ship fuel usage in the *I&S excluded* case indicates that there is less-utilization of the purchased ships (which are bought in integer steps of a fixed size; cf. Section 3.1.3 and Table 4) compared to the other cases, giving higher ship fuel use per transported tonne of CO_2.

The *early mover* case results in a slightly higher specific system cost due to the model choosing a system that needs to capture biogenic CO_2 before the targets imposed on BECCS come in to play. The ship and truck fuel intensities are higher than in the *base* case, indicating that with respect to infrastructure considerations, this solution is not optimal from a societal perspective. Fig. 9 compares the use of transport hubs over time, between the *base* case and the *early mover* case. In the *early mover* case, the hub in Stockholm is used from Year 2022 onwards, compared to the *base* case, where it is used from Year 2030. The first implementation of fossil emissions capture in the *early mover* case is at the iron and steel plant in Oxelösund in Year 2023, capturing around 30% of the total emissions from this site and transporting it to the hub in Stockholm. In Year 2024, with the implementation of the hubs in Oxelösund, Lysekil, Luleå and Slite, which are mostly used for transporting CO_2 from large fossil emitters, full capture is installed at the steel plant, and the CO_2 is instead transported to Oxelösund, similar to the *base* case. In other words, this rather large change in initial conditions has only a minor impact, limited in time to 1 year, on how the fossil capture system is developed. The transport hub in Helsingborg is used from Year 2030 in the *early mover* case (Year 2045 in the *base* case) and receives captured CO_2 from waste-fired CHP plants in southern Sweden. Although the *early mover* case results in a slightly higher societal cost, the increase in specific system cost is only around 2% compared to the *base* case, while the increase in the cumulative amount of biogenic CO_2 is around 10%.

Fig. 10, a and b show the cost structure of the system. Both the CAPEX and OPEX are dominated by capture and liquefaction, so the cost is most sensitive to the *Site CAPEX*1.5* case and the *Heat integration* case. The cost structure of the truck transportation stands out in that the OPEX is significantly higher than the CAPEX. The ship transportation CAPEX is similar in magnitude to the OPEX, and all in all, significantly higher than the truck costs, which makes the transportation infrastructure more-sensitive to ship-related cost uncertainties. Note that the OPEX for capture and liquefaction is high compared to what has been proposed in previous studies (Garðarsdóttir et al., 2018; Johnsson et al., 2020). The OPEX is sensitive to the energy cost and the integration into the plant energy system (Biermann et al., 2018; Eliasson et al., 2022). Heat integration with the existing site energy system is investigated in only one sensitivity case in this work and should be investigated further.

Fig. 11 shows the incremental annualized CAPEX (M€/year), i.e., the size of additional investments taken each year, and the cumulative CO_2 capture (Mtonne) for the sensitivity analysis of Scenario 3. The *Site CAPEX*1.5* case delays the break-even point between emitting and capturing fossil CO_2, and thus the first investment in CCS equipment, by 2 years compared to the *base* case, which leads to a lower cumulative level of CO_2 captured over the modeled period. Conversely, the *Heat integration* case brings the break-even point, and the first investments, forward by 2 years, resulting in the highest level of cumulative capture and the lowest annual system cost over the period. The *early mover* case does not differ notably from the *base* case in terms of the cumulative level of CO_2. However, it differs in terms of how much biogenic versus fossil CO_2 is captured and overall requires higher investments in relation to the CO_2 captured. The *I&S excluded* case, which removes the option for the model to invest in capture at three large fossil sources, expectedly results in lower cumulative CO_2 capture and lower levels of early investments. The *Fuel costs*2* case delays a significant part of the investments by 3 years, albeit not to the extent seen in the *Site CAPEX*1.5* case. Although the sensitivity cases shift investments in time, the fossil point sources tend to send CO_2 to the same transport hubs once capture is implemented (apart from the iron and steel mill in Oxelösund sending CO_2 to Stockholm in the *early mover* case in Year 2023). The only minor difference relates to whether the chemical manufacturing plant on the west coast makes use of the transport hub in Lysekil or Göteborg or both. This shows that the configuration of the fossil CCS system is rather robust to the investigated sensitivity cases.

5. Conclusions

A MIP optimization model is developed and applied to study the development of CCS infrastructure systems that include capture, liquefaction, and transportation applied to fossil and biogenic (BECCS) emissions sources in Sweden.

The results show that the CCS system configuration differs according to the incentive offered – applying a cost only for fossil emissions, a cost only for BECCS targets, or a combination of these. The system configurations differ both in terms of the sites chosen for capture and the transportation infrastructure used. Waste-fired heat and power plants in this work are assumed to emit 65% biogenic CO_2 and 35% fossil CO_2. Therefore, combining the cost for fossil fuel emissions and targets for biogenic CO_2 capture has a strong effect on the waste-to-energy sector, in which captured emissions both assist in reaching the capture targets for BECCS and decrease the total system cost by mitigating fossil-derived emissions. This means that the value gained by the system in mitigating costs from fossil emissions by capturing CO_2 at waste-fired CHP plants outweighs the cost benefit of implementing capture at larger pulp mills, which would otherwise have a lower specific CCS cost (€/tCO_2). Based on these results, it is important to investigate further the impacts of different policy schemes to motivate BECCS and fossil CCS in combination, to be used as the basis for designing policies that would incentivize BECCS and fossil CCS. With the fossil emissions cost in the model (based on the Net Zero Emissions by 2050 scenario in the World Energy Outlook) and the cost data and assumptions used for CCS equipment, fossil capture is ramped up rapidly. In principle, this outcome is similar to that achieved when setting capture targets in terms of the MtCO_2 captured in a specific year. The configuration of the infrastructure that transports the CO_2 from the large fossil point sources in the model, i.e., using hubs to which the captured CO_2 is sent, is resilient to the changes investigated in the sensitivity analysis. However, the implementation is shifted in time when changes are made to the cost structure.

Although the results show that the on-site equipment items (for capture and liquefaction) dominate the cost structure, the design of the CCS system is not based solely on minimizing the capture and liquefaction costs. Proximity to transport hubs, especially those that require short-distance ship transportation routes to reach the final storage location, is also an important factor in deciding where capture is to be implemented. The cost for transportation infrastructure (trucks, ships and transport hubs) is, for the most part, affected by ship transportation, such that the infrastructure costs show a positive correlation with increased ship transportation distances. These results highlight the importance of considering the costs for CO_2 transportation in techno-economic evaluations of CCS. Finally, it should be pointed out that the present work minimizes the societal cost based on the available cost data and is, therefore, not necessarily representative of the conditions faced by individual companies implementing CCS (e.g., the *price* offered for transportation at present seems to be significantly higher than the costs listed in the literature).

CRediT authorship contribution statement

Sebastian Karlsson: Methodology, Writing – original draft, Visualization. **Fredrik Normann:** Conceptualization, Writing – review & editing. **Mikael Odenberger:** Methodology, 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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Appendix A

Table A1 and Eqs. (A1) and (A35) give the nomenclature and complete description of the model presented and used in this work.

The objective function of the model is given by Eq. (A1):

$$\min c_{tot,NPV} \geq \sum_{y\in Y} \frac{c_y^{annual}}{(1+r)^{y-2020}} \tag{A1}$$

The annual costs c_y^{annual} are calculated using Eq. (A2):

$$c_y^{annual} \geq \sum_{i\in I}\sum_{j\in J}\left(c_{i,j,y}^{CAP,\ capture\&liq} + c_{i,j,y}^{OP,\ capture}\right) + \sum_{i\in I}\left(c_{i,y}^{OP,\ liq} + c_{i,y}^{CAP,storage,\ site} + c_{i,y}^{OP,storage,\ site}\right) + \sum_{i\in I}\sum_{l\in L}\left(c_{i,l,y}^{CAP,truck} + c_{i,l,y}^{OP,truck}\right)$$
$$+ \sum_{l\in L}\left(c_{l,y}^{CAP,storage,\ hub} + c_{l,y}^{OP,storage,\ hub}\right) + \sum_{l\in L}\left(c_{l,y}^{CAP,ship} + c_{l,y}^{OP,ship}\right) + \sum_{et\in ET} c_{et,y}^{emission}\ \forall\ y\in Y \tag{A2}$$

The annuity factor is calculated with Eq. (A3):

$$\alpha = \frac{r}{1-(1+r)^{-LT}} \tag{A3}$$

The annualized CAPEX for capture and liquefaction and OPEX for capture are calculated using Eqs. (A4 and A5):

$$c_{i,j,y}^{CAP,\ capture\&liq} \geq b_{i,\ j,y}^{capture} \cdot CAPEX_{capture\&liq,i,j} * \alpha\ \forall\ i\in I,\ j\in J,\ y\in Y \tag{A4}$$

$$c_{i,j,y}^{OP,\ capture} \geq b_{i,\ j,y}^{capture} \cdot CAPEX_{capture\&liq} \cdot O\&M_{capture} + x_{i,j,y} \cdot q_{d,r} \cdot f_{steam}^{cost}\ \forall\ i\in I,\ j\in J,\ y\in Y \tag{A5}$$

Operating costs for liquefaction equipment are calculated using Eq. (A6):

$$c_{i,y}^{OP,\ liq} \geq b_{i,y}^{liq} \cdot OPEX_{liq}\ \forall\ i\in I,\ y\in Y \tag{A6}$$

The parameter values used to calculate capture and liquefaction costs can be found in Table 2. Annual costs for on-site storage of liquefied CO_2 are calculated with Eqs. (A7) and (A8):

$$c_{i,y}^{CAP,storage,\ site} \geq b_{i,y}^{storage,site} \cdot CAPEX_{storage} \cdot \alpha\ \forall\ i\in I,\ y\in Y \tag{A7}$$

$$c_{i,y}^{OP,storage,\ site} \geq b_{i,y}^{storage,site} \cdot CAPEX_{storage} \cdot O\&M_{storage}\ \forall\ i\in I, y\in Y \tag{A8}$$

The parameter values used for storage tank costs can be found in Table 3. Yearly costs for truck transportation of CO_2 between sites and hubs are described by Eqs. (A9) and (A10):

$$c_{i,l,y}^{CAP,truck} \geq b_{i,l,y}^{truck} \cdot CAPEX_{truck} \cdot \alpha\ \forall\ i\in I,\ l\in L,\ y\in Y \tag{A9}$$

$$c_{i,l,y}^{OP,truck} \geq b_{i,l,y}^{truck} \cdot CAPEX_{truck} \cdot M_{truck} + \frac{\frac{z_{i,l,y}}{t^{op}}}{\frac{p_{truck}}{t_{i,l}^{rt}}}\left(d_{i,l} \cdot f_{truck}^{use} \cdot f_{truck}^{cost} \cdot t^{op} + w_{truck}\right)\ \forall\ i\in I\ , l\in L,\ y\in Y \tag{A10}$$

The parameter values used for truck transportation can be found in Table 4. Yearly costs for storage tanks at a given transport hub are described by Eqs. (A11) and (A12):

$$c_{l,y}^{CAP,storage,\ hub} \geq b_{l,y}^{storage,hub} \cdot CAPEX_{storage} \cdot \alpha\ \forall\ l\in L,\ y\in Y \tag{A11}$$

$$c_{l,y}^{OP,storage,\ hub} \geq b_{l,y}^{storage,hub} \cdot CAPEX_{storage} \cdot O\&M_{storage}\ \forall\ l\in L,\ y\in Y \tag{A12}$$

Annual costs for ship transportation are described by Eqs. (A13) and (A14):

$$c_{l,y}^{CAP,ship} \geq b_{l,y}^{ship} \cdot CAPEX_{ship} \cdot \alpha \ \forall \ l \in L, \ \ y \in Y \tag{A13}$$

$$c_{l,y}^{OP,ship} \geq b_{l,y}^{ship} \left(O\&M_{ship} \cdot CAPEX_{ship} + \frac{t^{op}}{t_l^{RT}} \ \left(f_{ship}^{use} \cdot f_{ship}^{cost} + h \right) \right) \ \forall \ l \in L, \ \ y \in Y \tag{A14}$$

The parameter values used for calculating ship costs are listed in Table 4. The installation of capture equipment and amount of CO_2 captured from a given stack are given by Eqs. (A15) and (A17):

$$x_{i,j,y} \leq s_{i,j} \ \forall \ i \in I, \ j \in J, \ \ y \in Y \tag{A15}$$

$$x_{i,j,y} \leq b_{i,\ j,y}^{capture} \forall \ i \in I, \ j \in J, \ \ y \in Y \tag{A16}$$

$$b_{i,\ j,y}^{capture} = b_{i,\ j,(y-1)}^{capture} - a_{i,\ j,(y-LT)}^{capture} + a_{i,\ j,y}^{capture} \ \forall \ i \in I, \ j \in J, \ \ y \in Y \tag{A17}$$

The annual mass balances over sites are described by Eq. (A18). Investments in and installed capacity of liquefaction plants are calculated by Eqs. (A19) and (A20):

$$\sum_{j \in J} x_{i,j,y} \leq \sum_{l \in L} z_{i,l,y} \ \forall \ i \in I, \ \ y \in Y \tag{A18}$$

$$\sum_{l \in L} z_{i,l,y} \leq \ b_{i,y}^{liq} \ \forall \ i \in I, \ \ y \in Y \tag{A19}$$

$$b_{i,y}^{liq} = b_{i,(y-1)}^{liq} - a_{i,(y-LT)}^{liq} + a_{i,y}^{liq} \ \forall \ i \in I, \ \ y \in Y \tag{A20}$$

Investments in and installed capacity of storage on-site, and at the transport hubs, are described by Eqs. (A21-A23) and (A25), respectively:

$$b_{i,y}^{storage,site} \geq \ \sum_{l \in L} \frac{z_{i,l,y}}{t^{op}} \ \forall \ i \in I, \ \ y \in Y \tag{A21}$$

$$b_{i,y}^{storage,site} = b_{i,(y-1)}^{storage,\ site} - a_{i,(y-LT)}^{storage,\ site} + a_{i,y}^{storage,site} \ \forall \ i \in I, \ \ y \in Y \tag{A22}$$

$$b_{l,y}^{storage,hub} \geq u_{storage,hub} \cdot \gamma_{l,y} \ \forall \ l \in L, \ \ y \in Y \tag{A23}$$

$$b_{l,y}^{storage,hub} = b_{l,(y-1)}^{storage,\ hub} - a_{l,(y-LT)}^{storage,\ hub} + a_{l,y}^{storage,hub} \ \forall \ l \in L, \ \ y \in Y \tag{A24}$$

$$\sum_{i \in I} z_{i,l,y} \leq p_{hub,storage} \cdot \gamma_{l,y} \forall \ l \in L, \ \ y \in Y \tag{A25}$$

The number of trucks required for transporting the yearly captured CO_2 between a site and a transport hub is described by Eq. (A26). Investments in truck capacity are described by Eq. (A27).

$$b_{i,l,y}^{truck} \geq \frac{z_{i,l,y}}{t^{op}} \cdot \frac{t_{i,l}^{rt}}{p_{truck}} \ \forall \ i \in I, \ \ l \in L, \ \ y \in Y \tag{A26}$$

$$b_{i,l,y}^{truck} = b_{i,l,(y-1)}^{truck} - a_{i,l,(y-LT_{truck})}^{truck} + a_{i,l,y}^{truck} \ \forall \ i \in I, \ \ l \in L, \ \ y \in Y \tag{A27}$$

The number of ships used is described by Eq. (A28). Investments in ship capacity are described by Eq. (A29).

$$b_{l,y}^{ship} \geq \frac{\sum_{i \in I} z_{i,l,y}}{t^{op}} \cdot \frac{t_l^{rt}}{p_{ship}} \ \forall \ l \in L, \ \ y \in Y \tag{A28}$$

$$b_{l,y}^{ship} = b_{l,(y-1)}^{ship} - a_{l,(y-LT)}^{ship} + a_{l,y}^{ship} \ \forall \ l \in L, \ \ y \in Y \tag{A29}$$

To control and keep track of CO_2 emissions and captured CO_2 in the system, Eqs. (A30)–(A34) are used.

$$e_{et,y}^{capture,annual} = \sum_{i \in I} \sum_{j \in J} x_{i,j,y} \cdot m_{j,et} \ \forall \ y \in Y, \ \ et \in ET \tag{A30}$$

$$e_{et}^{capture,total} = \sum_{y \in Y} e_{et,y}^{capture,annual} \ \forall \ et \in ET \tag{A31}$$

$$e_{et,y}^{capture,annual} \geq e_{et,y}^{target} \ \forall \ et \in ET, \ \ y \in Y \tag{A32}$$

$$e_{et,y}^{em,annual} = \ \sum_i e_{i,et}^{CO_2} - e_{et,y}^{capture,annual} \ \forall \ et \in ET, \ \ y \in Y \tag{A33}$$

$$e_{et}^{em,total} = \sum_y e_{et,y}^{em,annual} \ \forall \ et \in ET \tag{A34}$$

Emission costs are considered according to Eq. (A35):

$$c_{et,y}^{emission} \geq e_{et,y}^{em,annual} \cdot c_{et,y}^{CO_2} \ \forall \ et \in ET, \ \ y \in Y \tag{A35}$$

Table A2 shows the sites and stacks included in the modeling and the biogenic and fossil CO_2 emissions from the sites.

Table A1
Nomenclature for the model.

Y	Time-steps in years, $Y \in [year_{start}, \cdots, year_{end}]$
I	Sites included in the model $I \in [site_1, \ldots, site_n]$
J	Stack type $J \in [stack\ type_1, \ldots, stack\ type_n]$
L	Coastal transport hubs $L \in [hub_1, \ldots, hub_n]$
ET	CO_2 emission type $ET \in [biogenic, fossil]$
$x_{i,j,y}$	Flow of CO_2 captured at site $i \in I$ from a stack of type $j \in J$ in year $y \in Y$ [tCO_2]
$z_{i,l,y}$	Flow of CO_2 between site $i \in I$ and hub $l \in L$ in year $y \in Y$ [tCO_2]
$\gamma_{l,y}$	Binary variable determining whether hub $l \in L$ is used in year $y \in Y$ [$\gamma_{l,y} \in 0, 1$]
$c_{tot,NPV}$	Total net present value of system [M€]
c_y^{annual}	Annual cost of system in year $y \in Y$ [M€]
$c_{et,y}^{emission}$	Annual cost of emitting CO_2 of type $et \in ET$ in year $y \in Y$ [M€]
$c_{i,j,y}^{CAP,\ capture\&liq}$	CAPEX for capture and liquefaction installations at site $i \in I$ and stack type $j \in J$ in year $y \in Y$ [M€]
$c_{i,y}^{OP,\ capture}$	OPEX for capture installations at site $i \in I$ in year $y \in Y$ [M€]
$c_{i,y}^{OP,\ liq}$	OPEX for liquefaction site $i \in I$ in year $y \in Y$ [M€]
$c_{i,y}^{CAP,storage,\ site}$	CAPEX for on-site storage at site $i \in I$ in year $y \in Y$ [M€]
$c_{i,y}^{OP,storage,\ site}$	OPEX for on-site storage at site $i \in I$ in year $y \in Y$ [M€]
$c_{i,l,y}^{CAP,truck}$	CAPEX for trucks transporting CO_2 between site $i \in I$ and hub $l \in L$ in year $y \in Y$ [M€]
$c_{i,l,y}^{OP,truck}$	OPEX for trucks transporting CO_2 between site $i \in I$ and hub $l \in L$ in year $y \in Y$ [M€]
$c_{l,y}^{CAP,storage,\ hub}$	CAPEX for storage at hub $l \in L$ in year $y \in Y$ [M€]
$c_{l,y}^{OP,storage,\ hub}$	OPEX for storage at hub $l \in L$ in year $y \in Y$ [M€]
$c_{l,y}^{CAP,ship}$	CAPEX for ships transporting CO_2 between hub $l \in L$ and the final storage location in year $y \in Y$ [M€]
$c_{l,y}^{OP,ship}$	OPEX for ships transporting CO_2 between hub $l \in L$ and the final storage location in year $y \in Y$ [M€]
$e_{et}^{capture,total}$	Total CO_2 of type $et \in ET$ captured [tCO_2]
$e_{et,y}^{capture,annual}$	CO_2 of type $et \in ET$ captured in year $y \in Y$ [tCO_2]
$e_{et}^{em,total}$	Total CO_2 of type $et \in ET$ emitted by the system [tCO_2]
$e_{et,y}^{em,annual}$	CO_2 of type $et \in ET$ emitted by the system in year $y \in Y$ [tCO_2]
$a_{i,\ j,y}^{capture}$	Investment in CO_2 capture capacity at site $i \in I$ on stack of stack type $j \in J$ in year $y \in Y$ [tCO_2]
$a_{i,y}^{liq}$	Investment in liquefaction capacity at site $i \in I$ in year $y \in Y$ [tCO_2]
$a_{i,y}^{storage,site}$	Investment in on-site storage capacity at site $i \in I$ in year $y \in Y$ [tCO_2]
$a_{l,y}^{storage,hub}$	Investment in CO_2 storage capacity at transport hub $l \in L$ in year $y \in Y$ [tCO_2]
$a_{i,l,y}^{truck}$	Investment in truck transport capacity between site $i \in I$ and hub $l \in L$ in year $y \in Y$ [tCO_2]
$a_{l,y}^{ship}$	Investment in CO_2 ship transport capacity at hub $l \in L$ in year $y \in Y$ [tCO_2]
$b_{i,\ j,y}^{capture}$	Installed capture capacity at site $i \in I$ on stack of stack type $j \in J$ in year $y \in Y$ [tCO_2]
$b_{i,y}^{liq}$	Installed liquefaction capacity at site $i \in I$ in year $y \in Y$ [tCO_2]
$b_{i,y}^{storage,site}$	Installed on-site storage capacity at site $i \in I$ in year $y \in Y$ [tCO_2]
$b_{l,y}^{storage,hub}$	Installed storage capacity at transport hub $l \in L$ in year $y \in Y$ [tCO_2]
$b_{i,l,y}^{truck}$	Installed truck transport capacity between site $i \in I$ and hub $l \in L$ in year $y \in Y$ [tCO_2]
$b_{l,y}^{ship}$	Number of ships installed to transport CO_2 from hub $l \in L$ in year $y \in Y$ [$b_{l,y}^{ship} \in [0, 1, 2 \ldots n]$]
$q_{d,r}$	Specific reboiler heat demand [MWh/tCO_2]
r	Depreciation rate [%]
t^{op}	Yearly operating time
t^{rt}	Round trip time between two points in the CCS chain
d	Round trip distance between two points in the CCS chain
$O\&M$	Operation and maintenance cost of equipment as a percent of the investment cost [%]
M_{truck}	Maintenance cost for trucks as percent of the investment cost [%]
$CAPEX$	Capital expenditures for equipment [M€/tCO_2]
$OPEX$	Operating expenditures for equipment [M€/tCO_2]
p	Yearly CO_2 handling capacity of ships, transportation hubs, trucks [tCO_2]
$u_{storage,hub}$	Size of storage tank at transportation hubs [tCO_2]
f^{use}	Fuel use for trucks [l/km] and ships [t_{fuel}/h]
f^{cost}	Fuel cost for trucks [M€/l] ships [M€/t] and reboiler steam [M€/MWh]
w	Cost of wages [M€/year]
h	Cost for one stop at a harbor for a ship [M€]
$s_{i,j}$	Yearly supply of CO_2 emissions available for capture on site $i \in I$ from stack type $j \in J$ [tCO_2]
$m_{j,et}$	The ratio of emission type et to total CO_2 emissions from stack of type $j \in J$
LT	Lifetime of equipment [years]
$e_{et,y}^{target}$	Emissions capture target for emission type $et \in ET$ in year $y \in Y$ [tCO_2]
$e_{i,et}^{CO_2}$	Yearly emissions from a given site $i \in I$ of type $et \in ET$ [tCO_2]
$c_{et,y}^{CO_2}$	Cost for emitting CO_2 of type $et \in ET$ in year $y \in Y$ [M€/tCO_2]

Table A2
Included sites and stacks for the modeling performed in this work. The site ID abbreviations are as follows: PP, Pulp and paper; Ce, Cement; R, Refinery; IS, Iron and steel; C, Chemical; HP, Heat and power.

Site ID	Stacks	Biogenic emissions [tonnes/year]	Fossil Emissions [tonnes/year]
PP1	Recovery boiler, lime kiln, Pulp & paper other	1833,871	0
PP2	Recovery boiler, lime kiln, Pulp & paper other	1826,328	0
PP3	Recovery boiler, lime kiln, Pulp & paper other	1543,453	0
PP4	Recovery boiler, lime kiln, Pulp & paper other	1295,578	0
PP5	Recovery boiler, lime kiln, Pulp & paper other	1256,049	0
PP6	Recovery boiler, lime kiln, Pulp & paper other	1166,416	0
PP7	Recovery boiler, lime kiln, Pulp & paper other	1133,103	0
PP8	Recovery boiler, lime kiln, Pulp & paper other	1007,489	0
PP9	Recovery boiler, lime kiln, Pulp & paper other	968,872	0
PP10	Recovery boiler, lime kiln, Pulp & paper other	968,473	0
PP11	Recovery boiler, lime kiln, Pulp & paper other	942,634	0
PP12	Recovery boiler, lime kiln, Pulp & paper other	910,739	0
PP13	Recovery boiler, lime kiln, Pulp & paper other	882,147	0
PP14	Recovery boiler, lime kiln, Pulp & paper other	775,238	0
PP15	Recovery boiler, lime kiln, Pulp & paper other	705,944	0
PP16	Recovery boiler, lime kiln, Pulp & paper other	695,698	0
PP17	Recovery boiler, lime kiln, Pulp & paper other	648,213	0
PP18	Recovery boiler, lime kiln, Pulp & paper other	609,965	0
PP19	Recovery boiler, lime kiln, Pulp & paper other	545,887	0
PP20	Recovery boiler, lime kiln, Pulp & paper other	487,496	0
PP21	Recovery boiler, lime kiln, Pulp & paper other	476,134	0
PP22	Recovery boiler, lime kiln, Pulp & paper other	466,017	0
PP23	Pulp & paper other	337,434	0
PP24	Pulp & paper other	239,838	0
PP25	Pulp & paper other	235,079	0
PP26	Pulp & paper other	221,346	0
PP27	Recovery boiler, lime kiln, Pulp & paper other	180,897	0
PP28	Pulp & paper other	141,429	0
PP29	Pulp & paper other	114,091	0
Ce1	Cement combined	174,174	1567,567
Ce2	Cement combined	0	369,441
R1	HPU, Refinery other	0	1428,122
R2	HPU, Refinery other	0	535,225
R3	HPU, Refinery other	0	503,504

(*continued on next page*)

Table A2 (*continued*)

Site ID	Stacks	Biogenic emissions [tonnes/year]	Fossil Emissions [tonnes/year]
IS2	Iron and steel power plant, iron and steel other	0	3305,880
IS3	Iron and steel power plant, iron and steel other	0	1501,718
IS4	Iron and steel power plant, iron and steel other	0	239,048
C1	Cracker furnace	0	664,228
HP1	Heat and power bio	1075,267	0
HP2	Heat and power waste	575,241	0
HP3	Heat and power bio, heat and power waste	626,899	171,524
HP4	Heat and power waste	325,264	175,142
HP5	Heat and power waste	278,633	150,033
HP6	Heat and power waste	308,404	166,064
HP7	Heat and power waste	307,896	165,790
HP8	Heat and power bio, heat and power waste	526,486	88,560
HP9	Heat and power waste	127,659	68,739
HP10	Heat and power bio, heat and power waste	327,691	61,873
HP11	Heat and power bio	338,207	0
HP12	Heat and power bio	326,880	0
HP13	Heat and power bio	334,602	0
HP14	Heat and power bio, heat and power waste	172,970	88,367
HP15	Heat and power bio	122,806	0
HP16	Heat and power bio	765,401	0
HP17	Heat and power bio	317,910	0
HP18	Heat and power bio, heat and power waste	267,594	60,993
HP19	Heat and power bio	339,332	0
HP20	Heat and power bio	313,794	0
HP21	Heat and power bio	206,111	0
HP22	Heat and power bio	139,049	0
HP23	Heat and power waste	75,810	40,821
HP24	Heat and power waste	101,665	54,743
HP25	Heat and power waste	86,015	46,316
HP26	Heat and power bio	201,192	0
HP27	Heat and power bio	188,759	0
HP28	Heat and power bio	237,590	0
HP29	Heat and power waste	98,345	52,955
HP30	Heat and power waste	88,642	47,731
HP31	Heat and power bio	208,426	0
HP32	Heat and power bio	161,310	0
HP33	Heat and power bio	207,886	0
HP34	Heat and power waste	76,340	41,106
HP35	Heat and power bio	64,340	0
HP36	Heat and power waste	75,473	40,639
HP37	Heat and power bio	72,357	0
HP38	Heat and power bio	154,560	0
HP39	Heat and power bio	144,258	0
HP40	Heat and power bio	137,562	0
HP41	Heat and power bio	130,597	0
HP42	Heat and power bio	487,357	0
HP43	Heat and power waste	157,838	84,990
HP44	Heat and power waste	113,563	61,149
HP45	Heat and power waste	83,355	44,883
HP46	Heat and power bio	221,917	0
HP47	Heat and power bio, heat and power waste	118,918	17,139
HP48	Heat and power bio	329,245	0

Tabell A3
Distances (in kilometers) between the sites and hubs considered in the modeling.

	Ostrand	Oxelosund	Lysekil	Goteborg	Helsingborg	Stockholm	Lulea	Slite	Varberg	Kalmar	Gavle	Norrkoping	Ornskoldsvik	Umea	Skelleftea
PP1	780	231	430	375	343	347	1283	197	338	64	523	223	906	991	1145
PP2	265	287	555	591	756	194	776	437	639	581	14	304	389	483	637
PP3	172	689	910	964	1155	580	374	812	1025	984	404	710	30	92	236
PP4	541	312	199	256	480	368	1083	489	329	460	354	254	687	801	947
PP5	259	292	552	589	757	202	774	444	638	585	5	307	386	481	635
PP6	551	738	795	992	455	542	697	858	843	258	562	146	264	406	
PP7	486	1005	1223	1281	1475	890	59	1114	1344	1300	723	1029	342	245	93
PP8	572	92	340	333	446	199	1094	255	352	280	320	26	705	800	954
PP9	932	405	401	318	168	528	1453	390	243	147	680	374	1066	1160	1314
PP10	846	432	162	72	178	546	1387	520	17	340	626	372	991	1099	1249
PP11	532	289	213	263	479	344	1074	467	332	445	337	232	678	790	937
PP12	122	430	635	686	875	339	654	581	745	722	137	440	259	366	516
PP13	609	1110	1347	1403	1591	992	72	1207	1464	1403	836	1138	462	354	203
PP14	953	431	400	315	144	554	1476	418	235	175	703	397	1088	1183	1337
PP15	484	1000	1220	1279	1472	886	60	1108	1341	1295	719	1025	339	240	87
PP16	455	177	339	367	539	205	990	366	415	415	221	141	595	699	851
PP17	77	625	812	870	1069	525	468	765	934	918	332	638	78	199	333
PP18	186	365	593	638	819	274	710	516	693	657	72	377	317	418	571
PP19	528	230	242	275	467	292	1068	408	331	398	312	172	672	780	930
PP20	146	675	884	940	1134	568	397	803	1002	970	386	693	2	122	260
PP21	264	762	1000	1053	1238	647	292	872	1111	1056	483	787	121	2	153
PP22	567	173	263	271	427	260	1101	340	308	326	330	109	707	810	962
PP23	12	540	730	786	982	443	551	685	849	832	246	551	155	270	414
PP24	335	231	456	492	664	180	864	406	542	513	95	229	471	573	725
PP25	845	383	230	146	147	503	1382	446	79	252	611	329	987	1091	1243
PP26	311	296	438	487	682	258	852	478	547	563	129	281	455	565	714
PP27	618	366	120	190	429	437	1159	530	271	461	436	303	765	879	1024
PP28	568	76	356	349	457	185	1087	242	366	280	314	10	700	793	947
PP29	560	64	368	362	469	172	1076	236	379	286	304	3	690	783	937
Ce1	697	189	570	535	540	243	1157	518	244	446	236	803	871	1021	
Ce2	642	251	181	180	352	349	1181	393	221	318	415	185	785	891	1042
R1	730	432	11	101	350	520	1271	572	190	454	543	366	876	991	1136
R2	793	422	89	2	250	527	1335	535	90	382	585	358	939	1050	1198
R3	794	426	86	5	253	530	1336	539	93	386	587	361	940	1052	1199
IS2	542	1054	1280	1337	1529	938	3	1158	1400	1349	776	1080	397	295	141
IS3	549	2	433	425	516	122	1051	189	438	297	291	67	672	758	912
IS4	315	291	436	484	678	253	855	472	544	558	128	276	459	568	717
C1	747	409	40	57	305	506	1289	539	144	409	547	344	893	1006	1152
HP1	455	124	522	528	637	0	937	243	551	411	204	175	567	645	799
HP2	468	111	516	519	624	14	951	230	540	397	216	164	581	660	813
HP3	421	141	423	444	593	122	941	321	482	423	167	141	553	648	802
HP4	563	66	366	359	465	175	1080	236	376	284	308	1	693	786	940
HP5	596	114	320	309	418	226	1120	263	325	263	345	52	730	826	980
HP6	783	408	91	15	252	513	1325	521	91	371	573	344	929	1040	1188
HP7	1041	544	404	314	65	668	1574	549	225	308	799	502	1181	1281	1434
HP8	415	149	517	530	654	42	905	284	559	442	163	188	531	613	766
HP9	380	177	516	535	672	79	877	321	570	472	125	207	498	583	737
HP10	285	786	1022	1075	1262	672	268	897	1135	1081	507	812	139	26	128
HP11	485	167	318	342	509	214	1019	354	387	389	249	122	625	728	880
HP12	453	111	410	425	565	119	972	296	459	391	198	109	584	678	832
HP13	831	314	331	259	209	438	1355	335	205	126	581	276	966	1062	1215
HP14	755	346	138	82	247	456	1296	454	104	310	532	283	899	1007	1157
HP15	766	351	144	81	236	463	1306	455	94	306	542	290	910	1017	1168
HP16	477	85	485	488	596	41	970	229	510	377	221	133	595	678	831

(*continued on next page*)

Tabell A3 (*continued*)

	Ostrand	Oxelosund	Lysekil	Goteborg	Helsingborg	Stockholm	Lulea	Slite	Varberg	Kalmar	Gavle	Norrkoping	Ornskoldsvik	Umea	Skelleftea
HP17	519	283	226	276	490	334	1061	463	344	448	323	227	664	777	924
HP18	727	264	225	178	268	381	1261	358	172	228	487	207	867	969	1121
HP19	204	676	745	818	1044	604	584	844	894	951	400	669	266	375	471
HP20	149	677	887	943	1137	570	394	805	1005	972	389	696	3	119	257
HP21	484	104	518	518	617	29	965	214	537	385	232	161	596	674	826
HP22	262	290	544	582	751	202	779	444	631	582	5	303	390	486	640
HP23	646	298	135	153	359	389	1188	445	213	363	433	232	791	901	1050
HP24	986	507	334	245	7	630	1522	535	156	303	749	459	1127	1230	1382
HP25	903	439	259	169	91	561	1440	491	82	279	669	387	1045	1149	1301
HP26	795	415	100	13	241	521	1337	524	80	369	584	351	941	1051	1200
HP27	960	445	386	299	116	569	1487	442	216	200	712	409	1097	1194	1347
HP28	405	919	1143	1200	1391	804	137	1028	1262	1214	638	944	260	159	15
HP29	13	538	727	783	979	442	554	684	846	830	245	549	158	274	418
HP30	510	161	303	322	485	223	1044	344	364	367	273	109	649	752	904
HP31	785	410	90	13	252	515	1327	523	91	373	574	346	930	1041	1189
HP32	295	300	456	504	697	254	835	479	564	572	113	289	439	548	697
HP33	539	15	425	419	517	120	1044	203	435	306	281	60	663	751	904
HP34	558	1081	1292	1352	1549	967	51	1190	1417	1376	799	1105	415	321	169
HP35	599	117	318	306	415	229	1123	264	322	260	348	55	733	830	983
HP36	710	395	38	95	341	485	1252	535	181	423	515	329	856	970	1116
HP37	664	186	272	244	341	303	1193	298	250	226	418	128	801	900	1053
HP38	411	140	464	482	621	86	921	306	517	433	153	159	537	627	781
HP39	991	513	338	248	1	636	1528	540	160	308	755	465	1133	1236	1388
HP40	271	283	518	558	732	207	797	446	609	573	32	291	405	505	657
HP41	909	368	438	361	238	488	1421	328	295	84	653	346	1038	1128	1281
HP42	380	177	516	535	672	79	877	321	570	472	125	207	498	583	737
HP43	424	133	496	509	634	46	920	280	538	428	168	168	543	627	781
HP44	494	215	278	312	500	264	1033	399	366	412	275	164	637	745	895
HP45	796	1343	1496	1565	1781	1236	352	1468	1638	1637	1052	1358	669	602	462
HP46	841	295	432	366	294	413	1348	254	315	17	584	279	968	1055	1209
HP47	640	247	186	184	353	345	1179	389	223	315	413	181	783	889	1040
HP48	1013	515	386	296	56	639	1546	522	208	282	771	473	1153	1253	1406
HP49	794	422	91	2	249	527	1336	534	88	381	585	358	940	1051	1199
HP50	1047	550	409	319	70	674	1580	554	230	312	805	508	1187	1287	1440
HP51	380	177	517	535	672	79	877	321	570	472	126	207	498	583	737

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