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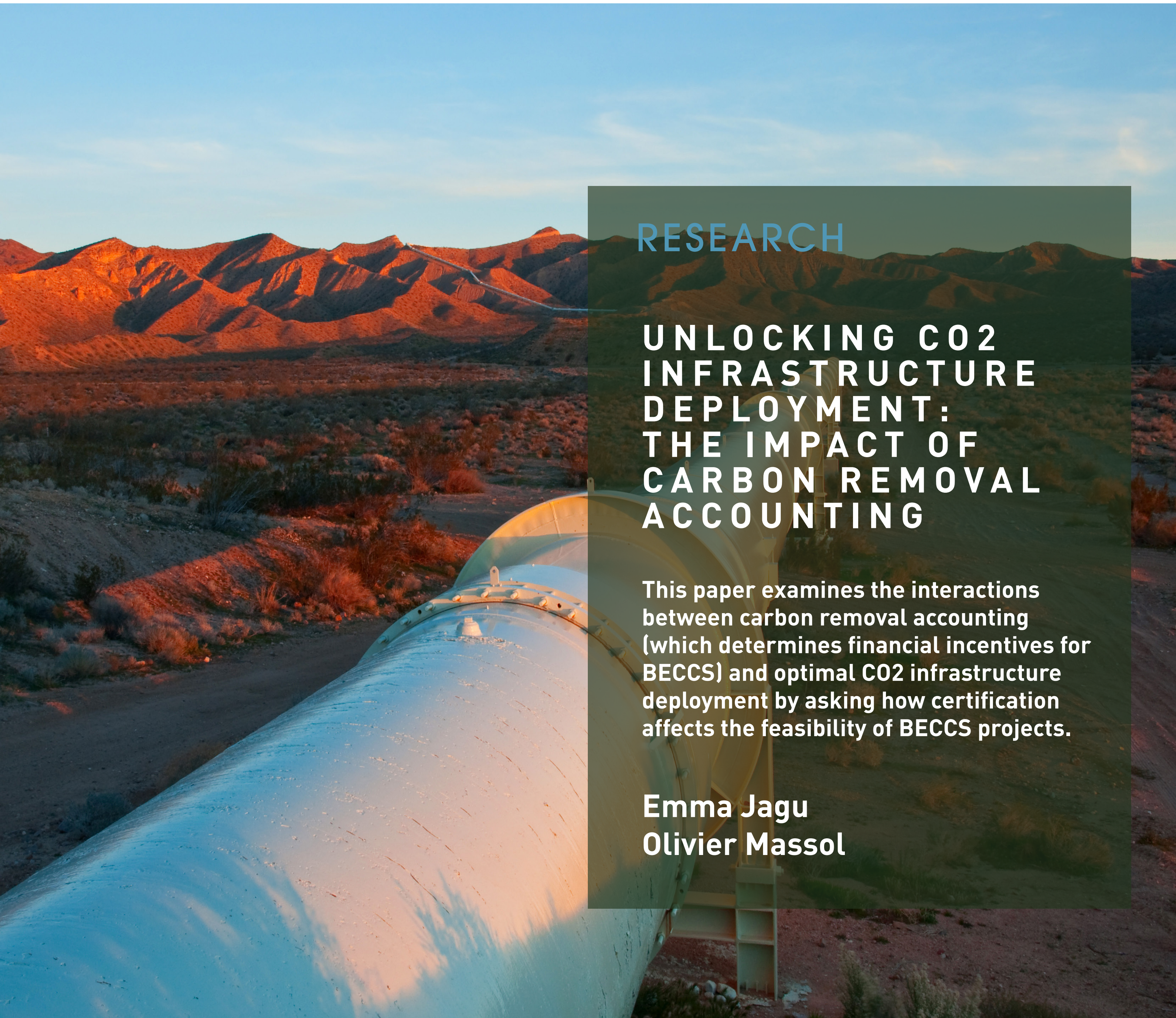

RESEARCH

UNLOCKING CO2 INFRASTRUCTURE DEPLOYMENT: THE IMPACT OF CARBON REMOVAL ACCOUNTING

This paper examines the interactions between carbon removal accounting (which determines financial incentives for BECCS) and optimal CO2 infrastructure deployment by asking how certification affects the feasibility of BECCS projects.

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Unlocking CO_2 infrastructure deployment: The impact of carbon removal accounting

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Abstract

Carbon removal certification may become a powerful instrument to accelerate decarbonization efforts. In Europe, its implementation is expected to foster the deployment of Bioenergy with Carbon Capture and Storage (BECCS). Yet, the large-scale adoption of BECCS is also limited by the availability of a costly CO_2 transportation infrastructure shared with fossil-fueled emitters. In this paper, we examine the interactions between carbon removal accounting (which determines financial incentives for BECCS) and optimal CO_2 infrastructure deployment by asking how certification affects the feasibility of BECCS projects. We propose an original economic framework to explore this question and apply it to a real case study in Sweden. We show that, although a carbon removal accounting framework based on a lifecycle methodology discourages investment in inefficient BECCS processes, it may lead to locking out BECCS from CO_2 infrastructures. Our results suggest that a trade-off must be found between accurately evaluating carbon removal and avoiding BECCS lock-out. We formulate two policy recommendations to overcome this trade-off: (i) deploying sustainable biomass certification to incentivize more carbon-efficient BECCS process, and (ii) stimulating public and private demand for carbon removal credits to induce a higher price for sustainable carbon removal than for carbon mitigation.

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Keywords: Carbon removal accounting, Carbon removal certification, Negative Emissions, Bioenergy Energy with Carbon Capture and Storage, CO_2 infrastructures

1. Introduction

Bio-energy with Carbon Capture and Storage (BECCS) and Fossil energy with Carbon Capture and Storage (FECCS) are frequently depicted as key to limiting global warming to 1.5°C (Bosetti et al., 2015; Koelbl et al., 2014; Nemet et al., 2018; Rogelj et al., 2018) and to reaching regional carbon budgets (Bistline et al., 2018; Di Sbroiavacca et al., 2016; Huang et al., 2020; Kalkuhl et al., 2015; Rajbhandari and Limmeechokchai, 2021; Ricci and Selosse, 2013; Solano Rodriguez et al., 2017). FECCS is expected to mitigate CO_2 emissions from otherwise difficult-to-decarbonize industries, especially when electrification is challenging (Benhelal et al., 2013; Griffin et al., 2018; IEA, 2017). BECCS has the potential of removing CO_2 from the atmosphere by combining the natural carbon sequestration potential of biomass growth with the permanent CO_2 storage potential of CCS (Gough and Upham, 2011; Smith et al., 2016). Although the global annual CO_2 removal capacity of BECCS is expected to scale up from the Megaton magnitude today to the Gigaton magnitude by 2050, its current uptake remains limited (Fuss et al., 2018; 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 deployment of CO_2 transportation and storage infrastructures, which are, by nature, costly, capital intensive, and likely to exhibit substantial economies of scale (Butnar et al., 2020; Krahé et al., 2013). A large and growing literature on CO_2 pipeline deployment has already highlighted the need for shared infrastructures with either a regional/national scale (Kemp and Kasim, 2010; Klokk et al., 2010; Massol et al., 2018, 2015; Middleton and Bielicki, 2009; Spiecker et al., 2014) or a continental (European) scale (Morbee, 2014; Morbee et al., 2012; Oei and Mendelevitch, 2016). It is important to stress that these studies concentrate on infrastructures that are solely connected to FECCS emitters, *de facto* overlooking the access of BECCS emitters to the infrastructure. This omission is not so surprising as the economics of joint BECCS-FECCS infrastructure projects have, to the best of our knowledge, never been examined before. Furthermore, FECCS and BECCS emitters do not face the same incentives to join a shared CO_2 infrastructure. While European fossil-fueled emitters can benefit from carbon tax reductions or quotas by installing CCS (Banal-Estañol et al., 2016; Comello and Reichelstein, 2014), carbon removal accounting frameworks for bioenergy-fueled emitters are still under development.

To incentivize the implementation of BECCS, several studies have suggested the creation of carbon removal credits (also called negative emissions credits) that could be auctioned to hard-to-decarbonize sectors (Cabral et al., 2019; Torvanger, 2019; Zakkour et al., 2014). Article 6.4. of the Paris Agreement – of which operational rules were finalized during COP26 – could be a relevant basis for such transfers (Honegger and Reiner, 2018). However, robust international carbon removal accounting frameworks are still missing. The carbon removal potential of BECCS is counterbalanced by process emissions, which could stem from: direct and indirect land use; biomass harvesting, transporting, and processing; or carbon capture, transportation, and storage processes (Fajardy and Mac Dowell, 2017). The amount of carbon removal credits allocated to a BECCS plant will hence depend significantly on the accounting scope – *i.e.*, which process emissions are accounted for when calculating how much CO_2 is removed from the atmosphere by a BECCS plant (Thornley and Mohr, 2018). A legislative proposal on carbon removal certification in the European Union is expected by the end of 2022 (European Parliament, 2021).

This paper contributes to the ongoing policy discussion on carbon removal and BECCS deployment by examining how the specific rules governing carbon removal accounting affect the feasibility of joint FECCS and BECCS CO_2 infrastructure projects. We find that a large scope for carbon removal accounting avoids adverse effects (*e.g.*, incentivizing a BECCS project that does not, in reality, remove CO_2 from the atmosphere), but it may also lead to locking out BECCS projects from CO_2 infrastructures if process emissions are too high. This lock-out effect of BECCS had been described in Lomax et al. (2015) and Vergragt et al. (2011) but had never been modeled.

The remainder of this paper is organized as follows. In the next section, we present the conceptual framework of our analysis. In Section 3, we detail an application of this methodology to the case of a contemporary project in Sweden. Section 4 contains our results. Finally, Section 5 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 the Supplementary Document.

2. Methodology

This section first introduces our assumptions and notations. We then develop a method to evaluate economically desirable CCS deployments. More specifically, we consider a set of fossil-fueled and bioenergy-fueled candidates for CCS adoption, and compute which ones would invest in carbon capture capabilities to form a shared CO_2 infrastructure under various carbon removal accounting scenarios. A graphical representation of the model can be found in Supplementary Document (Appendix A).

2.1 Assumptions and notations

We consider a finite set of industrial plants that can form a CCS coalition connected to a unique storage site. We assume that each CO_2 emitter represents an autonomous decision-making entity that can either adopt or renounce CO_2 capture. We let N denote the set of all the emitters and $|N|$ denote its cardinality. An emitter is either fossil- or bioenergy-fueled. This set is thus partitioned in two mutually exclusive subgroups: Fossil energy with Carbon Capture and Storage ($FECCS$) and Bioenergy with Carbon Capture and Storage ($BECCS$).

We let χ_i denote the unit cost incurred by emitter i for the carbon capture operations conducted at its industrial site. We let σ denote the unit carbon storage cost. The storage site is a sizeable underground geological structure located offshore. Consistent with the situation prevailing in the North Sea, we assume that its capacity is known and far larger than the cumulated volume of CO_2 that can be captured at the industrial sites under scrutiny. Finally, CO_2 transportation systems are, by nature, costly, capital intensive, and likely to exhibit substantial economies of scale. These properties effectuate the use of a shared infrastructure. Therefore, CO_2 transportation costs $C(S)$ depend on which coalition of emitters $S \subset N$ accepts to form a shared infrastructure. If Q_i^{stored} represents the quantity of CO_2 captured and stored at emitter i, total costs are:

$$Total\ costs = \sum_{i \in N} (\chi_i + \sigma) Q_i^{stored} + C(S)$$

In the application discussed in this paper, the transportation cost $C(S)$ incurred by a coalition S is computed using an engineering optimization model that is solved numerically. This optimization problem aims to determine the least-costly logistics for transporting the annual volumes of CO_2 captured at a given collection of emitters to the storage site. Following Morbee et al. (2012) and Massol et al. (2015), 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. From a cost perspective, each arc is characterized by a fixed and a unit cost component. Because of the fixed cost, there are arc-specific economies of scale. The complete specification of this problem is detailed in the Supplementary Document (Annex B).

2.2 Gross surplus: carbon accounting considerations

We let p_{CO_2} denote the prevailing price of carbon. Each emitter i can be attributed $Q_i^{avoided}$ tons of avoided CO_2 emissions. We can thus define the financial total gross income as:

$$Total\ gross\ income = p_{CO_2} \sum_{i \in N} Q_i^{avoided}$$

In the case of fossil-fueled emitters, we assume $Q_i^{avoided}$ the quantity of avoided CO_2 to be equal to Q_i^{stored} the quantity of captured and stored CO_2. This assumption is acceptable in our case study, as Sweden's electricity system is close to carbon neutral (Garðarsdóttir et al., 2018).

$$Q_i^{avoided} = Q_i^{stored} \qquad \forall i \in N^{FECCS}$$

In the case of bioenergy-fueled emitters, the quantity of avoided CO_2 corresponds to the amount of CO_2 removed from the atmosphere by the BECCS process (Torvanger, 2019). In a simplified view, carbon removal can be calculated by deducing process emissions[1] from stored emissions. We note τ the ratio between $Q^{process}$, the process emissions within the scope of the methodology and Q^{stored}, the CO_2 permanently stored.

$$Q_i^{avoided} = Q_i^{stored} - Q_i^{process} = Q_i^{stored}(1-\tau) \qquad \forall i \in N^{BECCS}$$

The calculation of carbon removal depends on the accounting scope – i.e., elements of the value chain – retained for accounting (Gough et al., 2018; Thornley and Mohr, 2018). An example best illustrates the consequences of the choice of the accounting scope. In a whole-system analysis, Fajardy and Mac Dowell (2017) assess the process emissions of a BECCS system in two cases. One where land-use change is included in the accounting scope, one where land-use change is excluded. When land-use change is excluded, τ reaches 60%. For each ton of stored emissions, 400 kilograms of CO_2 is effectively removed from the atmosphere. However, when land-use change emissions are included, the ratio τ between process and stored emissions is larger than 1: there is no carbon removal. We will assess the impact of carbon removal accounting on CO_2 infrastructure deployment by testing different scenarios on τ, the ratio between process emissions and stored emissions.

2.3 *Economically desirable CCS deployment*

We now want to assess which emitters should install carbon capture. Given the prevailing carbon price p_{CO_2}, the net surplus $W(p_{CO_2}, S)$ yielded by the deployment of CCS technologies at a given coalition S is obtained as the difference between the total gross income obtained by the participating emitters and the total cost incurred to conduct the capture, transportation, and storage operations, that is:

[1] *Process emissions could include, for example: greenhouse gas emissions stemming from biomass harvesting, transporting and processing, electricity consumption, CO_2 leakage.*

$$W(p_{CO_2}, S) = p_{CO_2}\left(\sum_{i \in S} Q_i^{avoided}\right) - \sum_{i \in S}(\chi_i + \sigma)Q_i^{stored} - C(S) \qquad (1)$$

A given coalition S is said to be dominated whenever there is no carbon price such that the net surplus obtained with S can be greater than or equal to that obtained with any other nonempty subgroup of emitters that can be formed in N. Hence, formally checking whether S is dominated is logically equivalent to verifying whether the set $\{p_{CO_2} \in \mathbb{R}^+ : W(p_{CO_2}, S) \geq W(p_{CO_2}, S'), \forall S' \subseteq N\{S, \emptyset\}\}$ is empty. From a practical perspective, the emptiness of this set can be verified for the specific coalition S by solving the following linear programming problem:

<u>LP1:</u>

$$\min_{p_{CO_2}} p_{CO_2}$$

$$\text{s.t.} \quad W(p_{CO_2}, S) \geq W(p_{CO_2}, S') \qquad \forall S' \subseteq N\{S, \emptyset\}$$

$$p_{CO_2} \geq 0$$

If the linear programming solver yields no solution to LP1, the coalition at hand is dominated.[2] In contrast, if a solution is found, there exists a nonempty range of carbon prices such that the coalition S provides the largest net surplus among all the coalitions that can be formed. The solution of LP1 also provides the minimum carbon price at which that coalition is dominating the other coalitions. Hereafter, we let $\underline{p_{CO_2}^S}$ denote the carbon price that is a solution to LP1.

By iteratively solving this problem for each of the $2^{|N|}$ coalitions that can be formed in N, we can thus partition the list of possible coalitions in two sets depending on whether they are dominated or not. We discard the dominated coalitions and concentrate our attention on the undominated ones. Ordering the undominated coalitions ascending values of $\underline{p_{CO_2}^S}$, we can identify a range of carbon price values

[2] *Indeed, one can remark that the objective function is bounded from below (because the carbon price is compelled to be nonnegative). The Fundamental Theorem of Linear Programming indicates that there exists at least one optimal solution to the program LP1 whenever the feasible set is nonempty. Hence, if a solution cannot be yielded using a LP solver, we can conclude that the feasible set is empty which means that, for any nonnegative carbon price, there exists at least an alternative cluster of emitters capable to yield a larger net surplus than the one obtained with the cluster at hand.*

such that this particular coalition is desirable. For a given coalition S_j in the ordered list $\{S_1, \dots, S_k\}$, that range is: $\left[\underline{p_{CO_2}^{S_j}}, \underline{p_{CO_2}^{S_{j+1}}}\right)$.

It is important to stress that this range is not necessarily such that a positive net surplus can be yielded by that coalition. Indeed, if an undominated coalition S_j is such that $W\left(p_{CO_2}, S\right) < 0$ for a prevailing carbon price in the range $\underline{p_{CO_2}^{S_j}} \leq p_{CO_2} \leq \underline{p_{CO_2}^{S_{j+1}}}$, the gross income is not sufficient to recoup the cost of the CCS chain. This desirable coalition can only adopt carbon capture and storage at that price unless some form of public support is provided (*e.g.,* through subsidies or tax relief (Cox and Edwards, 2019)). We thus also compute the break-even price, the minimum carbon price needed for S to obtain a nonnegative surplus:

$$\overline{p_{CO_2}^{S}} := \frac{\sum_{i \in S} (\chi_i + \sigma) Q_i^{stored} + C(S)}{\sum_{i \in S} Q_i^{avoided}} \tag{2}$$

3. Data: a Swedish 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 suitable decarbonisation path. The country’s power sector is already dominated by low emissions technologies (nuclear and hydroelectricity), and 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 (Adriana et al., 2021). Regarding CO_2 infrastructure deployment, cabotage is envisioned to connect large Swedish coastal emitters to the Norwegian storage site.

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 BECCS deployment 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.

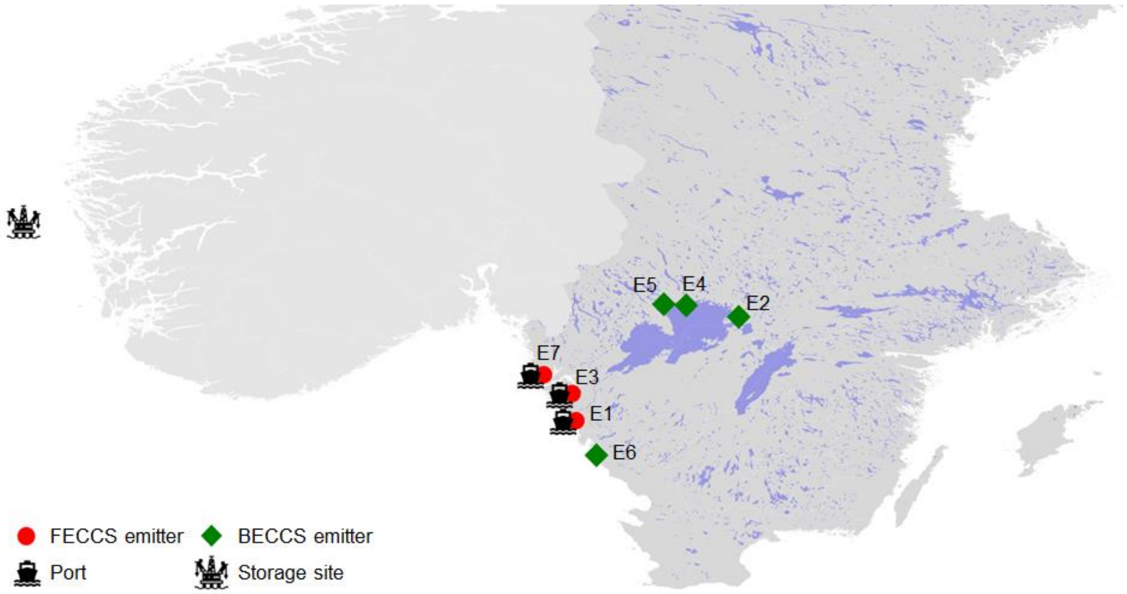
3.1 The emitters, the storage site, and the associated logistics

We focus on the southwestern part of Sweden, where industrial plants could be connected to the Northern Lights project in the future. Following Kjärstad et al., (2016), we select a coalition of emitters within a 300km range from Lysekil[3] that have annual emissions volumes larger than 500 ktCO_2 per annum in 2017 (EEA, 2017).

The resulting list includes seven industrial sites where carbon capture capabilities can be installed (see Table 1 and Figure 1). 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 these 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 assume that all emissions are directed to a single storage site in Norway – the storage site deployed within the Northern Lights project – Figure 1).

[3] *A FECCS project is currently under scrutiny at the Preem refinery in Lysekil which calls for further appraisal of the FECCS/BECCS potential in that area* (Adriana et al., 2021; Gardarsdottir et al., 2021).

Figure 1: The envisioned BECCS/FECCS project: the Norwegian storage site and the Swedish emission nodes



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 in favor of shipping lines. 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.

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 1).

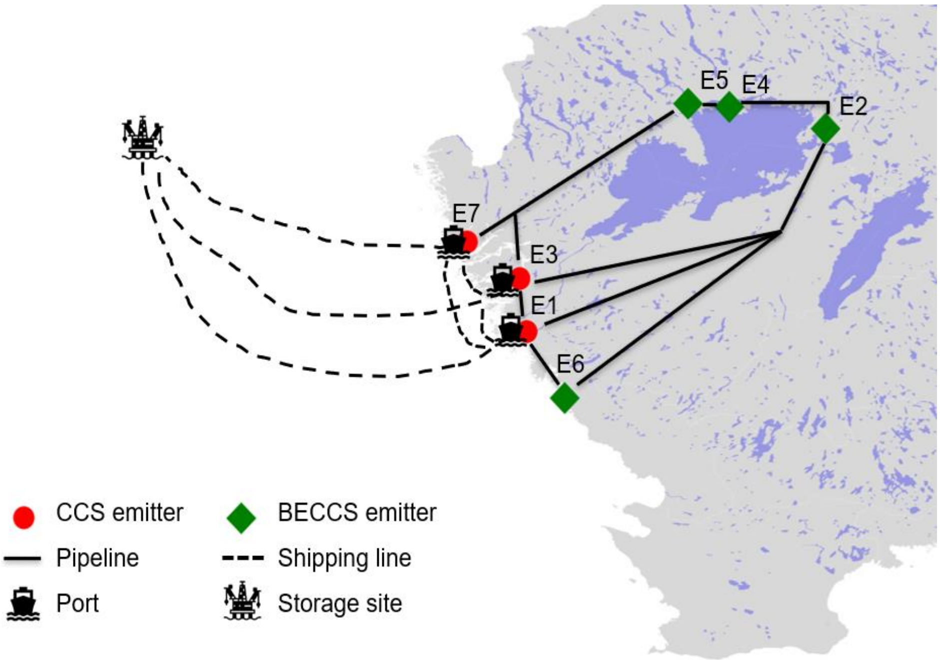
Table 1: The nodes

Node	Nature	Facility name	Industry
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 Figure 2). These pipelines are located along the region's main transport corridors. Point-to-point shipping is selected for offshore transportation between the three ports and the storage site located on the Norwegian continental shelf. Cabotage is also allowed between portal locations. The exact lengths of pipelines and shipping lines are available in the Supplementary Document (Appendix D).

Figure 2: The candidate pipelines and shipping lines



3.2 Cost data

Our cost data is extracted from earlier techno-economic studies (Garðarsdóttir et al., 2018; Johnsson et al., 2020; Roussanaly et al., 2014; ZEP, 2011). Costs are reported in €$_{2015}$ and are levelized assuming 25 years of economic lifetime and a 7.5% discount rate.

CO_2 capture

Carbon dioxide capture costs vary significantly depending on the considered sector and technology. CO_2 combustion emissions are most cost-effectively captured at stacks with high flue gas concentration and volumes. We use specific cost estimations from the work of Garðarsdóttir et al. (2018) and Johnsson et al. (2020). We assume that carbon capture is only installed at the industrial units with the lowest carbon capture cost of each plant (*e.g.*, the recovery boiler in the pulp and paper plants). Table 2 gathers the share of emissions of the industrial unit, capture rates and costs for the selection of facilities in our application case. The total quantity of captured CO_2 emissions in our case study is 3.542 $MtCO_2$/y per annum, out of which 2.534 $MtCO_2$/y biogenic emissions.

Table 2: Captured volumes and costs in for each emitter (Garðarsdóttir et al., 2018; Johnsson et al., 2020)

Node	Sector	Total CO_2 emissions ($MtCO_2$/y)	% of emissions captured	Capture rate	Capture cost €/(tCO_2/y)
E1	**Refinery**	0.535	30%	90%	66
E2	**Pulp and Paper**	0.546	75%	90%	64
E3	**Petrochemical**	0.664	80%	90%	61
E4	**Pulp and Paper**	0.943	75%	90%	56
E5	**Pulp and Paper**	1.296	75%	90%	53
E6	**Pulp and Paper**	0.968	75%	90%	52
E7	**Refinery**	1.428	30%	90%	50

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).[4] The annual equivalent investment

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

cost of a 100km-long pipeline with an output of q $MtCO_2$/y is: $(A_0 + B_0 q)\gamma$, where $A_0 = 4.6045$ is the fixed cost coefficient (in million 2015 euros), the variable cost coefficient is $B_0 = 0.1647$ in 2015 euros per (tCO_2×100 km) and γ = 1.1 is the dimensionless terrain correction factor described in IEAGHG (2002).[5] Concerning operations and management costs, 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 follow the "pseudo data" method proposed in Griffin (1979, 1978, 1977) to specify and estimate 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. The estimation uses the cost-engineering data presented in Roussanaly et al. (2014). The estimation procedure and the retained specifications are detailed in the Supplementary Document (Appendix C).

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.

4. Results

This section examines the desirable deployment of a CCS cluster in Sweden under several carbon removal accounting scenarios for BECCS. A crucial decision to be made by policymakers regarding carbon removal is the scope retained for carbon removal accounting (Fajardy and Mac Dowell, 2017; Thornley and Mohr, 2018). Since the wider the scope of carbon removal accounting, the larger the amount of process emissions that is accounted for, we use the ratio τ between process emissions and stored emissions as a proxy for accounting rules.

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

We first examine a scenario where process emissions are ignored completely ($\tau = 0\%$, Case 1). Then, we assume that the ratio is $\tau = 60\%$, based on a case study by Fajardy and Mac Dowell (2017) (Case 2). In both scenarios, we identify the undominated coalitions[6] (see Section 2.2), their CO_2 price ranges[7], and their break-even prices[8].

4.1 Case 1: Ignoring process emissions ($\tau = 0\%$)

We assume here that each ton of permanently stored CO_2 is considered carbon removal and can be exchanged at the prevailing CO_2 value. This scenario illustrates a still frequent reasoning: process emissions are already accounted for by other stakeholders in other sectors and could therefore be ignored. It is the same rationale that allows bioenergy to be considered carbon neutral. A similar scenario was presented in Laude and Jonen (2013).[9]

The successive undominated coalitions are depicted in Figure 3, and the CO_2 price ranges are gathered in Table 3. The first coalition is emitter E1, a chemical plant. E1 yields the lowest absolute costs due to its small size and coastal location. Therefore, it minimizes losses for CCS investment when the CO_2 value is between 0 and 67€/tCO2. But Coalition 1 requires up to 210€/tCO_2 subsidies to ensure that all costs are covered. Coalition 2 consists of E7, the existing FECCS pilot PreemCCS (Adriana et al., 2021; Gardarsdottir et al., 2021). It becomes undominated starting at a carbon value of 67 €/tCO_2, which is lower than current European Emission Trading System (EU ETS) levels (around 80 €/tCO_2 at the time of writing) but insufficient to cover the total costs of investment. At 80€/tCO_2, a 40€/tCO_2 subsidy is needed for Preemraff Lysekil's CCS pilot to be economically viable. Additionally, Coalition 2 initiates a consistent sequence of coalitions. With Coalition 3, two new emitters join: E4 and E5, two large pulp and paper plants located inland with lower capture costs. Then E3, E1 and E6, three coastal

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[6] *Recall that at a given CO_2 price, a undominated coalition is a subgroup of emitters that yields more surplus than any other subgroup by investing in CCS.*

[7] *Recall that the CO_2 price range of a coalition is the CO_2 price range for which the coalition is undominated.*

[8] *Recall that the break even price of a coalition is the CO_2 price for which the coalition yields a positive surplus.*

[9] *It should be noted, however, that such accounting method can result is adverse effects (incentivizing a BECCS projects that do not, in reality, remove CO_2 from the atmosphere).*

emitters with lower incremental infrastructure costs join in Coalitions 4. At 95 €/tCO_2, Coalition 4 yields a positive surplus, hence subsidies become unnecessary to initiate investment. Finally, E2, a small pulp and paper plant with high capture cost and incremental infrastructure cost joins in Coalition 5.

Figure 3: Case 1 – undominated coalitions

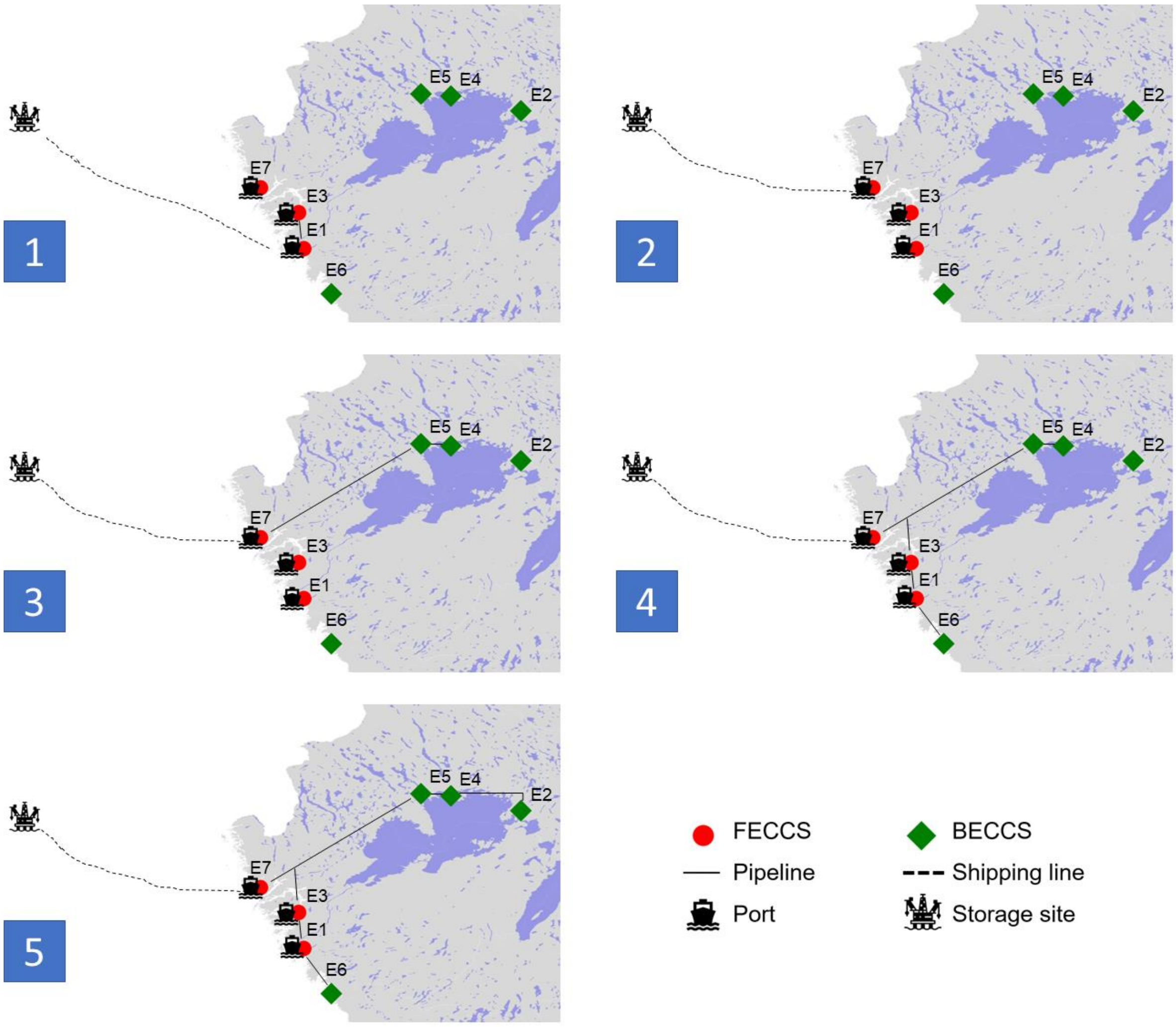


Table 3: Case 1 – CO_2 price ranges of the undominated coalitions

Coalitions S_j								Price range (€/tCO2) (a)	Break-even price (€/tCO2) (b)
N°	E1	E2	E3	E4	E5	E6	E7	$[\underline{p_{CO_2}^{s_j}}, \underline{p_{CO_2}^{s_j+1}}[$	$\underline{p_{CO_2}^{s_j}}$
1	x							[0, 66[	210
2							x	[66, 91[	120
3				x	x		x	[91, 93[	97
4	x		x	x	x	x	x	[93, 105[	95
5	x	x	x	x	x	x	x	[105, …[	96

(a): the range of carbon price values for which Coalition s_j is undominated
(b): the break-even CO_2 price for which Coalition s_j yields a positive surplus

4.2 Case 2: Lifecycle based accounting ($\tau = 60\%$)

We now assume that carbon removal accounting is based on a lifecycle assessment, which results in only a fraction of permanently stored CO_2 being considered as carbon removal and exchangeable at the prevailing CO_2 value. In this example, the total process emissions of BECCS represent 60% of the volume of stored emissions, consistent with a case study in Fajardy and Mac Dowell (2017), where land-use change is out of the accounting scope. The undominated coalitions and respective CO_2 price ranges are represented in Figure 4 and Table 4.

As expected due to the lower financial incentives for BECCS, the first coalitions to be built only gather FECCS emitters. In absence of subsidies, CCS investment is initiated starting at 107 €/tCO_2 (the break-even price of Coalition 3) – instead of 99 €/tCO_2 as the previous scenario. The first coalition that includes BECCS emitters is undominated at a carbon value of 214 €/tCO_2; twice the carbon value needed to initiate a CO_2 infrastructure deployment for FECCS emitters. Although lifecycle carbon removal accounting frameworks avoid the adverse effects described in Section 2., it globally raises the carbon value needed to trigger CCS adoption, whether in fossil-fueled industries or bioenergy-fueled industries.

More importantly, our results suggest that the CO_2 infrastructure will first be built for FECCS emitters, and hence may not be accessible for BECCS emitters. Let us assume that the CO_2 value is 112€/tCO_2 and Coalition 4 – E7, E3 and E1 – is built (see Figure 4). The pipeline design likely doesn't account for future investment in BECCS because their investment will only happen at 214€/tCO_2. Hence, when the CO_2 value does reach 214€/tCO_2, the pipeline may not be accessible to emitter E6 (Coalition 5). CO_2 pipeline construction has an irrevocable nature: once installed, their diameter cannot be modified. This is the lock-out effect described in Vergragt et al. (2011) and Lomax et al. (2015).

Figure 4: Case 2 – undominated coalitions

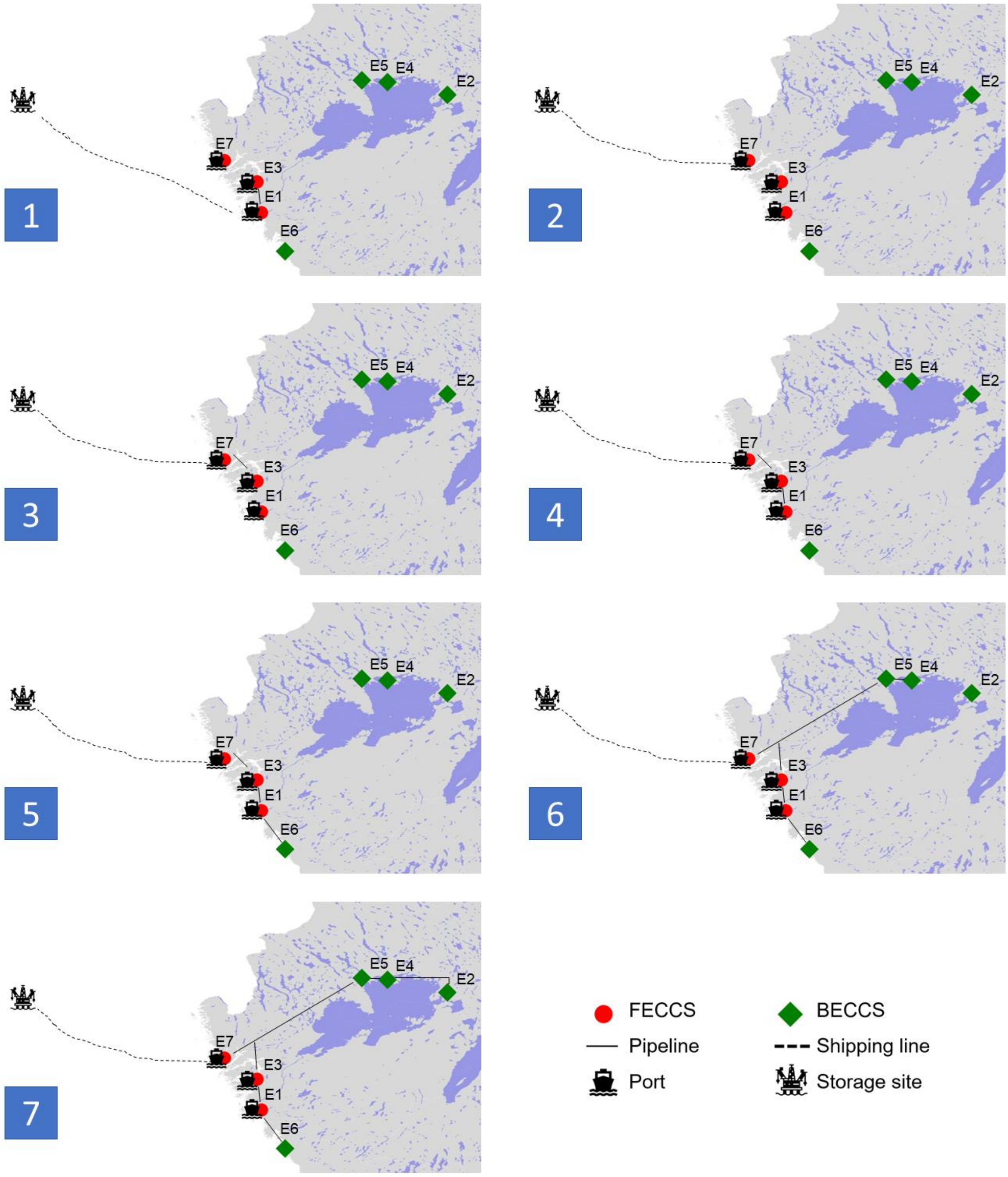


Table 4: CO_2 price ranges of the socially undominated coalitions

Coalitions S_j								Price range (€/tCO_2) [a]	Break-even price (€/tCO_2) [b]
N°	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	$[\underline{p_{CO_2}^{s_j}}, \underline{p_{CO_2}^{s_j+1}}[$	$\underline{p_{CO_2}^{s_j}}$
1	x							[0, 66[	210
2							x	[66, 98[	120
3			x				x	[98, 112[	107
4	x		x				x	[112, 214[	108
5	x		x			x	x	[214, 227[	130
6	x		x	x	x	x	x	[227, 263[	161
7	x	x	x	x	x	x	x	[263,…[	169

(a): the range of carbon price values for which Coalition s_j is undominated
(b): the break-even CO_2 price for which Coalition s_j yields a positive surplus

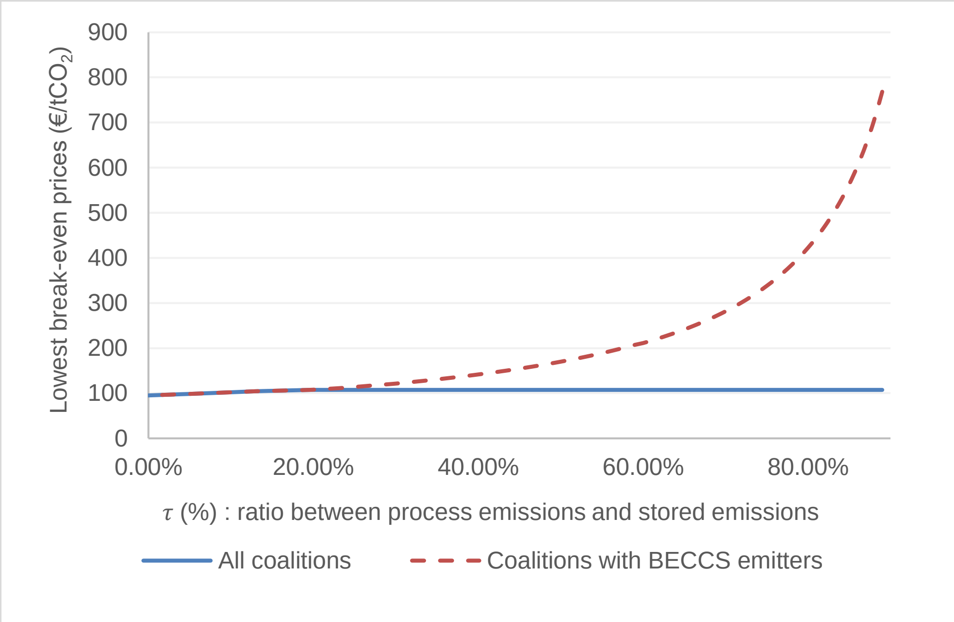
4.3 Lock-out effects ($\tau \in [0\%, 100\%[$)

To evaluate the lock-out effect of BECCS within our model, we compare two variables. The lowest break-even price[10] amongst all coalitions regardless of the nature of the emitters – and the minimum CO_2 price for which a coalition that includes BECCS emitters is built (Figure 5). The greater the difference between these two values, the less likely CO_2 infrastructure planning will anticipate investments in BECCS.

We let τ vary from 0 to 100%. If the accounted process emissions are low (no more than 20% of stored emissions), there is no difference between the lowest break-even price and the minimum CO_2 price for coalitions with BECCS emitters. However, the difference between break-even prices quickly increases with process emissions, already doubling when process emissions reach 60%. The lock-out effect is thus tightly linked to τ, the ratio between the accounted process emissions and the permanently stored emissions.

[10] *The break-even price of a coalition is the CO_2 value needed to trigger CCS investment without subsidies*

Figure 5: Comparison between the lowest break-even price and the minimum CO_2 value needed to initiate BECCS investment



5. Conclusion and policy implications

Bioenergy with Carbon Capture and Storage (BECCS) is expected to significantly contribute to limiting global warming to 1.5°C by removing CO_2 from the atmosphere (Rogelj et al., 2018). The upscaling of carbon removal technologies – or negative emissions technologies – requires carbon removal accounting and certification frameworks that have been repeatedly called for in the scientific literature in the past few years (Cabral et al., 2019; Fajardy and Mac Dowell, 2020; Gough et al., 2018; Mac Dowell et al., 2019; Mayer, 2019; Torvanger, 2019). Policy decisions on these frameworks are currently underway: the European Parliament has announced a proposal for European carbon removal certification by the end of 2022 (European Parliament, 2021). Furthermore, the deployment of BECCS relies on the creation of CO_2 infrastructures, which may be shared with Fossil Energy with Carbon Capture and Storage (FECCS) plants. This paper aims to inform the ongoing policy discussions on carbon removal by evaluating the impact of accounting scopes on the deployment of CO_2 infrastructures for BECCS and FECCS. Here accounting scopes refer to the choice of value chain steps that are included in carbon removal calculation. We represent the choice of accounting scopes in the ratio τ between process emissions and permanently stored CO_2 emissions, and apply a CO_2 infrastructure optimization model to a topical case study in Sweden.

In our first scenario, the carbon removal accounting scope is minimal (all process emissions are ignored, τ=0%). We find that a shared CO_2 infrastructure gathering FECCS and BECCS emitters can be deployed without subsidies starting at 95€/tCO_2. However, ignoring process emissions can lead to adverse effects: there is no guarantee that BECCS processes effectively remove CO_2 from the atmosphere.

In our second scenario, we assume a carbon accounting method based on lifecycle assessment, which leads to a ratio between process and stored emissions of τ=60%. This ratio is inspired by a case study in Fajardy and Mac Dowell (2017), where the accounting scope includes value chain steps from biomass farming to CO_2 storage but excludes land-use change. We find that FECCS plants start investing in carbon capture and forming a CO_2 infrastructure at 107€/tCO_2 (without subsidies). We also find that BECCS plants join the infrastructure at 214€/tCO_2. Consequently, the BECCS plant in our second scenario would not benefit from the typical economies of scale related to the pipeline infrastructure, which would already be tailored for the needs of FECCS plants.

Finally, we let the ratio τ vary from 0% to 100%. Up to τ=20%, CO_2 infrastructures include both FECCS and BECCS emitters. Above τ=20%, the CO_2 value needed to trigger an infrastructure that includes BECCS emitters increases quickly, so infrastructures with only FECCS emitters are built first. Altogether, our results illustrate the challenge of BECCS lock-out, which had first been described by Vergragt et al. (2011) but had never been modeled numerically. Lomax et al. (2015) comprehensively discuss carbon removal technologies lock-out. They stress that BECCS could be locked out of future developments due to unfit infrastructures, as illustrated in our case study. CO_2 transportation and storage infrastructures may be built for FECCS before BECCS can be deployed, hence leaving no capacity for BECCS emitters to join a shared, less costly infrastructure.

Two main policy recommendations can be drawn from our results. First, the risk of BECCS lock-out can be reduced by incentivizing low carbon biomass supply through sustainable biomass certification.

The risk of BECCS lock-out is lower when the ratio between process emissions and stored CO_2 emissions is low (τ<20%). There are two ways to reduce that ratio: reducing the accounting scope, and, hence, environmental integrity; or stimulating the reduction of process emissions, in particular those related to biomass sourcing (74% of process emissions, from biomass farming to pellet grinding in Fajardy and Mac Dowell (2017)). Sustainable biomass certification frameworks – which have already been repeatedly recommended to favor BECCS deployment (Cox and Edwards, 2019; Fuss et al., 2016; Gough et al., 2018; Mac Dowell et al., 2019; Torvanger, 2019) – could ease access to low carbon biomass supply.

Second, the risk of BECCS lock-out can be reduced by encouraging a higher price for carbon removal than for carbon reduction while setting rigorous carbon removal accounting rules. In our model, we have assumed – for cost efficiency reasons – that carbon removal credits would be sold at the prevailing CO_2 value, which may lead to delays in BECCS investment compared to FECCS investments as BECCS is less cost-efficient. BECCS and other carbon removal options are expected to scale up soon to help contain global warming, indicating that investments should be happening now (Lomax et al., 2015; Nemet et al., 2018). Earlier investment in BECCS will stimulate learning effects and potentially long-term cost reduction (Bui et al., 2018). However, the price of carbon removal credits can only be higher than the price of carbon mitigation (e.g., within the EU ETS system) if there is enough demand for carbon removal. Some large companies aim to become carbon negative in the coming decades and have already shown a high willingness to pay for carbon removal (UNFCCC, 2021). But long-term strategies on carbon removal investment should not rely solely on private demand. Strong national commitments are needed to ensure demand for sustainable and credible carbon removal credits – for example through Nationally Determined Contributions within the Paris Agreement (Honegger et al., 2021).

As with any modeling effort, some simplifying assumptions were made. The main simplification was the use of a time-invariant carbon accounting rule that was uniformly applied to every BECCS project. The modeling presented in this paper assumes that the ratio τ between accounted process emissions and stored emissions solely depended on the carbon removal accounting scope. Verifying whether that assumption needs to be revised to adequately capture the complex dynamics of process emissions is a potential area for future research. Such an extension calls for the use of time-varying and project-specific ratios, requiring a much more detailed representation of the entire BECCS supply chain that is out of the scope of this paper. Should future research provide this representation, the development of an extended version of our framework could offer greater insight into the impact of carbon removal accounting on the deployment of BECCS.

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Supplementary document

Appendix A – Graphical representation of the model

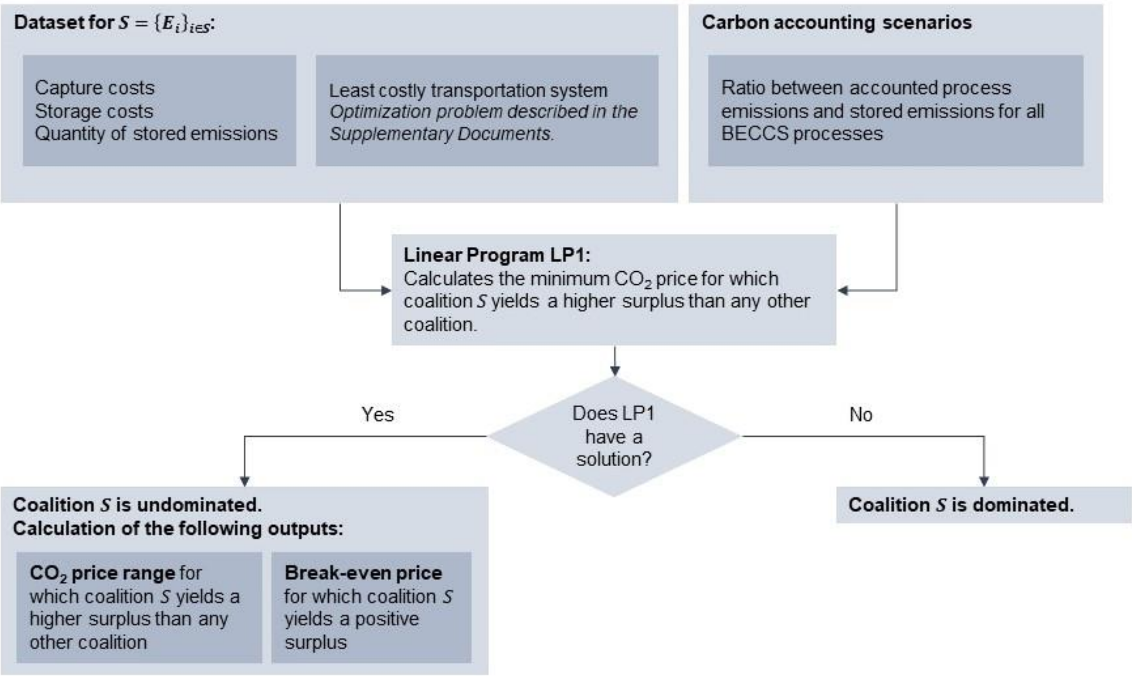

Figure 1: Graphical representation of the model

Appendix B – 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;[1]

- $R = \{1,...,r,...,|R|\}$ 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;

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

[1] *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.*

- $I_{p,z}$ 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:

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

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

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

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

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

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

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

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

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.[2] 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.[3]

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.

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[2] *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.*

[3] *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 $q_{p'}^{+**} + q_{p'}^{-**} = |q_{p'}^{+*} - q_{p'}^{-*}|$ and thus $C_{p'}^{pipe}(\, q_{p'}^{+**} + q_{p'}^{-**}) < C_{p'}^{pipe}(q_{p'}^{+*} + q_{p'}^{-*})$. Hence, we have a contradiction because x_N^* cannot be a solution of the optimization problem.*

Appendix C – 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 (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.[4]

We posit the following parsimonious specification[5] 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.

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[4] *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)).*

[5] *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.*

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.

Table 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.

Appendix D – Supplementary data

Table 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

Table 3 The candidate shipping lines and their lengths

Line	Origin	Destination	Distance (km)
L1	E7	S1	613
L2	E3	S1	639
L3	E1	S1	641
L4	E1	E3	98
L5	E1	E7	102
L6	E3	E7	83

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