

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. Assuming carbon removal credits will be integrated into the prevailing carbon market, we show that, although a carbon removal accounting framework based on a lifecycle methodology discourages investment in inefficient BECCS processes, it may induce BECCS lock-out from CO_2 infrastructures. We formulate two policy recommendations to overcome such a BECCS lock-out: (i) forward-looking CO_2 infrastructure planning and (ii) complementary policy support.

Keywords: Carbon dioxide removal accounting, Negative Emissions, Bioenergy with Carbon Capture and Storage (BECCS), CO_2 infrastructures, CO_2 pipelines

1. Introduction

Bioenergy 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 for 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 can 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). In contrast, BECCS can remove 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). However, 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 at the commercial stage (Hammond, 2018). One of these crucial yet often-overlooked barriers is the deployment of CO_2 transportation and storage infrastructures, which are costly, capital intensive, and likely to exhibit substantial economies of scale (Butnar et al., 2020; Krahé et al., 2013). A growing literature on CO_2 pipeline deployment has already highlighted the need for shared infrastructures on 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) and a continental (European) scale (Morbee, 2014; Morbee et al., 2012; Oei and Mendelevitch, 2016). These studies concentrate on infrastructures connected to FECCS emitters and thus overlook the integration of BECCS emitters into the infrastructure. Importantly, 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 (Rickels et al., 2021; Zakkour et al., 2014). However, carbon removal accounting frameworks are yet to be standardized to design such credits (Torvanger, 2019). The question of how carbon removal accounting affects BECCS deployment is especially timely, as the European Union is currently drafting a proposal for carbon removal certification, planned for year end 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 carbon removal accounting, which has been largely ignored in the literature on CO_2 infrastructure, 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 was described in Lomax et al. (2015) and Vergragt et al. (2011) but has never been modeled.

The remainder of this paper is organized as follows. Section 2 gives some background information on carbon removal accounting. In Section 3, we present the conceptual framework of our analysis. Then, Section 4 details an application of this methodology to the case of a contemporary project in Sweden. Section 5 contains our results, and Section 6 includes a discussion. Finally, Section 7 offers a summary and some concluding remarks highlighting the policy implications of our analysis. For the sake of clarity, the detailed structure of a computerized model given in Section 3 and the cost parameters of the case study are both presented in the Supplementary Document.

2. Background: Carbon removal accounting

Accounting for net carbon removal is complex, as carbon removal methods differ in how carbon dioxide is removed from the atmosphere and how long it stays in the carbon sink (Carton et al., 2021; Minx et al., 2018). In the case of BECCS, carbon dioxide is removed through biomass growth, while permanent storage is achieved through industrial carbon capture, transportation, and storage. Therefore, the main challenge lies in the accounting scope, *i.e.*, which process emissions should be accounted for. Process emissions include biomass-related process emissions (emissions from biomass growth, harvesting, transformation, and transportation) and CCS-related process emissions (emissions from carbon capture, transportation, and storage) (Fajardy and Mac Dowell, 2017; Thornley and Mohr, 2018; Torvanger, 2019). In other words, the calculation of the net carbon removal effect achieved by a BECCS process should take into account the greenhouse gas emissions emitted at all relevant value-chain steps for the carbon dioxide removal activity.

The European Union is currently working on a legislative proposal on carbon removal certification (European Parliament, 2021), which could allow the inclusion of removal credits into the European Union Emissions Trading System (EU ETS) (Rickels et al., 2021; Tamme and Beck, 2021). In the meantime, voluntary carbon markets have already proposed methodologies and standards for carbon removal credits (e.g., Puro Earth or Verra). Such credits allow companies to reach their internal net-zero objectives but not to comply with national and international CO_2 reduction obligations (Nehler and Fridahl, 2022).

Importantly, carbon removal accounting should incentivize the most CO_2 and resource-efficient biomass usage[1] while avoiding double counting. As an illustration, a recently proposed methodology proposes an accounting scope for BECCS that depends on the biomass purpose (Puro Earth, 2022). If biomass is purpose-grown for carbon removal, all direct biomass-related process emissions are attributed to the BECCS process. If biomass is a co-product from another process, only emissions from purpose-built equipment and facilities are considered. In the following sections, we will assume that a similar carbon removal accounting framework is institutionalized. Carbon removal credits can then be integrated into the prevailing carbon market, as suggested by Rickels et al. (2021). We will also assume that carbon removal credits are the only available revenues for BECCS.

[1] *We will focus solely on CO_2 efficiency, but it should be noted that resource efficiency includes many other dimensions, such as energy, water, nutrients, land, and biodiversity (Fajardy et al., 2018; Smith et al., 2018, 2016).*

3. 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 the Supplementary Document (Appendix A).

3.1 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 into 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 sizable underground geological structure located offshore. Consistent with the situation prevailing in the North Sea, we assume that its capacity is known and is far larger than the cumulated volume of CO_2 that can be captured at the industrial sites under scrutiny. Finally, CO_2 transportation costs $C(S)$ depend on which coalition of emitters $S \subset N$ agrees to form a shared infrastructure[2]. Q_i^{stored} represents the quantity of CO_2 captured and stored at emitter i.[3] Total costs are:

$$Total\ costs = \sum_{i \in N} (\chi_i + \sigma) Q_i^{stored} + C(S) \qquad (1)$$

[2] *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.*

[3] *We assume there is no CO_2 leakage during transportation and storage operations.*

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 to choose 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 (see Figure 2). 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 (Appendix A).

3.2 Carbon accounting considerations

We let p_{CO_2} denote the prevailing price of carbon. We note $Q_i^{rewarded}$ the quantity of stored emissions that can be rewarded at the CO_2 price for each plant i. As detailed in Section 2., we argue that carbon accounting should favor the most CO_2 and resource-efficient carbon reduction and removal options. In that sense, we assume that $Q^{rewarded}$ depends on CCS process emissions q_i^{CCS} (also called the energy penalty), and on upstream biomass emissions $q_i^{biomass}$ in the case of BECCS. We also note τ^{CCS} and $\tau^{biomass}$ the ratio between process emissions and stored emissions. We assume that these ratios are the same for all plants. [4]

$$\tau^{CCS} = \frac{q_i^{CCS}}{Q_i^{stored}} \qquad \forall\, i \in N$$

[4] *Ideally, CCS process emissions and biomass process emissions should be evaluated for each plant. However, our work does not aim to offer a precise and accurate representation of industrial carbon capture processes. Rather we attempt to provide economic insights on the inclusion of BECCS in the deployment of CO_2 infrastructures. The main driver of this inclusion (or exclusion) is the asymmetry between the economic incentives accessible to BECCS and FECCS, which is driven by the inclusion (or exclusion) of biomass process emissions in the calculation of carbon removal. We therefore apply the same ratio between CCS (or biomass) process emissions and stored emissions for all plants.*

$$\tau^{biomass} = \frac{q_i^{biomass}}{Q_i^{stored}} \qquad \forall\, i \in N^{BECCS}$$

For FECCS plants, we assume $Q_i^{rewarded}$ is the quantity of avoided CO_2.

$$Q_i^{rewarded} = Q_i^{stored} - q_i^{CCS} = Q_i^{stored}(1 - \tau^{CCS}) \qquad \forall i \in N^{FECCS}$$

In the case of bioenergy-fueled emitters, we assume $Q_i^{rewarded}$ is the amount of CO_2 removal from a life cycle perspective (Torvanger, 2019). In a simplified view, carbon removal can be calculated by deducting total process emissions from stored emissions.[5]

$$Q_i^{rewarded} = Q_i^{stored} - q_i^{CCS} - q_i^{biomass} = Q_i^{stored}\left(1 - \tau^{CCS} - \tau^{biomass}\right) \qquad \forall i \in N^{BECCS}$$

The difference in the treatment between BECCS and FECCS lies in the different services provided by both technologies. Applied to existing fossil-energy facilities, CCS serves as a means to reduce otherwise hard-to-abate emissions. Applied to bioenergy-fueled facilities, CCS is only one step within a process that removes CO_2 from the atmosphere.

CCS process emissions: $\tau^{CCS} = 0$

Although we argue that CCS process emissions should be accounted for within carbon quotas and removal credits, we will normalize them to zero in the present instance of our model to focus on biomass process emissions. Two lines of argument support this simplification. First, CCS process emissions can be low in the Swedish case. The electricity mix is low carbon, and emission-free excess heat could be available to power carbon capture (Garðarsdóttir et al., 2018).[6] Second, biomass process emissions have a higher weight on the difference in revenue available to BECCS plants compared to FECCS plants. In other words, CCS process emissions can be comparable for BECCS and FECCS plants, but biomass process emissions are only applicable to BECCS plants, thereby driving the difference in revenue.

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[5] *For the sake of simplicity, we ignore here the global carbon cycle dynamics described in* Jones et al. (2016)*. Carbon cycle feedback effects could indeed reduce the amount of carbon removal that effectively stays out of the atmosphere.*

[6] *Importantly, Garðarsdóttir et al. (2018) do not suggest that excess heat will systematically be available in the plants they studied. In one chemical production facility, they even state that there are "modest opportunities for excess heat utilization."*

Higher values of τ^{CCS} would mainly lead to overall higher CO_2 prices needed to trigger CCS deployment, as both BECCS and FECCS emitters would receive less revenue per ton of stored CO_2. But the effect on whether BECCS plants are included or excluded from CO_2 infrastructures would be limited.

<u>Case 1: Biomass is a local co-product: $\boldsymbol{\tau^{biomass} = 0\%}$</u>

Here, we assume that biomass comes from local co-products, as is largely the case for pulp and paper (Garðarsdóttir et al., 2018; Kuparinen et al., 2019). Assuming there are no additional process emissions to transform and transport the biomass co-product, we posit $\tau^{biomass} = 0\%$.

<u>Case 2: Biomass is purpose-grown for BECCS: $\boldsymbol{\tau^{biomass} = 46\%}$</u>

In this scenario, biomass is purposely grown for BECCS, which means we attribute the totality of the biomass process emissions to the carbon removal activity. We assume that the ratio between process and stored emissions is the same as in Fajardy and Mac Dowell (2017): 54%. This value is based on multiple assumptions that do not stand in our case study,[7] but it illustrates high process emissions. We also let $\tau^{biomass}$ vary in a subsequent sensitivity analysis.

3.3 Economically desirable CCS deployment

We now want to assess which emitters should install carbon capture. Given the prevailing carbon price p_{CO_2}, the 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:

$$W(p_{CO_2}, S) = p_{CO_2}\left(\sum_{i\in S} Q_i^{rewarded}\right) - \sum_{i\in S}(\chi_i + \sigma)Q_i^{stored} - C(S) \qquad (7)$$

The economically desirable CCS deployment consists of choosing the coalition S that yields the largest surplus depending on the CO_2 price. Importantly, the surplus should be positive to ensure that

[7] *The biomass source in Fajardy and Mac Dowell (2017) is switchgrass imported from the United States to the United Kingdom.*

CCS is economically viable. The method to determine the coalitions that form the economically desirable CCS deployment (the undominated coalitions) is described below.

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>

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

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

$$p_{CO_2} \geq 0$$

$$W(p_{CO_2}, S) \geq 0$$

If the linear programming solver yields no solution to LP1, the coalition at hand is dominated.[8] 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 into two sets depending on whether they are dominated or

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[8] *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 an 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 of yielding a larger net surplus than the one obtained with the cluster at hand.*

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 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: $\left[\underline{p_{CO_2}^{S_j}}, \underline{p_{CO_2}^{S_{j+1}}}\right)$.

4. 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 decarbonization 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 municipality of Øygarden, where an offshore pipeline will transport the CO_2 to a platform in the North Sea. The CO_2 will then be injected into a geological formation for permanent storage.

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.

4.1 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[9] that had 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).

[INSERT FIGURE 1 HERE]

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 seagoing 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

[9] *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).

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).

[INSERT TABLE 1 HERE]

Regarding onshore transportation, we consider a predefined set of 10 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).

[INSERT FIGURE 2 HERE]

4.2 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 in 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.

[INSERT TABLE 2 HERE]

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).[10] The annual equivalent investment 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), and the variable cost coefficient is $B_0 = 0.1647$ in 2015 euros per (tCO_2×100 km) and $\gamma = 1.1$ is the dimensionless terrain correction factor described in IEAGHG (2002).[11] 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

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

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

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.

5. Results

This section examines the desirable deployment of a CCS cluster in Sweden under several carbon removal accounting scenarios for BECCS. We first examine a scenario where biomass is a co-product ($\tau^{biomass} = 0\%$, Case 1). Then, we assume that biomass is purpose-grown for carbon removal and $\tau^{biomass} = 54\%$, based on a case study by Fajardy and Mac Dowell (2017) (Case 2).

5.1 Case 1: Biomass is a local co-product: $\tau^{biomass} = 0\%$

We assume here that no additional process emissions are attributed to the BECCS processes. This can happen if the combusted biomass is a local co-product, hence not purpose-grown for carbon removal, as in the pulp and paper industry (Kuparinen et al., 2019). In particular, our assumption implies that no additional operations are needed to prepare the biomass co-product: no transportation, no drying, no pelleting. Under such extreme conditions, BECCS and FECCS are rewarded at the same level for their stored emissions. The successive undominated coalitions are depicted in Figure 3, and the CO_2 price ranges are gathered in Table 3. The first coalition is optimal between 95 €/tCO2 and 105 €/tCO_2 and includes all emitters except E2, a small pulp and paper plant located furthest from the coast. For higher CO_2 prices, it becomes optimal to include E2 in the shared infrastructure.

[INSERT FIGURE 3 HERE]

[INSERT TABLE 3 HERE]

5.2 Case 2: Biomass is purpose-grown for BECCS: $\tau^{biomass} = 54\%$

We now assume that the total biomass process emissions of BECCS plants represent 54% of the volume of stored emissions. This ratio is consistent with a case study in Fajardy and Mac Dowell (2017), where the 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. CCS investment is initiated starting at 107 €/tCO_2 instead of 95 €/tCO_2 as in the previous scenario. The first coalition that includes BECCS emitters is undominated at a carbon value of 186 €/tCO_2. 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 107 €/tCO_2, and Coalition 1 – E7, E3 – is built (see Figure 4). The pipeline design may not account for future investment in BECCS because their investment will only happen at 186 €/tCO_2. Hence, when the CO_2 value does reach 186 €/tCO_2, the pipeline may not be accessible to emitter E6 (Coalition 5). CO_2 pipeline construction has an irrevocable nature: once installed, pipeline diameters cannot be modified. This is the lock-out effect described in Vergragt et al. (2011) and Lomax et al. (2015).

[INSERT FIGURE 4 HERE]

[INSERT TABLE 4 HERE]

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

To evaluate the lock-out effect of BECCS within our model, we compare two variables. The lowest CO_2 price needed to trigger CCS deployment $\overline{p_{CO_2}}$ regardless of the nature of the emitters – and the minimum CO_2 price for which a coalition that includes BECCS emitters is built $\overline{p_{CO_2}^{BECCS}}$ (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 $\overline{p_{CO_2}}$ and $\overline{p_{CO_2}^{BECCS}}$. However, the difference quickly increases with biomass process emissions, already doubling when process emissions reach 60%. The lock-out effect is thus tightly linked to $\tau^{biomass}$, the ratio between the accounted biomass process emissions of BECCS processes and the permanently stored emissions.

[INSERT FIGURE 5 HERE]

6. Discussion

In this section, we highlight the implications and limitations of our analysis. First, we discuss the drivers of BECCS lock-out that amplify the carbon accounting considerations described in the previous section. Then, we note that building ahead-of-demand could weaken BECCS lock-out. Finally, we discuss our assumption on the value of carbon removal and its policy implications.

6.1 The drivers of infrastructure lock-out

We have illustrated that BECCS plants can be locked out from the CO_2 infrastructure if their biomass process emissions are too high ($\tau^{biomass} > 20\%$ in our case). Such an exclusion is the logical consequence of lower revenue under carbon removal accounting rules. The magnitude of this effect is, however, case-dependent, as other factors influence the lock-out. The most important one is the choice of CO_2 transportation modes. The risk of a lock-out is most important in the case of pipelines, which have long contract durations and little capacity flexibilities. In our model, the choice between shipping and pipelines was driven solely by cost considerations.[12] Hence, pipelines were selected to connect coastal locations. In reality, investors could favor shipping, when possible, because of the high uncertainty of future demand and shorter contract durations, especially in Sweden, where Garðarsdóttir et al. (2018) reference many more coastal emitters in the east. In our case – one CCS cluster among many possible in Sweden – BECCS plants are mostly inland and depend on pipelines, amplifying the lock-out effect. This is particularly visible in Case 1, where one BECCS plant – E2, a small pulp and paper plant located far from the coast – is included last in the infrastructure, even when there is no distinction in the revenue received by BECCS and FECCS plants (see Table 3).

[12] *Pipelines are generally more cost-effective than shipping for smaller distances (Kjärstad et al., 2016; Roussanaly et al., 2014, 2013)*

6.2 Building CO_2 infrastructures ahead-of-demand

One important limitation of our model is that it is static. There are no anticipated changes to the emitter's investment decisions or potential for future connection. In that regard, the literature on pipeline infrastructures offers several insights. The construction of pipeline systems is irreversible and shows strong economies of scale. Together, these two characteristics make it logical to engage in "building ahead-of-demand" in the event of increasing future use, as adding some excess capacity may reduce the present value of the infrastructure's overall cost (Chenery, 1952; Manne, 1961). Early CCS adopters must thus choose between operating the infrastructure with low capacity utilization during the early years or installing a suboptimal infrastructure. As future CO_2 prices are unknown, such a decision has to account for uncertainty. The question has, however, rarely been modeled in the case of CCS (some examples include Mechleri et al., 2017, and Wang et al., 2014) while being frequently discussed in the context of gas infrastructure projects (Hirschman, 2014; Perrotton and Massol, 2020). Another important dimension is whether central planning by a third party or governmental regulation is useful and needed to ease such forward-looking planning, as suggested by Krahé et al. (2013) or Mack and Endemann (2010).

6.3 The value of removing carbon dioxide from the atmosphere

In our model, one ton of net carbon removal achieved by BECCS processes is allocated the same value as one ton of carbon reduction – e.g., within the EU ETS – but net carbon removal represents only a fraction of stored emissions. Global carbon cycle dynamics could reduce that fraction even further, as one ton of carbon removal results in a less than one ton net effect on atmospheric concentrations (Jones et al., 2016). Consequently, BECCS – especially BECCS based on purpose-grown biomass – would be costlier than FECCS.[13] Additionally, the increasing demand for biomass may negatively affect other sustainability goals, such as water, land, or biodiversity. As a consequence, it appears that BECCS

[13] *Regulators may choose to simplify the accounting system by assuming that the climate effect of avoided/reduced CO_2 emissions is equivalent to CO_2 removal, even if that is an incorrect simplification in scientific terms. In that case, the systematic difference between the cost of FECCS and BECCS per ton of avoided or removed CO_2 is reduced.*

projects should not be prioritized compared to FECCS or non-biomass-related carbon removal options like direct air capture.

However, reducing and removing carbon are two different and complementary activities. The upcoming need for global net negative CO_2 emissions pictured in the latest IPCC report (IPCC, 2022; Rogelj et al., 2018) may justify setting separate targets for carbon reductions and carbon removal (McLaren et al., 2019). The European Union, for example, recently suggested a 5 $MtCO_2$ carbon removal target by 2030 (Nehler and Fridahl, 2022). These separate targets could generate a higher shadow price for carbon removal, considering the current scarcity of carbon removal technologies. Integrating carbon removal in compliance markets like the EU ETS may not suffice to adequately value carbon removal. Public support is needed, such as contracts for difference (Bui et al., 2018) or reverse auctions (Lundberg and Fridahl, 2022). Alternatively, carbon removal credits can be exchanged at a higher price in offset markets as long as there is sufficient demand. 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). However, long-term strategies for carbon removal investment should not rely solely on private demand. Strong national commitments would be 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).

7. Conclusion and policy implications

Carbon removal accounting and certification frameworks will be essential for deploying Bioenergy with Carbon Capture and Storage (BECCS) (Torvanger, 2019). Their design is underway in Europe, where a carbon removal certification proposal is expected by year end 2022 (European Parliament, 2021). If carbon removal credits are integrated into the prevailing carbon market (*e.g.*, the EU ETS, as suggested by Rickels et al., 2021), BECCS plants would access fewer revenues per ton of stored CO_2 compared to Fossil Energy with Carbon Capture and Storage (FECCS) emitters due to their reduced net carbon removal effect. Such considerations could affect CO_2 infrastructure deployment, which may be shared BECCS and 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, with a focus on the biomass supply. In the first scenario, we assume no biomass process emissions, which supposes using a local co-product and no additional operation for biomass transportation or transformation. In a second scenario, we assume that biomass is purpose-grown for BECCS, leading to significant biomass process emissions, hence a reduced net carbon removal effect. We find that investments start at a higher CO_2 price in the second scenario and that CO_2 infrastructures initially only include FECCS emitters. Consequently, the BECCS plants in our second scenario do not benefit from the typical economies of scale related to the pipeline infrastructure, which would already be tailored for the needs of FECCS plants. In a sensitivity analysis of our case study, the exclusion of BECCS emitters starts at a ratio of 20% between biomass process emissions and stored emissions. While there are other – case-specific – drivers to the inclusion or exclusion of BECCS plants from CO_2 infrastructures, the systematic difference in revenues accessible to BECCS compared to FECCS due to carbon removal accounting appears decisive. These results illustrate the challenge of BECCS infrastructure lock-out (Lomax et al., 2015; Vergragt et al., 2011), which had not been modeled numerically before.

Overall, we stress that carbon removal accounting and certification frameworks should evaluate the CO_2- (and resource-) efficiency of biomass, regardless of any BECCS lock-out effect. Consequently, BECCS processes may not be prioritized within compliance carbon markets (should carbon removal credits be integrated, e.g., within the EU ETS) because of their reduced net carbon removal effect. Two policy implications follow from the lower revenue available to BECCS processes and the resulting impact on CO_2 infrastructures. First, BECCS processes may become economically viable in the future as CO_2 prices increase or more CO_2-efficient biomass is sourced. CO_2 infrastructure planning should therefore be forward-looking, anticipating future investments in BECCS and building pipelines ahead of demand. Second, additional policy support for BECCS, such as contracts for difference or reverse auctions, could have two functions: (i) countering the lack of long-term visibility of CO_2 prices for infrastructure planning and (ii) bridging the gap between the CO_2 market price and the shadow price for carbon removal if regional policies favor a separate target for carbon removal, as could be the case in the European Union (Nehler and Fridahl, 2022).

Further studies can be carried out to examine the economics of these policy implications. For example, forward-looking planning calls for the use of a dynamic representation of the entire CCS supply chain, which 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 integration of BECCS plants in CO_2 infrastructures.

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

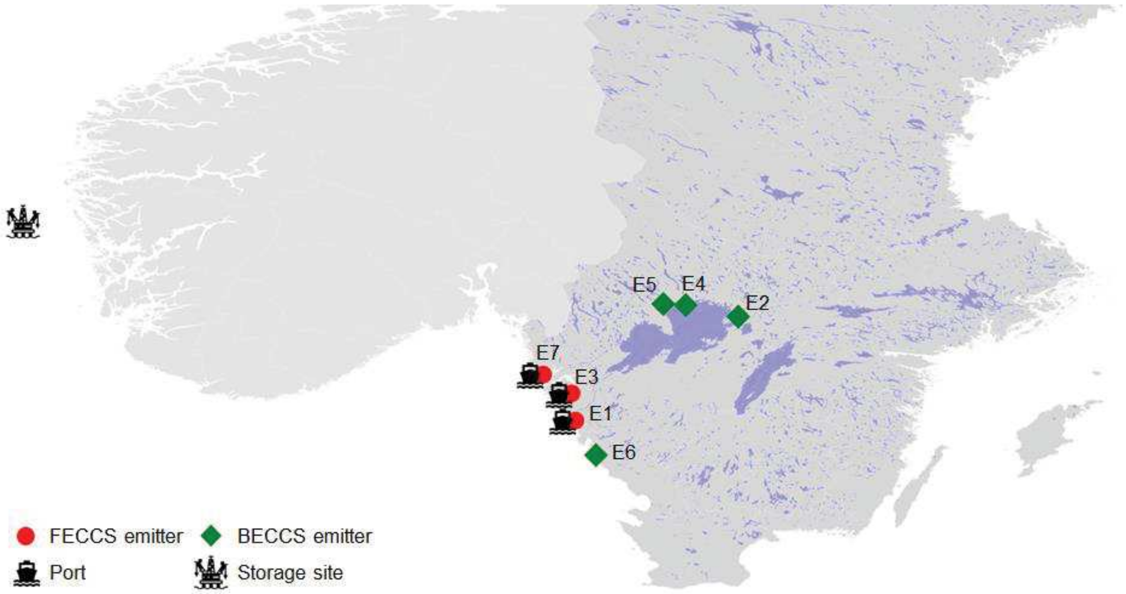

Figure 2: The candidate pipelines and shipping lines

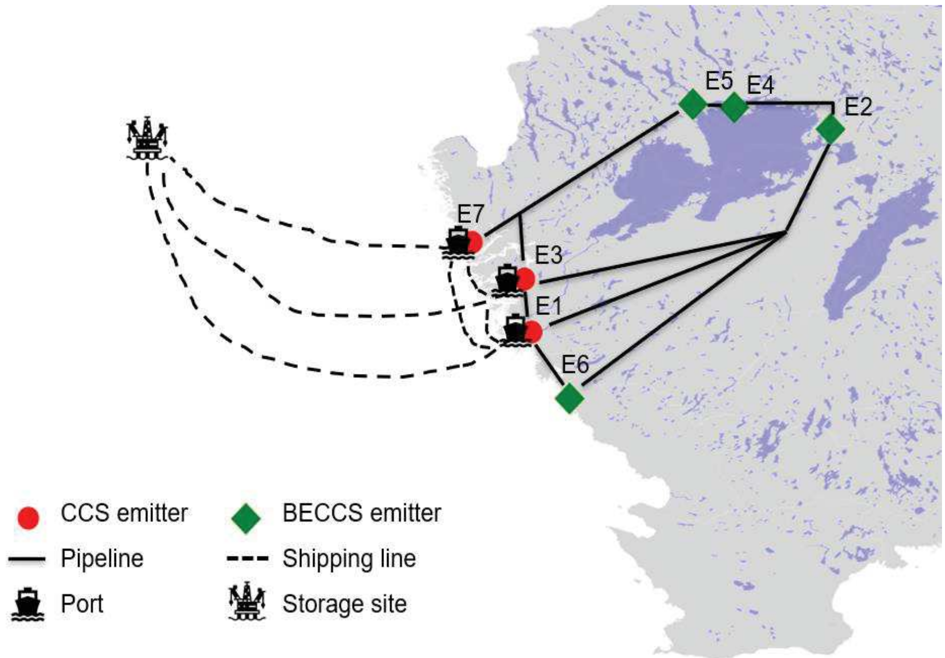

Figure 3: Case 1 – undominated coalitions

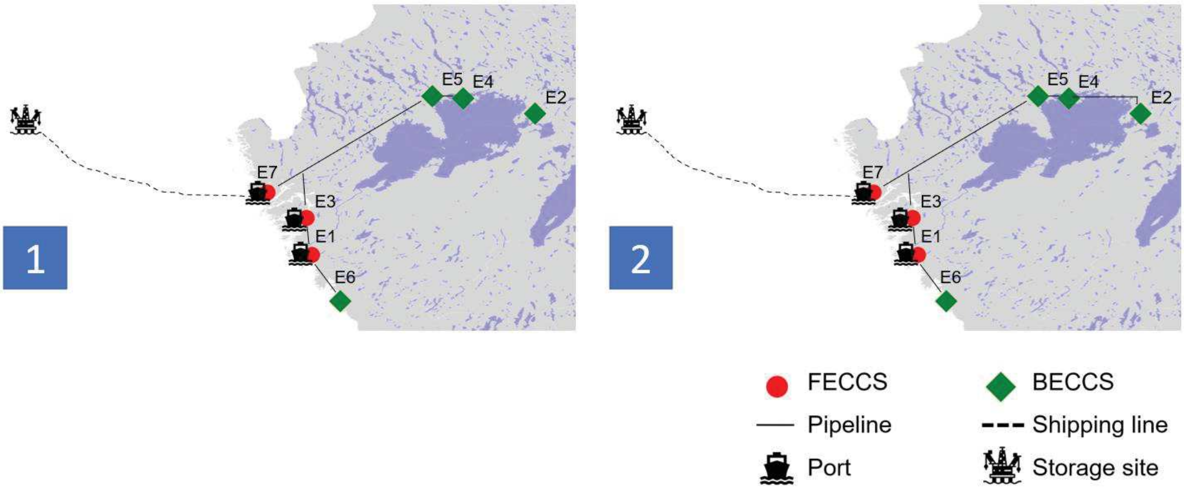

Figure 4: Case 2 – undominated coalitions

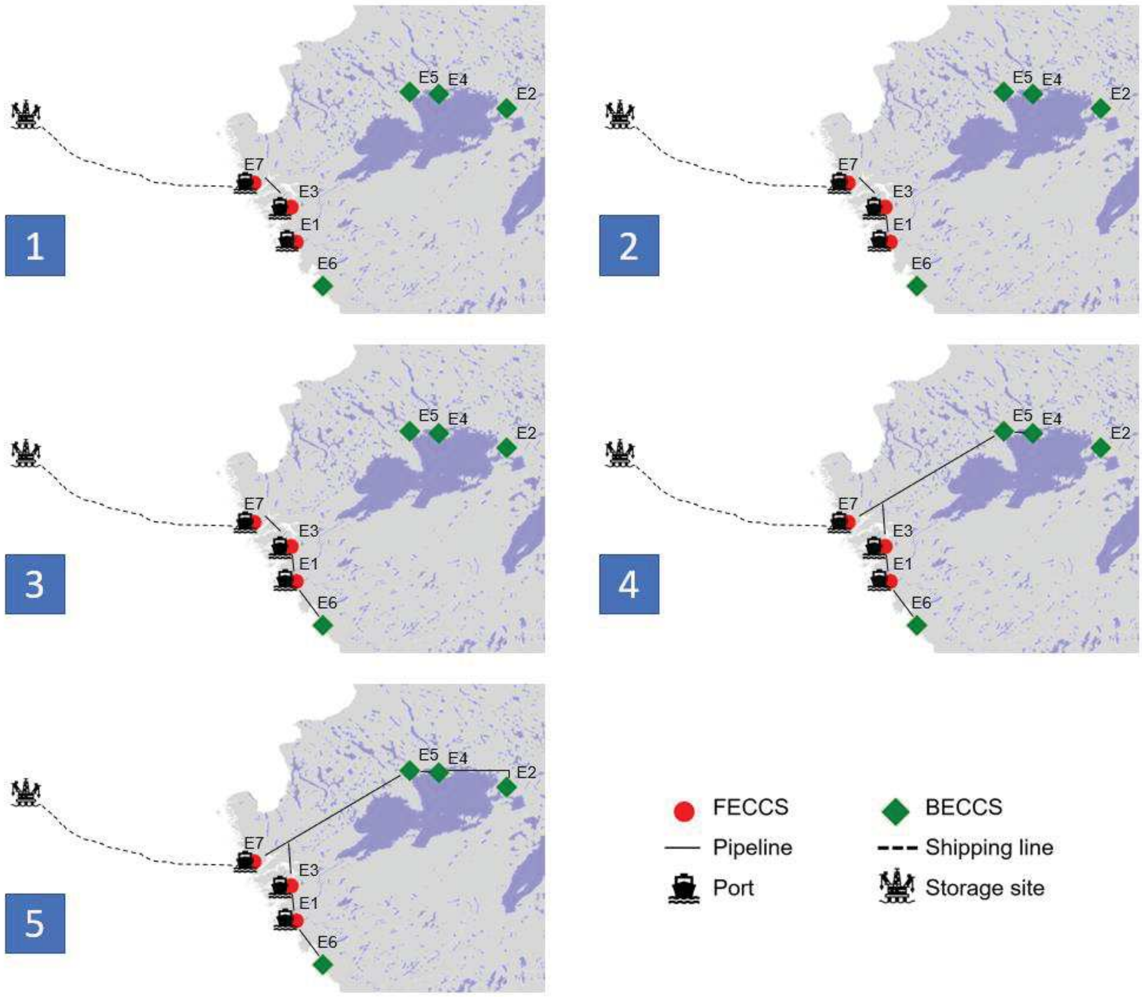

Figure 5: Comparison between the CO_2 price needed to trigger CCS investment and the minimum CO_2 value needed to initiate BECCS investment

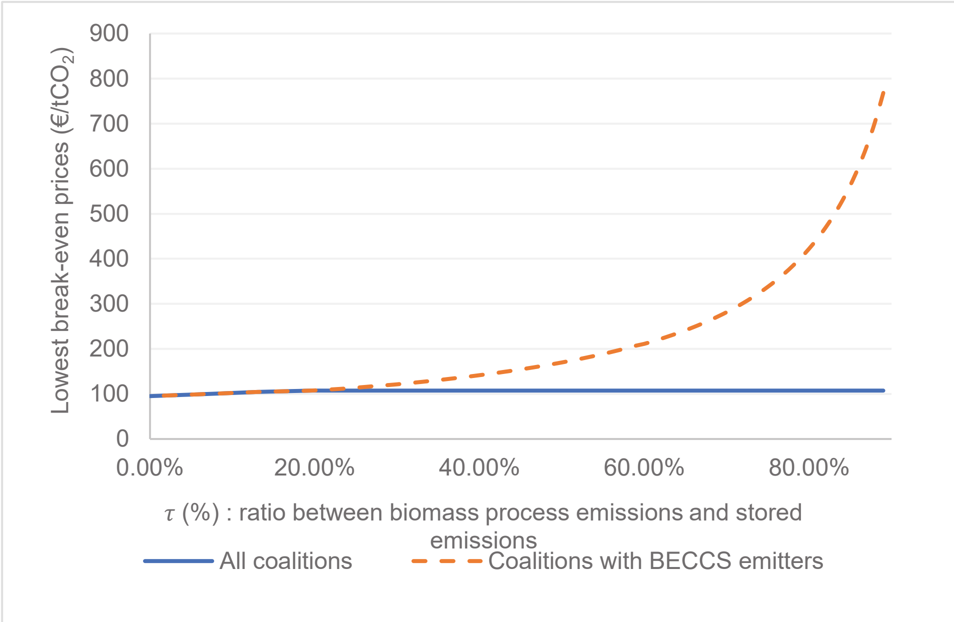

Table 1: the nodes

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	

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

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

Coalitions S_j								Price range (€/tCO_2) [(a)]
N°	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	$[\underline{p_{CO_2}^{s_j}}, \underline{p_{CO_2}^{s_j+1}}[$
1	x		x	x	x	x	x	[95, 105[
2	x	x	x	x	x	x	x	[105, …[

(a): the range of carbon price values for which Coalition s_j is undominated

Table 4: CO_2 price ranges of the socially undominated coalitions

Coalitions S_j								Price range (€/tCO_2) [(a)]
N°	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	$[\underline{p_{CO_2}^{s_j}}, \underline{p_{CO_2}^{s_j+1}}[$
1			x				x	[107, 112[
2	x		x				x	[112, 186[
3	x		x			x	x	[186, 198[
4	x		x	x	x	x	x	[198, 229[
5	x	x	x	x	x	x	x	[229,…[

(a): the range of carbon price values for which Coalition s_j is undominated