Building CO_2 infrastructures for Fossil- and Bio-energy with Carbon Capture and Storage: insights from a cooperative game-theoretic perspective ☆

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Abstract

This paper examines the deployment of a shared CO_2 transportation infrastructure needed to support the combined emergence of Bio-energy with Carbon Capture and Storage (BECCS) and Fossil energy with Carbon Capture and Storage (FECCS). We develop a cooperative game-theoretic approach to determine the break-even CO_2 value needed to build such a shared infrastructure and examine whether coordination issues may impede socially optimal investments. Moreover, we highlight that, as biogenic emissions are overlooked in currently implemented carbon accounting frameworks, BECCS and FECCS emitters face asymmetric conditions for joining a shared infrastructure. We thus further examine the influence of these carbon accounting considerations by assessing and comparing the break-even CO_2 values obtained under alternative accounting rules. We apply this modeling framework to a large contemporary BECCS/FECCS case study in Sweden. Our results indicate that sustainable and incentive-compatible cooperation schemes can be implemented if the value of CO_2 is high enough and show how that value varies depending on the carbon accounting framework retained for negative emissions and the nature of the infrastructure operators. In the most advantageous scenario, the CO_2 value needs to reach 99€/tCO_2, while the current Swedish carbon tax amounts to 110€/tCO_2. Overall, these findings position pragmatic policy recommendations for local BECCS deployment.

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1. Introduction

Bio-energy with Carbon Capture and Storage (BECCS) and Fossil energy with Carbon Capture and Storage (FECCS) could become instrumental in reaching the Paris Agreement “below 2°C” global warming target (Azar et al., 2013; Kalkuhl et al., 2015; Koelbl et al., 2014; Nemet et al., 2018; Rogelj et al., 2018; Solano Rodriguez et al., 2017). Indeed, Carbon Capture and Storage (CCS) allows for industrial CO_2 mitigation in three steps: (i) separating CO_2 from other combustion flue gases through a chemical carbon capture process, (ii) transporting CO_2 via pipelines or shipping to a geological storage site and (iii) ensuring that these CO_2 emissions are permanently stored in the geological storage site, which can be a depleted gas field or a saline aquifer (Bui et al., 2018). In the case of fossil-fuelled industries, FECCS is expected to mitigate CO_2 emissions from otherwise difficult-to-decarbonize industries, especially when electrification is challenging (Benhelal et al., 2013; Griffin and Hammond, 2019; IEA, 2017). In the case of bioenergy-fuelled industries, BECCS can produce negative emissions, *i.e.*, net removal of CO_2 from the atmosphere in a life cycle perspective (Fajardy and Mac Dowell, 2017; Fuss et al., 2014; Gough and Upham, 2011; Thornley and Mohr, 2018). This is done by combining the natural carbon sequestration potential of biomass growth with the permanent CO_2 storage potential of CCS. However, the production of negative emissions relies on the assumption that biomass growth’s natural carbon sequestration is not outweighed by the process emissions of the whole chain. Considering the BECCS value chain’s complex nature, negative emissions production is achievable but not trivial (Fajardy and Mac Dowell, 2017; Forster et al., 2020; Vaughan et al., 2018).

In many scenarios, the annual carbon dioxide removal capacity, mainly achieved through BECCS, is expected to scale up from the Megaton scale today to the Gigaton scale by 2050 (Fuss et al., 2018). However, the current uptake of CCS technologies remains limited and barely compatible with the ambitious development plans depicted in the scenarios (Nemet et al., 2018). The barriers to the up-scaling of BECCS and FECCS are mostly economic, political, and social rather than technical, as some carbon capture, transport, and storage technologies are already in commercial stages (Hammond, 2018). One of these crucial yet often-overlooked barriers is the implementation of a CO_2 transportation and storage system which is, by nature, costly, capital intensive, and likely to exhibit substantial economies of scale (Albanito et al., 2019; Baik et al., 2018; Butnar et al., 2020; Krahé et al., 2013; Sanchez et al., 2018; Stavrakas et al., 2018). These properties effectuate the use of a shared infrastructure that requires cooperation between the industrial CO_2 emitters and raises the question of cost allocation.

The purpose of this paper is thus to examine the conditions for the construction of a CO_2 transportation and storage infrastructure for BECCS and FECCS emitters. We develop a cooperative game-theoretic approach to examine the coordination issues faced by a collection of heavy-emitting industrial plants that can install carbon capture capabilities and join a common CO_2 supply chain. We then compare the CO_2 value needed to trigger the infrastructure under the cooperative approach with the CO_2 value needed under a centralized welfare-maximizing approach. Additionally, the influence of two parameters is assessed: the accounting system applied to negative emissions and the nature of the infrastructure operator – which can be either vertically integrated or vertically separated.

This paper contributes to the small and very much needed literature attempting to shed light on CO_2 infrastructure economics. In recent years, the deployment of CO_2 infrastructure systems has yielded an emerging body of literature that can be clustered in two categories, depending on the methodology retained for the analysis: optimization and game theory. Optimization-based analyses are by far the most numerous ones (Bakken and Velken, 2008; Kemp and Kasim, 2010; Klokk et al., 2010; Kuby et al., 2011; Mendelevitch et al., 2010; Middleton and Bielicki, 2009; Morbee et al., 2012; Oei et al., 2014; Oei and Mendelevitch, 2016). In these contributions, a single decision-maker (modeled as a benevolent social planner) is posited to control the entire value chain, including all the agents involved (e.g., the emitters where carbon capture is implemented or the countries in the case of an international value chain). Remarking that the latter agents are autonomous decision-making entities, a handful of contributions have recently emerged to investigate whether cooperation can be a rational move for these agents using game-theoretic notions. For example, Morbee (2014) analyzes the country-level negotiation process needed to develop a pan-European CCS infrastructure using a Shapley value approach. Massol et al. (2015) focus on the individual emitters' decisions to adopt carbon capture capabilities and clarifies the conditions for sharing of the infrastructure costs among them. In a subsequent contribution, Massol et al., (2018) examine the case of a collection of independent industrial clusters that can be connected to a meshed, national pipeline network aimed at transporting CO_2 to a few capacity-constrained storage sites. Overall, it is important to stress that the literature on CO_2 infrastructures has been primarily motivated by purely FECCS applications and thus overlooks the possibility of installing a combined BECCS/FECCS chain. The present paper extends these earlier analyses to study the associated gain/cost-sharing problem.

The scenarios based on the nature of the infrastructure operator allow us to position pragmatic policy recommendations for local BECCS deployment. But, more importantly, the scenarios based on different negative emissions accounting frameworks address an essential barrier to BECCS deployment: the lack of economic incentives for the deployment of BECCS. Bio-energy-fuelled industries are yet out of the scope of any carbon accounting framework because they have long been considered carbon-neutral – meaning that the volume of CO_2 that is removed from the atmosphere through biomass growth corresponds to the volume of CO_2 emissions released during combustion (Fuss et al. 2014). As a result, the CO_2 captured in BECCS facilities is neither eligible for tax reductions nor rewarded by carbon quota allowances.

Finally, we apply our model to a realistic case study in the south-west of Sweden, a region that is especially relevant for the following three reasons: (i) it is home to both biomass-fuelled pulp and paper plants and large industries that could be equipped with carbon capture capabilities (EEA 2017); (ii) it is geographically close to a sizable underground CO_2 storage site that is currently being developed offshore Norway (CCS Norway 2019); and (iii) a private sector-led initiative is now examining the possibility of deploying a dedicated CO_2 transportation infrastructure connecting these Swedish emitters with the Norwegian storage site (Global CCS Institute, 2020; Preem, 2019).

This paper is organized as follows. In the next section, we give some background considerations on the accounting and rewarding of negative emissions. In Section 3, we present the conceptual framework of our analysis. In Section4, we detail an application of this methodology to the case of a contemporary project in Sweden and present an overview of the computerized model used to determine the cost of the required CO_2 transportation infrastructure. Section 5 contains our results. Finally, Section 6 offers a summary and some concluding remarks highlighting the policy implications of our analysis. For the sake of clarity, the detailed structure of the computerized model and the cost parameters are presented in a series of appendices.

2. Background: Accounting and rewarding negative emissions

Negative emissions are defined as the net volume of CO_2 emissions that is permanently removed from the atmosphere by a given process. This could be achieved by BECCS because the CO_2 emissions caused by bioenergy combustion can be directly linked to the CO_2 that had been sequestered during the biomass's growth. However, at least two lines of arguments indicate that one ton of stored CO_2 emissions from a BECCS facility can hardly equate to one ton of negative emissions. First, producing negative emissions and abating one's emissions are two different activities. The production of negative emissions (*i.e.,* net CO_2 removal from the atmosphere) should be accounted for in a full Life Cycle Assessment perspective, including emissions from the upstream bioenergy chain (Fajardy and Mac Dowell, 2017; Thornley and Mohr, 2018). Second, only a fraction of CO_2 removal will stay permanently out of the atmosphere – and therefore become negative emissions – because of the complex dynamics of global carbon cycles (Jones et al., 2016). These considerations led Torvanger (2019) to reflect on the suitable carbon accounting values that should be retained for negative CO_2 emissions: *"Given the complexities and insufficient understanding of calculating the net negative effect of CO_2 removal due to interactions with the global carbon cycle, the best way forward is likely* *to agree on a discounting factor for negative emissions, and then also for BECCS. This implies that less than 100% of one ton of CO_2 removal is approved."*

Designing a standardized rewarding system for BECCS is hence a complex issue. A first approach consists in remunerating BECCS for their net CO_2 abatement, *i.e.*, the volume of stored CO_2 emissions, minus the volume of CO_2 emissions attributed to the CO_2 capture process (Cabral et al., 2019; IEAGHG, 2014; Zakkour et al., 2014). In that case, the remuneration is identic to the carbon tax reduction achieved by FECCS, and could be translated by credits auctioned to hard-to-decarbonized sectors (Cabral et al., 2019). However, this approach neglects the process emissions stemming from the upstream bioenergy chain and the global carbon cycles (Torvanger, 2019), potentially leading to perverse effects. In a life-cycle perspective, a BECCS plant using sustainable domestic biomass may produce more negative emissions than a similar BECCS plant using internationally sourced biomass (due to transport and land-use emissions.) Moreover, the upstream process emissions could exceed the volume of stored emissions, hence resulting in net positive emissions instead of negative emissions (see an example in Fajardy and Mac Dowell, 2017.) Under the above-mentioned framework, both plants would be rewarded identically, leading BECCS plants to choose the cheapest available biomass regardless of upstream process emissions. On a large scale, this could cause an overall increase in CO_2 emissions instead of a net CO_2 removal as BECCS technologies scale-up. To avoid these perverse effects, BECCS plants could be rewarded for their negative emissions production – which can be seen as an environmental service – rather than net CO_2 abatement. This would result in a lower remuneration for BECCS CO_2 storage that accounts both for upstream process emissions and global carbon cycles. In practice, this option is difficult to implement because it would require a standardized life cycle assessment methodology for BECCS processes (Thornley and Mohr, 2018). Sustainable biomass certification mechanisms could provide a solution by explicitly allocating a carbon footprint to biomass. In this paper, we won't further elaborate on the feasibility and consequences of both rewarding frameworks for BECCS (*i.e.* rewarding either net CO_2 abatement or net negative emissions production), but we will assess their effect on the deployment of CO_2 infrastructures.

3. Methodology

In this section, we first present the notation and then the conditions for the construction of a shared BECCS/FECCS chain that involves a unique private operator controlling both the pipeline infrastructure and the maritime shipping of CO_2.[1] Then, we show how the critical CO_2 price needed for the implementation of such a combined BECCS/FECCS project can be determined. In the sequel, we extend the analysis to examine the case of a vertically segmented organization whereby the logistics are provided by two separate firms: one pipeline operator and one for the maritime shipments. Lastly, we explain how we have compared our results from the cooperative game-theoretic approach with a centralized welfare-maximizing approach. A summary of the notations can be found in Table 1.

3.1 Notation and assumptions

We consider a finite set of industrial plants that: (i) are eligible to install carbon capture units and (ii) can form a shared CO_2 transportation system. We assume that each of these CO_2 emitters represents an autonomous decision-making entity that can either adopt carbon capture and feed the volume of CO_2 to a shared logistic system or renounce CO_2 capture.

We let N denote the grand coalition gathering all these emitters and $|N|$ denote the cardinality of this set. An emitter i can either be fossil-fuelled (FECC), or bioenergy-fuelled (BECCS).

Let C be the real-valued function on the subsets of N that gives the long-run costs for transporting the emissions captured by any coalition of emitters to the storage site. Here, $C(S)$ denotes the standalone cost for serving the coalition S, that is, the costs incurred from building and operating the least-costly infrastructure capable of connecting the emitters in S to the storage site.[2] We assume that this cost function is subadditive – i.e., $C(S \cup T) \leq C(S) + C(T)$ for any coalitions $S,T \subseteq N$, with

[1] This specific infrastructure set-up is motivated by the application case study that will be presented in Section 3.

[2] In the empirical section of this paper, the values taken by the function are obtained using an optimization model that is solved numerically (see Appendix A).

$S \cap T = \varnothing$ – and that it verifies $C(\varnothing) = 0$ and $C(S) \geq 0$ for any non-empty S in N. We also assume that the technology used in CO_2 transportation is standard, not proprietary, and that market entry is possible and free in that activity.

The transportation costs $C(S)$ incurred for serving a coalition S verifies $C(S) = C_{pipeline}(S) + C_{ship}(S)$ where $C_{pipeline}(S)$ and $C_{ship}(S)$ are the costs of the onshore and offshore transportation subsystems.

3.2 The provision of a combined and integrated BECCS/FECCS infrastructure

a) CO2 transportation: a cooperative game-theoretic framework

We posit a subadditive CO_2 transportation cost function, which characterizes the natural monopolistic nature of that industry (Berg and Tschirhart, 1988).[3] We also assume that the technology is not proprietary and that entry is free in the CO_2 transportation industry. Therefore, the pricing decisions of a monopolistic organization controlling CO_2 transportation has to take into consideration the rivalry that could result from the potential entry of a competitor. Following the theory of contestable markets (Baumol et al., 1977; Sharkey, 1982), a natural monopoly serving the grand coalition N is said to be sustainable if there exists a discriminatory infrastructure pricing scheme $r = \left(r_1, ..., r_{|N|}\right)'$ such that: (i) the monopoly recovers its costs, and (ii) a potential entrant cannot find any financially viable opportunity to serve any submarket S with $S \subseteq N$. Formally, these conditions for a sustainable monopoly are:

$$\sum_{i \in N} r_i \geq C(N) \ . \qquad (1)$$

$$\sum_{i \in S} r_i \leq C(S), \qquad \forall S \subset N \ , \ S \notin \{\varnothing, N\} \ . \qquad (2)$$

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[3] *An industry is a natural monopoly whenever no combination of multiple firms can collectively provide the industry's output at a lower cost than a monopolist.*

Together, these conditions compel the monopolist to charge a pricing vector r that recovers the exact total cost, *i.e.* $\sum_{i \in N} r_i = C(N)$, which indicates that even in the absence of a profit constraint, the total revenue charged by that firm cannot depart from its costs (Sharkey 1982).

In cooperative game theory (see, e.g., Young, 1985), the set of pricing vectors that verifies conditions (1) and (2) is named the core of the cooperative cost game (N, C). A non-empty core thus indicates that the infrastructure operator can charge a pricing vector that recovers its costs while preventing the secession of its customers (i.e., the emitters).[4]

b) The individual decisions regarding carbon capture

We now examine the emitters' decisions regarding the adoption of carbon capture (and thus the connection to a shared CO_2 transportation system). We let χ_i denote the unit cost for installing and operating a carbon capture unit and Q_i the quantity of emissions that can be captured at plant i. We also let σ denote the unit storage cost and p_{CO_2} be the prevailing carbon value. The emitter's total cost thus amounts to $(\chi_i + \sigma)Q_i + r_i$.

The revenue obtained by a given emitter for capturing CO_2 emissions equates $p_{CO_2}(Q_i - q_i)$, where q_i represent process emissions. For FECCS plants, q_i corresponds to the emissions related to the carbon capture process[5]. For BECCS plants, q_i can also include upstream process emissions[6] for negative emissions accounting purposes, as described in Section 2. As discussed in Massol et al. (2015), it is thus judicious for an emitter to adopt carbon capture whenever its total revenue $p_{CO_2}(Q_i -$

[4] *From an empirical perspective, it is possible to verify the nonemptiness of the core by solving a linear programming problem similar to the one in Massol et al. (2015, Appendix B).*

[5] *We will assume that the process emissions related to carbon capture represent roughly 10% of the volume of stored emission* (Fajardy and Mac Dowell, 2017; Johnsson et al., 2020)

[6] *As an example, for the BECCS project considered in Fajardy and Mac Dowell (2017), the total volume of process emissions represents roughly 40% of the volume of stored CO_2 emissions. Additionally, if the global carbon dynamics are taken into account, only 60 to 90% of the negative emissions will effectively remain out of the atmosphere.*

q_i) exceeds the total cost incurred for the carbon capture $\chi_i Q_i$, for the storage operations[7] σQ_i and the amount charged by the infrastructure operator, that is:

$$\left(p_{CO_2}\left(1-\frac{q_i}{Q_i}\right)-\chi_i-\sigma\right)Q_i-r_i \geq 0 \qquad (3)$$

3.3 The break-even price for combined BECCS/FECCS adoption

The implementation of a grand infrastructure connecting all the emitters requires the operator to charge a revenue vector that is both in the core of the cooperative cost game (N,C) and such that each emitter obtains a non-negative profit (i.e., a vector that verifies the conditions (1), (2), (3) and (4)).

The prevailing carbon price p_{CO_2} has a direct influence on the emitters' individual profits and, thus, on the possibility for the infrastructure operator to determine a revenue vector that is a core allocation. One can thus determine the break-even price for combined BECCS/FECCS adoption, which is defined as the minimum CO_2 price that is compatible with conditions (1), (2), and (3). We let $p^*_{CO_2}$ denote that critical value. It can be determined by solving the following linear programming problem:

[7] *We assume that there are no CO_2 losses during transport and storage.*

LP1 (integrated operator):

$$\min_{r, p_{CO_2}} \quad p_{CO_2}$$

s.t.

$$\sum_{i \in N} r_i = C(N),$$

$$\sum_{i \in S} r_i \le C(S), \qquad \forall S \subset N \setminus \{\varnothing, N\},$$

$$\left(p_{CO_2}\left(1 - \frac{q_i}{Q_i}\right) - \chi_i - \sigma\right) Q_i - r_i \ge 0, \qquad \forall\, i \in N$$

$$r_i \ge 0, \qquad \forall\, i \in N$$

3.4 Extension: The case of a vertically separated transportation chain

The analysis above posits the existence of a single operator controlling both the onshore and offshore components of the supply chain. However, pipeline systems and sea-going vessels are different activities, which can justify a vertically separated organization with two specialized operators. Such a separated industrial structure calls for an adaptation of our modeling framework, and the four lines of considerations below have to be considered.

First, regarding the pipeline operator, we let $r_{pipe} = \left(r_{pipe_1}, \dots, r_{pipe_{|N|}}\right)$ denote the revenue vector it charges. To be financially viable, the operator has to recover its costs and, because of the threat resulting from our free entry assumption, that firm cannot charge more than its costs. Thus, the condition $\sum_{i \in N} r_{\text{pipe}_i} = C_{pipe}(N)$ has to be verified.

Second, regarding the shipping operator, similar considerations related to cost recovery and free entry also compel that firm to charge a total revenue that exactly recovers its total cost $C_{ship}(N)$, which we assume to be decomposable into a fixed component f_{ship} and a variable one with a constant marginal cost equal to c_{ship}. Furthermore, it is important to stress that once transported to the departure port, the CO_2 emanating from the industrial emitters is fungible, which drastically restricts the shipping operator's ability to implement discriminatory pricing among the emitters. To put it simply, that firm can hardly charge different prices for handling a given volume of CO_2. As a result, the shipping company has to use non-discriminatory pricing schemes while the pipeline operator continues to set discriminatory pricing schemes. We note the shipping pricing vector $r_{\text{ship}} = \left(r_{\text{ship}_1}, \dots, r_{\text{ship}_{|N|}}\right)$.

Third, because of the entry considerations above, the total amount jointly charged by the pipeline and shipping operators to any coalition S cannot exceed the standalone cost $C(S)$ it would incur with a potential entrant.

Lastly, the emitters' individual decisions to implement carbon capture (and thus the individual net benefits in conditions (3) and (4)) have to account for the sum of the total revenues charged by the pipeline and the shipping operators.

Altogether, these considerations indicate that, in the case of vertical separation, the break-even price for a combined BECCS/FECCS adoption can be determined using an adapted version of the linear programming problem above, as in LP2.

<u>LP2 :</u>

$$\min_{r_{\text{pipe}}, p_{CO_2}} \; p_{CO_2}$$

$$\text{s.t.} \quad \sum_{i \in N} r_{\text{pipe}_i} = C_{\text{pipe}}(N)$$

$$\sum_{i \in S} \left(r_{\text{pipe}_i} + r_{\text{ship}_i}\right) \le C(S) \qquad \forall S \subset N \;\; \{\emptyset, N\}$$

$$\left(p_{CO_2}\left(1 - \frac{q_i}{Q_i}\right) - \chi_i - \sigma\right) Q_i - r_{\text{pipe}_i} - r_{\text{ship}_i} \ge 0\,, \qquad \forall\, i \in N$$

In the sequel, we consider the two usual cases of shipping pricing schemes: (case #1) a single price set equal to the average shipping cost (i.e., $C_{ship}(N) / \sum_{i\in N} Q_i$) and (case #2) a two-part tariff that includes a fixed charge set to recoup the fixed cost[8] and a variable component with a slope set equal to the marginal shipping cost.[9]

$$r_{\text{ship}_i} = \frac{C_{\text{ship}}(N)}{\sum_{i\in N} Q_i} \qquad \text{(\#case1, average cost pricing)}$$

$$r_{\text{ship}_i} = \frac{f_{\text{ship}}}{|N|} + c_{\text{ship}} Q_i \qquad \text{(\#case2, two-part tariff)}$$

3.5 Comparison with a centralized welfare-maximizing approach

In the previous sections, we have described a cooperative game-theoretic model that allows us to determine the minimum CO_2 value needed to trigger a shared infrastructure that connects a given coalition N of $|N|$ emitters to a storage site. We find the minimum CO_2 value such that: (i) there exists a mutually acceptable infrastructure cost allocation: no subgroup of emitters faces a higher cost by joining the grand coalition than by standing alone, and (ii) emitters get a non-negative benefit from joining the shared infrastructure: the revenue from the carbon price (or carbon tax reduction) exceeds capture, transport and storage cost.

Now we take a reverse approach: assuming a given CO_2 value (the social cost of carbon), we determine which subgroup $S \subset N$ should adopt carbon capture and join a shared infrastructure to maximize welfare, which we define as the difference between revenue from abated emissions and total costs:

$$\max_S W(S) = -\sum_{i\in S} (\chi_i - \sigma) Q_i - C(S) + p_{CO_2} \sum_{i\in S} (Q_i - q_i)$$

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[8] *Accordingly, the fixed cost f_{ship} incurred by the shipping firm is simply apportioned into $|N|$ equal shares.*

[9] *In case of a linear cost function (as in the present) case, the proposed two-part pricing scheme is identical to the serial cost-sharing mechanism proposed in Moulin and Shenker (1992).*

Within this "first-best" approach, we can link the subgroups S with their respective volumes of abated emissions $\sum_{i \in S}(Q_i - q_i)$ and let the Social Cost of Carbon p_{CO_2} increase to examine which coalitions should be built. However, such an approach neglects the coordination issues that can be faced among emitters, which can lead to a higher CO_2 value needed to trigger the construction of the infrastructure for any subgroup S. To showcase this effect, we used the output of the previously described model as a condition to our welfare-maximizing problem. Let us denote $p^*_{CO_2}(S)$ the minimum CO_2 price needed to cooperatively trigger the construction of the shared infrastructure of subgroup S, whether it is obtained through the linear program LP1 or LP2. We then solve the following maximization problem:

$$\max_S W(S) = -\sum_{i \in S}(\chi_i - \sigma)Q_i - C(S) + p_{CO_2}\sum_{i \in S}(Q_i - q_i)$$

$$\text{s.t.} \quad p^*_{CO_2}(S) \geq p_{CO_2}$$

Table 1: Notations

Notation	**Description**
N	Grand coalition formed by all emitters
S	A sub-group of *N*
$C = C_{shipping} + C_{pipeline}$	Real-valued subadditive function on the subsets of N that gives CO_2 transportation costs
Q_i	The CO_2 emissions captured by emitter *i*
q_i	Process emissions attributable to emitter *i*
χ_i	Unit capture costs faced by emitter *i*
σ	Unit storage costs
$r = \left(r_1, \ldots, r_{\lvert N \rvert}\right)'$	Infrastructure cost vector when the infrastructure operator is vertically integrated
$r_{\text{pipe}} = \left(r_{\text{pipe}_1}, \ldots, r_{\text{pipe}_{\lvert N \rvert}}\right)$	Pipeline infrastructure cost vector when the infrastructure operators are vertically separated
$r_{\text{ship}} = \left(r_{\text{ship}_1}, \ldots, r_{\text{ship}_{\lvert N \rvert}}\right)$	Shipping infrastructure cost vector when the infrastructure operators are vertically separated
(f_{ship}, c_{ship})	Fixed and variable shipping costs

4. A Swedish application

In this section, we first briefly present the Swedish situation regarding the potential for BECCS/FECCS technologies to clarify both the background and the motivation of our analysis. Then, we detail a hypothetical yet realistic combined BECCS/FECCS project in Sweden that serves as an application to the methodology detailed above.

4.1 Sweden as a topical case study

Sweden presents many features that scaffold BECCS and FECCS deployment as an effective decarbonization option to meet the nation's ambitious climate objectives. First, carbon capture represents a realistic path. The country's power sector is already dominated by low emissions technologies (nuclear and hydroelectricity). Therefore, decarbonization should take place in other sectors. Interestingly, Sweden hosts a number of large carbon-intensive industrial facilities that can potentially be equipped with carbon capture capabilities: refineries, petrochemical plants, iron and steel factories, cement production (Garðarsdóttir et al., 2018; Johnsson et al., 2020).

Second, Sweden is part of Scandinavia, a region endowed with favorable geology for CO_2 storage. Mature aquifer storage capacity has been identified in Norway, and a sizable offshore storage site has now been developed there as part of an ambitious CCS project labeled Northern Lights (Cozier, 2019). In its first phase, the project has a domestic nature as it is intended to store up to 1.5 million tons of CO_2/year ($MtCO_2$/y) captured in the Oslo region. However, given the large size of the storage site, the Norwegian authorities and the Northern Lights consortium envision scaling up the project to store CO_2 captured at other industrial clusters and, in particular, at the neighboring ones in Sweden (Global CCS Institute, 2020). That project is expected to unlock the deployment of carbon capture in Sweden.[10]

[10] *Preem – a Swedish oil refining and distribution firm – recently signed an agreement with the Northern Lights consortium to deploy a CCS chain. According to Preem's announcements, a carbon capture unit will be installed at its coastal refinery in*

Last but not least, the emergence of FECCS also provides Sweden with an opportunity to unlock its BECCS potential. The country is endowed with an important biomass-fueled pulp and paper industry, which also represents a primary source of industrial CO_2 emissions (EEA, 2017). Equipping these processing plants with carbon capture units is deemed to be technically feasible (Garðarsdóttir et al. 2018), and once equipped, the pulp and paper plants may be considered as BECCS. The deployment of such BECCS capabilities could provide the country with a credible option for generating negative CO_2 emissions. In recognition of this, the government has explicitly listed it as a supplementary measure to reach the country's carbon neutrality target by 2045 (Regeringskansliet, 2018). Altogether, these specific features make Sweden a realistic case for studying the economics of the combined deployment of FECCS and BECCS.

4.2 The emitters, the storage site, and the associated logistics

As an application, we focus on the southwestern part of Sweden, where the emitters could be connected to the Northern Lights project in the future. We select all emitters within a 300km range from Lysekil[11] that have annual emissions volumes larger than 500 ktCO_2 per annum, as indicated in the 2017 European Pollutant Release and Transfer Report (EEA, 2017).

The resulting list includes seven industrial sites where carbon capture capabilities can be installed (see Table 2 and Figure 1 – right). Each of these emitters is labeled from E1 to E7. Three of them have a coastal location, in the vicinity of deep-ports in Lysekil (E7), Stenungsung (E3), and Göteborg (E1). Conceivably, each of the three ports can be equipped with CO_2 loading facilities and is thus considered a potential maritime terminal. The four remaining emitters are located in the hinterland (notably, the pulp and paper plants located north of the Vänern lake). We suppose that all emissions are directed to

Lysekil, and the captured CO_2 will be shipped to the Norwegian storage site using dedicated sea-going vessels. The commencement of these CCS operations is expected in 2020 (Preem, 2019).

[11] A FECCS project is currently under scrutiny at the Preem refinery in Lysekil Preem (2019) which calls for further appraisal of the FECCS/BECCS potential in that area.

a single storage site in Norway – the storage site deployed within the Northern Lights project – Figure 1, left.

Figure 1: The envisioned BECCS/FECCS project: General geography of the emission area in Sweden and the Norwegian storage site and the Swedish emission nodes

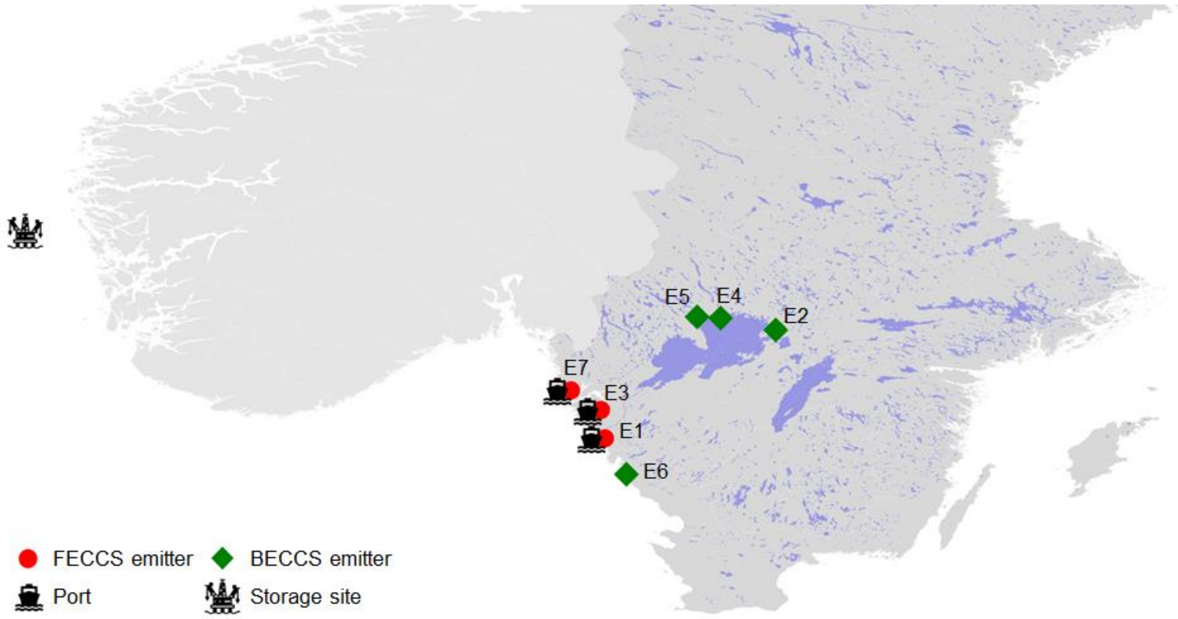


Table 2. The industrial facilities under scrutiny

Node	*Facility name*	*Sector*	*Total CO_2 emissions ($ktCO_2/y$)*
E1	St1 Refinery AB	Refinery	535
E2	Bäckhammars Bruk	Pulp and Paper	546
E3	Borealis Krackeranl.	Petrochemical	664
E4	Skoghalls Bruk	Pulp and Paper	943
E5	Gruvöns Bruk	Pulp and Paper	1,296
E6	Södra Cell Värö	Pulp and Paper	968
E7	Preemraff Lysekil	Refinery	1,428

The BECCS/FECCS chain in question thus requires the installation of (i) an onshore pipeline system aimed at gathering the emissions captured at the industrial sites and transporting them to the

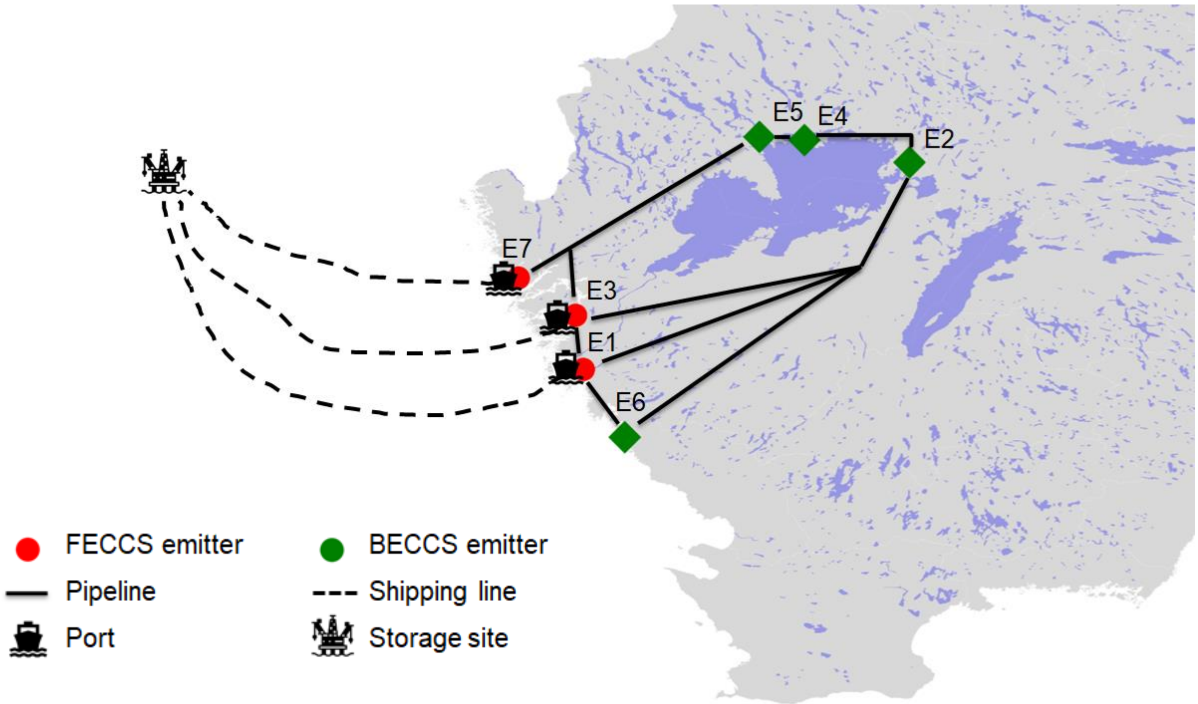
Swedish ports; and (ii) one or several maritime supply chain(s) based on sea-going vessels transporting the CO_2 from these Swedish ports to the offshore storage site in Norway. Regarding the maritime component of the chain, we disregard the possibility of building an offshore pipeline system because the analyses in Kjärstad et al. (2016) and Svensson et al. (2004) indicate that shipping provides the cheapest technological option for the volume and the distance under scrutiny.

4.3 Identification of the least-costly infrastructure

The application of our game-theoretic methodology requires the prior evaluation of the infrastructure cost incurred by each subgroup of emitters (see Section 3.2). We thus specify and parameterize an optimization problem aimed at determining the least-costly logistics for transporting the annual volumes of CO_2 captured at a given collection of Swedish emitters to the offshore storage site in Norway. We present an overview of the structure of this cost-minimization model below. The complete specification of this model is detailed in Appendix A.

This model aims at choosing the transportation routes (i.e., the pipelines and shipping routes) that minimize the total annual equivalent cost of building and operating the transportation and storage infrastructure. More precisely, it considers a predefined topology that includes a finite list of nodes representing the emitters, the possible maritime terminals, and the offshore storage site, as well as a predefined list of arcs representing the candidate pipelines and shipping routes connecting these nodes. The list of nodes and candidate routes is detailed in Appendix B. Figure 2 provides an illustration of the candidate infrastructure routes. From a cost perspective, each arc is characterized by a fixed and a unit cost component (see appendices C and D). Because of the fixed cost, there are arc-specific economies of scale.

Figure 2: The candidate pipelines and shipping lines



This cost-minimization model considers the following decisions. First, the model decides whether a given route should be opened or not given its fixed cost of deployment and its annual operating costs. That decision is modeled using route-specific binary variables whereby 1 indicates its installation and 0 means no construction. Second, for each of the installed routes, the model determines the transported quantity on that route. Lastly, the model decides the amount of CO_2 being injected at the storage site. These decisions have to verify a set of linear constraints that represent some fundamental requirements (*e.g.*, the mass balance equation at each node has to be verified; on each route, one cannot transport a positive flow of CO_2 if the construction of that route has not been decided).

The parameterization and the data retained in the present application, which are mainly taken from recent CCS techno-economic literature, are detailed in appendices C and D.

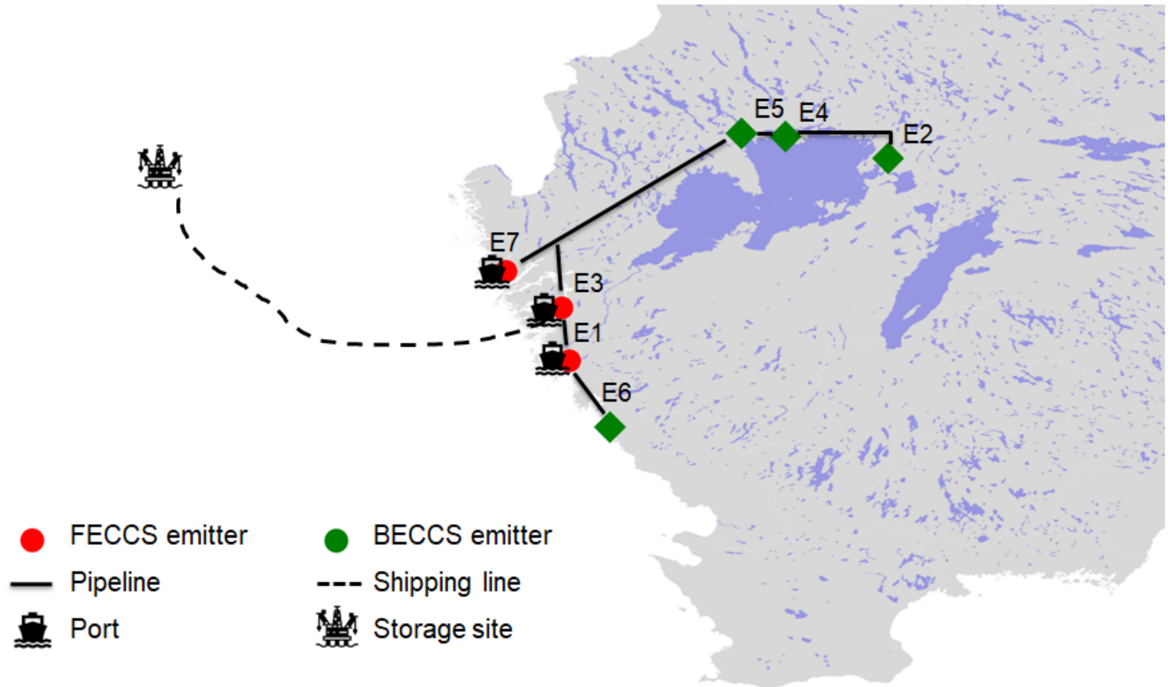
5. Results

In this section, we first present the least-cost design of the CO_2 transportation infrastructure and then report the break-even prices needed for its deployment obtained under alternative market structures and carbon accounting rules for negative emissions.

5.1 The least-costly infrastructure

We first use the optimization model above to determine the least-costly infrastructure connecting our seven emitters (i.e., the grand coalition N) with the storage site.

Figure 3: The least costly infrastructure connecting the seven industrial emitters



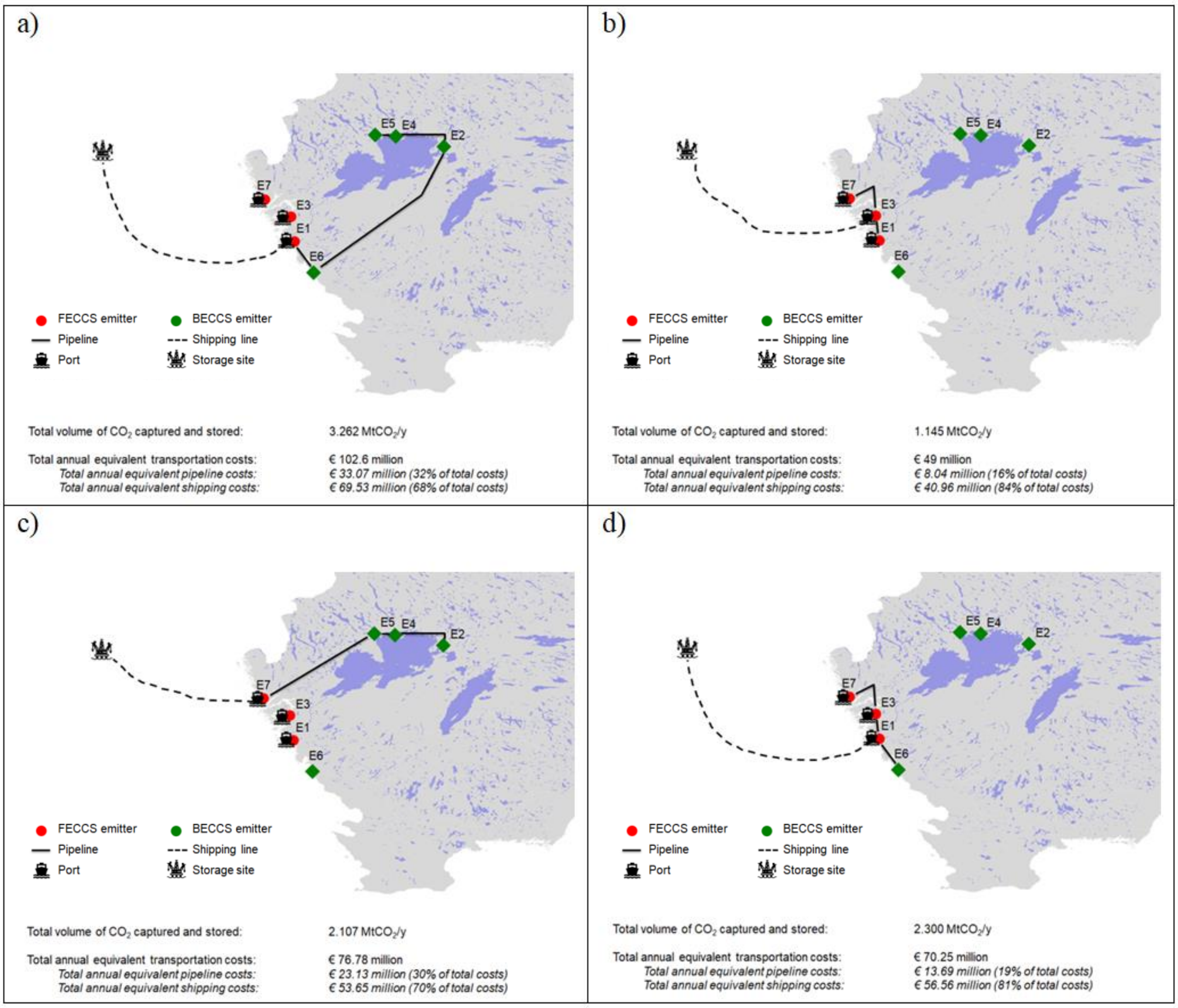
Total volume of CO_2 captured and stored:	4.407 $MtCO_2$/y
Total annual equivalent transportation costs:	€ 121.77 million
Total annual equivalent pipeline costs:	*€ 36.83 million (30% of total costs)*
Total annual equivalent shipping costs:	*€ 83.94 million (70% of total costs)*

The optimal infrastructure connecting all 7 emitters consists of a single pipeline system that goes around the Vänerm lake on its west side and directs the captured CO_2 to a single maritime terminal:

E3, a petrochemical plant. As a result, we are dealing with a fully connected pipeline system aggregating all the captured volumes to a unique shipping line. This finding is noteworthy, as prior research on optimal CO_2 pipeline systems has shown that a fragmented infrastructure can also be optimal in cases with different geographical set-ups (see Massol et al., 2018) for an illustration in a Spanish case).

To gain further insights into the economics of that optimal infrastructure, we also report below the results obtained for a few remarkable subgroups obtained by partitioning the grand coalition into two mutually exclusive subgroups. The first partitioning has a technological nature as we independently determine the least-costly infrastructures needed to serve the BECCS and the FECCS emitters separately (see Figure 4 (a) and (b)). The second one focuses on geography as we independently consider the emitters located in the coastal regions and the ones located in the hinterland (see Figure 4 (c) and (d)). In all cases, it is preferable to use a single shipping line with a unique departure port. As expected, the total infrastructure cost of serving two subgroups separately is substantially higher than serving the full coalition (56% larger for a BECCS/FECCS partitioning, 50% larger for the geographical partitioning).

Figure 4 Least costly infrastructure for several noteworthy coalitions, respectively: (a): BECCS emitters, (b): FECCS emitters, (c): Hinterland emitters, (d): Coastal emitters



5.2 "First best" infrastructure deployment

We now examine which coalitions would be constructed under increasing Social Costs of Carbon (SCC) by maximizing welfare, as described in Section 3.5. To do so, we have evaluated the total costs – including carbon capture and storage costs – for every possible subgroup of emitters and resolved the welfare maximization problem step-wise. Figure 5 showcases the abated emissions under increasing SCC, which can be seen as an inverted Marginal Abatement Cost Curve[12].

[12] *Because the quantities captured by each coalition are discrete, the interpretation is clearer when abated quantities are expressed as a function of SCC rather than the other way around.*

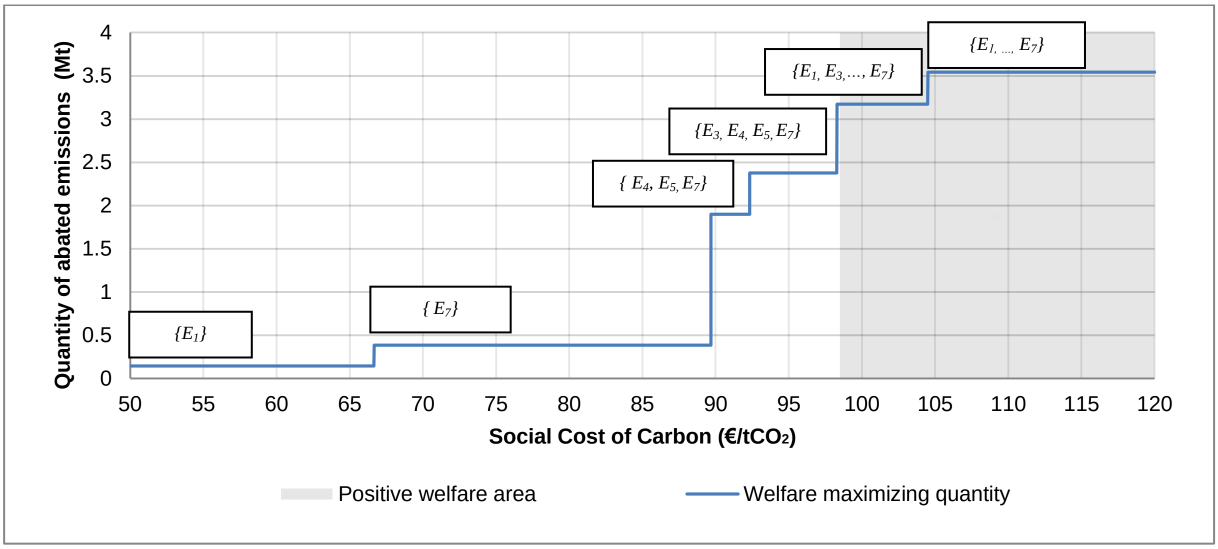


Figure 5: "First-best" coalitions under increasing SCC

A first remark is that our model is static; hence it doesn't give a coherent transitional infrastructure deployment pathway. The first coalition to maximize welfare (up to 67€/tCO_2) is the emitter E_1, mainly because it presents the lowest total capture and infrastructure costs; it is a small-scale coastal facility. As the SCC increases, the optimal coalition becomes E_7, a large-scale coastal refinery that is, in fact, already a CCS pilot (Preem, 2019). The first coalition to provide positive welfare would be implemented at 99€/tCO_2; it includes all emitters except E_2, a small-scale pulp and paper plant that is the most distantly located from any harbor. Only for an SCC higher than 104€/tCO_2 is the incremental infrastructure cost of E_2 compensated by its CO_2 abatement potential.

5.3 The cooperative approach: vertical integration vs. vertical separation

Conceivably, the consideration of coordination issues and strategic interactions between the seven emitters could be a barrier to reaching the socially optimal coalitions described above. Our cooperative game-theoretic approach models these constraining conditions by imposing that the infrastructure cost allocation should be mutually acceptable (no subgroup of emitters should have an incentive to disband) and that all individual emitters get a non-negative benefit from joining the infrastructure – assuming that both FECCS and BECCS plants are remunerated for their abated emissions. We computed the break-even CO_2 values for which these conditions are verified for all subgroups and added these constraints to our welfare-maximizing problem.

We successively consider three alternative industrial organizations for the infrastructure operator: (i) the case of a vertically integrated operator controlling both the onshore and offshore components of the logistics; (ii) the case of a vertical separation with two dedicated operators with a shipping operator charging a price set equal to its average cost; and (iii) the case of a vertical separation with a shipping operator charging the two-part tariff discussed in Section 3.4. The resulting coalitions are pictured in Figure 6. The welfare losses related to socially sub-optimal coalitions are reported in Figure 7. It may be noted that because of the individual net-negative benefit constraint, only coalitions allowing for positive welfare are represented.

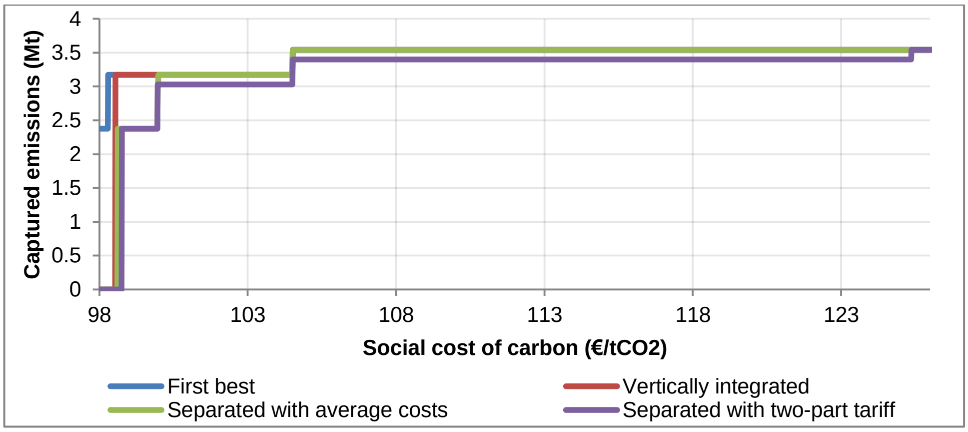


Figure 6: Coalitions under increasing SCC

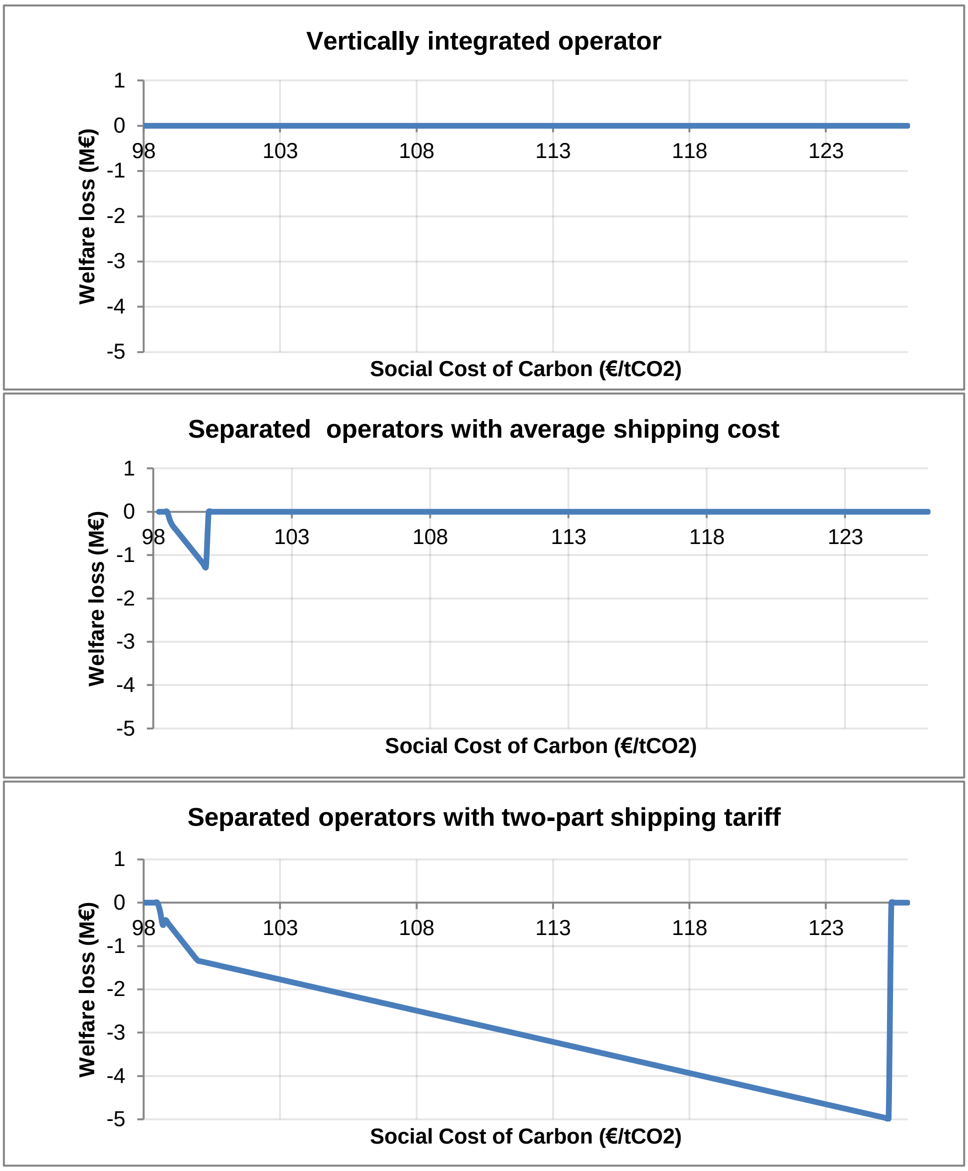


Figure 7: Welfare losses for different infrastructure operator nature scenarios

Interestingly, we see that the vertically integrated operator scenario yields socially optimal coalition infrastructure deployment, resulting in no welfare losses. This can be explained by the leeway allowed by discriminatory infrastructure pricing in reaching the largest possible coalitions. However, a vertically integrated operator combining both pipeline and shipping lines is, in fact, barely realistic; shipping lines have much shorter contracting times than pipelines and require significantly different expertise. When considering vertically separated operators, it appears that average shipping cost pricing allows for the construction of larger infrastructures than two-part tariff schemes. As an illustration, the infrastructure including all seven emitters is constructed for 104€/tCO_2 in the first two scenarios but is only achieved at 125€/tCO_2 in the case of a two-part shipping tariff scheme. The revenue from CO_2 abatement and the leeway allowed by discriminatory pipeline pricing is hence not sufficient to ensure that E_2 covers its total cost when it has to participate in fixed shipping costs.

5.4 The influence of a life-cycle based negative emissions rewarding system

We now consider the case of life-cycle negative emissions accounting for BECCS plants, which means that we also take into account upstream process emissions for BECCS plants. We assume that the total process emissions of BECCS represent 40% of the volume of stored emissions (Fajardy and Mac Dowell, 2017). The welfare-maximizing coalitions in both scenarios are shown in Figure 8. The "Abated emissions accounting" scenario represents the case where upstream process emissions are ignored.

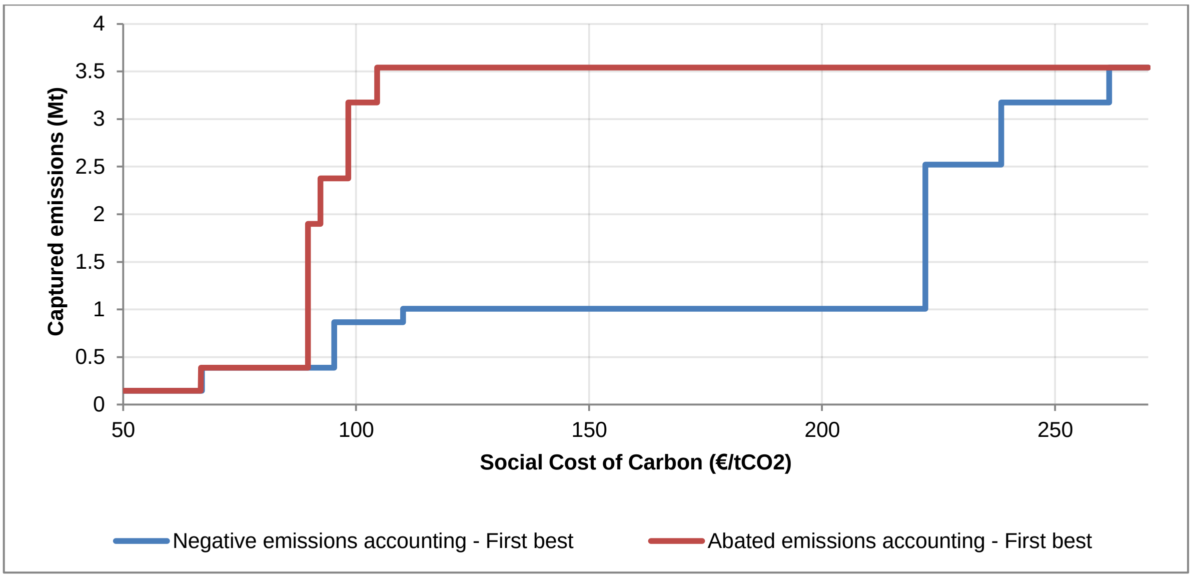


Figure 8: "First-best" coalitions under increasing SCC

As can be expected, the first coalitions to be built in the negative emissions accounting scenario only gather FECCS emitters. An SCC of 222€/tCO_2 is needed to trigger the construction of an infrastructure that includes BECCS plants, while positive welfare is reached for the coalition that includes the three FECCS emitters at 115€/tCO_2 –positive welfare was achieved for 104€/tCO_2 in the previous scenario. Here again, the cooperative approach shows that socially optimal coalitions are achieved in the vertically integrated operator scenario, while some sub-optimal coalitions appear for the separated operators scenarios (Figure 9).

Hence, although a life-cycle negative emissions accounting framework would avoid perverse effects described in Section 2., it globally raises the SCC needed to trigger CCS adoption, whether in fossil-fuelled industries or bioenergy-fuelled industries. Additionally, bioenergy-fuelled plants may be locked out of CO_2 infrastructures because of the irrevocable nature of CO_2 pipeline construction: BECCS facilities may not benefit from the economies of scale of sharing a common infrastructure with FECCS emitters, as their adoption of carbon capture will come much later (Vergragt et al., 2011).

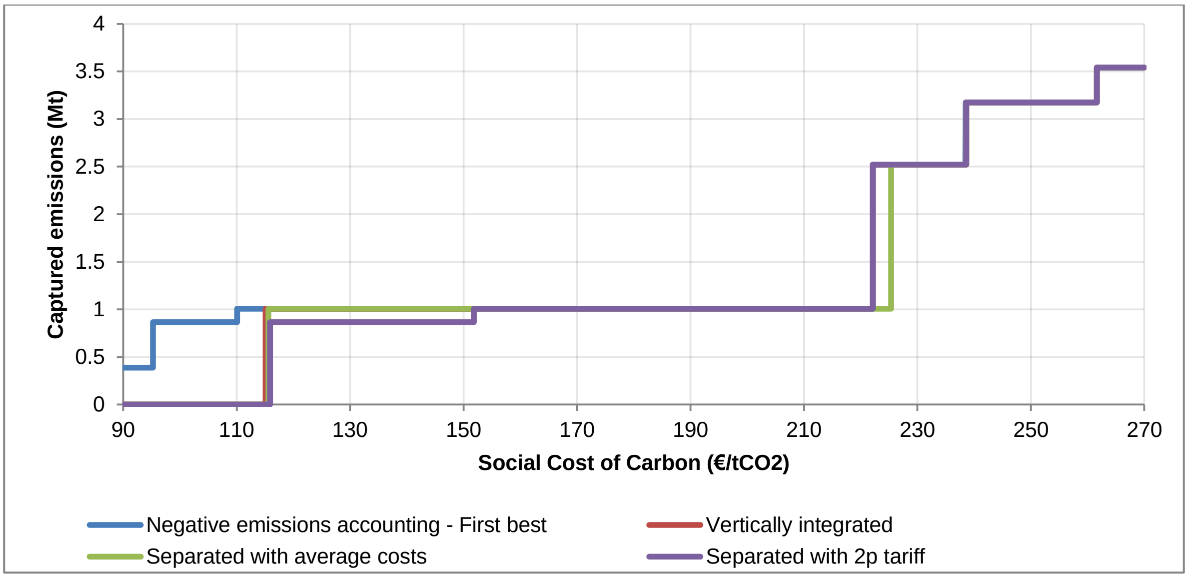


Figure 9: Coalitions under increasing SCC

6. Conclusion

Bio-energy with Carbon Capture (BECCS) as well as fossil Carbon Capture and Storage (FECCS) have been pictured as key technologies to limit global warming (Rogelj et al., 2018). BECCS, in particular, is expected to produce negative emissions, *i.e.*, net CO_2 removal from the atmosphere. The construction of a large-scale CO_2 transport and storage system is an essential issue that policymakers should address to support a rapid up-scaling of BECCS as well as FECCS. Accounting for the coordination of actors along the value chain is critical for identifying the viable and mutually agreed cooperation scheme at a regional level that is needed for accelerating the adoption. Furthermore, although BECCS and FECCS may share a common CO_2 infrastructure, they face different challenges and accounting methods.

This paper builds on a topical Swedish case study to clarify the conditions that enable the construction of a shared CO_2 transport and storage infrastructure. Using an adapted cooperative game-theoretic framework, we model the outcomes of the strategic interactions among emitters and use them to determine the critical value of CO_2 emissions that makes the construction possible: the break-even CO_2 value for BECCS and FECCS adoption. We can then compare the CO_2 infrastructures that are socially optimal at a given Social Cost of Carbon with the infrastructures that can be built under our cooperative assumptions. We find that, in the case of a vertically integrated CO_2 operator and discriminatory infrastructure prices, socially optimal infrastructures can be built with positive welfare starting at 99€/tCO_2 – an encouraging figure considering that current Swedish carbon taxes are around 110€/tCO_2 (Government offices of Sweden, 2020). However, vertically integrated pipeline and shipping operators may not be realistic, considering the different expertise and contracting times of both technologies. In the case of vertically separated operators, a sustainable and incentive-cooperation scheme is achievable above 99€/tCO_2 as well. However, the triggered infrastructures are slightly sub-optimal in the case of discriminatory prices for pipelines and average shipping cost tariffs. Large welfare losses are observed in the case of two-part shipping tariffs.

Biogenic emissions, however, remain beyond the scope of carbon taxes and markets. The previous results assumed that BECCS plants can be remunerated for their abated CO_2 (for example, through carbon "credits" that can be auctioned to hard-to-decarbonized sectors). This option can lead to perverse effects, as the carbon footprint of biomass is neglected; there is no guarantee that BECCS indeed produces negative emissions. We examine the effects of a negative emissions accounting framework by assuming that BECCS emitters are rewarded at the CO_2 market price for the negative emissions they produce. These may represent only a fraction of the sequestered CO_2, as upstream process emissions need to be accounted for; we test a scenario where total process emissions reach 40% of stored emissions at BECCS plants. The lowest SCC needed to trigger an infrastructure that includes BECCS reaches 222€/tCO_2, while an infrastructure gathering only FECCS actors could be built as of 115€/tCO_2.

These results lead us to position two main policy recommendations on the deployment of a shared BECCS and FECCS infrastructure. First, a vertically integrated infrastructure should be preferred, as it allows a more advantageous cost allocation between participants. And second, the creation of a negative emissions accounting and rewarding framework is of paramount importance to enable the deployment of BECCS; such a framework must be agreed upon internationally in the coming years in order to allow the upscaling of BECCS. Furthermore, if negative emissions produced by BECCS facilities are to be rewarded in a life-cycle perspective, BECCS will only become an economically viable mitigation option if a large amount of sequestered CO_2 can be considered negative. Therefore, a sustainable and low emitting bio-energy value chain needs to be incentivized with an international sustainable biomass certification framework.

Notwithstanding the value of our findings, our analysis can be extended in several directions. For instance, an implicit premise of our model is that all emitters are simultaneously connected to the infrastructure. As the historical evidence gained from other infrastructure networks (e.g., natural gas or electricity) indicates that infrastructure can grow organically from a small territory to a larger one by gradually connecting adjacent users, future research could explore the conditions for such an organic deployment of BECCS and FECCS infrastructures. Given the importance of capacity constraints in pipeline-based transportation techniques, one could also explore the need for an optimal degree of overcapacity on some critical components of the infrastructure (e.g., on some important transportation corridors). As that overcapacity is likely to be costly, another strand of research could also extend the analysis to examine the (fair) recouping of the associated extra cost.

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Appendix A – Designing an optimal infrastructure

This appendix details the specifications of the optimization problem used to determine the least-cost design of an integrated transportation and storage infrastructure involving both pipelines and shipping lines.

Notation

To begin with, we define three sets to identify the nodes of the network:

- $N = \{1, ..., i, ..., |N|\}$ the set gathering the emission nodes where emissions are captured;
- $K = \{1, ..., k, ..., |K|\}$ the set gathering the storage nodes where CO_2 is injected into an underground storage site;[13]
- $R = \{1, ..., r, ..., |R|\}$ the set of the network routing nodes that are not connected to either an emission node or to a storage site. These nodes typically represent an intersection between several pipeline links.

The three sets are mutually exclusive so: $N \cap K = \varnothing$, $K \cap R = \varnothing$ and $N \cap R = \varnothing$. For notational convenience, we also let $Z = N \cup K \cup R$ denote the macro-set regrouping all the nodes and z is used as a generic notation for a given node in Z. We also let $P = \{1, ..., p, ..., |P|\}$ denote the set of candidate pipeline links and $L = \{1, ..., l, ..., |L|\}$ denote the set of candidate shipping lines.

We now present the exogenous parameters.

- Q_i is the total quantity captured and injected into the network at emission node i;

[13] In the present application, that set has only one element: the Norwegian storage site. That said, the model has a generic nature and it could be applied in other cases involving several storage sites.

- $\overline{Q}_k$ is the maximum amount of CO_2 that can be injected into storage k;

- $I_{p,z}$ is an incidence parameter that only takes three values: -1 if pipeline p starts at node z, 1 if pipeline p ends at node z, and 0 otherwise;

- $J_{l,z}$ is an incidence parameter that only takes three values: -1 if shipping line l starts at node z, 1 if pipeline l ends at node z, and 0 otherwise;

- F_p^{pipe} is the fixed cost incurred to open the pipeline link p;

- C_p^{pipe} is the unit cost incurred by using pipeline p;

- F_l^{ship} is the fixed cost incurred to open the shipping line l;

- C_l^{ship} is the unit shipping cost incurred by using the shipping line l;

- C_k^{inj} is the unit cost of the CO_2 injection operations conducted at storage k;

- M_{pipe} and M_{ship} are two arbitrarily large constants. Their values will be discussed below.

The decision variables are:

- δ_p is a binary variable that describes whether the pipeline link p is opened (i.e., $\delta_p = 1$) or closed (i.e., $\delta_p = 0$);

- q_p^+ (respectively q_p^-) is the non-negative quantity transported using pipeline p that flows in the direction posited for pipeline p (respectively in the opposite direction);

- γ_l is a binary variable that describes whether the shipping line l is opened (i.e., $\gamma_l = 1$) or closed (i.e., $\gamma_l = 0$);

- q_l^{ship} is the non-negative quantity transported using shipping line l that flows in the direction posited for that line;

- q_k^{inj} is the non-negative quantity injected into storage k.

For notational simplicity, we also let $x_N = \left(\delta_p, q_p^+, q_p^-, \gamma_l, q_l^{ship}, q_k^{inj}\right)$ be the decision vector to transport and store the emissions captured at the emission nodes in N.

<u>Optimization problem</u>

The cost-minimizing design of an infrastructure gathering the emissions captured at the emissions nodes in N and transporting them to the storage site can be determined using the following mixed integer linear programming problem:

$$\min_{x_N} \quad Cost = \sum_{p \in P}\left[F_p^{pipe}\delta_p + C_p^{pipe}\left(q_p^+ + q_p^-\right)\right] + \sum_{l \in L}\left[F_l^{ship}\gamma_l + C_l^{ship} q_l^{ship}\right] + \sum_{k \in K} C_k^{inj} q_k^{inj} \qquad \text{(A.1)}$$

$$\text{s.t.} \quad \sum_{p \in P} I_{p,i}\left(q_p^+ - q_p^-\right) + \sum_{l \in L} J_{l,i}\ q_l^{ship} + Q_i = 0, \qquad \forall i \in N, \qquad \text{(A.2)}$$

$$\sum_{p \in P} I_{p,k}\left(q_p^+ - q_p^-\right) + \sum_{l \in L} J_{l,k}\ q_l^{ship} = q_k^{inj}, \qquad \forall k \in K, \qquad \text{(A.3)}$$

$$\sum_{p \in P} I_{p,r}\left(q_p^+ - q_p^-\right) + \sum_{l \in L} J_{l,r}\ q_l^{ship} = 0, \qquad \forall r \in R, \qquad \text{(A.4)}$$

$$q_p^+ + q_p^- \le \delta_p M_{pipe}, \qquad \forall p \in P, \qquad \text{(A.5)}$$

$$q_l^{ship} \le \gamma_l M_{ship}, \qquad \forall l \in L, \qquad \text{(A.6)}$$

$$q_k^{inj} \le \overline{Q}_k, \qquad \forall k \in K, \qquad \text{(A.7)}$$

$$q_k^{inj} \ge 0,\ \forall k \in K;\ \delta_p \in \{0,1\},\ q_p^+ \ge 0,\ q_p^- \ge 0,\ \forall p \in P \text{ and } \gamma_l \in \{0,1\},\ q_l^{ship} \ge 0,\ \forall l \in L \qquad \text{(A.8)}$$

In this optimization problem, the objective function (A.1) to be minimized is the sum of the total pipeline costs, the total shipping costs, and the storage annual equivalent cost. The objective function is linear, and so are the constraints. The linear constraints (A.2), (A.3) and (A.4) respectively represent the mass balance equations at the source, storage, and intersection nodes. For each pipeline p, the constraint (A.5) forces the binary variable δ_p to be equal to 1 whenever a positive quantity of gas is flowing into that pipeline (whatever the flow direction) and imposes a zero flow whenever it is optimal to not build it.[14] For each shipping line l, the constraint (A.6) forces the binary variable γ_l to be equal to 1 whenever a positive quantity of gas is shipped using that shipping line and imposes a zero flow whenever it is optimal to not open it. The constraints (A.7) represent the sink injectivity constraints: at each storage node, the quantity injected cannot exceed the local injection capacity.

We let $x_N{}^*$ be the solution to that problem. Observe that this solution is such that on each pipeline p, at least one of the two directed flows q_p^{+*} and q_p^{-*} must be equal to zero.[15]

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[14] *It should be noted that the value of the parameter* M_{pipe} *(respectively* M_{ship}*) is arbitrarily set at a level that is large enough for the constraint (B.5) (respectively (B.6) to be non-binding whenever the pipeline is built (respectively the shipping line is iused). In the present case, we assume that these constants equal 10 times the sum of the quantity of* CO_2 *injected at all nodes (i.e.,* $\sum_{i\in N} Q_i$ *). Such « big M » constraints are commonly used in the operations research (O.R.) literature.*

[15] *Indeed, we assume that* $x_N{}^*$ *is a solution and that there is at least one pipeline* p' *with* $q_{p'}^{+,*} > 0$ *and* $q_{p'}^{-,*} > 0$*, we consider the decision vector* $x_N{}^{**}$ *where the pipeline flows are the net non-negative flows in each direction* $q_{p'}^{+**} = \max(q_{p'}^{+*} - q_{p'}^{-*}, 0)$, $q_{p'}^{-**} = \max(q_{p'}^{-*} - q_{p'}^{+*}, 0)$ *and the other variables have the same values as the ones in* $x_N{}^*$*. By construction,* $x_N{}^{**}$ *also verifies the constraints (B.2)–(B.7) while yielding a lower value for the objective function (B.1) because* $q_{p'}^{+**} + q_{p'}^{-**} = \left| q_{p'}^{+*} - q_{p'}^{-*} \right|$ *and thus* $C_{p'}^{pipe}\left(q_{p'}^{+**} + q_{p'}^{-**}\right) < C_{p'}^{pipe}\left(q_{p'}^{+*} + q_{p'}^{-*}\right)$*. Hence, we have a contradiction because* $x_N{}^*$ *cannot be a solution of the optimization problem.*

This optimization problem is a mixed-integer linear programming problem). Given its modest size in the instances considered in the present study, a numerical solution to that problem can be obtained in a few seconds using a standard solver and a laptop.

Appendix B – Topology

Our parameterization considers a total of nine nodes including: the seven emission nodes E1 to E7, an intersection node labeled R1 that represents a possible network intersection between candidate pipelines, and a unique offshore storage site (Table B.1.).

Table B.1. The nodes

Node	Nature	Facility name	Comment
E1	Emission	St1 Refinery AB	Refinery
E2	Emission	Bäckhammars Bruk	Pulp and Paper plant
E3	Emission	Borealis Krackeranl.	Petrochemical
E4	Emission	Skoghalls Bruk	Pulp and Paper plant
E5	Emission	Gruvöns bruk	Pulp and Paper plant
E6	Emission	Södra Cell Värö	Pulp and Paper plant
E7	Emission	Preemraff Lysekil	Refinery
R1	Routing		
S1	Storage	The Norwegian storage site	

Regarding onshore transportation, we consider a predefined set of ten candidate pipelines that can be installed in that part of Sweden (see Table B.2). These pipelines are located along the region's main transport corridors, and the associated distances range from 30 to 284km, as represented in Table B.2.

Table B.2. The candidate pipelines and their lengths

Pipeline	Origin	Destination	Distance (km)
P1	E1	E3	72
P2	E3	E4	30
P3	E4	R1	168
P4	R1	E6	28
P5	R1	E2	60
P6	E2	E0	54
P7	E0	E5	70
P8	E1	E2	217
P9	E1	E0	238
P10	E1	E5	284

Point-to-point shipping is selected for offshore transportation between the three ports and the storage site located on the Norwegian continental shelf. The distance of these shipping lines varies between 613 and 641km.[16]

Table B.3. The candidate shipping lines and their lengths

Line	Origin	Destination	Distance (km)
L1	E7	S1	613.0
L2	E3	S1	638.9
L3	E1	S1	640.8

Appendix C – Cost data

In this appendix, we present the cost data used in our study. All costs are reported in €$_{2015}$ and are levelized assuming 25 years of economic lifetime (except when stated otherwise) and a 7.5% discount

[16] *The shipping line distances were calculated using an online calculator available at https://www.searoutes.com/, using the port of Bergen, Norway, as an approximation of the storage site location.*

rate. These assumptions are consistent with earlier techno-economic studies (Garðarsdóttir et al., 2018; Johnsson et al., 2020; Roussanaly et al., 2014; ZEP, 2011).

CO_2 capture

Carbon dioxide capture costs vary significantly depending on the considered sector and technology. As an illustration, the techno-economic review carried out by Leeson et al. (2017) provides unit capture costs for petroleum refineries ranging from 28.7 to \$250/tCO_2. Here, we assume that a monoethanolamine-based (MEA) CO_2 absorption process is implemented.

CO_2 combustion emissions are most cost-effectively captured at stacks with high flue gas concentration and volumes. In petroleum refineries, this represents 30% of the total emissions (stemming from the H_2 production unit), whereas in the pulp and paper industry, 75% of emissions can be captured by equipping the recovery boiler. Finally, in the petrochemical plant considered here, 80% of emissions may be captured at the cracker furnace (Garðarsdóttir et al., 2018). We use specific capital cost estimations from the work of Johnsson et al. (2020). Table C.1. gathers the assumed capture rates and costs for the selection of facilities in our application case.

Table C.1. Capture rates and costs in for each emitter (Garðarsdóttir et al. 2018)

Node	Sector	Total CO_2 emissions (1,000 tCO_2/y)	Capture rate	Total €/(tCO_2/y)
E1	**Refinery**	535	30%	66
E2	**Pulp and Paper**	546	75%	64
E3	**Petrochemical**	664	80%	61
E4	**Pulp and Paper**	943	75%	56
E5	**Pulp and Paper**	1296	75%	53
E6	**Pulp and Paper**	968	75%	52
E7	**Refinery**	1428	30%	50

In should be noted that in this case, considering the low emissions of the Swedish power system, capture costs are close to the cost of avoided CO_2 and will be considered equal in this study.

CO_2 transportation: a pipeline system and a maritime supply chain

Following Morbee et al. (2012) and Massol et al. (2018), the construction cost of an onshore point-to-point CO_2 pipeline infrastructure is assumed to be directly proportional to its length. In the present study, we retain the cost parameters presented in Massol et al. (2018).[17] The annual equivalent investment cost of a 100km-long pipeline with an output of q $MtCO_2$/y is: $(A_0 + B_0 q)\tau$, where $A_0 = 4.6045$ is the fixed cost coefficient (in million 2015 euros), the variable cost coefficient is $B_0 = 0.1641$ in 2015 euros per (tCO_2×100 km) and τ = 1.1 is the dimensionless terrain correction factor

[17] *Original monetary values are in 2010 euros and were corrected for inflation to obtain 2015 euros.*

described in IEAGHG (2002).[18] Concerning O&M, IEA (2005) indicates operation costs ranging from 1.0 to 2.5 euros per (tCO_2×100 km). We use a value of 1.5 euros per (tCO_2×100 km).

Regarding maritime shipping, we use an empirical function that gives the total annual cost (in M€/y) incurred for transporting a given annual flow of CO_2 over a given distance. This function has been estimated using the cost-engineering data presented in Roussanaly et al. (2014). The estimation procedure and the retained specifications are detailed in Appendix D.

CO_2 storage

We use a cost estimation given for offshore depleted gas oil fields by ZEP (2011), namely 9€/tCO_2 (high-cost scenario). Indeed, the storage site considered in the Northern Lights project will be exploited using existing oil and gas infrastructure on the Norwegian continental shelf (CCS Norway, 2019). In this case, an economic lifetime of 40 years is assumed.

Appendix D – The cost of maritime transportation

In the present study, we use an empirical approach to model how the cost of a maritime shipment of CO_2 varies with the volume shipped and the distance to the storage site.

The Scandinavian cost engineering literature provides several detailed evaluations of the total annual cost of a maritime CO_2 supply chain. That chain is aimed at transporting a given annual volume of CO_2 on a given distance using dedicated sea-going vessels that commute between a departure port equipped with specific loading and temporary storage facilities and an offshore site where the CO_2 is aimed at being stored permanently (Kjärstad et al., 2016; Roussanaly et al., 2014). In this paper, we leverage on these detailed cost evaluations to identify an approximate total cost function. More specifically, we use the information in Roussanaly et al. (2014), Table 13 – a data set comprising 100 observations for the unit transportation costs incurred for a supply chain shipping a given volume

[18] *Here, we assume that the pipelines are installed on cultivated lands which explains the retained value for that parameter.*

(from 2 to 20 $MtCO_2$/y by regular steps of 2 $MtCO_2$/y) over a given distance (between 200 and 2,000 kilometers by regular steps of 200km) – to estimate an empirical cost function.[19]

We posit the following parsimonious specification[20] whereby the total annual cost C (in millions €) is modeled as a linear function of the distance D (in 1,000km), the volume shipped Q (in $MtCO_2$/y) and the product $D \times Q$ aimed at capturing the interactions between these two variables:

$$C = \alpha + \beta D + \gamma Q + \delta \left(D \times Q \right) + \varepsilon \qquad \text{(D.1)}$$

where α, β, γ and δ are coefficients to be estimated and ε is an error term.

An ordinary least squares estimation yields the results presented in Table D.1. The estimated coefficients are highly statistically significant, the model has an excellent goodness-of-fit, and its residuals show no signs of non-normality. Unsurprisingly, the coefficients are positive, which indicates that the cost increases with both the distance and the volume shipped. For a given distance, that shipping cost function thus exhibits a positive fixed cost component $\alpha + \beta D$, and the variable cost is linear with a marginal shipping cost that is equal to $\gamma + \delta D$. By construction, the shipping cost function obtained for a given distance, thus exhibits pronounced economies of scale.

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[19] *By construction, this approach is similar to the "pseudo data" method proposed to approximate complex engineering models using empirically-determined, single-equation cost functions (see e.g., Griffin (1979, 1978, 1977) or Massol (2011)).*

[20] *As there is no theoretical basis on which to select a particular functional form for that cost function, we have also tested a variety of other possible specifications including the simpler linear function with two explanatory variables (the distance and the volume) and several extensions including either quadratic, cubic or logged values of these variables). However, as the goodness-of-fit obtained with these more complex models was not substantially better than that obtained with our simple linear model.*

Table D.1. Estimation results

	Total annual cost	
Constant	24.051	***
	(1.141)	
Distance	2.307	**
	(0.920)	
Volume	10.924	***
	(0.092)	
(Distance × Volume)	4.004	***
	(0.074)	
R^2	0.9993	
Adjusted R^2	0.9993	
Normality *(p-value)*	1.178	*(0.555)*

Note: The standard deviations of the estimates is reported in brackets. Asterisks indicate significance at 0.1*, 0.05** and 0.01*** levels, respectively. Normality refers to the Jarque-Bera test for the null hypothesis of normally distributed residuals.