

14 January 2025

## Competition for carbon storage

### Abstract

It is widely recognized that a cost-efficient way to achieve the climate targets of the Paris agreement requires investment in carbon capture and storage (CCS). However, to trigger sizeable investment in CCS the carbon price must exceed the historic carbon prices. This paper examines whether a higher price of carbon enhances competition of storage services and thus leads to lower costs of CCS. Using a model with two storage sites, each being located at each end of the Hotelling line, we show that there are three alternative competition regimes. The level of the carbon price determines which regime materializes. For “low” carbon prices, there is no competition between the two storage firms. For “high” carbon prices, there is standard Bertrand competition between the two storage firms. Finally, for “intermediate” carbon prices, there is so called partial competition with multiple equilibria. Contrary to the standard conclusion on competition, we find that when each storage firm is imposed to charge the same price for all its clients, the price under monopoly is lower than under partial competition. We offer several extensions of the model as well as numerical illustrations. With our reference parameter values and a carbon price sufficiently high to reach the Paris targets, we find that we may end in a partial competition regime.

**Key words:** Hotelling line, kinked demand curve, duopoly, multiple equilibria, carbon price, carbon capture and storage

**JEL classification:** L13, Q35, Q38

## 1 Introduction

Carbon capture and storage (CCS) is a technology for avoiding point-source emissions entering the atmosphere, but also to store carbon removed from the atmosphere in processes like for example Direct Air Capture with subsequent storage (DACCS). According to IPCC (2022), CCS is a necessary technology to meet the climate targets because all mitigation options on the “menu” have to be taken into account.

With increased demand for CCS, more suppliers of storage services may enter. What will then be the impact on the price of storage services? Also, will a higher price of carbon trigger entry of storage suppliers and thus enhance competition, thereby pushing down costs of CCS? These are the main questions to be analyzed in the present paper.

For years, investments in CCS were small, in particular compared to the cost-efficient path to the Paris Agreement targets (IEA, 2023). However, while total capture capacity decreased every year between 2011 and 2017, there has been a significant growth after 2017. There are several reasons for this, such as higher carbon prices, especially in Europe (Golombek et al., 2023), but also that a majority of countries have net-zero emission targets in the long run; 131 countries according to IPCC (2022).

Captured CO<sub>2</sub> from plants is transported to terminals, where it is collected and transported, for instance by pipeline or by ship, to a storage place. The potential number of storage places is large. Yet, the current number of storage sites in operation is small. As the amount of captured CO<sub>2</sub> increases, partly because a number of countries aim to reach a net-zero emission target, the demand for storage will increase, which may trigger development in new storage sites. This may impact the price of storage service through increased competition.

One example is the North Sea. Here, empty oil fields are suitable for carbon storage; Equinor (former Statoil) has stored CO<sub>2</sub> in the Sleipner field since 1996. So far only a small share of emissions has been stored in the North Sea. However, the Northern Lights project (Northern Lights, 2023), which includes a terminal in the western part of Norway and a pipe from the terminal to the storage site, may be a game changer.

The first phase of Northern Lights became operational in 2024. While Northern Lights is the first large storage site in the North Sea, it may not be the only one. Several industries in other countries around the North Sea have shown interest in storing CO<sub>2</sub> under the seabed, and Scotland, the Netherlands and Denmark have all plans for investing in storage facilities in the North Sea (see, e.g., Greensand, 2023; Porthos, 2023; SCCS, 2021). With the amendments of

the London Protocol in 2019, export of CO<sub>2</sub> for storage in sub-seabed geological formations is now allowed, which may give transboundary competition and cooperation (Wettestad et al., 2024).<sup>1</sup>

This paper studies how competition for carbon storage may affect the market for CCS by focusing on (i) how the carbon price impacts the supply of storage services, (ii) how the supply of storage services impacts the price of storage, (iii) whether any market structure comply with the socially optimal solution for storage, and (iv) whether there is a first-mover advantage in the storage market.

To answer these questions, we set up a theoretical model where *plants* are located on a Hotelling line (Hotelling, 1929). All plants emit CO<sub>2</sub> and they have to choose between paying a carbon price for the emissions or to invest in capture facilities and transport the captured CO<sub>2</sub> to a storage place. At each endpoint of the line, a storage site may be developed. If a plant decides to invest in capture facilities, it can sign credible contracts with a storage *firm* at a fixed price.

We study the social optimum for this market and compare it to alternative market outcomes. One possible outcome is no competition between the storage sites, which happens if the carbon price is sufficiently low (but high enough to make CCS profitable for some plants). With no competition, both storage sites may be developed but there is a segment on the Hotelling line where no plant invests in capture facilities as the carbon price is too low to make this profitable due to transport costs. Thus, the two storage sites are local monopolies.

When the carbon price reaches a certain level, however, competition may evolve. Two competition regimes may exist. For intermediate levels of carbon prices, there is partial competition, whereas there is full competition if the carbon price is high. The latter regime has strong similarities to the standard duopoly model with price competition, but contains a spatial element. With partial competition, the marginal plant is indifferent in the choice of whether it should invest in capture facilities or not, and also indifferent from which storage provider it should buy storage service. This gives a kinked demand curve for storage services, and several Nash equilibria exist under partial competition. We find that the range of the carbon price giving a kinked demand curve increases in the transport costs for captured CO<sub>2</sub>. Thus, if transport costs

---

<sup>1</sup> According to Riviera (2024), 53 countries, and also the European Union, have signed the London Protocol. However, only 10 countries have fully ratified amendments which classify CO<sub>2</sub> streams as cargo rather than waste.

fall to zero, the kink will disappear. In contrast, there is a unique equilibrium with full competition.

Contrary to the standard conclusion on competition, we find that when each storage firm is imposed to charge the same price for all its clients, the price under monopoly is lower than under partial competition and it is also lower than under full competition if the price of carbon is not “very high” (see details in Section 9). We also find that if cost of storage differs between the two suppliers of storage services, competition leads to too much use of the most expensive storage site. With equal cost of storage, the splitting of the market under full competition is socially efficient. This is also the case under partial competition if the two storage firms have equal cost of storage and charge the same price.

We analyze different extensions of the basic model, such as more than two storage firms, perfect price discrimination, economies of scale, sequential move and heterogeneous plants. Finally, we also illustrate the model results by numerical simulations based on data for industries around the North Sea and provide sensitivity analysis to show the robustness of the results.

The paper is organized in the following way. In the next section, we describe our contributions to the literature, while we specify the theoretical model in Section 3. The social optimum is derived in Section 4, and the different market outcomes are analyzed in Sections 5-9. Section 10 studies extensions of the model, and numerical illustrations are shown in Section 11. The final section concludes.

## **2 Contribution to the literature**

Our study contributes to four strands of literature: the game theoretic literature for markets with limited competition; the literature on spatial competition; the literature on kinked demand curves; and the literature on CCS.

There is an extensive literature on markets with limited competition. One market with limited competition that shares some similarities to the CCS market, is the market for natural gas. Natural gas suppliers extract gas from areas given by nature, and then transport the gas to a range of customers located at different places. This market is modelled as a game between different gas suppliers, see, for instance, Golombek et al. (1998), Gabriel et al. (2012) and Massol and Banal-Estañol (2018).

While these studies apply Cournot games where players use their production level as the strategic variable, in our paper the actors play a Bertrand game where they set prices (see, e.g., Tirole, 1988; Pindyck and Rubinfeld, 2018). One reason is that we assume that the storage sites are large and the plants can deliver as much CO<sub>2</sub> as they want to these sites. This is in line with the EU net zero industry act, which aims at establishing a European market for storage of CO<sub>2</sub> with an annual storage capacity of at least 50 million ton by 2030 and 280 million ton by 2050, see Europe (2024). Such amounts of storage capacities justify to assume price competition, not quantity competition, between storage firms. Section 3 gives a further discussion of our assumption of a Bertrand game.

Our paper is also related to the literature on spatial economics. Studies on spatial economics mainly apply two different specifications of localization, either along a line (Hotelling, 1929) or around a circle (Salop, 1979). The original Salop circle model assumes that firms enter endogenously around the circle until profit is zero. One application of the Salop circle model to CCS, which shares similarities to our model, is Golombek et al. (2023). The latter paper analyzes a chicken and egg problem, which for CCS is a coordination challenge between potential suppliers and potential purchasers of storage services: an actor considering to develop a storage site may not be willing to invest before being confident that there will be demand for storage services. Likewise, a potential purchaser of storage services may not be willing to invest in capture facilities prior to having a reliable solution for storage of CO<sub>2</sub>.

Golombek *et al.* (2023) studies the game between these two types of actors and show that there exists three types of equilibria: one without any investment, one with moderate investment, and one with high investment. However, because of a number of market failures it is necessary to use instruments to correct even the last type of equilibrium with high investment.

In the present paper, plants are located along a Hotelling line. The Hotelling location model is particularly suitable for our problem as it allows us to examine price competition with differentiated products (here different transport costs), see, e.g., Brenner (2010) for a survey. The Hotelling line has been used to study several markets, in particular, agricultural product markets, where producers are spatially distributed over the line and there is a limited number of buyers, see Graubner *et al.* (2021) for a survey.

The original Hotelling location model is a two-stage game. In the first stage, firms decide on their location, and in the second stage, they choose prices. We do not study the entry decision of firms as in the original model (see also Osborn and Pitchik, 1987), but building on Tirole (1988) we assume that two firms may develop storage sites at the end points of the line (one site at each end point).<sup>2</sup> The reason for not studying the choice of location is that geological formations that are suitable for storage are predetermined. Furthermore, we follow Golombek *et al.* (2023) assuming exogenous location of plants (i.e., units that can invest in capture facilities). Whereas Golombek *et al.* (2023) have only one storage site, we model competition between storage sites.

Markets with limited competition can in some cases give kinked demand curves (Bhaskar, 1988; Maskin and Tirole, 1988), and a multiplicity of kinked demand curve equilibria may exist (see, e.g., Economides, 1984; Yin, 2004; Merel and Sexton, 2010; Vatter, 2017; Cumbul and Virág, 2018; Dupraz, 2023). Merel and Sexton (2010) apply the Hotelling line model and show that with fixed locations at the end points, three competition regimes exist. The middle regime is referred to as weak duopoly. Here, there is a kinked demand curve, which supports multiple equilibria. The existence of the regimes depends on what they call the normalized transportation cost. While in the original Hotelling model consumers can buy one unit of the good only, Merel and Sexton (2010) show that if consumer demand is elastic so that the number of units bought vary with the price, multiple equilibria will not exist.

Our paper builds on Merel and Sexton (2010), with an application to carbon capture and storage. If plants install capture facilities, they will capture (almost) all CO<sub>2</sub> emissions so that the original Hotelling model with a fixed unit of demand is still relevant. We show that there are three alternative competition regimes and which regime that materializes depends on the level of the carbon price. For “low” carbon prices, there is no competition between the two storage firms, each being located at each end of the Hotelling line. For “high” carbon prices, there is standard Bertrand competition between the two storage firms. Finally, for “intermediate” carbon prices, there is so called partial competition with multiple equilibria.

Relative to the literature, we make extensions of the basic model along two dimensions. First, with the basic structure of the model we examine heterogeneous firms, i.e., storage firms differ with respect to cost of storage, and we compare the outcome of the three different

---

<sup>2</sup> As shown in d’Aspremont *et al.* (1979), the ends points are also the optimal locations of firms if there are quadratic transportation costs.

competitive regimes with the case of monopoly and the social efficient outcome. Whereas Merel and Sexton (2010) derive closed forms of kink-demand curves and use these to show the existence of multiple equilibria under weak duopoly, we offer an alternative approach to obtain the same type of result.<sup>3</sup>

Second, we change the basic structure of the model by studying the market solutions (i) with more than two storage firms, (ii) perfect price discrimination (instead of requiring that each storage firm has to charge the same price on all its clients), (iii) economics of scale, and (iv) sequential moves (instead of simultaneous moves as in the basic model).

Finally, our paper is related to the CCS literature in economics. One main focus in this literature is why the technology has not had an international breakthrough in spite of the need for this technology to meet climate targets (Durmaz, 2018). Several suggestions have been proposed, including too lax emission constraints (Hainsch et al., 2021); uncertainty about CCS investment costs (Lohwasser and Madlener, 2012); public resistance to storage and fear of leakages from storage sites (van der Zwaan and Gerlagh, 2016); lack of professionals to undertake R&D in CCS (Budins et al., 2018); and legal matters (Herzog, 2011). Further, Golombek et al. (2023) focus on network effects and coordination problems. We contribute to this literature as we find that in many cases, it is better to be the second mover than the first mover in developing storage sites. Thus, potential storage firms may wait for other firms to establish storage sites before they start investing themselves; this may be one reason why few storage sites have been developed.

### 3 The theory model

We assume that a fixed number of plants are located evenly along a Hotelling line with length  $L$ . Initially, all plants emit the same amount of CO<sub>2</sub> and total emissions are equal to  $E$ . Hence, emissions per unit of distance is  $E/L$ .

Plants emitting CO<sub>2</sub> have to pay a carbon price  $\tau$  per unit of emission, which is set equal to the social cost of carbon, thereby correcting for the negative environmental externality.<sup>4</sup> Alternatively, a plant can install capture facilities and transport the CO<sub>2</sub> to a storage site. Denote

---

<sup>3</sup> The competitive regime referred to as weak duopoly in Merel and Sexton (2010) corresponds to the partial competition regime in our paper.

<sup>4</sup> The analysis below is also valid for negative emissions, i.e., plants that store emissions from bioenergy combustion or direct air capture, if they receive  $\tau$  per unit of stored emission.

$A$  and  $B$  the two ends of the Hotelling line. At each of these points, a storage site may be developed. We refer to the storage sites/actors as firm  $A$  and firm  $B$ . Let  $z_i$  be the unit cost of storage of firm  $i$ ,  $i = A, B$ ; it is the sum of cost of investment in storage and cost of operating the storage facilities. Without loss of generality, we assume throughout that  $z_A \leq z_B$ .

Let  $x$  be cost of investment in capture facilities of a plant. As a starting point, we assume that cost of investment does not differ across plants. We will later relax this assumption. Moreover, we assume that without capture facilities each plant emits one unit of  $\text{CO}_2$ . Let  $d$  denote the distance from storage site  $A$  to a plant, and hence  $L - d$  is the distance between the plant and storage site  $B$ . Hence, prior to investment in capture facilities aggregate emissions from all plants located closer to storage site  $A$  than  $d$  is  $dE / L$ .

Let  $t$  be cost of transport per unit of distance along the Hotelling line. One interpretation is that this price has been determined through an efficient auction where potential suppliers of transport services compete: each offers a unit cost of transport and also informs the regulator what type of transport technology that will be developed (ship versus pipe). The winner of the auction is the actor with the lowest price, and the winner has to commit to use this price in order to obtain a license to develop a transport network.

Initially, there are no facilities neither to catch, nor to store,  $\text{CO}_2$ . Plants are forward-looking, rational actors and they realize that once they have invested in capture facilities, i.e., this cost is now sunk, a storage firm has an incentive to charge a price for its services that makes the plant (almost) indifferent between (i) using the capture facilities, transporting the captured  $\text{CO}_2$  to the storage site, and paying the price for deposit services, and (ii) paying the carbon price. Hence, once investment in capture facilities has materialized, the storage actor has an incentive to set a very high price. Therefore, plants may not be willing to invest in capture facilities until they know for sure that storage facilities will be available at a predetermined price.

Likewise, once storage sites have been developed, plants may reconsider to which site they will deliver their captured  $\text{CO}_2$ . Hence, a storage firm may receive less captured  $\text{CO}_2$  than expected. Therefore, a storage firm may not be willing to invest before it is confident that plants will invest in capture facilities and deliver captured  $\text{CO}_2$  to his storage site. Both plants and storage actors may therefore be willing to mutually commit in order to avoid future problems. Through commitments, the strategic uncertainty can be removed and the market coordinates for mutual benefits.

To capture the game with its key characteristics, we specify a Bertrand game with three stages of decisions. In stage one, each storage firm commits to a price for storage services. In addition, each storage firm commits to store the entire amount of captured CO<sub>2</sub> that is delivered to its storage site. In stage two, plants decide whether to invest in capture facilities and to which storage site they will transport their captured CO<sub>2</sub>, subject to the commitments of the storage firms in stage one. Plants and storage firms then sign credible contracts. In stage three, where there is no strategic uncertainty, plants invest in capture facilities and storage firms develop storage sites, and then plants transport their captured CO<sub>2</sub> to a storage site according to the contract. We solve the game by backward induction.

#### 4 Social Optimum

The social value of capturing carbon is equal to the social damage from non-abated emissions, which is measured by  $\tau$ . Furthermore, the social cost of abatement (i.e., of capturing carbon) consists of three terms: cost of investment in carbon capture facilities, cost of transporting the captured CO<sub>2</sub> from plants to storage facilities, and cost of investment in and operation of storage facilities.

If it is socially optimal to capture carbon from a plant located at  $d_A$  and store it at site  $A$ , the same must be true for all plants located closer to  $A$  than  $d_A$ . Similarly, if it is socially optimal to capture carbon from a plant located at  $d_B$  and store it at site  $B$ , the same must be true for all plants located closer to  $B$  than  $d_B$ . Using this and the notation from the previous section, the social surplus of carbon capture and storage is

$$S = \tau [d_A + (L - d_B)] E / L - \left[ x + z_A + t \frac{d_A}{2} \right] d_A E / L - \left[ x + z_B + t \frac{L - d_B}{2} \right] (L - d_B) E / L \quad (1)$$

The first term is the social value of the captured carbon. The two others terms are the total abatement costs associated with the two storage sites: The second bracket is the sum of capture cost ( $x$ ), storage cost at  $A$  ( $z_A$ ) and average transportation cost to storage site  $A$  from plants located between 0 to  $d_A$ . The third bracket gives the corresponding costs associated with storage site  $B$ .

We assume that  $x + (z_A + z_B)/2 < \tau$ ; it is socially efficient with at least some investment in capture facilities and storage.

The conditions for the social optimum are found by setting the derivatives of  $S$  with respect to  $d_A$  and  $d_B$  equal to zero. This gives us the following interior solution:

$$\hat{d}_A = \frac{\tau - x - z_A}{t} \quad (2)$$

$$\hat{d}_B = L - \frac{\tau - x - z_B}{t} \quad (3)$$

Unsurprisingly, we get  $\hat{d}_A = L - \hat{d}_B$  if  $z_B = z_A$ , while  $\hat{d}_A > L - \hat{d}_B$  if  $z_B > z_A$ . In other words, more than half of the captured carbon is transported to the storage site with the lowest storage cost. If storage costs are identical, the two storage sites receive the same amount of captured carbon.

Assume first that the solution above gives  $\hat{d}_A < \hat{d}_B$ . In this case, storage firm  $A$  serves the segment  $\hat{d}_A$ , whereas storage firm  $B$  serves the segment  $L - \hat{d}_B$ , while there is a segment between  $\hat{d}_A$  and  $\hat{d}_B$  where plants do not invest in capture facilities. The length of this segment is

$$\hat{d}_B - \hat{d}_A = L - \frac{2(\tau - x)}{t} + \frac{z_A + z_B}{t}$$

which is larger the higher the transportation cost  $t$ . It is straightforward to verify that this segment is non-negative provided

$$\tau \leq x + \frac{tL}{2} + \frac{z_A + z_B}{2} \equiv \tau^0 \quad (4)$$

If  $\tau > \tau^0$ , and hence  $\hat{d}_A \geq \hat{d}_B$ , it is socially efficient that all plants invest in capture facilities. For this case, let  $\tilde{d}$  be the location of the plant that determines the social optimal division between which plants should be served by  $A$  and which plants should be served by  $B$ ; plants located closer to  $A$  than  $\tilde{d}$  should be served by storage firm  $A$ . The location of  $\tilde{d}$  can be found by replacing  $d_A$  and  $d_B$  in (1) by  $\tilde{d}$  and setting the derivative of  $S$  with respect to  $\tilde{d}$  equal to zero. This gives

$$\tilde{d} = \frac{L}{2} + \frac{z_B - z_A}{2t} \quad (5)$$

The larger is the cost difference between the two storage sites, the more of the captured carbon should be stored at the storage site with the lowest storage cost. With equal storage costs, the captured carbon should be split equally between the two storage sites.

It is socially optimal to use both storage sites if  $\tilde{d} < L$ , i.e., if

$$z_B - z_A < tL \quad (6)$$

When this inequality holds, the extra costs of storage due to using storage site  $B$  instead of only site  $A$  is lower than the extra transportation costs of using only site  $A$ . As we shall see in Section 7, both storage sites may be used in the market outcome even if the inequality in (6) does not hold, i.e., even if it is socially optimal to use only one storage site.

## 5 Market outcomes

The game between providers and purchasers of storage services evolves as the three-stage game described in the end of Section 3. In the subsequent sections, we consider three possible market outcomes. The first outcome, *no competition*, is the outcome with a “low” carbon price. More precisely, the carbon price is so low that plants located “far” from both storage sites, i.e., in the middle of the Hotelling line, do not invest in carbon capture facilities. In contrast, plants located “close” to a storage site invest in capture facilities. Hence, in this case the existence of storage firm  $B$  is of no importance to storage firm  $A$ , and vice versa.

The second market outcome, *full competition*, is for a “high” carbon price. More precisely, the carbon price is so high that all plants want to invest in capture facilities. Each plant chooses the storage facility that has the lowest price plus transportation cost. Moreover, if one storage site increases its price slightly above its equilibrium price, some plants will buy from the other storage site instead.

The third market outcome, *partial competition*, is for a “medium” carbon price. As is the case of full competition, all plants invest in capture facilities in the equilibrium outcome. However, if one storage site increases its price slightly above its equilibrium price, some plants will respond by not investing in capture facilities (instead of buying from the other storage firm).

## 6 No competition

Let  $p_i$  be the price set by storage firm  $i$  in stage one of the game in order to be willing to receive captured CO<sub>2</sub>,  $i = A, B$ . Let  $d_A$  be the location of the plant that is indifferent between i) paying the carbon price  $\tau$ , and ii) investing in capture facilities and delivering its captured CO<sub>2</sub> to storage site  $A$ , i.e.,

$$\tau = x + td_A + p_A \quad (7)$$

where the right hand side of (7) is the sum of cost of investment in capture facilities ( $x$ ), cost of transport along the Hotelling line ( $td_A$ ), and the price charged by storage firm  $A$ , ( $p_A$ ).

Demand for storage services from storage site  $A$  is then given by

$$d_A \frac{E}{L} = \frac{\tau - x - p_A}{t} \frac{E}{L} = d_A(p_A) \frac{E}{L} \quad (8)$$

where we have used (7). Note that

$$d_A'(p_A) = -\frac{1}{t} \quad (9)$$

In stage one of the game, each storage firm sets its price so that its profit is maximized. The profit of storage firm  $A$  is

$$\pi_A = (p_A - z_A)d_A(p_A)\frac{E}{L} \quad (10)$$

Like in the text-book monopoly model, there are two opposing effects of increasing the price. First, a higher price increases the income from each client, i.e.,  $(p_A - z_A)$  increases, but a higher price also lowers the number of clients, i.e.,  $d_A(p_A)$  decreases. Maximizing profit with respect to the price  $p_A$  and using (9) we obtain

$$\pi_A'(p_A) = \left[ d_A + (p_A - z_A)\left(-\frac{1}{t}\right) \right] \frac{E}{L} = 0 \quad (11)$$

giving

$$p_A = \frac{\tau + z_A - x}{2} \quad (12)$$

Then using (7) we obtain

$$d_A = \frac{\tau - z_A - x}{2t} \quad (13)$$

To ensure a positive net price,  $p_A - z_A > 0$ , we need  $\tau > x + z_A$ , i.e., the sum of the unit cost of investment in capture facilities and the unit cost of storage has to be less than the social cost of carbon. Note that this condition is identical to the condition requiring a positive distance ( $d_A > 0$ ), and also identical to the condition that it is socially efficient with at least some development of storage site  $A$ .

In this simple model with linear functions, the price for storage services,  $p_A$ , is independent of the unit cost of transport,  $t$ , see (12). Furthermore, combining this result with the observation that it is only the product  $td_A$  that matters in (7), i.e., these two factors are tied together, it

follows from (7) that a higher cost of transport lowers the number of plants delivering captured CO<sub>2</sub> to storage firm A, see (13).

Profit of storage firm B is  $\pi_B = (p_B - z_B)(L - d_B(p_B))E/L$  where  $d_B$  is the location of the plant being served by storage firm B that is located farthest away from this storage site. The location of this plant can be found in the same way as we determined  $d_A$ , i.e.,  $d_A$  in (7) is replaced by  $L - d_B$  (and  $p_A$  is replaced by  $p_B$ ). This gives

$$p_B = \frac{\tau + z_B - x}{2} \quad (14)$$

and

$$d_B = L - \frac{\tau - z_B - x}{2t} \quad (15)$$

In order to have no competition between the storage firms, there must be a segment on the Hotelling line where no plant wants to invest in capture facilities when the storage firms set the prices derived above. This requires that  $d_A + (L - d_B) < L$ , i.e., that  $d_A < d_B$ , which implies that

$$\tau < x + tL + \frac{z_A + z_B}{2} \equiv \tau^* \quad (16)$$

Hence, if costs of abatement activities are sufficiently high relative to the social cost of carbon, there will be no competition.

Inserting the inequality (16) into (12) and (14) we find

$$p_A < z_A + \frac{tL}{2} + \frac{z_B - z_A}{4} \equiv p_A^* \quad (17)$$

and

$$p_B < z_B + \frac{tL}{2} - \frac{z_B - z_A}{4} \equiv p_B^* \quad (18)$$

The average upper price limit for the region of no competition is

$$\bar{p}^* = \frac{p_A^* + p_B^*}{2} = \frac{z_A + z_B}{2} + \frac{tL}{2} \quad (19)$$

Finally, in the special case of identical storage suppliers, i.e.,  $z_A = z_B = z$ , then  $p_A = p_B < z + tL/2$  and  $d_A = L - d_B < L/2$ .

## 7 Full Competition

We now consider the case where the carbon price is so high that all plants invest in carbon capture facilities. In this case, the two storage firms compete for a given total demand. We will search for Nash equilibria in prices.

Plants will invest in capture facilities and buy storage services from the firm with the lowest gross price (i.e., price of storage services plus transport cost). The market will be split between firm  $A$  and  $B$  according to  $p_A + t\bar{d} = p_B + t(L - \bar{d})$ , which implies:

$$d_A = \bar{d} = \frac{p_B - p_A + tL}{2t} = d(p_A, p_B) \quad (20)$$

and  $d_B = L - \bar{d}$ . Profits of firm  $A$  and  $B$  are now given by  $\pi_A = (p_A - z_A)d(p_A, p_B)E/L$  and  $\pi_B = (p_B - z_B)(L - d(p_A, p_B))E/L$ . Firm  $A$  chooses  $p_A$  so that its profits are maximized for the given value of  $p_B$ . Using (20) this gives us<sup>5</sup>

$$\bar{d} + (p_A - z_A)\left(-\frac{1}{2t}\right) = 0 \quad (21)$$

Similarly, maximizing firm  $B$ 's profits gives

$$L - \bar{d} + (p_B - z_B)\left(-\frac{1}{2t}\right) = 0 \quad (22)$$

Taken together, the three equations (20)-(22) give us

$$p_A = z_A + tL + \frac{z_B - z_A}{3} \equiv p_A^{**} \quad (23)$$

$$p_B = z_B + tL - \frac{z_B - z_A}{3} \equiv p_B^{**} \quad (24)$$

---

<sup>5</sup> Alternatively, we can derive the response functions for the two firms,  $p_A = (p_B + tL + z_A)/2$  and  $p_B = (p_A + tL + z_B)/2$ , and then combine them. Note that under full competition, each response curve is increasing in the price of the competitor, with slope  $1/2$ . See further discussion at the end of Section 8, including Figure 2.

$$\bar{p}^{**} = \frac{p_A^{**} + p_B^{**}}{2} = \frac{z_A + z_B}{2} + tL \quad (25)$$

From these equations we see that a higher cost of storage of firm A ( $z_A$ ) tends to decrease the net price  $p_A - z_A$  of this firm, whereas the net price of the competitor tends to increase. Note that the terms with  $z_A$  and  $z_B$  cancel if  $z_A = z_B$ . In the special case of identical firms, the common net price equals  $tL$ , which can be regarded as a mark-up over costs. Comparing these prices with the case of no competition, it is straightforward to verify that  $p_A^{**} > p_A^*$  and  $p_B^{**} > p_B^*$  where  $p_A^*$  and  $p_B^*$  are defined in (17) and (18), whereas  $p_A^{**}$  and  $p_B^{**}$  are defined in (23) and (24).

Inserting (23) and (24) into (20), we find

$$\bar{d} = \frac{L}{2} + \frac{z_B - z_A}{6t} \quad (26)$$

There will be two storage firms in this market outcome if  $\bar{d} < L$ , i.e., if

$$z_B - z_A < 3tL \quad (27)$$

Comparing with (6), it is clear that this inequality will hold if it is socially optimal to use two storage sites. However, if  $tL < z_B - z_A < 3tL$ , both storage sites will be used in the market outcome, although it is socially optimal to use only storage site A.

In the special case of identical storage firms, we have  $\bar{d} = L/2$ ; the two competitors split the market. Note that if  $z_A < z_B$ , then a higher unit cost of transport ( $t$ ) will lower  $\bar{d}$ , i.e., the market of firm A decreases, whereas the market of firm B increases correspondingly. The reason A loses market shares is that initially, the marginal plant (at  $\bar{d}$ ) transports its captured CO<sub>2</sub> longer than  $L/2$  on the way to storage site A, i.e., cost of transport is more important to firm A than to the competitor. Finally, in the special case of identical firms, profit of each firm is  $tLE/2$ .

Existence of the full competition equilibrium requires that the carbon price is so high that all plants want to invest in capture facilities when the storage firms set the prices derived above. This will be the case if

$$x + p_A + t\bar{d} = x + p_B + t(L - \bar{d}) < \tau \quad (28)$$

Inserting from (23)-(26) we obtain

$$\tau > x + \frac{3tL}{2} + \frac{z_A + z_B}{2} \equiv \tau^{**} \quad (29)$$

From (16) and (29), we see that  $\tau^{**} - \tau^* = \frac{tL}{2} > 0$ .

## 8 Partial competition

We have found the equilibrium for  $\tau < \tau^*$  and for  $\tau > \tau^{**}$ . We now turn to the case where the carbon price lies between these values, i.e.,  $\tau \in [\tau^*, \tau^{**}]$ . The size of this interval is  $tL/2$ , which means that the higher the transport cost, the larger is this interval. For these values of  $\tau$  we have partial competition, meaning that the *marginal* plant, which is located at  $\bar{d}$ , is indifferent between whether it should invest in capture facilities or not (like the marginal plant under no competition), and also indifferent with respect to from which firm it should buy storage services (like the marginal plant under full competition). Hence, the equilibrium must satisfy

$$x + p_A + t\bar{d} = \tau \quad (30)$$

and

$$x + p_B + t(L - \bar{d}) = \tau \quad (31)$$

The demand function facing *A* for a given  $p_B$  is now kinked: The quantity response is larger when  $p_A$  is increased than when it is reduced. An *increase* in  $p_A$  will reduce demand for storage from firm *A*, but will not affect those plants that initially chose firm *B*. Hence, the demand response will be the same as in the monopoly case (given by (9)):

$$\bar{d}'(p_A^+) = -\frac{1}{t} \quad (32)$$

On the other hand, if  $p_A$  is *reduced*, demand facing firm *A* will be increased while demand facing firm *B* will be reduced, just as in the case of full competition. Hence, from (20) it follows that

$$\bar{d}'(p_A^-) = -\frac{1}{2t} \quad (33)$$

A Nash equilibrium under partial competition must as a minimum satisfy equations (30) and (31), which include the three endogenous variables  $p_A$ ,  $p_B$  and  $\bar{d}$ . Define

$$\Delta = p_B - p_A \quad (34)$$

For any given value of  $\Delta$ , the three equations (30), (31), (34) can be solved for  $p_A$ ,  $p_B$  and  $\bar{d}$ .

We find

$$p_A = \tau - x - \frac{tL}{2} - \frac{\Delta}{2} \quad (35)$$

$$p_B = \tau - x - \frac{tL}{2} + \frac{\Delta}{2} \quad (36)$$

$$\bar{p} = \frac{p_A + p_B}{2} = \tau - x - \frac{tL}{2} \quad (37)$$

$$\bar{d} = \frac{L}{2} + \frac{\Delta}{2t} \quad (38)$$

The prices in (35) and (36) are candidates for an equilibrium. For any such price combination to actually be a Nash equilibrium, none of the two firms must be able to increase its profit by either increasing or reducing its own price.

With a kinked demand function facing A, the profit function  $\pi_A(p_A)$  must also have a kink.

For  $p_A$  to be optimal, profits cannot increase by *increasing*  $p_A$ , i.e.,

$$\pi_A'(p_A^+) \leq 0 \quad (39)$$

The condition for not being able to increase  $\pi_A$  by *reducing*  $p_A$  is

$$\pi_A'(p_A^-) \geq 0 \quad (40)$$

Similar inequalities must hold for  $p_B$ .

In the Appendix A it is shown that for each of the two limiting cases of  $\tau = \tau^*$  and  $\tau = \tau^{**}$  there is a unique value of  $\Delta$  satisfying the inequalities above. Hence, we have a unique

equilibrium in these two cases. Not surprisingly, we find that the equilibrium prices are the same as under no competition (given by (12) and (14)) if  $\tau = \tau^*$  and the same as under full competition (given by (23) and (24)) if  $\tau = \tau^{**}$ .

The case of  $\tau \in (\tau^*, \tau^{**})$  is analyzed in detail in the Appendix A and it is shown that for these carbon prices there is a range of  $\Delta$ -values satisfying the inequalities above. Hence, the equilibrium values of the prices are not unique.<sup>6</sup> However, it is clear from (37) that there is a unique *average* price, and this average price is higher the higher is the carbon price. In the Appendix A we derive the lower and upper bounds for  $p_A$  and  $p_B$ , and show that these bounds are higher the higher is the carbon price  $\tau$ .

Figure 1 illustrates how  $p_A$  depends on the carbon price  $\tau$ . The shaded area for  $\tau \in (\tau^*, \tau^{**})$  shows the range of equilibrium values of  $p_A$  for these carbon prices. The horizontal length of this area is  $\tau^{**} - \tau^* = tL/2$ , while the horizontal length of the first segment is

$\tau^* - (x + z_A) = tL + (z_B - z_A)/2$ , where we have used (16). Hence, if the transport cost  $tL$  is small and the difference in cost of storage is small, the range of carbon prices giving no competition or partial competition will be relatively narrow.

## FIGURE 1 ABOUT HERE

**Figure 1** *Effect of price on emissions ( $\tau$ ) on price of storage charged by firm A ( $p_A$ ) when cost of storage may differ across storage firms ( $z_A \leq z_B$ ).*

What outcome can we expect under partial competition and do firms prefer to have the highest or the lowest storage price when there are many Nash equilibria? Let us consider how profits for firm A under partial competition vary with  $\Delta$ . Profit of firm A is

$$\pi_A(\Delta) = \left[ (p_A(\Delta) - z_A) \bar{d}(\Delta) \right] \frac{E}{L} \quad (41)$$

---

<sup>6</sup> This result has previously been shown by Merel and Sexton (2010) for a model similar to our model with  $z_A = z_B$ . Note that we also consider the general case  $z_A \neq z_B$ .

where  $p_A(\Delta)$  and  $\bar{d}(\Delta)$  are given by (35) and (38). Differentiating and using (35) and (38) gives

$$\pi_A'(\Delta) = \left[ (p_A - z_A) \bar{d}'(\Delta) + p_A'(\Delta) \bar{d} \right] \frac{E}{L} = \left[ p_A - z_A - t \bar{d} \right] \frac{E}{2tL} \quad (42)$$

Inserting from (35) and (38) gives

$$\pi_A'(\Delta) = \left[ \tau - x - z - tL - \Delta \right] \frac{E}{2tL} \quad (43)$$

In the Appendix A it is shown that  $\pi_A'(\Delta) > 0$ , so that the best value of  $\Delta$  for storage firm A is the highest value that is consistent with the inequalities (39) and (40). From the definition of  $\Delta$  this means that firm A (B) would prefer the Nash equilibrium with the lowest  $p_A$  ( $p_B$ ).

Consider next the joint profits  $\Pi = \pi_A + \pi_B$  of the two firms. These are given by

$$\Pi(\Delta) = \left[ (p_A(\Delta) - z_A) \bar{d}(\Delta) + (p_B(\Delta) - z_B)(L - \bar{d}(\Delta)) \right] \frac{E}{L} \quad (44)$$

In the Appendix A it is shown that the value of  $\Delta$  that maximizes  $\Pi(\Delta)$  is

$$\Delta = \frac{z_B - z_A}{2} \quad (45)$$

If storage costs are equal, it follows that joint profits are maximized for  $\Delta = 0$ , i.e., when the two prices are equal. This result is intuitive as total transport costs (and thus also overall costs) are minimized when  $\bar{d} = L/2$ , which is the case when prices are equal. If  $z_B > z_A$ , joint profits are maximized for a  $p_A < p_B$  (from (34) since  $\Delta > 0$  in this case).

The key results from the analysis of market outcomes are summarized in Proposition 1:

**Proposition 1.** *Assume there are two storage firms and that each firm is imposed to charge the same price for all its clients. Then for each  $\tau \leq \tau^*$  there exists a unique no-competition equilibrium, and for each  $\tau \geq \tau^{**}$  there exists is a unique full-competition equilibrium. In addition, for each  $\tau \in (\tau^*, \tau^{**})$  there exists a continuum of partial-competition equilibria.*

*Under partial-competition, each storage firm prefers the equilibrium with the lowest price for itself. If the two firms are identical, joint profits are maximized under partial competition when the firms charge the same price. With different storage costs, joint profits are maximized under partial competition when the lowest-cost firm has the lowest price.*

The solutions to the outcomes in sections 6-8 may be illustrated using price response curves for the two storage firms:  $p_A(p_B)$  and  $p_B(p_A)$ , see footnote 5. Panel (i) in Figure 2 shows a price response curve for firm A,  $p_A(p_B)$ . If  $p_B$  is sufficiently low, we are in the full competition segment, in which case the price response curve of firm A is linearly increasing with slope  $\frac{1}{2}$ . For “intermediate” values of  $p_B$  we are in the partial competition segment. In this regime, (35) and (36) are valid and these two equations imply that the sum of  $p_A$  and  $p_B$  only depends on the model parameters. Therefore, the slope of the price response curve under partial competition is -1. Finally, if  $p_B$  is sufficiently high, we are in the no competition segment. Then the price response curve of firm A is independent of firm B’s price, and hence the price response curve is constant.<sup>7</sup>

The other panels in Figure 2 show the Nash equilibria under different assumptions about  $\tau$  relative to  $\tau^*$  and  $\tau^{**}$ , where we have assumed that the storage firms have equal costs and thus symmetric response curves (similar figures are shown in Merel og Sexton, 2010). A no competition equilibrium ( $\tau < \tau^*$ ) is shown in Panel (ii), whereas a full competition equilibrium ( $\tau > \tau^{**}$ ) is shown in Panel (vi). Under partial competition,  $\tau \in (\tau^*, \tau^{**})$ , there is a continuum of equilibria as illustrated in Panel (iv). Finally, Panels (iii) and (v) show the unique equilibrium in the special cases  $\tau = \tau^*$  and  $\tau = \tau^{**}$ .

---

<sup>7</sup> In the figure, we have assumed that the response curve consists of all three segments. This obviously depends on the parameters of the model, in particular  $\tau$ .

FIGURE 2 ABOUT HERE

**Figure 2.** Price response curves and Nash equilibria for different levels of the price of emission,  $\tau$ . From top left: (i) price response curve for firm A, (ii) equilibrium under no competition ( $\tau < \tau^*$ ), (iii) equilibrium in the limiting case of  $\tau = \tau^*$ , (iv) equilibrium under partial competition ( $\tau^* < \tau < \tau^{**}$ ), (v) equilibrium in the limiting case of  $\tau = \tau^{**}$ , and (vi) equilibrium under full competition ( $\tau > \tau^{**}$ ).

## 9 Monopoly versus competition vs. social optimum

We now consider the equilibrium price in more detail for the case  $z_A = z_B = z$  when there is a symmetric equilibrium under partial competition. The common price for the cases *no competition (NC)*, *partial competition (PC)* and *full competition (FC)* are given by (from our previous results and in obvious notation)

$$p^{NC} = \frac{\tau + z - x}{2} \quad \text{for } x + z < \tau < \tau^* \equiv x + z + tL \quad (46)$$

$$p^{PC} = \tau - x - \frac{tL}{2} \quad \text{for } \tau \in [\tau^*, \tau^{**}] \quad (47)$$

$$p^{FC} = z + tL \quad \text{for } \tau > \tau^{**} \equiv x + z + \frac{3}{2}tL \quad (48)$$

Note that  $\lim_{\tau \rightarrow \tau^*} p^{NC} = p^{PC}(\tau^*)$  and  $p^{PC}(\tau^{**}) = p^{FC}$ , so that the equilibrium price is a continuous function of  $\tau$ . Furthermore, as  $\tau$  increases from  $x + z$  to  $\tau^{**}$ , the price also increases until it reaches its maximal value  $p^{FC}$ , which is the equilibrium price for all  $\tau \geq \tau^{**}$ . Notice also that the partial derivative of the equilibrium price with respect to  $\tau$  is twice as high for medium values of  $\tau$  (partial competition) as it is for low values of  $\tau$  (no competition).

We now compare the equilibria above with the case of monopoly, where firm A is the monopolist.

For the monopoly case, we derived  $p_A$  and  $d_A$  in Section 6, see (12) and (13). Clearly, this solution is only valid for  $d_A < L$ . Using (13), this implies  $\tau < x + z + 2tL \equiv \tau^M$ . For higher values of  $\tau$ , it will be optimal for the monopolist to charge the highest possible price that is consistent with the plant located farthest away buying storage services. This price is determined by  $p + x + tL = \tau$ . The monopoly price  $p^M$  is hence given by

$$p^M = \frac{\tau + z - x}{2} \quad \text{for } x + z < \tau < \tau^M \quad (49)$$

$$p^M = \tau - x - tL \quad \text{for } \tau \geq \tau^M \quad (50)$$

We now compare the monopoly price  $p^M$  with the prices under competition for  $\tau > \tau^*$  (for lower values of  $\tau$  there is no competition). It follows from (47)-(50) that

$$p^M - p^{PC} = \frac{\tau + z - x}{2} - \left(\tau - x - \frac{tL}{2}\right) = \frac{1}{2}(z + x + tL - \tau) < 0 \quad \text{for } \tau \in [\tau^*, \tau^{**}] \quad (51)$$

$$p^M - p^{FC} = \frac{\tau + z - x}{2} - (z + tL) = \frac{1}{2}(\tau - (z + x + 2tL)) < 0 \quad \text{for } \tau \in [\tau^{**}, \tau^M] \quad (52)$$

$$p^M - p^{FC} = (\tau - x - tL) - (z + tL) = \tau - (x + z + 2tL) > 0 \quad \text{for } \tau > \tau^M \quad (53)$$

The intuition for the higher price under partial competition and full competition than under monopoly (when  $\tau < \tau^M$ ) is the following (see also Cowan and Yin, 2008, and Chen and Riordan, 2008): In all cases with market power, there is a trade-off between a high price and a high demand. Under monopoly, firm A takes into account that a lower price will lead to a higher demand. Also under partial competition and full competition, a lower price from firm A will lead to a higher demand for this firm. However, as shown in the previous sections (see in particular (9), (21) and (33)), the demand effect of reducing the price is smaller in the competition cases ( $1/2t$ ) than under monopoly ( $1/t$ ) (when  $\tau < \tau^M$ ), reflecting that under monopoly a lower price increases total demand (when  $\tau < \tau^M$ ), whereas under competition, where all plants invest in capture facilities, a lower price has only a “business stealing effect”.

To be more specific, when firm A lowers its price and thus starts cutting into the client base of firm B, the more plants that is captured by firm A, the longer from site A are these plants located and the closer they are situated from site B. Thus the number of clients captured by firm A

because of its reduced price is lower than the quantity effect under monopoly, reflecting that under partial and full competition plants have two alternative suppliers.

Because the demand effect is lowest under competition, also the incentives to choose a low price is *lower* under partial competition and full competition than under monopoly (when  $\tau < \tau^M$ ). Therefore, the price under competition will be higher than the price under monopoly (when  $\tau < \tau^M$ ). For  $\tau > \tau^M$ , the monopolist will supply the entire market, i.e.,  $d_A = L$ . Then a higher monopoly price—as a response to a higher price on emissions—has no impact on demand as long as  $d_A = L$ .

The results are illustrated in Figure 3. With two identical firms, the firms do not compete if  $\tau \leq \tau^*$ . However, the common price, as well as the market share of each firm, are increasing in  $\tau$ . For  $\tau = \tau^*$ , the market is split between the two firms. For  $\tau^* < \tau < \tau^{**}$  (partial competition), and under the additional assumption that the firms charge the same price, this common price is increasing in  $\tau$  and it increases at a higher rate than under no competition (1 vs. 1/2); see (46) and (47), due to the kinked demand curve. For  $\tau \geq \tau^{**}$ , there is full competition. However, in this regime the common price is not dependent on the level of  $\tau$ , see (48).

Turning to monopoly, the monopoly price is always increasing in  $\tau$ , and at a higher rate once the monopolist covers the entire market ( $\tau \geq \tau^M$ ), see (49) and (50). Finally, the monopoly price is below the price under partial competition, and it is also below the price under full competition as long as  $\tau < \tau^M$ .

FIGURE 3 ABOUT HERE

**Figure 3.** *Effect of price on emissions ( $\tau$ ) on price of storage and market size of firm A when cost of storage does not differ across firms ( $z_A = z_B$ ).*

Our discussion above is summarized in Proposition 2:

**Proposition 2.** *Assume the two storage firms are identical and that each firm is imposed to charge the same price for all its clients. Then the price under monopoly is lower than under partial competition ( $\tau^* < \tau \leq \tau^{**}$ ) when the two firms charge the same price. The price under monopoly is also lower than under full competition as long as  $\tau^{**} < \tau < \tau^M$ .*

We now compare the equilibria under full competition with the social optimum. For this comparison, the question is how the market is split between the two storage firms. From (5), which shows the split under social optimum ( $\tilde{d}$ ), and (26), which shows the split under full competition ( $\bar{d}$ ), we see that with non-identical storage firms,  $\bar{d}$  is closer to  $L/2$  than the first-best level  $\tilde{d}$ . Hence, competition leads to too much use of the most expensive storage site. Note that with identical storage firms, the split of the market under full competition is socially efficient. This is also the case with identical firms under partial competition if the two firms charge the same price.

## 10 Numerical simulations

In this section, we offer empirical illustrations of the market outcomes discussed above.

### 10.1 Data and reference parameter values

#### The Hotelling line

We apply our model under the assumption that all emitting plants are located i) Belgium, Denmark, the Netherlands, Norway and the UK, ii) all plants are situated either at the coast or close to the coast and their cost of transport to a CO<sub>2</sub> storage site differs. Clearly, these plants are not situated along a straight line. In the Appendix B, we have constructed three alternative piece-wise lines. For each piece-wise line, we assume that its endpoints are located at Northern Lights in Øygarden (Norway) and at Captain X in St Fergus Beach Head (the UK). The lines differ with respect to length. In the reference case, we use the piece-wise line with the intermediate length  $L=2000$  km.

#### Cost of capture

Estimates for cost of capture vary a lot. While Bennæs *et al.* (2023) and Bennæs *et al.* (2024) suggest 30 to 90 EUR/tCO<sub>2</sub> for the North Sea, National Petroleum Council (2019) provides estimates between €77/tCO<sub>2</sub> and €14/tCO<sub>2</sub>. Carbon limits (2022) has estimates of unit capital cost, unit non-energy cost and cost of energy (20 years lifetime). The average estimate in this source is EUR 95/tCO<sub>2</sub>. The latter is used in our study because it represents an intermediate case. For other sources of cost of capture, see part II in the Appendix B.

#### Cost of transport

In addition to geographic and geologic conditions, as well as institutional settings, cost of transport depends on transport distance and volume/scale (Smith, 2021). Substantial economies of scale makes in general pipelines the cheapest way of CO<sub>2</sub> transport. However, transport by ships is the cheapest option for small CO<sub>2</sub> quantities (IEA, 2020).

According to IEA (2020), cost of offshore pipeline transport ranges from approximately 2 to 16 USD/tCO<sub>2</sub> for a distance of 250 km (for quantities between 3 and 30 Mtpa), which corresponds to 0.0075 – 0.06 EUR/tCO<sub>2</sub>/km. For transport by ship, cost ranges from 20 to 30 USD/tCO<sub>2</sub> for distances between 100 to 1000 km. This corresponds to 0.028 - 0.19 EUR/tCO<sub>2</sub>/km (for an annual quantity of 2 Mt).

CATF (2022) suggests a cost range of 0.006 – 0.15 EUR/t/km, depending on type of transport. Based on the available estimates, in this study we use a common value for cost of transport, namely  $t = 0.04$  EUR/tCO<sub>2</sub> km.

### Cost of storage

According to the Norwegian Ministry of Petroleum and Energy (2019), the estimated cost of storage for the Northern Lights project, including cost of pipe transport from the Western part of Norway to the storage site, amounts to 18 EUR/tCO<sub>2</sub>. This number is in line with the figures in CATF (2022), which builds on Carbon Limits (2022). Pale Blue Dot Energy and Axis Well Technology (2015) presents a slightly lower estimate for cost of storage (16.5 £/tCO<sub>2</sub>). Because the cost estimates do not differ much, we assume equal cost of storage for the two sites:  $z_A = z_B = z = 18$  EUR/tCO<sub>2</sub>. For more information on costs of CCS, see part II in the Appendix B. Table 1 shows the reference parameter values.

TABLE 1 ABOUT HERE

*Table 1. The reference parameter values.*

## **10.2 Simulations**

### Reference parameters

We now present the numerical simulations, using the reference parameter values in Table 1. Figure 4 shows the intervals for the carbon price ( $\tau$ ) for the three equilibrium regimes. As seen from Figure 4, if the carbon price is below 113 EUR/tCO<sub>2</sub>, there is no equilibrium as the carbon price is too low to trigger investment. For carbon prices between 113 and 193 EUR/tCO<sub>2</sub> we have the no competition equilibria. Here, the two storage firms act as local monopolists. Because we have assumed that the two storage firms have equal cost, they charge the same price for storage services. This price is increasing in  $\tau$  and independent of the transport cost,  $t$ , see eq. (46).

FIGURE 4 ABOUT HERE

**Figure 4.** Competition regimes and carbon prices,  $\tau$ , in EUR/tCO<sub>2</sub>. No competition (  $113 < \tau < 193$ ), partial competition (  $193 < \tau < 233$ ) and full competition (  $\tau > 233$  ).

For a carbon price between  $\tau^* = 193$  EUR/tCO<sub>2</sub> and  $\tau^{**} = 233$  EUR/tCO<sub>2</sub>, we have partial competition: the marginal plant is now indifferent between investing in capture facilities or not, and also indifferent between buying storage services from firm A or firm B. In the symmetric equilibrium, the price of storage varies between  $p^* = 58$  EUR/tCO<sub>2</sub> (at  $\tau^* = 193$  ) and  $p^{**} = 98$  EUR/tCO<sub>2</sub> (at  $\tau^{**} = 233$ ), see the red curve in Figure 4. Under partial competition, the price of storage service is increasing in the carbon price,  $\tau$ , but decreasing in the cost of transport, see eq. (47).

The black curve in Figure 4 shows the price of storage charged by the storage firm when it is a monopolist. As seen from Figure 4, the monopoly price is always lower than the price under partial competition.

For carbon prices exceeding 233 EUR/tCO<sub>2</sub>, there is full competition. As explained in section 7, the carbon price is now so high that all plants on the Hotelling line invest in capture facilities. In this regime, the price charged by the storage firms does not depend on  $\tau$  and therefor the last segment of the red curve depicted in Figure 4, which shows the price of storage under full competition, is flat. However, under full competition the price of storage services is increasing in i) the unit cost of storage,  $z$ , ii) the unit cost of transport,  $t$ , and iii) the length of the Hotelling line,  $L$ , see equation (48). As illustrated in Figure 4, the price charged by the storage firms under full competition is higher than the price charged by a storage firm being a monopolist, but only if  $\tau^{**} < \tau < \tau^M$ . For  $\tau \geq \tau^M$ , the carbon price is so high that the monopolist charges the highest possible price consistent with serving the entire market.

### Robustness

Below, we examine how alternative values of the parameters and the length of the Hotelling line impact the outcomes. We investigate a number of cases:

- a) Parameters are increased by one third relative to their reference values
- b) Parameters are decreased by one third relative to their reference values
- c) The length of the Hotelling line takes another value (500 km or 2400 km) than in the reference case (2000 km).

For each case, we find the carbon prices that sustain the various regimes and the corresponding equilibrium prices of storage service. The results are shown in Table 2.

## TABLE 2 ABOUT HERE

**Table 2.** *Sensitivity analysis of the case with simultaneous moves. Lowest price of carbon that triggers investment ( $x+z$ ), highest price of carbon sustaining no competition ( $\tau^*$ ) and the associated price of storage ( $p^*$ ), lowest price of carbon sustaining full competition ( $\tau^{**}$ ) and the associated price of storage ( $p^{**}$ ), and price of carbon sustaining the same price of storage under full competition and monopoly ( $\tau^M$ ).*

As shown in the table, an increase by one third in the cost of investment in capture facilities,  $x$ , changes the interval of carbon prices that sustain partial competition from 193-233 EUR/tCO<sub>2</sub> (prior to the increase) to 225-265 EUR/tCO<sub>2</sub>. The highest price of carbon under no competition,  $p^*$ , does not change; this follows from equation (17). Also, the price under full competition does not change; this follows from equation (23).

A higher cost of storage (by one third) and a higher cost of transport (also by one third) change the interval of carbon prices sustaining partial competition from 193-233 EUR/tCO<sub>2</sub> (prior to the increase) to 199-239 EUR/tCO<sub>2</sub> (higher cost of storage) and 220-273 EUR/tCO<sub>2</sub> (higher cost of transport). With these shifts, also the prices of storage,  $p^*$  and  $p^{**}$ , increase.

If the length of the Hotelling curve is reduced from 2000 km (reference value) to 500 km, the highest price of carbon sustaining no competition, which is identical to the lowest price of carbon sustaining partial competition ( $\tau^*$ ), decreases from 193 to 133 EUR/tCO<sub>2</sub>. For this border value, the corresponding price  $p^*$  decreases substantially; from 58 EUR/tCO<sub>2</sub> to 28 EUR/tCO<sub>2</sub>.

## 11 Extensions

In this section, we consider the following extensions or changes in the reference model:

- Economies of scale in storage
- Sequential moves of the storage firms, not simultaneous moves
- Heterogeneous plants
- More than two storage firms
- Perfect price discrimination.

## 11.1 Economies of scale in storage

In the reference model, the unit cost of storage was constant. It seems more plausible that there are economies of scale, i.e., declining unit costs. The simplest way to model this is to assume that on the one hand, marginal costs are constant (as before), but now there is also a fixed cost for each storage site. With this assumption, the previous analysis remains valid, provided it is optimal to use both storage sites also when there are fixed costs.

In Section 7 we showed that if marginal costs differed between storage sites, both storage sites could be used in the market outcome even if it was socially optimal to use only site *A*, see the discussion after (27). However, if marginal costs were equal across storage sites, it would be socially optimal to use both sites. Both sites would in this case also be used in the market equilibrium. We shall now show that with fixed costs, it may be socially optimal to use only one site even if marginal costs are equal across sites. Moreover, the market outcome may in this case give storage in both sites even if it is socially optimal to use only one. Similarly, the market outcome may have only one storage site, while it is socially optimal to use both sites.

To demonstrate the claims above, we consider the simple case where marginal costs are the same at the two sites ( $z_i = z$ ), and where site *B* has a fixed cost  $F$  that is at least as high as the fixed cost of *A*. Moreover, we assume that the carbon price is so high that it is socially optimal for all plants to invest in carbon capture, i.e.,  $\tau \geq \tau^0$ , see (4).

With these assumptions, it will be socially optimal to use both storage sites instead of only site *A* if the cost savings due to lower transportation costs are larger than the extra fixed cost  $F$  of using both storage sites instead of only site *A*. Formally, this condition is

$$F < \frac{tLE}{4} \quad (54)$$

because the average transportation distance decreases from  $L/2$  to  $L/4$  when going from using only site *A* to also using site *B*; this decreases transportation costs by  $tLE/4$ .

Consider next the market outcome. The gross profit  $\pi$  (i.e., profit before subtracting the fixed cost) for each storage site is increasing in the carbon price for carbon prices up to  $\tau^{**} > \tau^* > \tau^0$ . For the borderline case between no competition and partial competition, gross profit follows from (10) and (17):

$$\pi^* = (p^* - z) \frac{L E}{2 L} = \frac{tL L E}{2 2 L} = \frac{tLE}{4} \quad (55)$$

We immediately see that for gross profit equal to or larger than  $\pi^*$ , gross profit will exceed the fixed cost  $F$  if the inequality (54) holds. In other words, if the carbon price is at least  $\tau^*$ , both storage firms will be used in the market outcome if this is socially optimal. Since the gross profit  $\pi$  of a storage firm is increasing in  $\tau$ , we may have  $\pi - F > 0$  even if (54) does *not* hold. In other words, we may have a market outcome with both storage sites in use even if it is socially optimal to use only storage site  $A$ .

If the carbon price lies between  $\tau^0$  and  $\tau^*$ , gross profit  $\pi$  is lower than  $\pi^*$  given by (55). In this case we may have  $\pi - F < 0$  even if (54) holds. In other words, we may have a market outcome with only storage site  $A$  even if it is socially optimal to also use storage site  $B$ . If this is the case, it will be important to establish a storage site before another firm invests in storage.

In the Appendix C we discuss the value of  $F$ . We find that  $F < \frac{tLE}{4} = 2340$  million EUR.

Hence, it is optimal to use both storage sites.

## 11.2 Sequential moves

### Theory

We now examine the case where firm  $A$  sets the price before firm  $B$ , assuming equal storage costs. Hence, in stage one firm  $A$  decides the price and the share of the market it would like to cover, taking into account the response of firm  $B$  in the second stage. We refer to the Appendix D for more details. Here we just give the main conclusions:

**Proposition 3.** *With full competition, sequential moves and equal storage costs, the lowest carbon price sustaining full competition,  $\tau^{***}$ , must be higher than the lowest carbon price in the simultaneous move game,  $\tau^{**}$ . This follows as both firms charge a higher storage price under sequential moves than under simultaneous moves, and the price charged by the leader increases more than the price charged by the follower. Finally, both storage firms obtain a higher profit under sequential moves than under simultaneous moves but the increase in profits is greatest for the follower.*

Since the price charged by the firms differ, the market split between  $A$  and  $B$  will also change: with identical cost of storage, the market share of the leader is  $3/8$ , whereas the market is split equally under simultaneous moves. We find that there is an advantage being the follower as the increase in profits is greatest for the follower. The advantage is even higher if we introduce *learning* from  $A$  to  $B$  in this model.

The advantage of being the second mover can be one possible explanation why investments in CCS have been small. A potential storage firm investor may wait for the other storage firm to develop first.

### Simulations

We now simulate the sequential move game above. With no competition, the storage firms operate in separate markets. Therefore, in the absence of learning effects the outcome is similar to the simultaneous move game.

The results of the simulations for the full competition case are shown in Table 3. When using the reference parameter values, see Table 1, the price charged by storage firm  $A$  (leader) and  $B$  (follower) is  $p_A^{***} = 138$  EUR/tCO<sub>2</sub> and  $p_B^{***} = 118$  EUR/tCO<sub>2</sub>, respectively. From Proposition 3 we know that the leader charges the highest price and also that the price charged by the leader exceeds the price under simultaneous moves ( $p_A^{**} = p_B^{**} = 98$ ). To sustain a full

competition equilibrium under sequential moves, the price of carbon has to be at least  $\tau^{***} = 263$  EUR/tCO<sub>2</sub>, which exceed the corresponding carbon price under simultaneous moves ( $\tau^{**} = 233$ ). From the discussion above, we also know that the leader covers 3/8 of the market, which translates to  $\bar{d} = 750$  km when the length of the Hotelling line equals 2000 km.

Table 3 also offers results from a sensitivity analysis of the sequential move game and compare these to the simultaneous move game. In general, changes in parameter values lead to the same type of effects on storage prices in the two cases.

### TABLE 3 ABOUT HERE

**Table 3.** *Sequential moves (full competition equilibrium values marked by three stars) and simultaneous moves (full competition equilibrium value marked by two stars) with two storage firms (A and B). Firm A moves first under sequential moves and serves  $\bar{d}$  km of the Hotelling line. The price of carbon has to be at least  $\tau^{***}$  ( $\tau^{**}$ ) in order to sustain full competition under sequential (simultaneous) moves.*

### 11.3 Heterogeneous plants

Above, we have assumed that cost of investment is the same for plants. In the Appendix E we analyze the case where cost of investment differs across plants. Here, we argue that in the special case where cost of investment is uniformly distributed, there will still be a kinked demand curve for each plant at each location. However, these kinks will vanish when we aggregate all demand curves, since the demand curve for each plant will be of measure zero relative to the aggregate demand curve. Hence, the aggregate demand curve will not be kinked, and the equilibrium will be unique. However, with more realistic heterogeneity than the unit costs being uniformly distributed between a lower and an upper bound—unit costs typically vary discretely, as do location of plants—we may again have a situation with multiple equilibria under partial competition.

## 11.4 More storage firms

In the reference model, there is one storage firm at each end of the Hotelling line. In the Appendix F we consider the case of  $N > 2$  firms. Hence  $N - 2$  firms have two neighbors, whereas each firm at the end of the line has one neighbor only. The distance between each pair of neighbors is still  $L$ . We show the following proposition:

**Proposition 4.** *Assume the parameters ensure full competition with two identical storage firms*

*( $\tau > \tau^{**} = x + z + \frac{3}{2}tL$ ), i.e., each firm charges  $p^{**}$ . If the number of firms as well as the length of the Hotelling line are increased in such a way that the distance between each pair of neighboring firms is unchanged, then the Nash equilibrium is still characterized by each firm charging  $p^{**}$ .*

## 11.5 Price discrimination

Above we analyzed the game under the assumption that each storage firm has to impose the same price on all its clients. In the Appendix G we consider the opposite case; each storage firm can perfectly price discriminate across its clients. Here we prove the following proposition:

**Proposition 5.** *Assume there is perfect price discrimination when storage firm A is a monopolist and also when there is competition between storage firms A and B ( $z_B \geq z_A$ ). Moreover, assume it is socially efficient that all plants invest in capture facilities. If the monopoly is replaced by two competing firms, there will be full competition, whereas a partial competition regime does not exist under perfect price discrimination. All plants benefit from competition relative to monopoly. Moreover, under competition the distribution of plants being served by storage firms A and B is socially efficient.*

## 12 Conclusions

In this paper we have analyzed the market for carbon storage, focusing on the competition between storage firms. Whereas storage firms supply storage of CO<sub>2</sub>, emitting plants demand storage if they choose to capture their CO<sub>2</sub> emissions. Using a combination of theoretical analysis (through applying the Hotelling line) and numerical illustrations, we have investigated how different carbon prices may affect the degree of competition between storage firms and the price of storage.

If the carbon price is only moderate and transport costs are relatively high, there will be no competition between the storage firms. With higher carbon prices, competition emerges. However, we identify two quite different competition regimes. With intermediate levels of carbon prices, we have “partial competition”, in which case the marginal emitting plant is indifferent between investing in CCS or not and also indifferent between buying storage service from either of the two storage firms. We show that this leads to a kinked demand function for carbon storage, and multiple Nash equilibria. Furthermore, we find that the price under partial competition is in fact *higher* than in the case with a monopoly storage firm.

With higher carbon prices than those sustaining partial competition, there is “full competition”, meaning that the marginal plant is *not* indifferent between investing in CCS or not, but only indifferent between buying storage service from either of the two storage firms. Comparing with the socially optimal solution, we find (not surprisingly) that there is too little CCS under no competition. Under full competition, there is too much use of the most expensive storage site.

Furthermore, we have analyzed the market outcome under different alternative assumptions about the market. In particular, we have shown that if the storage firms decide their prices

sequentially instead of simultaneously (as assumed above), both firms gain but the follower gains the most. Hence, this might lead to delayed investments in storage sites, and could explain why development of storage sites have been rather slow.

The numerical illustrations in the context of the North Sea and surrounding countries suggest that we may have partial competition (and hence multiple equilibria) for a quite large interval of carbon prices. However, the historic EU ETS prices have been too low to sustain even a no competition regime. As EU tightens its climate goals on the way towards a climate-neutral society and thus lowers the number of emissions allowances, the price of allowances may increase substantially. Hence, the path to a net zero society may cover a period with no competition for storage services, next a period with partial competition, and finally a full competition regime.

An important issue only vaguely touched upon in our analysis is technological improvements and learning. Both capture and storage are relatively immature technologies, and hence learning and cost reductions are expected. For investments in storage, an important question is whether learning effects are internal to the storage firm or if there are spillovers to other (potential) storage firms. If there are large spillovers, these may further delay early investments, as followers not only gain from the nature of price competition (as noted above), but also from having lower storage costs thank to its competitor. Hence, there may be several reasons for a regulator to support early investments in storage sites.

Our paper has given an extensive discussion of the consequences of market power of the two storage firms. Throughout the paper we have assumed that there is an efficient transport sector, characterized by a constant unit cost of transport and no capacity constraints. However, market power can be built credibly by sizing the infrastructure for transport, see, for example, Cremer and Laffont (2002) where the capacity of the transport network is determined by an unregulated supplier exerting market power. Hence, an obvious candidate for further research would be a closer analysis of the transportation sector: Also in the transportation sector there are relatively high fixed costs, and hence a limited number of suppliers. This is true for transportation by pipelines, but to some extent also for transportation by ships because there are a limited number of specialized ships that can handle liquefied CO<sub>2</sub>. A natural comparison here is natural gas pipelines, where the EU has established third party access and regulation of tariffs in order to avoid exploitation of market power in the natural gas transport segment (EU, 2003). A similar regulation could be implemented for CO<sub>2</sub> pipelines.

We have shown that the unregulated market outcome will differ from the social optimum. An obvious question for future research is how one might improve efficiency through regulation. If the regulator has perfect information about all costs and all other factors, and the social cost of public funds is ignored, there is a whole range of carbon prices, subsidies and direct regulations that could be used to achieve the social optimum. One obvious policy candidate would be direct price regulation of firms, perhaps combined with a subsidy in order to provide these firms with a sufficient income to cover their fixed costs.

In reality, there is asymmetric information between the regulator and the storage firms (and also the transportation firms) with respect to costs. In this case, it is much more difficult to design good policies to achieve a (second-best) social optimum. This is particularly true if one takes account of the social cost of public funds, implying a deadweight-loss associated with all types of subsidies. Optimal regulation of oligopolies is a broad and important topic, but is beyond the scope of the present paper. Also, the optimal regulation for e.g. Europe as a whole will typically differ from what is optimal from the point of view of a single country that is host to a storage site.

## References

- Bennæs, A., M. Skogset, T. Svorkdal, K. Fagerholt, L. Herlicka, F. Meisel and W. Rickels (2023). Designing pipeline networks for carbon capture and storage of CO<sub>2</sub>-sources in Germany: An Industry Perspective. In: Buscher, U., J.S. Neufeld, R. Lasch and J. Schönberger (eds): *Logistics Management. Lecture Notes in Logistics*. Springer, Cham.
- Bennæs, A., M. Skogset, T. Svorkdal, K. Fagerholt, L. Herlicka, F. Meisel and W. Rickels (2024). Modeling a supply chain for carbon capture and offshore storage—A German–Norwegian case study. *International Journal of Greenhouse Gas Control*, 132, 104028.
- Bentham, M., Mallows, T., Lowndes, J. and A. Green (2014). CO<sub>2</sub> Storage Evaluation Database (CO<sub>2</sub> Stored): The UK's Online Storage Atlas, *Energy Procedia*, 63, 4555-4562. doi: 10.1016/j.egypro.2014.11.486
- Bhaskar, V. (1988). The Kinked Demand Curve: A Game-Theoretic Approach, *International Journal of Industrial Organization*, 6: 373-384.
- Brenner S. (2010). Location (Hotelling) games and applications, in Cochran J. J. (ed.), *Wiley Encyclopedia of Operations Research and Management Science*, John Wiley & Sons, Inc.
- Budins, S., S. Krevor, N. Mac Dowell, N. Brandon and A. Hawkes (2018). An assessment of CCS costs, barriers and potential, *Energy Strategy Reviews* 22, 61-81.
- Carbon Limits (2021). Study on the reuse of oil and gas infrastructure for hydrogen and CCS in Europe. Re-Stream. Retrieved 8 February 2024 from [https://www.concawe.eu/wp-content/uploads/Re-stream-final-report\\_Oct2021.pdf](https://www.concawe.eu/wp-content/uploads/Re-stream-final-report_Oct2021.pdf)
- Carbon Limits (2022). *CCS in Europe — mapping of cost*. Clean Air Task Force. Retrieved 14 January 2025 from <https://www.catf.us/2023/02/mapping-cost-carbon-capture-storage-europe/>
- Chen, Y. and M. H. Riordan (2008). Price-increasing competition, *RAND Journal of Economics*, 39(4): 1042-1058.
- Cowan, S. and X. Yin (2008). Competition can harm consumers, *Australian Economic Papers*, 47: 264-271.
- Cremer, H. and J.J. Laffont (2002). Competition in gas markets. *European Economic Review*, 46(4-5), 928-935.
- Cumbul, E. and G. Virág (2018). Multilateral limit pricing in price-setting games, *Games and Economic Behavior*, 111: 250-273.
- d'Aspremont, C. J., J. Gabszewicz and J.-F. Thisse (1979). On Hotelling's "Stability in Competition", *Econometrica*, 47(5): 1145-1150.
- Dupraz, S. (2023). A Kinked-Demand Theory of Price Rigidity, *Journal of Money, Credit and Banking*, <https://doi.org/10.1111/jmcb.13067>.
- Durmaz, T. (2018). The economics of CCS: Why have CCS technologies not had an international breakthrough?, *Renewable and Sustainable Energy Reviews* 95, 328-340.
- Economides, N. S. (1984). The principle of minimum differentiation revisited, *European Economic Review*, 24, 345–368.
- EU (2003). Directive 2003/55/EC of the European Parliament and of the Council of 26 June 2003 concerning common rules for the internal market in natural gas and repealing Directive 98/30/EC <https://eur-lex.europa.eu/eli/dir/2003/55/oj>
- Europe (2024). The EU net zero industry act. Retrieved 15 August 2024 from <https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry->

[act\\_en](#)

- Gabriel, S. A., K. E. Rosendahl, R. G. Egging, H. Avetisyan and S. Siddiqui (2012). Cartelization in Gas Markets: Studying the Potential for a “Gas OPEC”, *Energy Economics* 34, 137-152.
- Gasunie and EBN (2018). Transport en opslag van CO<sub>2</sub> in Nederland, Verkennende studie door Gasunie en EBN in opdracht van het ministerie van Economische Zaken.
- Global CCS Institute (2021). Technology Readiness and Costs for CCS: 2021, Retrieved from <https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf>
- Golombek, R., E. Gjelsvik and K. E. Rosendahl (1998). Increased Competition on the Supply Side of the Western European Natural Gas Market, *The Energy Journal*, 19(3): 1-18.
- Golombek, R., M. Greaker, L. Ma and S. Kverndokk (2023). Policies to Promote Carbon Capture and Storage Technologies. *Environmental and Resource Economics*, 85: 267–302.
- Graubner, M., K. Salhofer and C. Tribl (2021). A Line in Space: Pricing, Location, and Market Power in Agricultural Product Markets, *Annual Review of Resource Economics*, 13: 85–107.
- Grensand (2023). <https://www.projectgreensand.com/en>. Data retrieved 23 March 2023.
- Hainsch, K., T. Burandt, K. Löffler, C. Kemfert, P.-Y. Oei and C. von Hirschhausen (2021). Emission Pathways Towards a Low-Carbon Energy System for Europe: A Model-Based Analysis of Decarbonization Scenarios. *Energy Journal*, 42(5), 41-66.
- Herzog, H. J. (2011). Scaling up carbon dioxide capture and storage: From megatons to gigatons, *Energy Economics* 33, 597-604.
- Holahan, W. (1985). The welfare effects of spatial price discrimination. *American Economic Review*, 65(3), 498-503.
- Hotelling, H. (1929). Stability in Competition, *Economic Journal*, 39: 41-57.
- IEA (2011). CO<sub>2</sub> storage resources and their development: An IEA/CCUS Handbook, Retrieved from <https://iea.blob.core.windows.net/assets/42d294af-ce07-44c7-9c96-166f855088e8/CO2storageresourcesandtheirdevelopment-AnIEACCUSHandbook.pdf>
- IEA (2020). Energy Technology Perspectives 2020, Retrieved from [https://iea.blob.core.windows.net/assets/7f8aed40-89af-4348-be19-c8a67df0b9ea/Energy\\_Technology\\_Perspectives\\_2020\\_PDF.pdf](https://iea.blob.core.windows.net/assets/7f8aed40-89af-4348-be19-c8a67df0b9ea/Energy_Technology_Perspectives_2020_PDF.pdf)
- IEA (2023). *World Energy Outlook 2023*, International Energy Agency, Paris.
- IPCC (2022). *Climate Change 2022: Mitigation of Climate Change*. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.
- Lohwasser, R. and R. Madlener (2012). Economics of CCS for coal plants: Impact of investment costs and efficiency on market diffusion in Europe, *Energy Economics* 34, 850-863.
- Maskin, E. and J. Tirole (1988). A Theory of Dynamic Oligopoly, II: Price Competition, Kinked Demand Curves, and Edgeworth Cycles, *Econometrica*, 56, 571-599.
- Massol, O. and A. Banal-Estañol (2018). Market power and spatial arbitrage between interconnected gas hubs. *The Energy Journal*, 39 (Special Issue 2).
- Mérel, P. R. and R. J. Sexton (2010). Kinked-Demand Equilibria and Weak Duopoly in the Hotelling Model of Horizontal Differentiation, *The B. E. Journal of Theoretical Economics*, 10(1), article 12.

- National Petroleum Council (2019). Meeting the dual challenge: A roadmap to at-scale deployment of carbon capture, use and storage. Chapter two – CCUS supply chains and economics, Updated March 12, 2021.
- Northern Lights (2023). <https://norlights.com/>. Data retrieved 23 March 2023.
- Norwegian Ministry of Petroleum and Energy (2019). Energi til arbeid – arbeid til energi: Nasjonal strategi for CO<sub>2</sub>-håndtering, Retrieved from <https://www.regjeringen.no/contentassets/943cb244091d4b2fb3782f395d69b05b/nno/pdfs/stm201920200033000dddpdfs.pdf>
- Osborne, M. J. and C. Pitchik (1987). Equilibrium in Hotelling's Model of Spatial Competition, *Econometrica*, 55(4), 911-922.
- Oslo Economics and Atkins (2020). Kvalitetssikring (KS2) av tiltak for demonstrasjon av fullskala CO<sub>2</sub>-håndtering, Rapport nummer D102b, Statens prosjektmodell.
- Pale Blue Dot Energy, Axis Well Technology (2015). Progressing Development of the UK's Strategic Carbon Dioxide Storage Resource. A Summary of Results from the Strategic UK CO<sub>2</sub> Storage Appraisal Project.
- Porthos (2023). <https://www.porthosco2.nl/en/>. Data retrieved 23 March 2023.
- Pindyck, R. and D. Rubinfeld (2018). *Microeconomics* (Global Edition). Ninth Edition. Pearson.
- Riviera (2024). Retrieved 28 August 2024 from <https://www.rivieramm.com/news-content-hub/news-content-hub/the-london-protocol-is-key-to-unlocking-international-co2-shipping-77700>
- Salop, S.C. (1979). Monopolistic competition with outside goods, *Bell Journal of Economics* 10(1), 141– 156.
- SCCS (2021). Building a CO<sub>2</sub> storage hub in the central North Sea, Scottish Carbon Capture & storage, <https://www.sccs.org.uk/images/expertise/briefings/SE-CO2-Hub.pdf>. Data retrieved 23 March 2023.
- Smith, E., Morris, J., Kheshgi, H., Teletzke, G., Herzog, H. and S. Paltsev (2021). The cost of CO<sub>2</sub> transport and storage in global integrated assessment modeling, *International Journal of Greenhouse Gas Control*, 109, 103367. <https://doi.org/10.1016/j.ijggc.2021.103367>.
- Thisse J.F. and X. Vives (1988). On the strategic choice of spatial price policy. *American Economic Review*, 78(1), 122-137.
- Tirole, J (1988). *The Theory of Industrial Organization*, MIT Press.
- Varian, H. (1989). Price discrimination, in Schmalensee R. and R. Willig (eds): *Handbook of industrial organization, volume 1*. North-Holland.
- Vatter, M. (2017). OPEC's kinked demand curve, *Energy Economics*, 63, 272-287.
- Wettstad, J., T. H. J. Inderberg and L. H. Gulbrandsen (2024). Exploring paths and innovation in Norwegian carbon capture and storage policy, *Environmental Policy and Governance* 34, 125–136.
- van der Zwaan, B and R. Gerlagh (2016). Offshore CCS and ocean acidification: a global long-term probabilistic cost-benefit analysis of climatic change mitigation, *Climatic Change* 137, 157-170.
- Yin, X. (2004). Two-part tariff competition in duopoly, *International Journal of Industrial Organization*, 22, 799-820.

## Appendix A: Additional material to Section 8 (Partial competition)

The right derivative  $\pi_A'(p_A^+)$ , see (39), is the same as  $\pi_A'(p_A)$  in (11) since in both cases demand is given by (8). Hence, inserting from (11) we get

$$\bar{d} + (p_A - z_A)\left(-\frac{1}{t}\right) \leq 0$$

i.e.,

$$p_A \geq z_A + t\bar{d} \quad (56)$$

Inserting (35) and (38) in (56), and rearranging we find

$$\Delta \leq \tau - x - z_A - tL \quad (57)$$

The left derivative  $\pi_A'(p_A^-)$ , see (40), is the same as the derivate under full competition.

Using (21), (40) can be written as

$$\bar{d} + (p_A - z_A)\left(-\frac{1}{2t}\right) \geq 0 \quad (58)$$

i.e.,

$$p_A \leq z_A + 2t\bar{d} \quad (59)$$

Inserting (35) and (38) and rearranging, we find

$$\Delta \geq \frac{2}{3}(\tau - x - z_A) - tL \quad (60)$$

Combining (57) and (60) gives us

$$\frac{2}{3}(\tau - x - z_A) - tL \leq \Delta \leq (\tau - x - z_A) - tL \quad (61)$$

Proceeding in the same way with storage firm B, we obtain

$$\frac{2}{3}(\tau - x - z_B) - tL \leq -\Delta \leq (\tau - x - z_B) - tL \quad (62)$$

For  $\tau = \tau^*$ , inserting (16) into the right inequalities in (61) and (62) gives

$$\Delta \leq \frac{z_B - z_A}{2}$$

and

$$-\Delta \leq -\frac{z_B - z_A}{2}$$

implying

$$\Delta = \frac{z_B - z_A}{2} \quad (63)$$

For this case there is hence a unique Nash equilibrium, giving (from (35))

$$p_A = z_A + \frac{tL}{2} + \frac{z_B - z_A}{4} \equiv p_A^* \quad (64)$$

i.e., the same price as we derived earlier for the limiting case of  $\tau = \tau^*$  when there was no competition, see (17).

Turning now to the case of  $\tau = \tau^{**}$ , inserting (29) into the left inequalities in (61) and (62) gives

$$\Delta \geq \frac{z_B - z_A}{3}$$

and

$$-\Delta \geq -\frac{z_B - z_A}{3}$$

implying

$$\Delta = \frac{z_B - z_A}{3} \quad (65)$$

Also for this case there is hence a unique Nash equilibrium, giving (from (35))

$$p_A = z_A + tL + \frac{z_B - z_A}{3} \equiv p_A^{**} \quad (66)$$

i.e., the same price as we derived earlier for the limiting case of  $\tau = \tau^{**}$  when there was full competition.

We now turn to the case of  $\tau \in (\tau^*, \tau^{**})$ . Let  $\tau = \tau^* + k$  where  $0 < k < \tau^{**} - \tau^*$ . Proceeding as we did after (62), the right inequalities in (61) and (62) give

$$\Delta \leq \frac{z_B - z_A}{2} + k \quad (67)$$

and

$$\Delta \geq \frac{z_B - z_A}{2} - k \quad (68)$$

Using  $\tau = \tau^* + k = \tau^{**} - [(\tau^{**} - \tau^*) - k]$ , the left inequalities in (61) and (62) give

$$\Delta \geq \frac{z_B - z_A}{3} - \frac{2}{3}[(\tau^{**} - \tau^*) - k] \quad (69)$$

and

$$\Delta \leq \frac{z_B - z_A}{3} + \frac{2}{3}[(\tau^{**} - \tau^*) - k] \quad (70)$$

Clearly, there is a range of  $\Delta$  values satisfying these two inequalities.

Finally, we study the range of possible equilibria for  $p_A$  (it is straightforward to repeat this analysis for  $p_B$ ). We first consider the lower bound  $\ell^A(\tau)$  for  $p_A$ . From (35) and the right inequality in (61) we have

$$p_A \geq \tau - x - \frac{tL}{2} - \frac{1}{2}(\tau - x - z_A - tL) = \frac{1}{2}(\tau - x + z_A) \quad (71)$$

From (35) and the left inequality in (62) we have

$$p_A \geq \tau - x - \frac{tL}{2} + \frac{1}{2} \left[ \frac{2}{3}(\tau - x - z_B) - tL \right] = \frac{4(\tau - x) - z_B - tL}{3} \quad (72)$$

It follows that the lower bound  $\ell^A(\tau)$  for  $p_A$  is

$$\ell^A(\tau) = \text{Max} \left[ \frac{\tau - x + z_A}{2}, \frac{4(\tau - x) - z_B - tL}{3} \right] \quad (73)$$

We now turn to the upper bound  $u^A(\tau)$  for  $p_A$ . From (35) and the right inequality in (62) we have

$$p_A \leq \tau - x - \frac{tL}{2} + \frac{1}{2}(\tau - x - z_B - tL) = \frac{3(\tau - x) - z_B}{2} - tL \quad (74)$$

From (35) and the left inequality in (61) we have

$$p_A \leq \tau - x - \frac{tL}{2} - \frac{1}{2} \left[ \frac{2}{3}(\tau - x - z_A) - tL \right] = \frac{2(\tau - x) + z_A}{3} \quad (75)$$

It follows that the upper bound  $u^A(\tau)$  for  $p_A$  is

$$u^A(\tau) = \text{Min} \left[ \frac{2(\tau - x) + z_A}{3}, \frac{3(\tau - x) - z_B}{2} - tL \right] \quad (76)$$

From the expressions for the lower and upper bounds for  $p_A$  it is clear that both bounds are higher the higher is the carbon price  $\tau$ .

Consider next the profit of storage site A, given by (41). It immediately follows from (43) and the right inequality in (61) that  $\pi_A(\Delta)$  is maximized when  $\Delta$  is at the highest level that is consistent with the inequalities (61) and (62).

Differentiating the expression (44) for joint profits and using (35)-(38) gives us

$$\Pi'(\Delta) = \left[ (p_A - p_B - z_A + z_B) \bar{d}'(\Delta) + p_A'(\Delta) \bar{d} + p_B'(\Delta)(L - \bar{d}) \right] \frac{E}{L} = \left[ (-\Delta + z_B - z_A) \frac{1}{2t} - \frac{\bar{d}}{2} + \frac{L - \bar{d}}{2} \right] \frac{E}{L}$$

Inserting from (38) and setting  $\Pi'(\Delta) = 0$  gives us (45).

## **Appendix B: Cost elements of CCS**

### **Part I The Hotelling line**

We have constructed three, alternative (piece-wise) lines to represent the fact that cost of transport of CO<sub>2</sub> to a storage site differs across plants, see Figure B.1. For each piece-wise line, we assume that its endpoints are located at Northern Lights in Øygarden (Norway) and at Captain X in St Fergus Beach Head (the UK).

The panel to the right in Figure B.1 shows the case with a piecewise line that runs from Norway to the UK through Denmark, Belgium and the Netherlands, using a route not along the coastlines. The panel in the middle shows the corner case of a straight line from Øygarden to St. Fergus. Whereas the panel in the middle clearly underestimates the distance between a plant and the closest endpoint on the line, the panel to the right may overestimate this distance. Therefore, we use the intermediate case (the panel to the left) with a piecewise line that runs from Norway to the UK through Denmark, Belgium and the Netherlands, using a route along the coastlines, as the reference case. Here, the length ( $L$ ) of the piece-wise line is 2000 km, whereas the length in the two other panels is 500 km and 2400 km.

### **FIGURE B.1 ABOUT HERE**

Figure B.1 *Three approximations of the Hotelling line.*

### **Part II: More information on cost of storage**

#### **Cost of capture**

Cost of capture in industrial processes depends on the concentration of CO<sub>2</sub> in the gas stream: the higher the concentration, the more efficient is the capture of carbon. Also, economies of scale is crucial for cutting costs of captures: a doubling of capture capacity is expected to lower unit capital cost by 25%, see Global CCS Institute (2021). Taking these factors into account, CATF (2022), building on National Petroleum Council (2019) and Carbon Limits (2021), provides estimates for different types of cost of capture and how these differ by emission source,

see Table B.1. The weighted average of the unit cost of capture, using the numbers in column 2 (CO<sub>2</sub> capture) as weights, is 95 EUR/tCO<sub>2</sub>.<sup>8</sup>

## TABLE B.1 ABOUT HERE

Table B.1 Cost of capture

In Norway, there are currently two CCS projects underway: Norcem and Hafslund Celsio (HC), former Fortum Oslo Varme. Oslo Economics and Atkins (2022) provides estimates of total capital expenditures (CAPEX) and total operational expenditures (OPEX) for cost of capture for these two projects. These estimates can be transformed to cost per ton of CO<sub>2</sub> captured, see Table B.2.

## TABLE B.2 ABOUT HERE

Table B.2 Cost of capture for the two Norwegian projects Norcem and Hafslund Celsio. The numbers are collected from Oslo Economics and Atkins (2020) and then transformed from NOK<sub>2021</sub> to EUR<sub>2023</sub>. The numbers in Oslo Economics and Atkins (2020) were constructed under the assumptions of a life time of 10 years, a real discount rate of 4%, and 0.4 million ton of captured CO<sub>2</sub> per year.

According to Table B.2, for the Norcem project there is a 50% probability that total cost of capture is lower than 111 EUR/tCO<sub>2</sub>, and a 85% probability that total cost of capture is lower than 129 EUR/tCO<sub>2</sub>. The cost estimates for Hafslund Celsio are even higher. On the other hand, the cost estimates in Bennæs *et al.* (2023) and Bennæs *et al.* (2024) for various sectors in Germany (energy, metal, chemical, minerals, paper and pulp) are much lower; they vary from 30 to 90 EUR/tCO<sub>2</sub>. As a compromise, in our reference scenario we use the weighted average of the cost estimates in Table B.1, 95 EUR/tCO<sub>2</sub>, but we also explore how the equilibrium

---

<sup>8</sup> In Table B.1 there are three alternatives for CCS from coal power plants, and also three alternatives for CCS from natural gas (NG) power plants. These differ with respect to level of CO<sub>2</sub> storage. We use the intermediate level to calculate the weights.

changes if this cost estimate is one third lower, see Section 11.2 under simulations. The latter corresponds to the average in Bennæs *et al.* (2023, 2024).

### **Cost of transport**

CO<sub>2</sub> can be transported by pipelines, ships, trucks, and rails. Studies clearly suggest that for large volumes, pipelines is the cheapest option. However, pipeline costs are remarkably high for small volumes, but unit costs are falling rapidly with quantity. Also, there is a potential cost reduction between 53% to 82% in using existing oil and gas pipes to transport captured CO<sub>2</sub>, see Carbon Limits (2021). Table B.3 provides cost of transport of captured carbon by different means of transport. In the present study, we use 0.04 EUR/tCO<sub>2</sub> km, which is close the cost of using ship to transport captured carbon in Table B.3.

### TABLE B.3 ABOUT HERE

Table B.3 Cost of transport of captured CO<sub>2</sub>.

### **Cost of storage**

The International Energy Agency (IEA, 2011) identifies three main types of storage for captured CO<sub>2</sub>: storage connected to enhanced oil recovery, storage in saline formations, and storage in depleted oil and gas fields.

Enhanced oil recovery has been used for the last 50 years. Even though the primary purpose is to maximize oil recovery as part of the oil extraction process, the CO<sub>2</sub> is permanently stored (IEA, 2020). Storage in saline formations has a high technology readiness level (TRL), and projects have shown that CO<sub>2</sub> can be injected at a rate of 1 million tonnes per annum (mtpa) (Global CCS Institute, 2021). Costs depend on characteristics like storage capacity and injection rate.

The majority of the storage capacity is located in saline formations in the North Sea. Table B.4 shows cost estimates and storage characteristics for some storage sites in the North Sea. Information on the first seven sites has been taken from Pale Blue Dot (2015). For these storage sites, the levelized unit cost for offshore transport and storage ranges from 7.81 to 16.5 £ per

ton. Bennæs (2024) uses a cost of storage at 6 euro per ton, assuming a saline aquifer geological storage with an annual capacity of 200 Mton.

#### TABLE B.4 ABOUT HERE

Table B.4 Cost of storage for North Sea sites.

Reported cost of CO<sub>2</sub> storage for the U.S. ranges from 6.24 to 16.47 USD<sub>2019</sub> per ton, depending on the amounts of stored CO<sub>2</sub> (Smith, 2021), and may be even higher if there are extra monitoring costs. The Clean Air Task force assumes that cost of transport and storage in Europe amounts to 18 EUR per ton of CO<sub>2</sub> (Carbon Limits, 2022), which is the estimate we use in the present study. Note that this number includes cost of transport from the mainland (i.e., the endpoint of the Hotelling line) to the storage site.

## Appendix C: Economies of scale

In Section 7, we showed that if it is socially optimal to use both storage sites, then this will be the outcome under full competition, see the discussion after (27). Furthermore, in Section 11.1 we showed that if: i) storage costs are equal for storage firms A and B, ii) firm B has a fixed cost  $F$  that is at least as high as the fixed cost of firm A, and iii) it is socially optimal for all plants to invest in capture facilities, then it is socially optimal to use both storage sites if  $F < tLE/4$ , see equation (54).

To estimate the parameter  $F$ , we need to identify how much of the total cost of storage that can be considered fixed. We use the following empirical strategy: First, we find total emissions prior to any investment in capture facilities. Here, we use data from Golombek et. al. (2021) on emissions in electricity generation and in some manufacturing sectors with large emissions, restricting attention to the countries on our Hotelling “line”. Next, we multiply this amount of emissions (117 mtCO<sub>2</sub>) with the reference unit cost of storage (18 EUR/tCO<sub>2</sub>), to obtain total cost of storage (1800 million EUR). Hence, with two identical storage sites total storage cost of each site amounts to 900 million EUR.

Next, we use information from Pale Blu Dot (2015) on the division between Capex and Opex for a number of potential storage fields in the UK. These data suggest that the share of Capex is roughly 50%, see Table C.1. With a Capex share of 50%, we find that the fixed cost of a storage site amounts to 450 million EUR. Hence,  $F = 450$  million EUR  $< \frac{tLE}{4} = 2340$  million EUR.<sup>9</sup> Hence, it is optimal to use both storage sites.

TABLE C.1 ABOUT HERE

Table C.1 *Capex and Opex for different storage sites in the UK in million £<sub>2015</sub>. Source: Pale Blu Dot (2015).*

---

<sup>9</sup> Under our assumptions on how to estimate the fixed cost  $F$ , the inequality  $F < tLE/4$  is in fact independent of the size of total emissions,  $E$ .

## Appendix D: Sequential moves

Under sequential moves, firm  $A$  moves first and decides its price, which again determines how much of the Hotelling line it will cover. When firm  $B$  invests in the second period, it decides if it wants to cover the rest of the market, i.e., what is left of the market after firm  $A$  has signed contracts with plants, or only a part of this market. In the latter case, condition (16) is met, and the carbon price is too low to make it profitable for all plants to invest in capture equipment. Thus, we enter into a situation with two separate markets, which is similar to the no competition case above. With *no-competition*, it does not matter if there is a first mover. The two storage actors operate in separate markets, and as long as there is no learning, the outcome will be as in Section 6.

If  $B$  decides to take the rest of the market, we will enter into a situation with competition. Firm  $A$  will not necessarily behave as a monopolist in this case. The reason is the following. As before, we assume that plants are forward-looking, rational agents. This means that if firm  $A$  invests in storage facilities, plants will predict the responses of storage firm  $B$ . Thus, whether they will sign a contract with  $A$ , depends on their predictions of the behavior of  $B$ . A plant will, therefore, not sign a contract with  $A$  if it predicts that it will be more profitable to wait for the offer from  $B$ , even if signing a contract and investing in capture equipment would be more profitable than paying the carbon price. Thus, as storage actor  $A$  knows this, it will take the response from  $B$  into account when setting its price, and pick the price on the response curve of  $B$  that gives her the highest profit.<sup>10</sup> In the analysis below, we start with the general case with heterogeneous storage firms, before we derive solutions with homogeneous firms.

### Full competition

Under full competition, equation (20) remains valid. Moreover, firm  $B$ 's response function is as before given by (22). These two equations give  $p_B$  and  $\bar{d}$  as functions of  $p_A$ . In particular, we find

---

<sup>10</sup> We can distinguish between two different cases when there is sequential moves. One possibility is that it will “take some time” before storage actor  $B$  invests after the investment of storage actor  $A$ . Now, even if plants located far away from  $A$  predict that they would benefit from signing a contract with  $B$  instead of  $A$ , they may still want to sign up with  $A$  at the price  $A$  offers, if it is profitable to invest in carbon capture instead of paying the carbon price. The reason is that they need to pay the carbon price while waiting for  $B$  to invest. The longer time it takes before  $B$  invests, the less profitable will it be to wait for  $B$ , and the more monopoly power is obtained by  $A$ . Thus,  $A$  will capture a higher market share and  $B$  will set its price so that it will cover the rest of the market. However, the more interesting case is when the time lag is “not too long”, which we discuss below.

$$\bar{d} = \frac{3}{4}L + \frac{1}{4t}(z_B - p_A) \quad (77)$$

implying

$$\frac{\partial \bar{d}}{\partial p_A} = -\frac{1}{4t} \quad (78)$$

As before, the profit of firm A is given by  $\pi_A = (p_A - z_A)\bar{d}E / L$ . Maximizing profits hence gives

$$\bar{d} + (p_A - z_A)\frac{\partial \bar{d}}{\partial p_A} = 0 \quad (79)$$

Inserting from (77) and (78) gives

$$p_A = \frac{3}{2}tL + \frac{z_A + z_B}{2} \equiv p_A^{***} \quad (80)$$

Inserting this equation and (77) into (20) gives

$$p_B = \frac{5}{4}tL + \frac{z_A + 3z_B}{4} \equiv p_B^{***} \quad (81)$$

For the further discussion of this case, we restrict ourselves to the special case where  $z_A = z_B = z$ . As in the simultaneous move game, the condition (28) must hold in order to have the equilibrium with full competition. Inserting (77) and (80) into (28) (with  $z_A = z_B = z$ ) we obtain

$$\tau > \frac{15}{8}tL + x + z \equiv \tau^{***} \quad (82)$$

With simultaneous moves, the corresponding limit for  $\tau$  was (from (29))

$$\tau > \tau^{**} = \frac{3}{2}tL + x + z = \frac{12}{8}tL + x + z \quad (83)$$

We immediately see that  $\tau^{***} > \tau^{**}$ .

The reason that the carbon price must be higher under sequential moves than under simultaneous moves to sustain an equilibrium with full competition is that the both storage actors charge a higher price than with simultaneous moves. To see this, we insert  $z_A = z_B = z$  in (80) and (81) and get

$$p_A^{***} = \frac{3}{2}tL + z \quad (84)$$

and

$$p_B^{***} = \frac{5}{4}tL + z \quad (85)$$

For the case of simultaneous moves we had (from (23) and (24))

$$p_A^{**} = p_B^{**} = tL + z \quad (86)$$

Comparing the two games, it hence follows that both firms have a higher price in the sequential move game than in the simultaneous move game. As in the textbook model (see, e.g., Pindyck and Rubinfeld, 2018), the price difference is largest for the first mover.

To see how the market is split between  $A$  and  $B$  when  $A$  is a first mover, we insert (84) into (77) and find

$$\bar{d} = \frac{3}{8}L. \quad (87)$$

With equal costs and simultaneous moves, we see from (26) that  $A$  and  $B$  will split the market equally. It therefore follows from the equation above that the market share of the first mover is lower than in the case with simultaneous moves, as in the standard textbook model. This follows from a higher price increase for  $A$  than for  $B$  with sequential moves, compared to the common price with simultaneous moves.

To see if the firms profit from sequential moves compared to simultaneous moves, we have to compare the profits. With simultaneous moves, we find the profits for  $A$  and  $B$  by setting (86) and  $\bar{d} = L/2$  into the profit functions:

$$\pi_A^{**} = \pi_B^{**} = \frac{1}{2}tLE \quad (88)$$

As the firms are equal and moves simultaneously, they obtain the same profit. In a similar way, we find profits with sequential moves by using (84), (85) and (87):

$$\pi_A^{***} = \frac{9}{16}tLE \quad (89)$$

$$\pi_B^{***} = \frac{25}{32}tLE \quad (90)$$

Thus, both  $A$  and  $B$  gain from sequential moves compared to simultaneous moves, but the second mover gains the most as is the standard textbook result. Using (88), (89) and (90), we find that the profit of  $A$  is 28% lower than the profit of  $B$  under sequential moves, whereas the profit of  $A$  under simultaneous moves is 1/16 lower than under sequential moves.

### Partial competition

In analyzing the case of partial competition, we restrict ourselves to the case of equal storage costs, i.e.,  $z_A = z_B = z$ . From the analysis above, we first note the interval of carbon prices that gives partial competition has increased with sequential moves compared to simultaneous moves as the outcome with no competition is the same, and the carbon price necessary to have full competition is higher with sequential moves ( $\tau^{***} > \tau^{**}$ ). As before, the equilibrium with partial competition must satisfy the equations (35)-(38). Since firm  $A$  now moves first, it can choose the value of  $\Delta$ , i.e.,  $p_B - p_A$ , that maximizes its profit, subject to the constraint that the equilibrium following from (35) – (38) is the best response for firm  $B$ . The values of  $\Delta$  that satisfy the best response conditions for  $B$  are the values that satisfy the inequalities (62), since these two inequalities followed directly from the profit maximization conditions for  $B$ .

Equations (41) and (43) remain valid, so that the preferred value of  $\Delta$  for firm  $A$  is  $\Delta = \tau - x - z - tL$ . This value satisfies the left inequality in (61) for “small” values of  $\tau$ . But for “large” values of  $\tau$  the optimal feasible value of  $\Delta$  for firm  $A$  is the upper limit of  $\Delta$  given by the right inequality in (61). More precisely, it is straightforward to derive the following:

$$\begin{aligned} \Delta = \tau - x - z - tL \quad & \text{for } \tau \in \left[ \tau^*, x + z + \frac{6}{5}tL \right] \\ \Delta = tL + x + z - \frac{2}{3}\tau \quad & \text{for } \tau \in \left[ x + z + \frac{6}{5}tL, \tau^{***} \right] \end{aligned} \tag{91}$$

Notice that  $\Delta$  increases from 0 as  $\tau$  increases from  $\tau^*$ , but declines once  $\tau$  reaches  $x + z + 6tL/5$ , and passes 0 as  $\tau$  passes  $\tau^{**}$ .

In the simultaneous move game, there was a continuum of equilibria for  $\tau \in (\tau^*, \tau^{**})$ . In the sequential move game the equilibrium is unique, and for  $\tau \in (\tau^*, \tau^{**})$  this equilibrium is equal to the equilibrium in the simultaneous move game that is best for firm  $A$  (and worst for firm  $B$ ).

As mentioned in Section 8,  $A$  prefers the Nash equilibrium with the lowest price, and it is now able to choose this price as it moves first.

For values of  $\tau$  between  $\tau^{**}$  and  $\tau^{***}$ , both storage firms have higher profits than they have in the simultaneous move game. For  $B$ , this follows from the fact that  $p_A$  is higher in the sequential move game than in the simultaneous move game, implying higher demand facing firm  $B$ . For  $A$ , the reason is that for  $\tau > \tau^{**}$ ,  $A$  could have set its price equal to  $p_A^{**}$  and obtained the same outcome as in the simultaneous move game. The reason why  $A$  instead chooses a higher price is that it obtains a higher profit by doing so.

To summarize, when firms have equal storage costs and there is partial competition with firm  $A$  moving first,  $p_A < p_B$  for  $\tau \in (\tau^*, \tau^{**})$  and  $p_A > p_B$  for  $\tau \in (\tau^{**}, \tau^{***})$ .

### Learning

If we introduce *learning* from  $A$  to  $B$  in this model, so that the storage cost of  $B$  falls if it is a second mover, the advantage of being the second mover will be even higher. In this case,  $B$  will profit from being the second mover also in the case with no competition, and what would be an equilibrium with no competition under simultaneous moves could end up as an equilibrium with competition under sequential moves and learning because the market that  $B$  covers,  $(L - d_B)$ , expands. Under competition,  $B$ 's response curve will shift with learning as its costs will be reduced, and it can easily be shown that a lower value of  $z_B$  will sustain a lower  $p_B$  for every  $p_A$ . Because  $B$  has the possibility to choose the same price as with no learning, the shift in the response curve reflects that  $B$  benefits from the new price.

## Appendix E: Heterogeneous plants

In the reference model, we assumed that the cost of investment was the same for plants. We now examine the case where the cost of investment differs across plants.

At each location  $d$  we assume that there is a continuum of plants with different unit capture costs, ranging uniformly from  $\underline{x}$  to  $\bar{x}$ , e.g., reflecting that plants belong to different sectors.<sup>11</sup> Let  $\hat{x}_d$  denote the unit cost of investment of a plant located at  $d$  which is indifferent between paying the carbon price  $\tau$  and investing in carbon capture facilities. Hence, plants with a lower unit cost than  $\hat{x}_d$  at location  $d$  will invest in capture facilities. Due to the difference in transport costs, at a location  $d'$  close to a storage site, all plants may invest, i.e.,  $\hat{x}_{d'} \geq \bar{x}$ , whereas at a location  $d''$  located far from the storage sites, no plant may invest, i.e.,  $\hat{x}_{d''} \leq \underline{x}$ .

The market outcome in the present case has two similarities and two differences compared with the market outcome studied in Sections 5-9. The similarities are for the cases of no competition and full competition, while the two differences are for partial competition.

As before, there is no competition if the carbon price is below  $\tau^*$ . As in our previous case,  $\tau^*$  is given by (16), except that instead of  $x$  in this expression we have  $\underline{x}$ , i.e., the lowest investment cost: when even the lowest-cost plants at a location do not invest, none of the other plants at this location will invest.

Also, as before, there is full competition for a carbon price above  $\tau^{**}$ . As in our previous case,  $\tau^{**}$  is given by (29), except that instead of  $x$  in this expression we have  $\bar{x}$ , i.e., the highest investment cost: when the highest-cost plants at a location invest, all of the other plants at this location will also invest.

For carbon prices between  $\tau^*$  and  $\tau^{**}$  we have partial competition. Note that the difference between  $\tau^{**}$  and  $\tau^*$  is now greater than in Section 8. In an equilibrium with partial competition, there will as before be a marginal location  $\bar{d}$  where any plants investing will be indifferent between storage sites  $A$  and  $B$ . Also, at the location  $\bar{d}$  there will be a plant with

---

<sup>11</sup> Alternatively, one can think that the Hotelling line is divided into many tiny segments, each being equally long, and that in each segment the unit cost of investment is uniformly distributed from  $\underline{x}$  to  $\bar{x}$ . We study the limiting case where the length of each segment approaches zero (and for any segment the unit cost of investment is uniformly distributed from  $\underline{x}$  to  $\bar{x}$ ).

marginal cost level  $\hat{x}_{\bar{d}}$ ; this plant will be indifferent both between investing or not, and between which storage site it uses if it invests. For this plant, the quantity response to a price change will be different for a price increase and a price reduction, as explained in Section 8.

At the location  $\bar{d}$ , there will be plants with lower costs than  $\hat{x}_{\bar{d}}$ . These plants will for sure invest in carbon capture, but they will be indifferent between storage sites *A* and *B*. Hence for these customers (i.e., plants) there is competition between storage firms *A* and *B*. For these plants, the quantity response to a price change will be symmetric for a price increase and a price reduction.

At all locations  $d < \bar{d}$  there will be plants with costs above  $\hat{x}_{\bar{d}}$  that are indifferent between investing or not, but if they invest they for sure will choose storage site *A*. The quantity response to a price change will also for these plants be symmetric for a price increase and a price reduction.

The market outcome under partial competition differs in two ways from our previous results. First, while all plants invested in carbon capture under partial competition in Section 8, in the present case there will be plants that do not invest. Therefore, in the present case the size of the carbon price will affect the total amount of carbon capture, while in Section 8 the carbon price only affected the distribution of the captured carbon across storage sites.

The second difference relates to the uniqueness of the equilibrium. With equal investment costs, the Nash equilibrium was not unique in Section 8. The reason for this was that the storage firms faced kinked demand curves. Also in the present case, the demand from the plant at location  $\bar{d}$  with unit cost  $\hat{x}_{\bar{d}}$  responds asymmetrically to a price increase and a price reduction. The demand curve from the plant at location  $\bar{d}$  is hence kinked.

There will be a kinked demand curve for each plant at each location. However, when investment costs differ, the kink will be at different prices for different plants. These kinks will vanish when we aggregate all demand curves, since the demand curve for each plant will be of measure zero relative to the aggregate demand curve. Hence, the aggregate demand curve will not be kinked, and the equilibrium will be unique. This is similar to the findings in

Merel and Sexton (2010) when they consider elastic demand instead of unitary demand combined with a reservation price.<sup>12</sup>

Although heterogeneous capture costs seem more realistic than identical costs, unit costs that are uniformly distributed between a lower and an upper bound is also a simplification. In reality, unit costs typically vary discretely, as do location of plants. Discrete location and costs are obviously more difficult to analyze than continuous location and costs. One interesting alternative would be to consider two discrete alternative cost levels (e.g.,  $\underline{x}$  and  $\bar{x}$ ). Then we may again have a situation with multiple equilibria under partial competition.

---

<sup>12</sup> Merel and Sexton (2010) write in their footnote 15: "This result corrects a misconception in the literature, namely that the kink survives the introduction of elasticity into consumer demands."

## Appendix F: More storage firms

In the reference model, there is one storage firm at each end of the Hotelling line. We now consider the case of  $N > 2$  firms. Hence  $N - 2$  firms have two neighbors, whereas each firm at the end of the line has one neighbor only. The distance between each pair of neighbors is still  $L$ .

Remember that the unit cost of each firm is constant. For a storage firm, the price game with its neighbor to the left therefore has no impact on the price game with its neighbor to the right from a cost perspective. We now examine whether the price game with the neighbor to the left has impact on the price game with the neighbor to the right with respect to the prices offered in the games. If not, the outcome discussed in Sections 7 and 8 are valid also for the case of  $N > 2$  firms.

In this particular extension, it makes most sense to focus on the case where storage costs are the same across storage firms, henceforth referred to as  $z$ . To economize with the notation, a firm  $i$  is referred to as  $A(B)$  in the game with the neighbor to the right (left). We consider the case where there is full competition when  $N = 2$ , i.e.,  $\tau > \tau^{**}$ . Then we know from (23) and (24) that  $p_i = z + tL \equiv p_i^{**}$  for  $i = A, B$ . Consider next the case where  $N > 2$ . We want to examine whether  $p_i = p_i^{**}$  is still a Nash equilibrium, or whether a storage firm has incentives to choose a different price, given that all other storage firms choose  $p_i = p_i^{**}$ .

Consider firm  $A$ , which is located at one end of the Hotelling line. The demand function for  $A$  is given by (20), which now reads:

$$d_A = \frac{p_i^{**} - p_A + tL}{2t}$$

Plugging this into the profit function, and maximizing with respect to  $p_A$ , we find that  $p_A = p_i^{**}$  is still the optimal price for  $A$ . The same holds if we consider a storage firm not located at the end of the Hotelling line. Thus, with more firms and given that the distance between each pair of neighboring firms remains unchanged,  $p_i = p_i^{**}$  for all  $i$  is still a Nash equilibrium. This gives us Proposition 4.

If instead the length of the Hotelling line is unchanged, so the distance between each pair of neighboring firms decreases as more storage firms enter, the outcome obviously changes. From the discussion above, however, it follows that this outcome would be the same as when reducing the length between firms  $A$  and  $B$  as long as  $\tau > \tau^{**}$ .

## Appendix G: Price discrimination

In Section 6-9, we analyzed the game under the assumption that each storage firm had to impose the same price on all its clients. We now consider the opposite case; each storage firm can perfectly price discriminate across its clients.<sup>13</sup>

It is well known that under monopoly, perfect price discrimination makes the market outcome identical to the social optimum.<sup>14</sup> Moreover, the whole social surplus is in this case captured by the monopolist. These results are valid for our model either when the social optimum has only one storage site, see discussion in Section 11.1, or when it is socially efficient that only some of the plants invest in carbon capture facilities. In these cases there is either one monopoly or two separate monopolies, and the monopolist therefore sets the price for a plant at location  $d$  equal to (or actually marginally below) this plant's maximum willingness to pay for storage. The latter is equal to the emission price minus the sum of the plants capture cost and transportation cost (i.e.,  $\tau - x - td$  for firm  $A$ ). Hence, all plants that have a willingness to pay that is above the storage cost will invest in capture facilities in this socially efficient equilibrium.

Next, consider the case where it is socially efficient that all plants invest in carbon capture. Here, we have a similar result. In this case, all plants have a willingness to pay for storage that exceeds the storage cost of at least one of the storage firms. Hence, it will always be optimal for one of the storage firms to offer a price to each plant that makes it optimal for the plant to invest in carbon capture. Hence, the equilibrium is characterized by all plants investing in carbon capture, like in the social optimum. It is socially efficient that each plant is served by the storage firm for which the cost of storage plus transportation is lowest. This is the outcome in the market equilibrium. To see this, consider the case  $z_A + td > z_B + t(L - d)$ , so that it is socially optimal for plant  $d$  to be served by storage firm  $B$ . In this case the lowest price  $A$  can offer (without making a loss) is higher than the lowest price  $B$  can offer. Hence, the equilibrium must be characterized by  $B$  winning the offer, and thus the social optimum is achieved.

Unlike the monopoly case, with two competing storage firms the sum of the profits of the storage firms will be lower than the social surplus, because competition between the storage firms will set an upper limit to the price a storage firm can offer without losing the customer to the other storage firm.

---

<sup>13</sup> For a discussion on price discrimination by buyers along a line, see, for example, Thisse and Vives (1988) and also Graubner *et al.* (2021) for an overview.

<sup>14</sup> See e.g. Varian (1989) and the references given there.

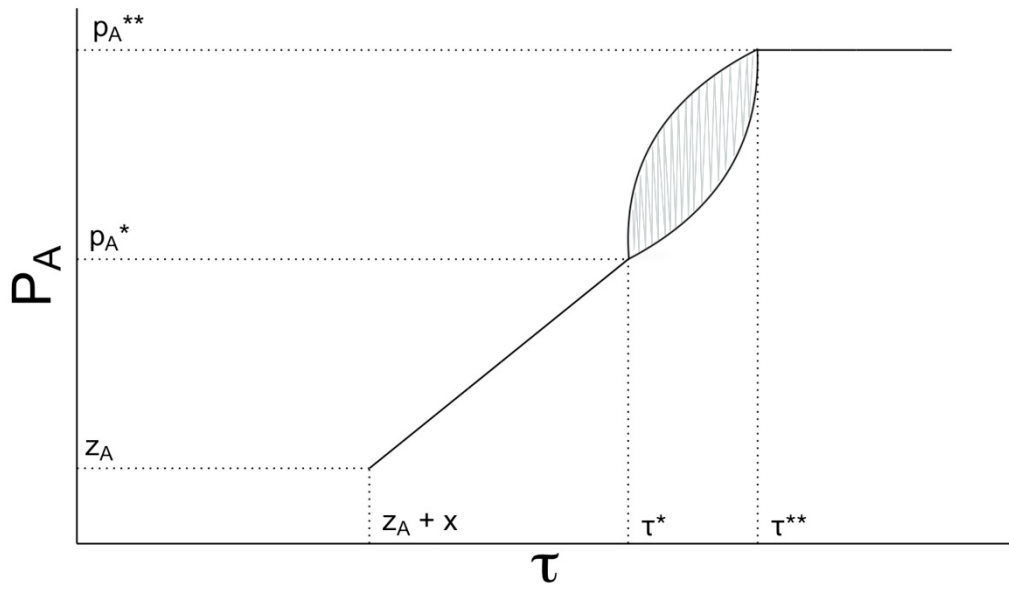


Figure 1

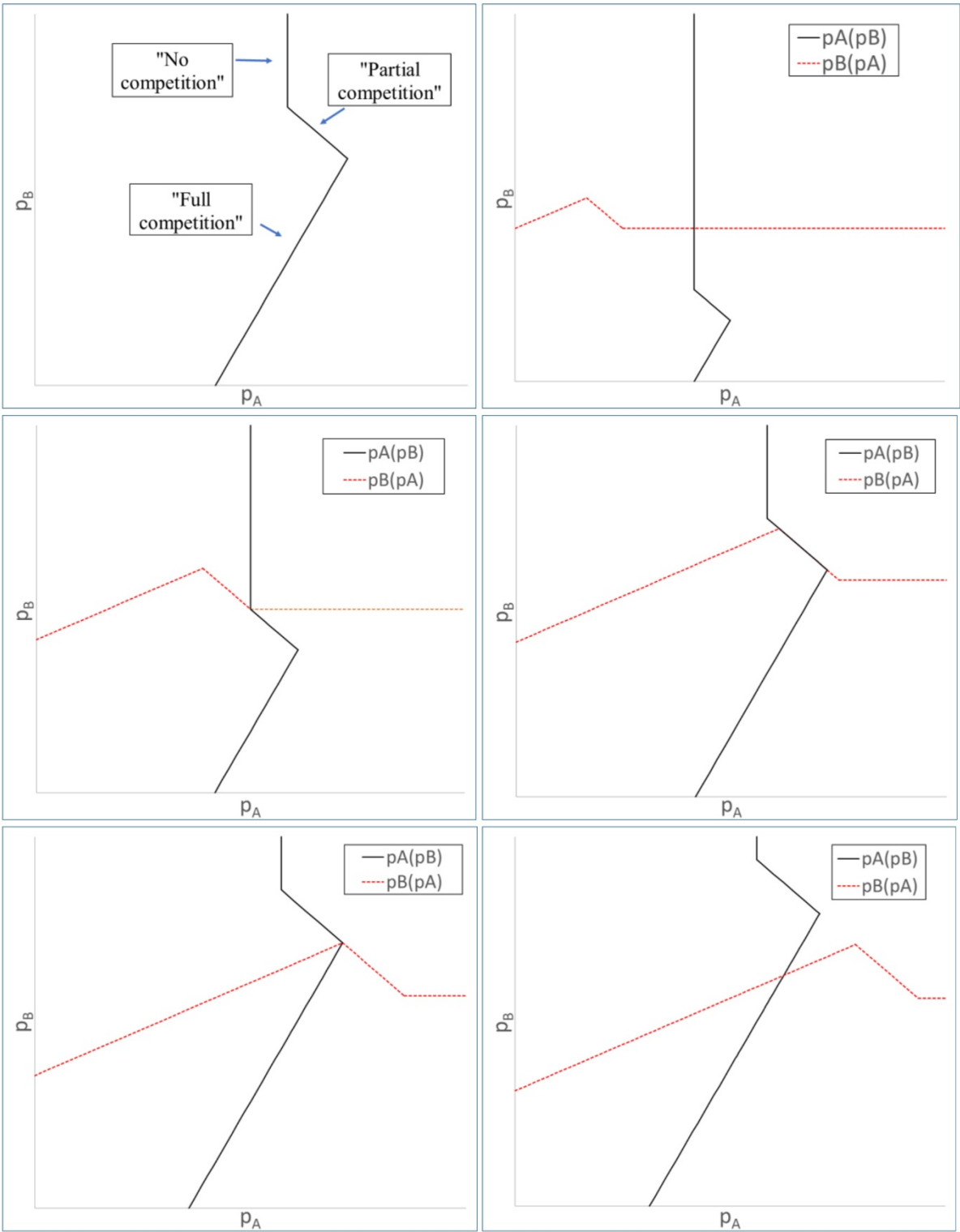


Figure 2

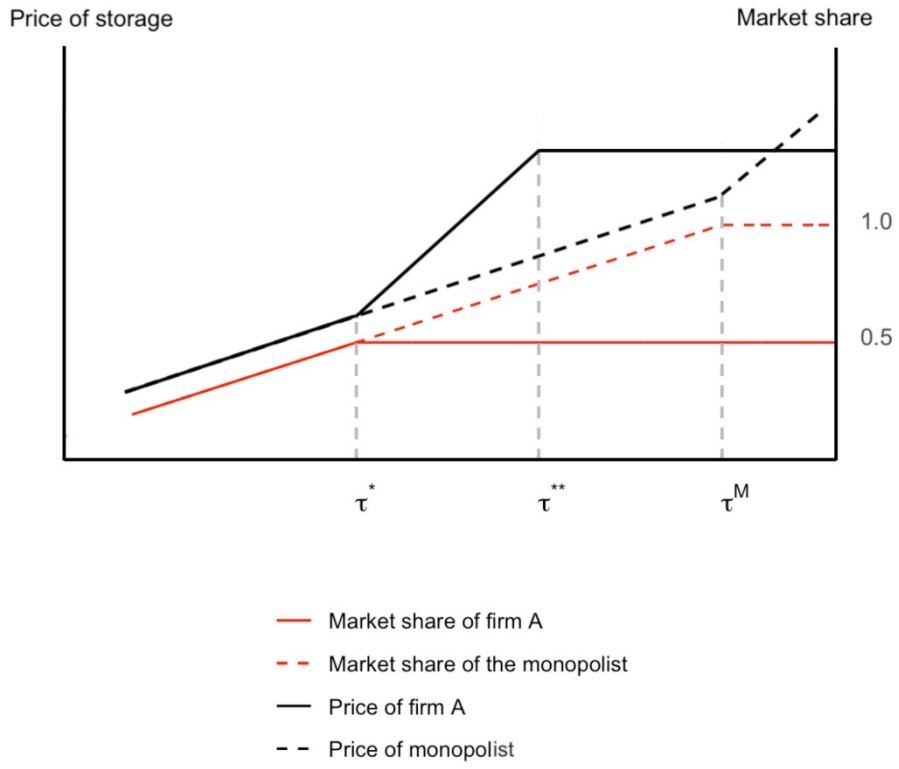


Figure 3

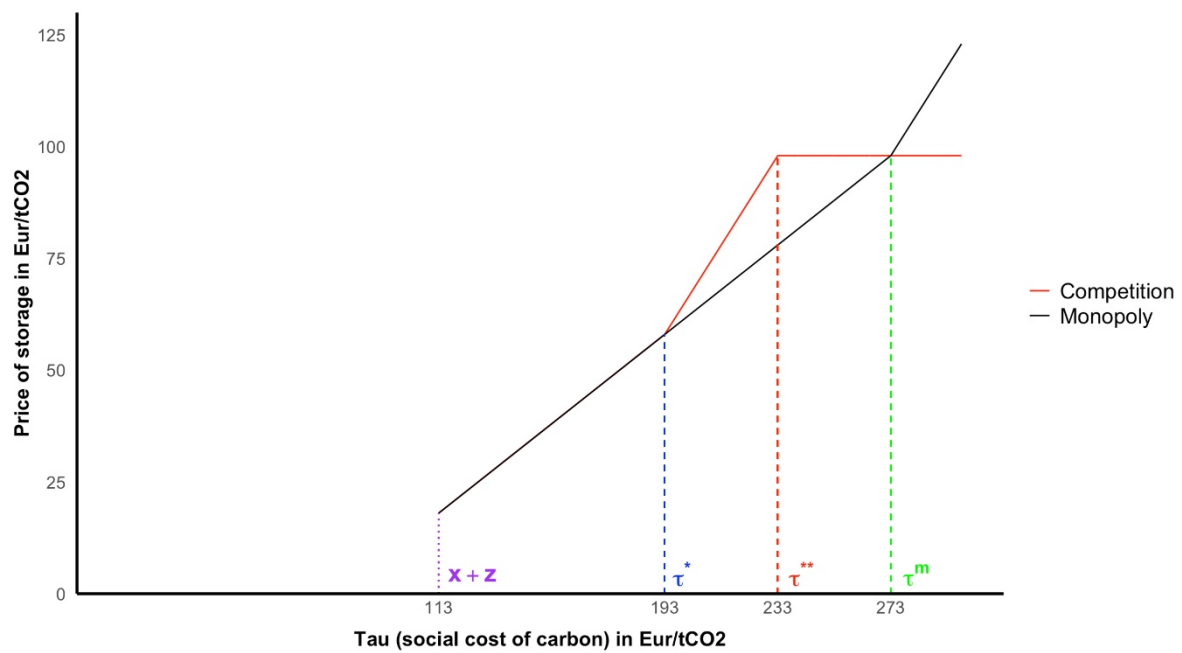


Figure 4

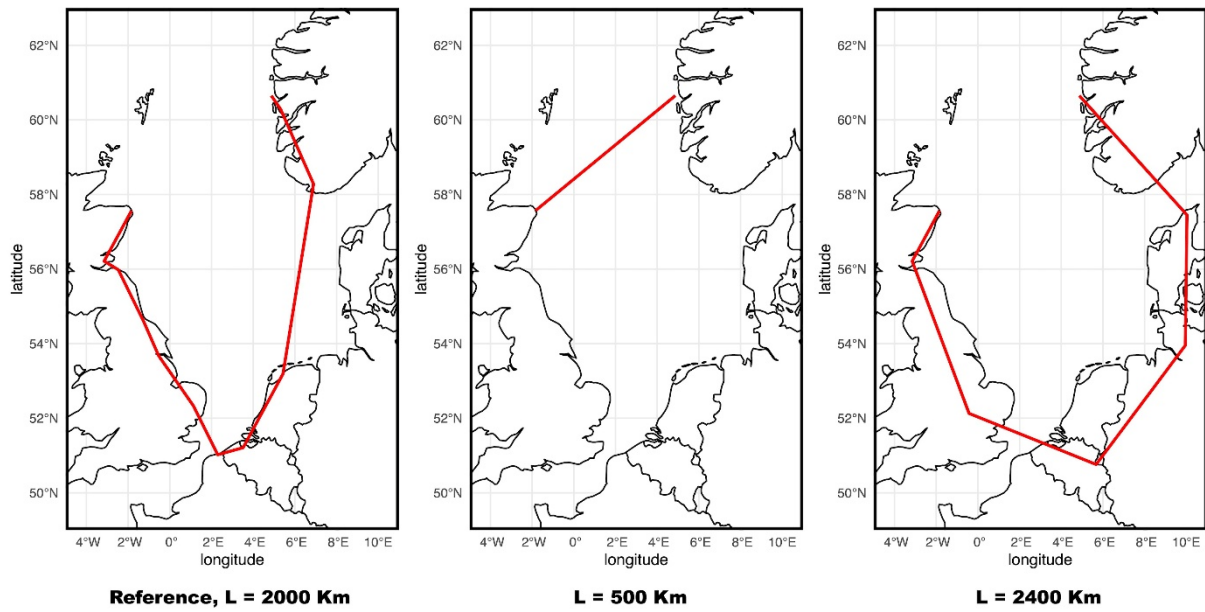


Figure B1

Parameter	Value	Unit	Data Source
Cost of investment in capture facilities $x$	95	Eur/tCO <sub>2</sub>	Carbon Limits (2022) Pale Blue Dot (2015)
Unit cost of storage $z$	18	Eur/tCO <sub>2</sub>	Norwegian Ministry of Petroleum and Energy (2019)
Cost of transport $t$	0.04	Eur/(tCO <sub>2</sub> · km)	Carbon Limits (2022)
Hotelling line length $L$	2000	km	Google Maps API

Table 1

	$x+z$ (Eur/tCO <sub>2</sub> )	$\tau^*$ (Eur/tCO <sub>2</sub> )	$\tau^{**}$ (Eur/tCO <sub>2</sub> )	$\tau^m$ (Eur/tCO <sub>2</sub> )	$p^*$ (Eur/tCO <sub>2</sub> )	$p^{**}$ (Eur/tCO <sub>2</sub> )
Reference	113	193	233	273	58	98
Cost of investment in capture ( $x$ ) increased by one third	145	225	265	305	58	98
Unit cost of storage ( $z$ ) increased by one third	119	199	239	279	64	104
Cost of transport ( $t$ ) increased by one third	113	220	273	326	71	125
Cost of investment in capture ( $x$ ) decreased by one third	81	161	201	241	58	98
Unit cost of storage ( $z$ ) decreased by one third	107	187	227	267	52	92
Cost of transport ( $t$ ) decreased by one third	113	166	193	220	45	71
Hotelling line $L = 500$ km	113	133	143	153	28	38
Hotelling line $L = 2400$ km	113	209	257	305	66	114

Table 2

	Sequential Moves				Simultaneous Moves	
	$p^{***a}$	$p^{***b}$	$d$	$\tau^{***}$	$p^{**a} = p^{**b}$	$\tau^{**}$
	(Eur/tCO <sub>2</sub> )	(Eur/tCO <sub>2</sub> )	km	(Eur/tCO <sub>2</sub> )	(Eur/tCO <sub>2</sub> )	(Eur/tCO <sub>2</sub> )
Reference	138	118	750	263	98	233
Cost of investment in capture (x) increased by one third	138	118	750	295	98	265
Unit cost of storage (z) increased by one third	144	124	750	269	104	239
Cost of transport (t) increased by one third	178	151	750	313	125	273
Cost of investment in capture (x) decreased by one third	138	118	750	231	98	201
Unit cost of storage (z) decreased by one third	132	112	750	257	92	227
Cost of transport (t) decreased by one third	98	85	750	213	71	193
Hotelling line L = 500 km	48	43	188	151	38	143
Hotelling line L = 2400 km	162	138	900	293	114	257

Table 3

Sector	CO2 capture	CO2 concentration	Average Capex	Non-Energy Opex	Energy Opex	Total cost
	kt/year	%	Eur/ton	Eur/ton	Eur/ton	Eur/ton
NG processing	24	98%	8	9	8	25
Ethanol production	342	98%	7	9	10	26
Ammonia production	389	98%	8	7	8	23
Hydrogen production	340	45%	23	18	25	66
Cement plants	842	21%	20	26	25	71
FCC plants	374	16%	51	33	26	110
Steel/Iron	3324	26%	31	27	26	84
Industrial furnaces	220	8%	59	39	28	126
Coal PP (1)	3089	13%	39	26	27	92
Coal PP (2)	1999	13%	65	42	23	130
Coal PP (3)	1272	13%	106	68	20	194
NG powerplants (1)	1279	4%	41	35	28	104
NG powerplants (2)	827	4%	68	56	23	147
NG powerplants (3)	527	4%	110	89	20	219

Source: Clean Air Task Force (CATF)

Table B1

	<b>Norcem</b>	<b>Hafslund Celsio</b>
Capex P50 (Eur/ton)	86	113
Opex P50 (Eur/ton)	25	48
Total cost of 1 ton of CO2 captured P50 (Eur/ton)	111	161
Capex P85 (Eur/ton)	100	132
Opex P85 (Eur/ton)	29	54
Total cost of 1 ton of CO2 captured P85 (Eur/ton)	129	186

Table B2

<b>Transport type</b>	<b>Cost in Eur/(t · km)</b>
New Pipeline Onshore	0.019
New Pipeline Offshore	0.043
Reuse Onshore	0.006
Reuse Offshore	0.014
Ship	0.048
Rail	0.149
Truck	0.150

Source: Clean Air Task Force (CATF)

Table B3

Storage site	Storage type	Storage size	Injection rate	Levelised unit cost of storage	Unit technical cost <sup>a</sup>
		Mt	Mt/yr		Eur/ton
<b>Viking</b>	Depleted Oil/Gas Field	130	5	12.00 £/t	-
<b>Captain X (Acorn)</b>	Saline Formation	60	3	16.50 £/t	-
<b>Forties 5</b>	Saline Formation	300	6 - 8	13.88 £/t	-
<b>Bunter Closure 36</b>	Saline Formation	280	7	9.12 £/t	-
<b>Goldeneye</b>	Depleted Oil/Gas Field	30	3	27.45 £/t	-
<b>Hewett</b>	Depleted Oil/Gas Field	200	5	12.50 £/t	-
<b>Endurance</b>	Saline Formation	520	13	7.81 £/t	-
<b>Northern Lights</b>	Geological Formation	t.b.d.	1.5-5	18.00 Eur/t	-
<b>P15/P18</b>	Depleted Gas Field	82	0.45	-	4.6
<b>L10</b>	Depleted Gas Field	103.4	0.45	-	5.9
<b>K7/K8</b>	Depleted Gas Field	104	0.45	-	2.1-5
<b>K14/K15</b>	Depleted Gas Field	171.2	0.45	-	4.4-9.4
<b>Q1/Q4</b>	Saline Aquifer/Depleted Gas Field	123.6	0.45	-	4.9
<b>P6</b>	Depleted Gas Field	33	0.45	-	5.3
<b>K12</b>	Depleted Gas Field	37	0.45	-	2.9-10.4

<sup>a</sup> The unit technical cost is the total technical cost divided by the total amount of CO<sub>2</sub> stored. The total technical cost includes estimates of CAPEX and OPEX during the entire storage period in €2017 but does not include financing costs, insurance and return requirements.

Source: Pale Blue Dot (2015), Norwegian Ministry of Petroleum and Energy (2019), Gausnie and EBN (2018)

Table B4

	<b>Viking A</b>	<b>Captain X</b>	<b>Forties 5, Site 1</b>	<b>Bunter CL36</b>	<b>Goldeneye</b>	<b>Hewett</b>	<b>Endurance</b>
<b>Pre-FID</b>	28	31	103	52	38	24	30
<b>CAPEX</b>	429	201	922	617	277	623	777
<b>OPEX</b>	639	385	1446	751	110	988	1085
<b>ABEX</b>	94	96	205	148	110	130	315
<b>MMV</b>	14	92	293	40	33	81	78
<b>TOT CAPEX</b>	551	328	1230	817	425	777	1122
<b>TOT OPEX</b>	653	477	1739	791	143	1069	1163
<b>TOT CAP + OP</b>	1204	804	2968	1609	568	1846	2285
<b>SHARE CAPEX</b>	46%	41%	41%	51%	75%	42%	49%
<b>SHARE OPEX</b>	54%	59%	59%	49%	25%	58%	51%

Table C1