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Abstract

We model the value chain of Carbon Capture, transport and Storage (CCS) by focusing on the decisions taking by actors involved in either capture, transport or storage of CO_2. Plants emitting CO_2 are located along a Salop circle. If these invest in carbon capture facilities, the captured CO_2 is transported to terminals, which again transport the received amount of CO_2 to a storage site. We study different market structures, all suffering from market imperfections such as network effects, market power and economics of scale in addition to the environmental externality from emissions. Thus, to ensure socially optimal CCS investments, the government must use more than one policy instrument. A numerical specification of the model finds that the actually observed CCS investments are much lower than what is socially optimal simply because the price of CO_2 emissions has been far too low. If the carbon tax is set equal to the social cost of carbon and is sufficiently high to justify CCS investments, but the government does not use other instruments to correct for the other market imperfections, CCS investments differ significantly between the alternative market structures. In particular, investment in terminals may be too high, while investment in capture facilities could still be too low.

Key words: Carbon capture and storage, indirect network effects, Salop circle, carbon tax, market imperfections, tipping points.

JEL classification: H23, L13, L51, Q35, Q38

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1 Introduction

According to IPCC (2014), Carbon Capture and Storage (CCS) is a key technology in the battle to reduce CO_2 emissions from power and industrial sources.[6] The costs of stabilizing CO_2 in the atmosphere at 450 ppm by 2100, which is in accordance with the two-degree Celsius target, will increase by 138% if CCS is not used. CCS is also important for a more ambitious climate target: The 1.5-degree report from IPCC finds that the CCS technology plays a pivotal role in three of the four illustrative emissions pathways, see IPCC (2019). Furthermore, several academic papers support that CCS should have a key role in reaching climate targets, see, for example, Gerlagh and van der Zwaan (2006); van der Zwaan og Gerlagh (2009, 2016); Farrell et al. (2019) and Weitzel et al. (2019). Investments in CCS have, however, not been in line with studies simulating the cost-efficient path to the Paris Agreement target. Whereas the current global CCS capacity in the power sector is only 2.4 $MtCO_2$ (IEA, 2020)[7], in the Sustainable Development Scenario in IEA (2018), this capacity should be 350 $MtCO_2$ in 2030 and 1500 $MtCO_2$ in 2040.

There may be several reasons for why actual investment in CCS has been unexpectedly low. Clearly, it is not obvious that countries will implement sufficiently stringent policy measures to ensure that the Paris Agreement target is met. If CCS is to be economically viable, investors must believe that the carbon price will increase significantly in the future. Other possible reasons found in the literature are uncertainty about investment costs, lack of safe storage facilities, shortage of professionals to undertake R&D in CCS as this activity tends to compete with oil and gas development projects, legal matters, public resistance to storage, and fear of leakages (Lohwasser and Madlener, 2012; Herzog, 2011; van der Zwaan and Gerlagh, 2016; Budins et al., 2018).[8] In this paper, we examine another potential reason for why investments in CCS is far behind the levels predicted by the IEA and IPCC models. We hypothesize that key characteristics of the CCS value chain have slowed down, or even blocked, the transition to CCS through so-called indirect network effects.

The CCS value chain is complex. Owners of fossil fuel-based power plants, and owners of industrial units like cement plants and waste-to-energy plants, must decide whether to invest

[6] For an overview of CCS technologies, see Leung et al. (2014).
[7] The aggregate capacity of the ongoing CCS pilot projects is 13 $MtCO_2$, see IEA (2019).
[8] Clearly, the models may also be wrong, that is, the real costs of implementing CCS is higher, and/or the real costs of other mitigation options, such as renewable energy, is lower than the associated parameter values used in the modelling analysis (Durmaz, 2018).

in carbon capture facilities. The profitability of this investment is dependent on the availability and price of two complimentary services; transport of the captured CO_2 to the storage site, and storage of the captured CO_2. We will show that it is by no means certain that these services will emerge by themselves. The CCS technology could hence be in a state of *excess inertia* as described by Farrell and Saloner (1986).[9] Moreover, there may be more market imperfections in the CCS value chain, like economies of scale in transporting the captured CO_2, and market power in the supply of storage services. These market imperfections will make the case for a successful introduction of CCS even more difficult. Because each imperfection is a source for deviation from the social optimum, we will study how government policy should be designed to ensure optimal investment in the different parts of the CCS value chain.

Our point of departure is the seminal paper by Chou and Shy (1990), which introduced the concept of indirect network effects in a formal model. However, instead of modelling the indirect network effects by monopolistic competition as in Chou and Shy (1990), we use the Salop model as in Greaker and Heggedal (2010). In the Salop model (Salop, 1979), firms pay a fixed entry cost to enter a market with a given demand. Firms are spatially differentiated along a circle and can charge a mark-up over marginal costs because consumers placed near them can save transport cost by buying from the nearest firm. Firms enter until profit is zero, which in the Salop model leads to excessive entry (Tirole, 1988).

In our application of the Salop model, there are plants along the circle; some of these may invest in captured facilities. There are also terminals along the circle. Terminals receive captured CO_2 from plants and transport the captured CO_2 to a storage site. A plant investing in capture facilities face three cost components: cost of investing in capture facilities, cost of transporting the captured CO_2 to a terminal, and cost of handing over the captured CO_2 to the terminal, which will transport the CO_2 to a storage site. If a plant does not invest in capture facilities, it has to pay a standard carbon tax for its CO_2 emissions. We extend the Salop model by introducing variable demand, e.g., the number of plants that choose to invest in capture facilities is endogenous. Because this number depends on the number of terminals along the Salop circle, and, *vice versa*, we have indirect network effects.

[9] *Excess inertia* refers to a situation in which a technology that could increase welfare is not adopted by firms due to a coordination failure.

In our base case, we assume that each terminal along the Salop circle supply both transport and storage services. One interpretation is that terminals can buy storage services to a regulated price, e.g., at the unit cost of storage. This implies that in the base case, which we refer to as regulated storage, we focus on the interaction between plants that may invest in capture facilities and terminals providing transportation of captured CO_2 to a storage site. In the first extension of the basic model, we separate between transport actors, which we refer to as terminals, and a single storage provider. We allow the storage provider to operate as a monopoly. Hence, in our second case, which we refer to as monopoly storage, there is a double marginalization problem in addition to the network effects because both the terminals and the storage actor charge a mark-up on their costs. There is therefore an incentive for the storage actor to vertically integrate with the terminals and form a cartel, which is our third case.

In order to illustrate our theoretical results, we calibrate the model to real data. We assume that the Salop circle crosses through six countries in Northern Europe and has its center in the North Sea, which is used for storage. Thus, we consider only one storage site. We solve the model numerically and compare the outcome to the first-best social outcome. Also, we identify which instruments should be used in order to achieve the first-best outcome, and calculate the magnitude of these instruments that will ensure the social outcome to materialize.

Both under regulated storage and monopoly storage, we show that two instruments are needed to correct for the imperfections, thereby achieving the first-best social outcome. One possibility is that the government imposes a tax on terminals and an extra carbon tax on plants that do not install capture facilities. The extra carbon tax will come in addition to the standard carbon tax, which, per assumption, is set equal to the social cost of carbon. The extra carbon tax provides the correct incentive for plants to invest in capture facilities. The tax on terminals corrects the market outcome for the net effect of more terminals: more terminals lowers the utilization of economies of scale in transportation to the storage site, but it also lowers the costs of transporting captured CO_2 from plants to terminals because the average distance between a plant and a terminal has decreased. Under a cartel, the network effect and the economies of scale effect are internalized, and it is enough to use only an extra carbon tax to achieve the first-best social outcome.

With our benchmark parameter values, where the social cost of carbon is set to 90 $euro_{2016}/tCO_2$, the additional carbon tax should be 10 euro/tCO_2 in the case of a regulated storage actor, whereas this instrument should be much higher (around 45 euro/tCO_2) under both monopoly storage and a cartel (to achieve the first-best social outcome). The reason is that exploitation of the additional market power in the latter two cases (relative to the case of regulated storage) pushes up the price terminals charge on plants delivering captured CO_2. The additional carbon tax must neutralize this effect in order to encourage plants to invest in capture facilities.

The extent to which *excess inertia* may occur depends on the parameter values. We find that if the social cost of carbon is at least 69 euro/tCO_2, the carbon tax is set equal to the social cost of carbon, and the government uses no other instrument than the carbon tax, all three market outcomes have internal solutions, i.e., there will be investments in capture facilities, terminals and storage (but the magnitudes differ from the first-best values). However, there may be more equilibria, and a temporary subsidy might be needed to kick start the investments. For a social cost of carbon between 61 and 68 euro/tCO_2, there is an internal solution for the cartel case only if the government uses no other instrument than a standard carbon tax. If the social cost of carbon is between 58 and 60 euro/tCO_2, it is still optimal from a social point of view to invest in CCS, but CCS investments will not materialize in any of the three market cases if the government uses no other instrument than a standard carbon tax. Below 58 euro/tCO_2, there should be no investment in CCS from a social point of view.

The paper is organized in the following way. Section 2 provides a short literature review and explains our contribution to the literature. In Section 3, we present the basic structure of the theory model, while we in Sections 4-7 find the first-best social optimum and the equilibrium under alternative market structures (regulated storage actor, monopoly storage, and cartel). We provide numerical illustrations of the four outcomes in Section 8, and in Section 9, we discuss which instruments can be used under alternative market structures to implement the first-best social optimum, and we calculate the magnitude of these instruments. Then, in Section 10, we examine how the outcomes and instruments depend on key parameters, like the social cost of carbon and the maximum size of the CCS market. Finally, Section 11 concludes.

2 Contribution to the literature

According to Farrell and Klemperer (2007), the consumption of a good has positive network effects if one agent's purchase of the good i) increases the utility to all others who possess the good, and ii) increases the incentive of other agents to purchase the good. This is exactly what happens in our model. If one more plant invests in a capture facility, demand for transportation services to the storage site increases, thereby making investment in terminals more profitable. With more terminals, the average distance between a plant and a terminal decreases, and therefore, the cost of transporting captured CO_2 from a plant to a terminal is reduced. This strengthen the incentive for plants to invest in capture facilities. However, the government must likely use policy instruments to kick off investment in captured facilities and/or terminals. In an uncoordinated market, i.e., without any policy instruments, network effects may hamper the introduction of a cleaner technology.

In the model of Greaker and Midttømme (2016), an old network entails environmental externalities (the dirty network), while a new network does not. Greaker and Midttømme (2016) shows that taxing the dirty network far above the Pigouvian rate temporarily may be desirable in order to coordinate a rapid transition to the clean network. While Greaker and Midttømme (2016) look at a general case, Greaker and Heggedal (2010) focus on the market for clean and dirty cars and the market for alternative refueling technologies. They are then able to discuss the different factors leading to a lock-in in the dirty fuel technology. Meunier and Ponssard (2020) extend the analysis of Greaker and Heggedal (2010) in several directions and analyze the optimal use of policy instruments for alternative fuel cars. They find that both re-fueling stations and alternative fuel cars should be subsidized in the early stages of market development.

In this paper, we contribute to the theoretical modelling of indirect network effects and to the empirical CCS literature. We adjust and extend the standard Salop model to capture the key features of the CCS value chain, including network effects. The consumers in Greaker and Heggedal (2010) are replaced by CO_2-emitting plants. These are located evenly around the Salop circle and differ with respect to the unit cost of removing CO_2 by investing in capture facilities. Hence, in equilibrium only a fraction of the emitting plants will invest. This fraction will *inter alia* depend on the number of terminals that enter along the Salop circle, each offering to receive captured CO_2 and transport the CO_2 to a storage site.

The empirical CCS literature encompasses two strands; one on CCS cost estimates, see, for example, ZEP (2011a) and Rubin et al. (2015), and one on the diffusion of CCS technologies. We build on the first strand and contribute to the second. There are a few papers using electricity market models to study diffusion of CCS in the electricity generation sector in Europe, see, for example, Golombek et al. (2011), Marañón-Ledesma and Tomasgard (2019), and Aune and Golombek (2021). However, to the best of our knowledge, there is no paper modeling the diffusion of CCS technologies explicitly that considers network effects.[10]

3 The theory model

We assume that plants are located evenly around a circle. Initially, all plants emit CO_2, but emissions may differ across plants. Let the distribution of emissions (e) over plants be denoted $f(e)$.

Plants emitting CO_2 have to pay a tax τ per unit of emission. Alternatively, a plant can install capture facilities and transport the CO_2 to a terminal, which is also located on the circumference. Each terminal has an entry cost that reflects investment in i) facilities to receive captured CO_2 from plants, and ii) an offshore pipeline that transports the received CO_2 to a storage site, which is located in the center of the circle. Plants are charged by the terminal for their delivered amount of CO_2, and correspondingly, terminals are charged by the storage actor for the amount of CO_2 they deposit.

Let x be cost of investment in capture facilities of a plant, per unit of emission. We assume that the unit cost of investment differs across plants (from $\underline{x}$ to $\bar{x}$), reflecting that plants belong to different sectors, for example, aluminum and cement production, waste management or fossil-fuel based electricity supply. Let $G(x)$ be a continuous function that measures the share of plants around the circle with unit cost of investment less or equal to x, $\underline{x} \leq x \leq \bar{x}$. We assume that the associated density function to $G(x)$ is uniformly distributed over $[\underline{x}, \bar{x}]$, i.e., $G'(x) = g(x) = 1/(\bar{x} - \underline{x})$. Further, for any segment along the circle with length θ, $0 < \theta \leq S$, where S is the circumference of the circle, we assume that the share of plants with cost of investment less or equal to x is described by $\frac{\theta}{S} G(x)$.

[10] There is, however, a techno-economic literature on the potential of CCS in various manufacturing industries, see, for example, Barker et al. (2009) and Leeson et al. (2017).

Let $\hat{x}$ be the unit cost of the marginal plant investing in capture facilities, that is, all plants with a lower unit cost of investment than $\hat{x}$ will invest in capture facilities. Total costs of investment in capture facilities is then:

$$\int_e \int_{\underline{x}}^{\hat{x}} exf(e)g(x)dedx = \int_e ef(e)de \int_{\underline{x}}^{\hat{x}} xg(x)dx = E \int_{\underline{x}}^{\hat{x}} \frac{x}{\bar{x}-\underline{x}} dx\,, \qquad (1)$$

where we have used that the distribution of emissions over plants, $f(e)$, and the distribution of unit cost of investment over plants, $g(x)$, are independent. Furthermore, we have used that total emissions prior to investment in capture facilities is $\int_e ef(e)de = E$.

Initially, there are no terminals. We assume, like in the standard Salop model, that once terminals enter, they locate evenly around the circle. In our model, this assumption can be justified by the fact that an actor needs a concession from the government to build a terminal: in order to minimize total social cost, the government will impose equally spaced apart terminals as this location pattern is a necessary condition to minimize cost of transporting captured CO_2 from plants to terminals.

Let n denote the number of terminals. Hence S/n is the distance between two neighboring terminals. The maximum distance between a plant and a terminal is then $S/2n$. Because plants are evenly distributed along the circle, the average distance between a plant and a terminal is $S/4n$. Further, let t be the cost of transporting one unit of CO_2 to a terminal per unit of distance. Then the average cost of a plant to transport one unit of CO_2 to a terminal is $tS/4n$.

Finally, q denotes the share of plants investing in capture facilities. Because $\theta g(x) = \theta/(\bar{x} - \underline{x})$ applies to any segment around the circle with length θ, the relationship between the share q and the cost of the marginal plant investing in capture facilities, $\hat{x}$, is

$$q = \frac{\hat{x}-\underline{x}}{\bar{x}-\underline{x}} \qquad (2)$$

Hence, total abatement is qE.

Each terminal transports its received amount of CO_2 to a storage site by a terminal-specific pipe. Under our assumptions, all terminals will receive the same amount of CO_2 from plants, qE/n, and thus this will be the equilibrium capacity of each terminal (where q and n are endogenous variables). We refer to the cost of investment of building the terminal and also the offshore pipe as the cost of entry. Because terminals, as well as pipes, are characterized by significant economies of scale, that is, the unit cost is lower the higher is capacity, we let the unit cost of entry be represented by a hyperbola, $a/(qE/n)+b$. Here, the parameter $a>0$ is the fixed cost of a terminal of handling the received carbon, whereas the parameter $b>0$ is the unit cost of investment if the received quantity is "very large" (strictly speaking, infinity). The cost of entry of all terminals of receiving the total amount of carbon, qE, is $(\frac{a}{(qE/n)}+b)qE=an+bqE$.

Below we will derive the social optimum, that is, how many terminals (n) should be set up and the share of plants (q) that should invest in capture facilities from a social point of view. The first-best outcome will be compared to the outcome under alternative market structures. These differ with respect to whether the price of storage is regulated or set by a profit-maximizing, monopoly storage actor. Also, we distinguish between the case of free entry of terminals and the case where one actor owns all terminals and also the (only) storage site. In the latter case, which we henceforth will refer to as the cartel, the common owner may lower the number of terminals (relative to free entry) in order to increase total profits of the cartel.

4 Social Optimum

The social cost consists of five terms: cost of emissions of those plants that are not abating, $(1-q)E\tau$, cost of those plants that are investing in capture facilities, $E\int_{\underline{x}}^{\hat{x}}\frac{x}{\bar{x}-\underline{x}}dx$, see (1), cost of plants to transport CO_2 to terminals, $\frac{tS}{4n}qE$, cost of entry of terminals (that is, investments in terminals and pipes), $an+bqE$, and cost of storage, vqE, where v is the unit cost of storage and qE is the capacity of the storage site, which is set equal to the received amount of CO_2. The objective of the planer is to minimize social cost with respect to the share of plants investing in capture facilities (q) and the number of terminals (n) entering the market. The social costs to minimize is thus:

$$(1-q)\tau E+E\int_{\underline{x}}^{\hat{x}}\frac{x}{\bar{x}-\underline{x}}dx+\frac{tS}{4n}qE+(an+bqE)+vqE$$

The first-order conditions are:

$$q=\frac{\tau-\frac{tS}{4n}-b-v-\underline{x}}{\bar{x}-\underline{x}} \tag{3}$$

$$n=\sqrt{\frac{qEtS}{4a}}, \tag{4}$$

where we have used used (2). Both (3) and (4) are relationships between the optimal share of plants investing in capture facilities, q, and the optimal number of terminals, n, and reflect a positive network effect. With more terminals, the average distance for a plant to transport CO_2 decreases $(S/4n)$, which makes it less costly to choose the abatement option. Hence the share of plants investing in CCS should increase in n, see (3). When more plants invest in capture facilities, the total amount of CO_2 received by terminals increases (qE), and hence for each terminal the unit cost decreases as the fixed cost a is distributed over a higher volume of CO_2. This suggests that the number of terminals increases, see (4).

Relations (3) and (4) determine the social optimal share of plants investing in CCS, q^{SO}, and the social optimal number of terminals, n^{SO}, where *SO* denotes the *S*ocial *O*ptimum.

We now turn to examine how the share of plants investing in capture facilities and the number of terminals that are set up are determined under three alternative market structures. Each case is analyzed as a multi-stage game.

5 A regulated storage actor

The terminal sets the price. In this game, terminals are free to charge whatever they want in order to be willing to receive CO_2 from plants, that is, each terminal sets the price that maximizes its profit. In contrast, the storage actor is regulated and must charge its unit cost v for each unit of CO_2 terminals deposit.

At the start of the game, plants emit CO_2, no terminals have been set up, and no storage site has been built. In stage one of the game, plants decide whether to invest in capture facilities. Furthermore, potential terminal actors decide whether to set up a terminal, and if so, decide the capacity of the terminal. Also, in stage one of the game, the storage actor determines its capacity.

In stage two of the game, terminals decide how much to charge plants for delivering their CO_2, and each plant with capture facilities decide to which terminal it will deliver its CO_2. Plants without capture facilities pay the carbon tax. We solve the game by backward induction.

Stage two

A plant that has invested in capture facilities (in stage one) chooses to which terminal to transport its captured CO_2. Denote the two terminals located closest to a plant by α and β, and let p_α and p_β be the prices charged by the two terminals, respectively, per unit of received CO_2. If a plant transports its CO_2 to terminal α, its cost of transport per unit of CO_2 will be td where d is the distance to terminal α. In addition, the plant has to pay p_α for each unit of CO_2 delivered to terminal α. The distance d that makes a plant indifferent between transporting its CO_2 to terminal α or terminal β is defined from equation (5),[11]

$$p_\alpha + td = p_\beta + t(\frac{S}{n} - d)\,, \quad (5)$$

where $S/n - d$ is the distance between the plant and terminal β, and p_β is the price charged by terminal β. Solving (5) with respect to d, we find

$$d = \frac{-p_\alpha + p_\beta + \frac{St}{n}}{2t} \quad (6)$$

Hence, plants with a lower distance to terminal α than the one in (6) will transport its CO_2 to terminal α.

Above, we defined q as the share of plants investing in capture facilities (in any segment along the circle). Therefore, a terminal receives CO_2 from a share q of all plants located less than d from its location; this is the case on both sides of its location. Furthermore, because qE/S is the average amount of CO_2 transported per unit of distance, the total amount of CO_2 received by a terminal is

$$D(p_\alpha, p_\beta) = \frac{qE}{S} 2d = \frac{qE}{S} \frac{-p_\alpha + p_\beta + \frac{St}{n}}{t}\,, \quad (7)$$

where we have used (6).

In this stage, the costs of investment are sunk and hence terminal α will choose its price p_α such that the profit $(p_\alpha - v)D(p_\alpha, p_\beta)$ is maximized, where v is the unit cost of the terminal, that is, the amount of money the terminal has to pay to the storage actor for each unit of CO_2 it deposits. All terminals solve the same type of problem, and in a symmetric equilibrium the common price will be

[11] Note that in the equations below, d notes the distance that makes a plant indifferent to where to deliver its captured CO_2.

$$p = v + \frac{tS}{n} \tag{8}$$

Here, the term $\frac{tS}{n}$ represents the mark-up of a terminal, which executes market power.

Stage one

The decision problem of the plant. Each plant decides whether to invest in capture facilities or pay the carbon tax τ. If the plant invests, it has three cost components: cost of investment (x), cost of transport $(tS/4n)$ and the price paid to the terminal (p). Per construction, the plant being indifferent between these two choices has unit cost of investment equal to $\hat{x}$, where $\hat{x}$ is the solution of

$$\tau = \hat{x} + \frac{tS}{4n} + p \tag{9}$$

In (9), the left hand side shows the marginal cost of a plant that is not abating, whereas the right hand side shows the abatement cost of the marginal plant. Using (2), (8) and (9)we find the equilibrium share of plants that chooses to abate:

$$q = \frac{\tau - \frac{5tS}{4n} - v - \underline{x}}{\bar{x} - \underline{x}} \tag{10}$$

Relation (10) is the optimal response of plants considering to invest in capture facilities, that is, for a given number of terminals, n, it shows the share of plants that will invest in capture facilities. Like in the social optimum, more terminals tend to increase the share of plants investing in capture facilities.

One difference between the optimal response of plants in the social optimum and the current case of regulated storage, is that the term $-\frac{tS}{4n}$ in (3) has been replaced by $-\frac{5tS}{4n}$ in (10). The difference $(-\frac{tS}{n})$ reflects execution of market power by terminals (under regulated storage), see (8), which tends to lower the share of plants investing in capture facilities. Another difference between (3) and (10) is that the parameter b, which is the minimum unit cost of transporting CO_2 from a terminal to the storage site, has a direct impact on the optimal response of plants in the social optimum, but no direct impact on the optimal response of plants under regulated storage. In the social optimum, a higher b tends to lower the share of plants investing in capture facilities (the higher the social cost of CCS, the fewer plants should invest in CCS), whereas under regulated storage, this parameter (along with the fixed cost a) determines the number of terminals from the free-entry condition, see (11) below. Hence, under regulated storage the parameter b only indirectly affects the share of plants investing in capture facilities.

The decision problem of the terminal. The profit of a terminal consists of revenues and costs in the two stages. First, cost of investment from stage one in the game consists of the unit cost of handling the received amount of CO_2 $(a/(qE/n)+b)$ times the capacity of a terminal (qE/n). Second, profits from stage two in the game is $(p_\alpha - v)D(p_\alpha, p_\beta)$. Because $p_\alpha = p_\beta = v + tS/n$, see (8), this profit is given by $tqES/n^2$, where we have used (7). We assume free entry so that terminals are built until profit from stage two minus investment costs from stage one is driven down to zero, that is,

$$-\left(\frac{a}{\frac{qE}{n}} + b\right)\frac{qE}{n} + \frac{tqES}{n^2} = 0\,,$$

which can be solved to yield the reduced form expression for n:

$$n = -\frac{bqE}{2a} + \frac{\sqrt{(bqE)^2 + 4aqES}}{2a} \tag{11}$$

Relation (11) is the optimal response of terminals, that is, for a given share of plants that has invested in capture facilities, q, it shows the number of terminals that will be set up. Note that a higher share of plants investing in capture facilities has in general an ambiguous effect on the number of terminals, as the captured amount of CO_2 increases, but so does the total costs of entry. If, however, the parameter b is sufficiently low, we obtain a positive network effect on the number of terminals of an increase in the share of plants investing in capture facilities.

Relations (10) and (11) determine the share of plants investing in capture facilities, q^v, and the number of terminals, n^v, where v denotes the current case of a regulated price of storage services.

The decision problem of the storage actor. Here, we simply assume that the rational, forward looking storage actor knows that total amount of received CO_2 will be q^vE, and thus chooses capacity equal to this magnitude.

Result 1: *The solution to* (10) *and* (11) *(q^v, n^v) may not be unique. We may have two solutions with a positive number of terminals and plants investing in capture facilities. Denote these two solutions (q_l^v, n_l^v) and (q_h^v, n_h^v). We then have $q_l^v < q_h^v$ and $n_l^v < n_h^v$.*

Proof: *For* $b = 0$, *relation* (10) *and* (11) *can be combined to yield the following cubic equation:*

$$Y^3 - \frac{\tau - v - \underline{x}}{\bar{x} - \underline{x}} Y + \frac{5t\sqrt{aS}}{4(\bar{x} - \underline{x})\sqrt{E}} = 0$$

where $= \sqrt{q}$.

For some values on the parameters, the cubic equation has two real roots yielding the two solutions (q_l^v, n_l^v) *and* (q_h^v, n_h^v)*. By continuity this will also hold for b > 0, see also Figure 1 below, and Greaker and Midttømme (2016) for a more detailed proof of a similar result.*

It can be shown that the equilibrium with the lowest number of terminals and plants investing in capture facilities will be unstable. Hence, this equilibrium is a tipping point: as long as the number of terminals and plants with capture facilities are below (q_l^v, n_l^v) , the market for CCS may never take off, and we end up with a stable solution with no investments in plants and terminals.

6 A monopoly storage actor

We now study the case in which the storage actor is free to set a storage fee z that maximizes his profits.[12] This game evolves over three stages. In stage zero, the rational, forward-looking storage actor sets the storage fee z. Capacities (by plants, terminals, and the storage actor) are set in stage one, and the price p that plants have to pay for delivering CO_2 is determined by each terminal in stage two.[13] Because stage one and two are identical to the previous case, equations (10) and (11) also apply in this case, except that now the parameter v has been replaced by the endogenous storage fee z. The profit of the storage actor is $(z - v)qE$. Hence, the Lagrangian of the optimization problem is

$$L^z = (z - v)qE - \lambda\left(q - \frac{\tau - \frac{5tS}{4n} - z - \underline{x}}{\bar{x} - \underline{x}}\right) - \mu\left(n - \frac{tSqE}{an + bqE}\right)$$

[12] This case will have strong resemblance to a case with Cournot competition between storage actors that may emerge when several countries plan to invest in storage facilities.

[13] As always in multi-stage games, one may question whether the storage monopolist, who sets the storage price in stage zero of the game, has an incentive to change the storage price in the last stage of the game, that is, whether the equilibrium is time consistent. Because the storage price maximizes the profit of the storage actor, there is no incentive to deviate from the pre-announced price. In particular, in stage one of the game the storage actor chooses a storage capacity that is in line with the pre-announced price from stage zero, thereby making it credible that the pre-announced price for storage services will be charged in stage two.

From the first-order conditions and using restriction (11), we find an expression for the profit-maximizing price of storage:

$$z = v + (\bar{x} - \underline{x})q - \frac{5atS}{4(2an + bqE)} \tag{12}$$

Relations (10) (with v replaced by z), (11) and (12) determine the triple (z, q^z, n^z) where $z > v$ (with $z = v$, profit of the storage actor is zero). As shown in Figure 1, this case may also involve two equilibria.

7 Vertical integration—cartel

In the previous two cases, there was per assumption no coordination between the n terminals, nor any coordination between the terminals and the storage actor. We now examine the corner case in which there is full coordination between these $n + 1$ actors, that is, we assume they merge and form a cartel that maximizes total profits. The game evolves as follows. In stage one, all capacities are determined. In stage two of the game, the cartel sets the price p that all plants have to pay when delivering CO_2 at a terminal. Moreover, plants having invested in capture facilities decide to which terminal they will transport their captured CO_2.

The cartel receives qE units of CO_2 from the plants and thus obtains the income pqE. The cartel has, however, two types of costs: cost for handling CO_2 and transporting the CO_2 to the storage site, $an + bqE$, and cost of building storage capacity, vqE.

When maximizing profits, the cartel takes into account how its price p affects the decision of plants of whether to invest in capture facilities, see (9). Combining this relation with (2), the definition of the share q, we obtain

$$q = \frac{\tau - \frac{tS}{4n} - p - \underline{x}}{\bar{x} - \underline{x}} \tag{13}$$

Relation (13) shows how a change in the price p has impact on the share q (for a given number of terminals). Therefore, the cartel (c) maximizes its profits

$$(p - b - v)\frac{\tau - \frac{tS}{4n} - p - \underline{x}}{\bar{x} - \underline{x}}E - an \tag{14}$$

with respect to p and n. The first-order condition with respect to p implies

$$p = b + v + (\bar{x} - \underline{x})q \tag{15}$$

Combing (15) with the first-order condition with respect to n that follows from maximizing (14), we obtain (4), which is part of the system that characterizes the social optimum. Inserting (15) into (13), we obtain

$$q = \frac{\tau - \frac{tS}{4n} - b - v - \underline{x}}{2(\bar{x} - \underline{x})} \tag{16}$$

Relations (4) and (16) determine the share q^c and the number of terminals n^c under a cartel, i.e., vertical integration. We then find the price p^c from (15). Note that the difference between the optimal response of plants in the social optimum, see (3), and the optimal response of plants under a cartel, see (16), is that the denominator is twice as high in the latter case than in the social optimum. Hence, an increase in the number of terminals triggers a lower increase in plants investing in capture facilities under a cartel than in the social optimum. This reflects the market power of the cartel; it charges the plants a high price p.

Why does (4) characterize both the social optimum and the market with vertical integration? The social planner chooses the number of terminals that minimizes total costs of plants, terminals and storage, thereby taking into account the network effect and the economies of scale effect. The cartel chooses the price p and the number of terminals n that maximizes the profits of the cartel, and thus will also take into account the network effect and the economies of scale effect.

Table 1 summarizes the three market outcomes and the first-best social outcome. For each case, we have specified the set of equations that determines the share of plants investing in capture facilities and the number of terminals that will be set up.

Table 1: Definition of outcomes

	Regulated storage Case 1	Monopoly storage Case 2	Cartel Case 3	Social optimum
Plants investing in capture facilities	Equation (10) $z = v$	Equation (10) $z = z^{opt} > v$	Equation (16)	Equation (3)
Terminals	Equation (11)	Equation (11)	Equation (4)	Equation (4)

By inspection, we note that the solution (q, n) to (4) and (16), and also to (3) and (4), may involve more than one set of (q, n). Hence, also in the cartel case and in the social optimum there may be more than one potential equilibrium. However, for these cases there are likely no coordination problem: The social planner simply sets the share of abatement among plants and also the number of terminals, whereas the cartel builds the desirable number of terminals and sets the price faced by plants such that the calculated level of investment in capture facilities emerges.

8 Empirical illustrations

In this section, we offer empirical illustrations of the three market outcomes and the first-best social outcome. We assume the Salop circle covers six countries (Norway, Denmark, Germany, Belgium, the Netherlands and the UK), and that the centre of the circle is in the North Sea, where there are suitable underwater geological formations for carbon storage. Table 2 shows the benchmark parameter values; these are ballpark estimates based on data from the geographical area and the general literature that ensure internal solutions of the four outcomes discussed above. We refer to the Appendix for a documentation of the data sources, and to Section 10 for an examination of how alternative parameter values impact the outcomes.

Table 2: Benchmark parameters ($euro_{2016}$)

Parameter	Description	Value	Unit	Data source
S	Circumference of circle (Diameter 850 km)	2669	km	
E	CO_2 emissions prior to abatement	200×10^6	tCO_2	United Nations Climate Change (2020)
$\underline{x}$	Cost of investment in carbon capture, lowest value	28	euro/tCO_2	Rubin et al. (2015)
$\bar{x}$	Cost of investment in carbon capture, highest value	132	euro/tCO_2	Atkins and Oslo Economics (2016;2018)
t	Cost of transport of CO_2 to a terminal	0.032	euro/tCO_2km	Rubin et al. (2015)
a	Unit cost function of terminal transport: slope	4.608×10^7	euro	Rubin et al. (2015)
b	Unit cost function of terminal transport: constant	3	euro/tCO_2	Rubin et al. (2015)
v	Storage cost	11	euro/tCO_2	Rubin et al. (2015)
τ	Carbon tax	90	euro/tCO_2	IPCC (2014)

Figure 1 shows the four outcomes when we use the parameter values in Table 2. For each case, there are two equations that give relationships between the share of plants investing in carbon capture, q, and the number of terminals, n, see Table 1. Note that for each of the four cases, there are two equilibria, e.g., two points where the relevant curves cross. The equilibrium with the lowest values is unstable, e.g., a tipping point, see the discussion following Result 1. Henceforth, we therefore focus, on the other equilibrium.[14]

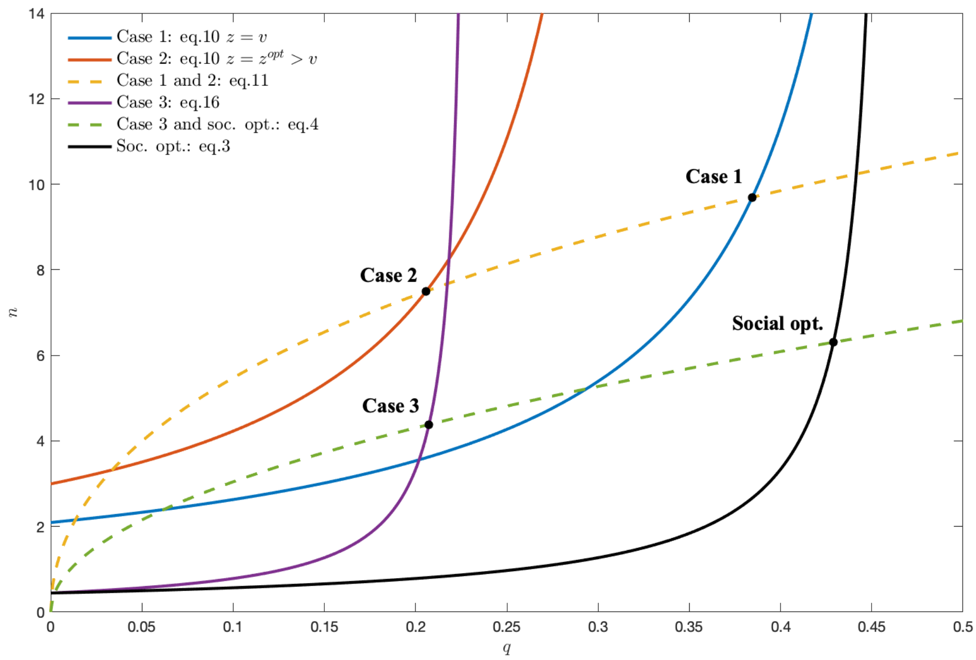

Figure 1: Outcomes. Regulated storage (Case 1), monopoly storage (Case 2), cartel (Case 3), and the social optimum.

The first-best social optimum is found where the curves representing relations (3) and (4) intersect. Here, 43 percent of the plants invest in CCS and there are 6.31 terminals, see Table 3.[15] Needless to say, the social cost is lowest in the social optimum.

In the case of a regulated storage actor (Case 1), the equilibrium is found where the curves illustrating relations (10) (with the price of storage services, z, being equal to the social cost of storage, v) intersects with the curve representing restriction (11). With a monopoly storage actor (Case 2), the actor sets the price for deposit services that maximizes profits. Like in Case 1, the equilibrium is found where the curves illustrating relations (10) and (11) intersect, but now the price of storage in relation (10) exceeds the social cost of storage ($z > v$). Therefore,

[14] For each of the four cases, the solution marked in Figure 1 has the lowest social cost. Moreover, only this equilibrium meets the standard condition of stability, see, for example, Greaker and Heggedal (2010). If the market fails in passing the unstable equilibrium, the outcome will be a stable equilibrium with zero investment in capture facilities and no terminals.

[15] Because the number of terminals is a continuous variable, the outcome is not an integer. In the literature, it is common to associate the integer closest to this continuous variable as the value that will materialize.

the curve illustrating relation (10) in the monopoly storage case is located above the curve illustrating relation (10) in the regulated storage case, see Figure 1.

As seen from Table 3, both under regulated storage and monopoly storage, the number of terminals (9.70 and 7.50) is greater than in the first-best social optimum (6.31). The reason for excessive investment in terminals is that neither the storage actor nor the individual terminal owner internalizes the network and economies of scale effects. On the other hand, with our reference parameter values, there is lower investment in carbon capture facilities under regulated storage (38%) and monopoly storage (21%) than in the social optimum (43%), which reflects market power of terminals (in Case 1 and Case 2), and also market power of storage supply in Case 2.

Table 3: Share of plants investing in carbon capture facilities and number of terminals. Benchmark parameter values.

	Regulated storage	**Monopoly storage**	**Cartel**	**Social optimum**
Share of plants investing in CCS (q)	0.38	0.21*	0.21*	0.43
Number of terminals (n)	9.70	7.50	4.38	6.31
Price paid by plants for delivering CO_2 at a terminal (p), euro$_{2016}$/toe	19.81	37.75	35.56	-
Price paid by terminals for storage service (z), euro$_{2016}$/toe	11	26.36	-	-
Profits of terminals, million euoro$_{2016}$	0	0	1010**	-
Profits of storage actor, million euoro$_{2016}$	0	632		-
Social cost, million euro$_{2016}$	16460	16930	16860	16380

* By chance, the two first digits are identical under monopoly storage and cartel.
** This is the total profits of terminals and storage under a cartel.

In the case of a cartel owning all terminals and the storage site (Case 3), the equilibrium is found where the curves illustrating relations (4) and (16) intersect. Here, 21 percent of the plants invest in carbon capture facilities and the number of terminals is 4.38. Hence, in Case 3 there are fewer plants investing in carbon capture facilities and also fewer terminals than in the social optimum (21% vs. 43%, and 4.38 vs. 6.31). The two outcomes differ because of the exploitation of market power by the cartel in determining the price p that plants face when delivering CO_2

to terminals. The mark-up of this price, tS/n, see (8), discourages plants to invest in carbon capture facilities, and potential terminal actors respond by setting up fewer terminals, see (4).

We summarize our findings in the following result:

Result 2: *In all market outcomes, the share of plants investing in* carbon capture *is lower than in the social optimum. On the other hand, with regulated storage and monopoly storage, the equilibrium number of terminals is greater than in the first-best social outcome, whereas the ranking is opposite for a cartel.*

9 How to achieve the first-best outcome?

The three market outcomes studied above differ from the first-best social outcome because of various deviations from a competitive economy. Below we discuss instruments the government can use in order to correct for the distortions.

In the case of *regulated storage (Case 1)*, we need one instrument to correct for the non-competitive price of delivering CO_2 to terminals. We also need one instrument to internalize the net effect of the network effect of terminals and the economies of scale in transporting CO_2 from terminals to the storage site, as these two imperfections can be corrected with a single instrument (see below).

From (8) we see that a lower cost of storage will, *cet. par.*, lower the price p plants have to pay in order to deliver CO_2 at terminals. Hence, one way to correct for the non-competitive price is to offer a subsidy for storage services, s_v, which will lower the regulated price of storage to $v - s_v$. This is confirmed from (10): A lower cost of storage will, *cet. par.,* increase the share of plants investing in CCS. However, $v - s_v$ may be negative and even the price p may become negative. The government should therefore use another instrument than a storage subsidy.

Suppose the government offers a subsidy to investment in capture facilities, s_I. Such a subsidy would lower $\underline{x}$ and $\bar{x}$ by the same amount. As seen from (10), the denominator will not change, whereas the nominator decreases in the same way as if a subsidy for storage services, s_v, is offered. Because $\underline{x} - s_I$ may become negative, also a subsidy to investment in capture facilities may not be a sound instrument.

Another possibility is to impose an extra tax on CO_2 emissions, t_τ. This instrument works in the same way as a storage subsidy, see (10). In fact, an extra tax on CO_2 emissions has the same impact on the share of plants investing in carbon capture facilities as an equally large storage subsidy: it provides an incentive for plants to invest in carbon facilities. Below, we therefore use a tax t_τ to correct for the non-competitive price charged by terminals.

To internalize the net effect of the network effect and economies of scale in terminal transport, one obvious instrument is to impose (a positive or negative) tax on terminal transport; a positive tax will discourage entry of terminals thereby encourage economics of scale, but also discourage plants to invest in CCS. Below, we let the government impose a tax t_b for each unit of CO_2 a terminal is transporting to the storage site, that is, the unit cost of handling CO_2 is now $a/(qE/n) + (b + t_b)$.[16]

Let q^{S0} denote the first-best social optimum. In order to find the optimal instruments under regulated storage, we solve the system (10) and (11) with $q = q^{SO}$ and $n = n^{SO}$ and where τ is replaced by $\tau + t_\tau$ and b is replaced by $b + t_b$. Hence, the new CO_2 price is $\tau + t_\tau$, whereas each terminal has to pay t_b to the government for each unit of CO_2 transported to the storage site.

The optimal instruments are shown in Table 4. The government uses a policy package that will change the price for CO_2 emissions from $\tau = 90$ euro/tCO_2 to $\tau + t_\tau = 90 + 10.55 = 100.45$ euro/tCO_2, whereas the fixed part of the unit cost of transport is changed from $b = 3$ euro/tCO_2 to $b + t_b = 3 + 7.16 = 10.16$ euro/tCO_2. The solution is illustrated in Figure 2. Here we have shown the market equilibrium under regulated storage *without* any instruments (Case 1), the first-best social outcome, and also the market equilibrium under regulated storage *with* optimal instruments, i.e., instruments that ensure that the first-best outcome is achieved. As seen from Figure 2, with optimal instruments the curves representing (10) and (11) both shift downwards and they intersect at the social optimum, as required.

Table 4: Instruments that achieve the first-best outcome ($euro_{2016}$/tCO_2).
Benchmark parameter values.

	Regulated storage	**Monopoly storage**	**Cartel**
Tax on terminal transport (t_b)	7.16	7.16	
Extra CO_2 tax(t_τ)	10.55	51.77	44.61

[16] Instead of imposing a tax t_b related to the fixed part of the unit cost of a terminal, b, the government may impose a tax t_a related to the variable part of the unit cost of a terminal, a. The amount of tax paid by a terminal to the government will then simply be t_a.

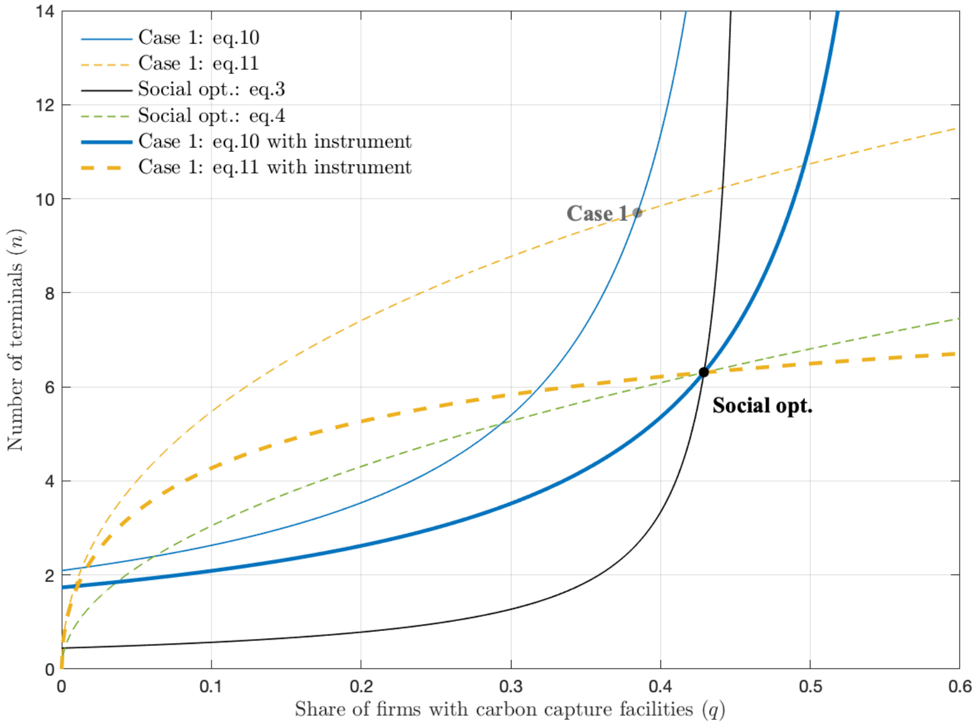

Figure 2: Regulated storage with instruments, and social optimum.

To correct the market outcome under *monopoly storage (Case 2)*, we can use the same type of instruments as we used in the case of regulated storage. The optimal instruments are found by solving the system (10), (11) and (12) with $q = q^{SO}$ and $n = n^{SO}$ and where v in (10) is replaced by z, see (12), τ in (10) is replaced by $\tau + t_\tau$, and b in (11) is replaced by $b + t_b$. As seen from Table 4, under monopoly storage the tax on terminal transport should be the same as in the previous case; this simply reflects that (11) is the optimal response of terminals both under regulated storage and monopoly storage. In contrast, the extra CO_2 tax should be much higher under monopoly storage (51.77) than under regulated storage (10.55). Under monopoly storage, the price for storage services is high, which pushes up the price faced by plants for terminal services. It is then necessary with a high extra tax on CO_2 emissions to provide sufficient incentive for plants to invest in carbon capture facilities.

With a *cartel (Case 3)*, the optimal response of terminals to plants investing in carbon capture facilities is given by relation (4), which is also part of the equation system determining the first-best social outcome. Hence, this part of the market should not be corrected. In contrast, the government should provide incentives to correct for the non-competitive price p faced by plants investing in carbon capture facilities, see (15). Here, $(\bar{x} - \underline{x})q$ represents the mark-up over marginal cost. By providing a subsidy s_v to the owner of the storage site, the price p is lowered, which suggests increased investment in carbon capture facilities by plants. This is confirmed by the optimal response of plants considering to invest in carbon capture facilities: a lower cost of storage will increase the share of plants investing, see (16). However, like in the previous two cases the subsidy s_v may be so large that p becomes negative. To avoid a negative price, the government may also in this case correct the market outcome by imposing an extra tax t_τ on CO_2 emissions.

From Table 4 we see that the optimal extra CO_2 tax under a cartel (44.61 euro/tCO_2) is almost as high as under monopoly storage (51.77 euro/tCO_2). The extra CO_2 tax shifts the curve representing relation (16) downwards so that it intersects with the curve representing (4) at the social optimum.

10 Robustness

The data in the calibration are uncertain. Below, we therefore discuss how the numerical solution of the market outcomes, and also the corresponding instruments needed to implement the first-best social outcome, depend on the parameter values. In particular, we are interested in parameter values that sustain a first-best social outcome with positive CCS investment, but where the corresponding market outcomes *without* additional instruments are corner solutions, that is, there is no CCS investment. We will consider three types of parameters: the carbon tax, cost parameters, and the size of the potential CCS market.

<u>The carbon tax</u>

The benchmark carbon tax is 90 euro_{2016}/tCO_2, which is in line with international studies on the emission price needed to reach the two-degree target of the Paris agreement, see Appendix A. However, the CO_2 price in the EU ETS market has always been lower than 90 euro/tCO_2; it has varied between 5 and 30 euro, see Ember (2020). While the government can impose an additional tax on top of the EU ETS price to reach a total price of 90 euro/tCO_2, such a policy is de facto not implemented in any European country. Below, we therefore consider the more interesting case where the social cost of carbon is lower than 90 euro/tCO_2 and (as above) the carbon tax τ is set equal to the social cost of carbon.

From (3) (social optimum), (10) (regulated storage and monopoly storage), and (16) (cartel) we see that a lower carbon tax (τ) tends to lower the share of plants investing in CCS. This will, *cet. par.*, lower the number of terminals, see (4) (social optimum and cartel), and (16) (regulated storage and monopoly storage). Because both the social outcome and the market outcomes change in the same direction, it is not obvious how the instruments should be adjusted in order to reach the new first-best outcome.

We find that as long as the carbon tax is at least 69 euro/tCO_2, all three market outcomes have internal solutions (when no additional instrument is used). With a carbon tax at 69 euro/tCO_2, the social optimal share of plants investing in carbon capture facilities is 22 percentage points lower than in the reference case (43 percent), whereas the social optimal number of terminals drops by around 2 from 6.31 in the reference case. In order to achieve the new first-best social outcome, under regulated storage and storage monopoly the optimal tax on terminal transport (t_b) has to be about 50 percent higher than in the reference case. Furthermore, the extra CO_2 tax (t_τ) under regulated storage has to be roughly 50 percent higher than in the reference case, whereas under monopoly storage the extra CO_2 tax has to be around 50 percent lower than in the reference case. The latter is also the case under a cartel.

With a somewhat lower carbon tax than 69 euro/tCO_2 and the government does not use any additional instruments, there is no internal solution for regulated storage and storage monopoly, whereas there is CCS investment under a cartel. This is the case until the carbon tax is less than 61 euro/tCO_2. Column three in Table 5 (Low carbon tax) shows the outcomes with a carbon tax at 61 euro/tCO_2 and the associated instruments needed to reach the first-best social outcome. For regulated storage, the instruments have to be around twice as high as in the reference case in order to reach the new social optimum where 12 percent of the plants invest in capture facilities and the number of terminals is 3.31. Under a cartel, an extra CO_2 tax at 12.90 euro/tCO_2 should be imposed to reach the first-best optimum; this is about 70 percent lower than the extra CO_2 tax in the reference case.

Once the carbon tax is below 61 euro/tCO_2, there is no CCS investment in any of the market cases if no additional policy instrument is introduced. However, as long as the carbon tax exceeds 57 euro/tCO_2, it is optimal from a social point of view to invest in CCS.

We summarize these findings in the following result:

Result 3: *For carbon taxes above 57 euro/tCO_2, it is socially optimal to invest in CCS. If no additional policy instruments are used, there will be no investment in CCS in the market Cases 1 and 2 for carbon taxes below 69 euro/tCO_2, whereas there will be no investment in CCS in market Case 3 if the carbon tax is below 61 euro/tCO_2.*

Result 3 suggests that there is a significant risk that CCS will be locked out from the market because the carbon tax is too low to sustain socially profitable CCS investments; the threshold value is 57 euro/tCO_2, which is far higher than the ETS price. With a carbon tax exceeding 68 euro/tCO_2, there will be positive CCS investment under all three market structures even if no additional policy instrument is imposed, but investments will differ from the first-best social values.

We now take a closer look at the instruments that are needed to ensure that the social outcome is achieved under the three market structures. Panel a in Figure 3 shows the social optimal number of terminals, and the social optimal share of plants investing in capture facilities, as a function of the social cost of carbon in the interval 57 to 90 euro/tCO_2. Like above, we have assumed that the government imposes a carbon tax which is set equal to the social cost of carbon. From the discussion above, we know that for these values of the carbon tax, it is socially optimal with CCS investments.

Panels b and c in Figure 3 show the instruments needed to ensure that the first-best social outcome is achieved as a function of the social cost of carbon (in the interval 57 to 90 euro/tCO_2). Panel b shows the value of the extra tax on CO_2 emissions, whereas Panel c shows that value of the tax on terminal transport.[17] Solid curves in Panels b and c reflect that the market outcome, without any instruments, is characterized by positive CCS investments (internal solution). In contrast, dashed curves in Panels b and c reflect that the market outcome, without any instruments, is characterized by no CCS investments (corner solution).

[17] For Cases 1 and 2, both instruments have to be used to reach the first-best social outcome, whereas for Case 3 only the extra tax on CO_2 emissions should be imposed, see discussion in Section 9.

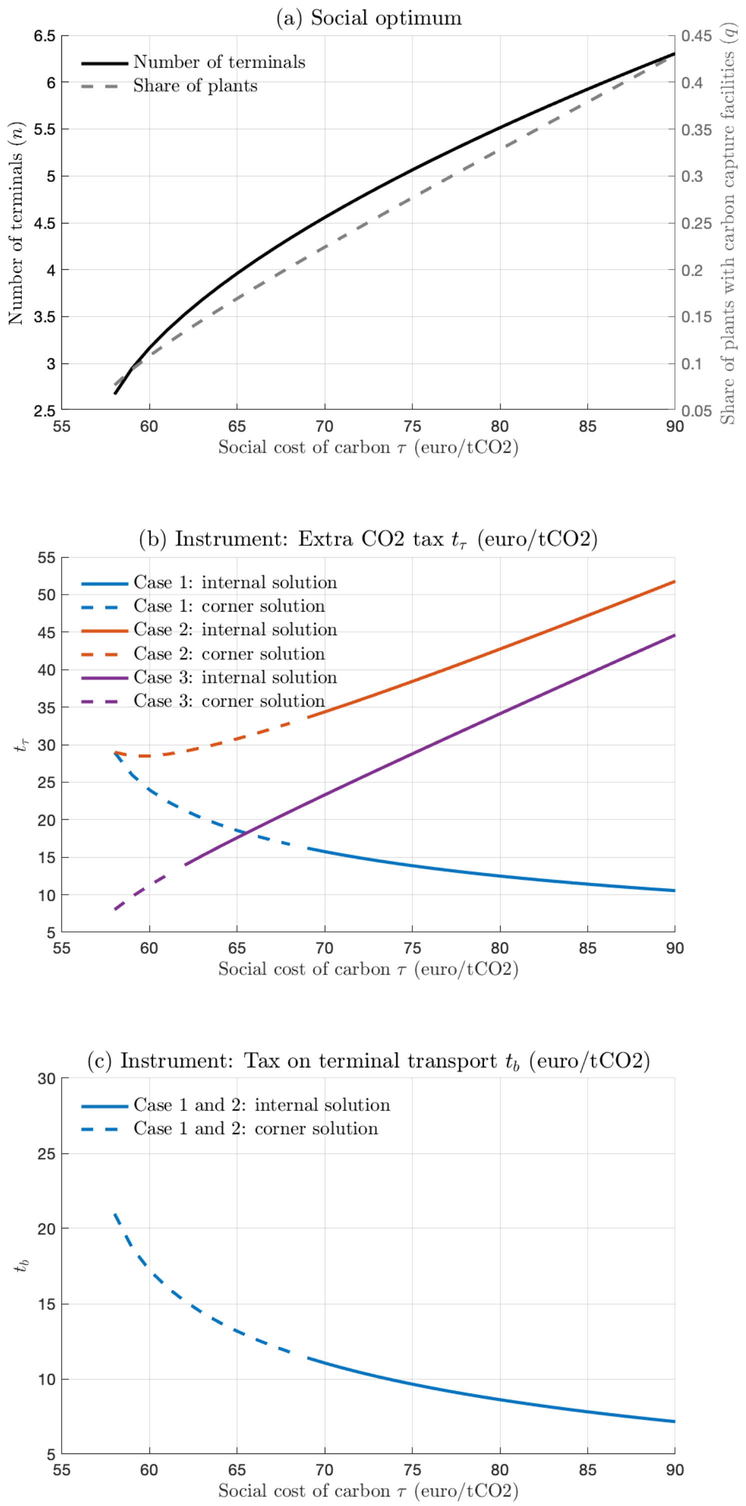

Figure 3: Social optimum and instruments under alternative values of the social cost of carbon.

As seen from Figure 3, a higher social cost of carbon sustains more plants investing in carbon capture facilities and more terminals. Under regulated storage and cartel, the extra CO_2 tax should be higher the higher is the social cost of carbon, whereas the relationship is opposite under monopoly storage. Finally, Panel c in Table 3 shows that the higher the social cost of carbon, the lower is the tax on terminal transport that ensures that the social outcome is reached.

Cost parameters

We now increase all cost parameters $(a, b, t, v, \underline{x}, \bar{x})$, but keep the social cost of carbon at 90 euro/tCO_2. If all cost parameters are increased by 30 percent (relative to their benchmark values) and no additional instrument is used by the government, there is still positive CCS investments in all three market outcomes. With a 40 percent cost increase (and no additional instrument), there is an internal solution only under one market structure, namely a cartel.

If all cost parameters are increased by 50 percent (and no additional instrument is used by the government), there is no CCS investment in any market outcome. This case is shown in column four in Table 5 (High costs): it is socially optimal with 3.17 terminals and 0.11 percent of the plants should invest in capture facilities. In order to obtain this social optimum, the tax on terminal transport (t_b) should be higher than in the reference case. Furthermore, the extra CO_2 tax (t_τ) should be higher under regulated storage than in the reference case, whereas the opposite is the case under monopoly storage cartel. Hence, there is no clear pattern in how the instruments should be adjusted if all cost parameters are increased by 50 percent.

Market size of CCS

In the reference case, we have assumed that all emissions from power plants are eligible for carbon capture, whereas only 25 percent of emissions from manufacturing are eligible. While in the electricity generation sector there are several ways to cut emissions, for example, by developing wind power, solar, hydro and nuclear, manufacturing has fewer possibilities for large emissions reductions. In particular, in some manufacturing sectors CCS may be the only option to cut emissions of CO_2. We have therefore examined the case in which power production is carbon free, whereas 25 percent of emissions from manufacturing are eligible for CCS. Relative to the reference case, eligible emissions for CCS have decreased by 86.5 percent.

Because our data sources clearly suggest that cost of carbon capture investment is higher for manufacturing plants than for power plants, we have increased the minimum unit cost of investment in carbon capture facilities, $\underline{x}$ (The reference value of $\underline{x}$ is 28 euro/tCO_2). Our main data source suggests that for most carbon capture projects in the manufacturing industries, $\underline{x}$ is 71 euro/tCO_2. Some projects, however, are as cheap 56 euro/tCO_2, and it is even possible to identify a few projects with unit cost around 35 euro/tCO_2, see the Appendix.

Table 5: Robustness. Social optimum, market outcomes and optimal instruments (euro$_{2016}$/toe).

	Reference	**Low carbon tax***	**High costs****	**Manufact-uring*****
Social optimum				
Share of plants investing in CCS (q)	0.43	0.12	0.11	0.31
Number of terminals (n)	6.31	3.39	3.17	1.97
Regulated storage				
Market outcome				
Share of plants investing in CCS (q)	0.38	0	0	0
Number of terminals (n)	9.70	0	0	0
Optimal instruments				
Tax on terminal transport (t_b)	7.16	15.89	25.83	29.47
Extra CO_2 tax (t_τ)	10.55	22.19	35.95	40.29
Monopoly Storage				
Market outcome				
Share of plants investing in CCS (q)	0.21	0	0	0
Number of terminals (n)	7.50	0	0	0
Optimal instruments				
Tax on terminal transport (t_b)	7.16	15.89	25.83	29.47
Extra CO_2 tax (t_τ)	51.77	28.79	42.72	59.65
Cartel				
Market outcome				
Share of plants investing in CCS (q)	0.21	0.04	0	0.12
Number of terminals (n)	4.38	1.84	0	1.24
Optimal instruments				
Extra CO_2 tax (t_τ)	44.61	12.90	16.89	30.18

* Carbon tax is 61 euro/tCO_2, that is, reduced by 32 percent relative to benchmark where $\tau = 90$ euro/tCO_2.
** All cost parameters are increased by 50 percent relative to benchmark.
*** Relative to the reference case, emissions eligible for CCS are reduced by 86.5 percent (E=27 MtCO_2), reflecting that only an amount corresponding to 25 percent of manufacturing emissions is eligible for CCS. Because power plants are now assumed carbon free, the minimum unit of cost of investment in carbon capture facilities, $\underline{x}$, is changed from 28 euro/tCO_2 (the reference parameter value) to 35 euro/tCO_2, which is an optimistic estimate, see the Appendix.

We find that if $\underline{x}$ is equal to 56 euro/tCO_2, it is not socially optimal to invest in CCS. If, however, $\underline{x}$ is equal to 35 euro/tCO_2, 31 percent of the plants should invest in capture facilities, see column five in Table 5 (Manufacturing). However, in this case there is no CCS investment neither under regulated storage nor under monopoly storage if no additional instrument is used by the government, whereas under a cartel, 12 percent of the plants invest in carbon capture facilities (if no additional instrument is used by the government). To obtain the social optimum under a cartel, the extra CO_2 tax (t_τ) should be lower than in the Reference case. In contrast, to achieve the first-best social outcome under regulated storage and monopoly storage, both the extra CO_2 tax and the tax on terminal transport should be higher than in the Reference case.

Finally, as long as the social cost of carbon is at least 78 euro/tCO_2, it is socially optimal with CCS investments. This critical value is 20 euro/tCO_2 higher than in the case where the potential CCS market has its benchmark values, see above.

11 Concluding remarks

While CCS has been mentioned as an important technology to reach the 1.5 and 2 degree climate targets in the long run (IPCC, 2014; 2019), the current capacity of CCS is still tiny (IEA, 2019). In this paper, we have studied whether imperfections in the different parts of the CCS chain, especially in transportation and storage, may explain the low investment. To do this, we have used a Salop type of model (Salop, 1979) where plants are located around a circle. These plants have the options to pay a tax per unit of their CO_2 emissions (equal to the social cost of carbon) or to invest in carbon capture facilities. If they invest in carbon capture, they need to transport the captured CO_2 to a terminal, which is also located on the circle. The terminal transports the CO_2 to a storage located in the center of the Salop circle.

In the model, there are four types of imperfections in the CCS value chain (we have assumed that the environmental externality is corrected through a carbon tax). First, terminals are local monopolies, and therefore charge a markup on their fee. This will lower investment in carbon capture facilities compared to the case with a competitive fee. Second, there is a network effect: if one plant invests in carbon capture facilities, investments in terminals will be more profitable, which again will benefit investments in carbon capture facilities for other plants. Third, there is economies of scale in handling the received CO_2 by the terminals: the lower the number of terminals, the more CO_2 each terminal transports to the storage site, the lower is the unit cost of a terminal to handle the received CO_2. Finally, the storage actor may have market power.

We study three different market situations, besides the social optimum. The first is regulated storage. Here, the storage monopolist has to charge its unit cost for its deposit services, i.e., it cannot impose a markup on terminals delivering CO_2. In the second market structure, this regulation is no longer present, while in the third market situation, there is vertical integration between the single storage actor and the terminals, i.e., a cartel is formed that maximizes profits. From the analytical results, we see that all market situations give different solutions than the social optimum even if the plants pay the socially optimal carbon tax. However, we also find that the cartel internalizes the combination of the network effect and the economies of scale in handling CO_2.

We provide numerical simulations based on a storage site in the North Sea. The simulations include power plants and manufacturing plants from six countries (Norway, Denmark, Germany, Belgium, the Netherlands and the UK). The numerical results show that all market situations provide a lower share of plants investing in carbon capture facilities than the socially optimal share if only the environmental externality is corrected (with a CO_2 price). The case of regulated storage gives a significantly higher share of plants investing in capture facilities than the other market solutions as the regulation corrects for a market failure. Under regulated storage and a monopoly storage, the number of terminals is higher than the socially optimal number, while the ranking is opposite under a cartel. The reason is that even though the cartel internalizes the network effect and the economies of scale in handling the received CO_2, the amount of stored CO_2 will be much lower than the socially optimal amount, because of the high fee faced by plants investing in capture facilities, and thus the need for terminals will be lower.

We have also provided some robustness tests. A sufficiently high CO_2 tax is a necessary condition for plants to invest in carbon capture facilities. Our simulations for Northern Europe shows that with a carbon tax less than 61 euro/tCO_2, there will be no investment in the market cases considered if no additional policy instrument is introduced. Note that this carbon tax is much higher than the historical CO_2 price path in the EU-ETS (Ember, 2020). One interesting result from the robustness tests is that the case of a cartel seems to be the most robust solution, as it will give CCS investments in cases where the other market situations do not lead to any CCS investment. The reason is, as mentioned before, that the cartel internalizes two imperfections, namely the network effect and the economies of scale in handling CO_2 by terminals. However, also under a cartel, plants face a high price for delivering captured CO_2 to a terminal, and thus it is necessary with a policy instrument to correct for this imperfection in order to ensure that the socially optimal outcome is achieved.

The main research question in this paper is whether imperfections in the different parts of the CCS chain, especially in transportation and storage, may explain the observed low investment in CCS. Our paper shows that the key reason for low CCS investment is simply that the price of CO_2 emissions has been far below the magnitude that makes this type of investment optimal from a social point of view; in our study, the social cost of carbon should be at least 57 euro/tCO_2 to justify CCS investment. We have also illustrated that if the price of CO_2 emissions is somewhat above 57 euro/tCO_2, there will be no CCS investment in the three market situations studied because of the various imperfections. If the social cost of carbon is at least 69 euro/tCO_2 and the carbon tax is set equal to the social cost of carbon, there will be CCS investment in all market situations, but these will differ from the first-best social outcome if no additional instrument is used by the government.

There are three equilibria without government support in our model; one stable equilibrium without any investment, one unstable equilibrium with "low" investment, and one stable equilibrium with "high" investment. The market needs assistance from the government to coordinate in order to ensure that the latter equilibrium is reached. One way to coordinate is to use policy instruments that ensure that the first-best social outcome is reached.

The role of the government to solve the coordination problem is interesting also because of the Northern Lights project in the North Sea, see Northern Lights (2021). The project was launched in 2015 and will cover a terminal in the Western part of Norway, and a pipe from the terminal to a storage site in the North Sea. The facilities will be owned and operated by a consortium consisting of Equinor, Shell and Total. According to the Norwegian government, which will provide significant financial support to the project, Northern Lights should prove that CCS is technically feasible, see OED (2020). Furthermore, the project should internalize learning- and scale effects, and trigger a boost in CCS activities in Northern Europe. Our model simulations suggest that this may be a rather robust construction, but policy instruments are still needed to reach the first-best social outcome.

Our modelling framework could be extended in several ways. For example, we have not considered economies of scale in transportation of captured CO_2 from plants to terminals. With economies of scale, it will be optimal for plants to cooperate on the transportation to terminals. This will reinforce the network effect, which again will impact the optimal number of terminals. Also, in our model we have not considered other options for mitigation than

CCS. Both in electricity supply and manufacturing, other options for mitigation exist (see, e.g., Vågerö (2020) for the cement industry). Introducing other mitigation options will shrink the CCS market, and we found in our robustness tests that such a change will lower the socially optimal number of terminals and also the share of plants investing in carbon capture facilities.

Finally, we have assumed there is one storage site. In the future, however, there may be competition between storage suppliers as Denmark, the Netherland, and the UK are considering, and Norway has decided, to invest in storage facilities, see, for example, Greensand (2021), Portofrotterdam (2021), SCCS (2021), and Northern Lights (2021). With more than one storage supplier, the price of storage will be lower than in the case of monopoly storage. This will tend to increase demand for storage services, and hence to trigger more investment in all parts in the CCS value chain.

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Appendix: Data and calibration

A1. The circle

We assume that our (Salop) circle covers six countries (Norway, Denmark, Germany, Belgium, the Netherlands and the UK). The circle has a diameter of 850 km, and thus the circumference is 2669 km. The center of the circle is in the North Sea, where there are suitable underwater geological formations for carbon storage, see Figure A.1.

Figure A.1: The Salop circle

A2. Emissions

We use data from United Nations Climate Change (2020) for CO_2 emissions for two sectors: electricity supply and manufacturing, see Table A.1. We assume that all emissions from the electricity sector can be captured, whereas only 25 percent of emissions in the manufacturing are eligible for carbon capture, for example from ammonia and cement. Furthermore, we assume that in each country a share of power stations and manufacturing plants is located so close to the circle that the cost of CO_2 transport to a terminal is not prohibitive for carbon capture investment. This location share differs across countries: it is as low as 25 percent for a big country like Germany, but as high as 100 percent for a small country like the Netherlands, see Table A.1. Combining data on emissions with the eligible parameters and the location parameters, we find that 200 $MtCO_2$ are eligible for carbon capture when there is a storage site in the North Sea. As seen from Table A.1, around 85 percent of eligible emissions are in the electricity sector.

Table A.1: Emissions ($MtCO_2$) by country and sector in 2018

	Emissions		Eligible parameter		Location parameter	Emissions eligible for CCS with storage in the North Sea		
	Power plants	Manufacturing	Power plants	Manufacturing		Power plants	Manufacturing	Total
Denmark	9	4	100%	25%	100%	9	1	10
Germany	262	129	100%	25%	25%	65	8	73
Netherlands	48	28	100%	25%	100%	48	7	55
United Kingdom	68	51	100%	25%	50%	34	6	40
Norway	2	3	100%	25%	100%	2	1	3
Belgium	15	14	100%	25%	100%	15	3	19
Total						**173**	**27**	**200**

A3. Costs of investment in carbon capture for power plants and manufacturing plants

Rubin et al. (2015) provides costs of investment in carbon capture facilities for coal power and gas power stations. Assuming a capacity factor as high as 85 percent, this study finds that annualized capture cost, measured in $euro_{2016}/tCO_2$, varies between 28 and 61, see Table A.2.

Atkins and Oslo Economics (2016; 2018) discuss cost of investment in carbon capture facilities for three sectors: ammonia, cement and waste management. Under the assumption that capture capital will last for 25 years, and taking into account costs of planning, implementation and operation, annualized cost varies between 71 and 132 $euro_{2016}/tCO_2$, see Table A.2.

Also, Atkins and Oslo Economics (2016; 2018) have alternative cost estimates that are based on higher volumes of production or preinstalled capture facilities. Then cost of carbon capture can be below 60 euro/tCO_2, in fact, the cost can be as low as 35 euro/tCO_2. This is more in line with the cost estimates in Leeson et al. (2017), where the capture cost for cement is set to 33 euro/tCO_2. In geneal, cost estimates are much lower in Leeson et al. (2017) than in Atkins and Oslo Economics (2016; 2018). In our study, we use the lowest and highest value in Table A.2.

Table A.2: Cost of carbon capture (euro$_{2016}$/toe)

Power stations				Manufacturing		
Pre-combustion		Post-combustion				
Integrated gasification combined cycle plant using bituminous coal	Integrated gasification combined cycle plant using pulverized coal	Super-critical pulverized coal plant using bituminous coal	Natural gas combined cycle plant	Ammonia	Cement	Waste
28	59	49	61	71	78	132

A4. Costs of transport to a terminal

Rubin et al. (2015), referring to three studies, provides cost of transport of CO_2 by onshore pipelines; these estimates are eligible for plants transporting CO_2 to a terminal. The cost estimates vary by study and also by amount of CO_2 being transported; there is significant economies of scale in pipe transport. Annualized cost (measured in euro$_{2016}$) of transporting one ton of CO_2 the distance 250 km varies between 0.9 and 8, see upper panel in Table A.3. Based on the equilibrium quantities in the reference scenario,[18] as well as a preference for choosing a conservative estimate (which may be rationalized by referring to cost of transport from the plant site to the circle), we use the estimate 8 euro, which implies 0.032 euro/tCO_2 per km.

Table A.3: Annualized cost for pipeline transport (euro$_{2016}$/tCO_2 per 250 km)

	3 MtCO_2/yr	**10 MtCO_2/yr**	**30 MtCO_2/yr**
Onshore			
IPCC (2005)	3.1-5.3	1.6-2.7	0.9-1.6
ZEP (2011a)	8.0	2.4	-
USDOE (2014)	3.6	-	1.2
Offshore			
IPCC (2005)	5.3-6.5	2.5-3.1	1.4-1.8
ZEP (2011a)	10.8	3.5	-

[18] In our model, the average volume of transported CO_2 from plants to a terminal ($qE / 4n$) is 3.4 MtCO_2 in the social optimum and varies between 1.4 and 2.4 MtCO_2 in the market outcomes (with benchmark parameter values).

A5. Costs of terminals

Rubin et al. (2015), drawing on two studies, also provides annualized costs for offshore pipeline transport, see lower panel in Table A.3. Offshore pipe costs are roughly 50 percent higher than onshore pipe costs. Like for onshore pipe cost, we use the estimate from ZEP (2011a) for the magnitude of 3 $MtCO_2$ per year, i.e., 10.8 $euro_{2016}/tCO_2$ per 250 km.[19] Taking into account that in our model, the distance to the storage site (i.e., the radius) is 425 km, we obtain the estimate 18.36 $euro/tCO_2$ per 425 km. We use this estimate as the cost of entry of a terminal, per tCO_2, that receives the magnitude 3 $MtCO_2$ per year.

To calibrate the parameters in the hyperbola for the unit cost of a terminal, $a/(qE/n) + b$, we first assume that if a terminal receives "a very large amount of CO_2" its unit cost (for a transport distance of 425 km) would be 3 $euro/tCO_2$; this estimate is in line with IPCC (2005) in Table A.3 for an annual offshore transport of 30 $MtCO_2$. This means that our estimate of the scale parameter b is 3 $euro/tCO_2$. Combining this with 18.36 $euro/tCO_2$ per 425 km when 3 $MtCO_2$ $(= qE/n)$ is transported, we find the value of the parameter a (4.608×10^7 euro).

A6. Costs of storage

Rubin et al. (2015), building on ZEP (2011b), has information on annualized offshore storage cost. These differ by reservoir type and capacity of storage, and vary between 2 and 18 euro/tCO2, see Table A.4. Again, we have a preference for choosing a conservative estimate; this may be rationalized by referring to other studies that due to low storage capacity have cost estimates exceeding 18, see, for example, Atkins and Oslo Economics (2016; 2018). In this study, we assume that cost of storage is 11 $euro/tCO_2$, which is roughly the average cost with saline formations in Table A.4.

Table A.4: Cost of storage by type of reservoir ($euro_{2016}/tCO_2$)

Depleted oil and gas fields – reusing of wells	2-8
Depleted oil and gas fields – no reusing of wells	3-13
Saline formations	5-18

[19] Kjärstad et al. (2016) offers a number of estimates for offshore pipeline costs. These are in the range of 6.6 to 37.4 $euro/tCO_2$ per 250 km, with an average significantly above 10.8.

A7. Carbon tax

IEA (2008) assumes a CO_2 price of \$90 to be consistent with the 2 degree target. Similarly, IPCC (2019) assumes a CO_2 price of \$100 to be consistent with the 1.5 degree target. In line with these predictions, we set the benchmark value of the carbon tax to 90 $euro_{2016}$ per tCO_2.