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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 Hotellling 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 tax determines which regime materializes. For "low" carbon taxes, there is no competition between the two storage firms. For "high" carbon taxes, there is standard Bertrand competition between the two storage firms. Finally, for "intermediate" carbon taxes, there is so called partial competition with multiple equilibria. Contrary to the standard conclusion on competition, we find that when each storage site 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 tax sufficiently high to reach the Paris targets, we find that we may end in a partial competition regime.

JEL-Codes: L130, Q350, Q380.

Keywords: Hotelling line, kinked demand curve, duopoly, multiple equilibria, emission tax, carbon capture and storage.

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1 Introduction

Carbon capture and storage (CCS) is a technology for avoiding emissions of CO_2 from industrial processes and electricity production to the atmosphere, as well as for removing CO_2 from the atmosphere. According to IPCC (2022), CCS is a necessary technology to meet the climate targets.[7] The reason is that emissions paths have to fall substantially over the next decades to reach the Paris Agreement targets, and 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 suppliers of storage services 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. For instance, from 2021 to 2022, the number of CCS facilities increased by 44 per cent (Global CCS Institute, 2022). 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_2 from plants is transported to terminals, where it is collected and transported, for instance by pipelines or by ship, to a storage place. The number of storage places is small compared to the number of terminals and capture facilities, mainly due to large fixed costs, which means that they are dependent on a relatively high demand to be profitable. However, as the amount of captured CO_2 increases, the demand for storage also increases, which will potentially give more competition for storage.

One example is the North Sea. Here, empty oil fields are suitable for carbon storage; Equinor (former Statoil) has stored CO_2 in the Sleipner field since 1996. However, so far only a small share of emissions has been stored in the North Sea. One game changer may be the Northern Lights project (Northern Lights, 2023), which includes a terminal in the western part of Norway

[7] Achieving deep decarbonization without CCS is difficult in several industries, such as steel, fertilizer and cement. Also, according to IPCC (2022) even negative emissions are necessary in the second half of this century to meet both the 1.5°C and the 2°C target. Negative emissions means that we need to remove more CO_2 from the atmosphere than the amount of CO_2 we emit into the atmosphere. To do this, carbon dioxide removal options, including CCS from bioenergy (BECCS) and direct air capture (DACCS), have to be used.

and a pipe from the terminal to the storage site. While being owned and operated by a consortium consisting of Equinor, Shell and Total, Northern Lights will receive financial support from the Government of Norway.

The first phase of Northern Lights will be operational in 2024. However, 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_2 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_2 for storage in sub-seabed geological formations is now allowed, which may give transboundary competition and cooperation (Wettestad et al., 2022, p. 9).[8]

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_2 and they have to choose between paying a carbon price for the emissions or to invest in capture facilities and transport the captured CO_2 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 the 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

[8] See also https://www.imo.org/en/OurWork/Environment/Pages/CCS-Default.aspx.

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 where to buy storage service, and also, whether it should invest in capture facilities or not. This gives a kinked demand curve for storage services, and several Nash equilibria exist with partial competition. We find that the range of the carbon tax giving a kinked demand curve increases in the transport costs for captured CO_2. Thus, if transport costs 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 site 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. We find for instance that if perfect price discrimination is allowed, plants benefit from competition (relative to being served by a monopolist). In the basic model, the two storage firms set their prices simultaneously. Relative to the model with simultaneous moves, both storage firms will benefit if one firm develops the site first. Further, it is always more advantageous to be the follower than the first mover, and this benefit will be even higher if there is learning from the first mover to the second mover. This may, therefore, be one explanation for the slow development in storage fields.

Finally, we also illustrate the model results by numerical simulations based on data for industries around the North Sea. We assess the estimates for the cost variables in the model, 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 builds on, and 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 analyzed in this paper, 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). However, 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). The reason is that we assume that the storage sites are large and the plants can deliver as much CO_2 as they want to these sites. Thus, the storage sites compete by setting prices and not quantities.

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). In our paper, however, 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 model 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).[9] 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). The maximum willingness of a plant to pay for capture and storage is determined by the carbon tax. However, 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, which is dependent on the reservation price. 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_2 emissions so that the original Hotelling model with a fixed unit of demand is still relevant.[10] We show that there are three alternative competition regimes and which regime that materializes depends on the level of the carbon tax. For "low" carbon taxes, there is no competition between the two storage firms, each being located at each end of the Hotelling line. For "high" carbon taxes, there is standard Bertrand competition between the two storage firms. Finally, for "intermediate" carbon taxes, there is so called partial competition with multiple equilibria.

Relative to the literature, we make extensions of the basic model along two dimensions. First, within the basic structure of the model studied by Merel and Sexton (2010), we examine heterogeneous firms, i.e., storage firms differ with respect to cost of storage. We compare the

[9] As shown in d'Aspremont et al. (1979), the ends points are also the optimal locations of firms if there are quadratic transportation costs.
[10] With present technologies, there will be a rest of emissions (at least 10%) that cannot be captured. However, as this is a relatively small amount, we follow Golombek at al. (2023) and disregard this.

outcome of the three different competitive regimes with the case of monopoly and also 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.[11] 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, (iv) sequential moves (instead of simultaneous moves as in the basic model), and (v) heterogeneous plants, i.e., cost of investment differs between *plants* (there is not one common cost of investment 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_2 and total emissions are equal to E. Hence, emissions per unit of distance is E / L.

Plants emitting CO_2 have to pay a tax τ per unit of emission, which is set equal to the social cost of carbon, thereby correcting for the negative environmental externality.[12] Alternatively, a

[11] The competitive regime referred to as weak duopoly in Merel and Sexton (2010) corresponds to the partial competition regime in our paper.

[12] 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 τ per unit of stored emission.

plant can install capture facilities and transport the CO_2 to a storage site. Denote *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 without capture facilities, each plant emits one unit of CO_2. Moreover, cost of investment does not differ across plants. We will later relax these assumptions. 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. Furthermore, let *t* be cost of transport per unit of distance along the Hotelling line.

Initially, there are no facilities neither to catch, nor to store, 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, the storage actor 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 CO_2 to the storage site, and paying the price for deposit services, and (ii) paying the carbon tax. Therefore, plants understand that they have to sign credible contracts with the storage actor that guarantee a specific price for storage services *before* they invest in capture facilities. According to these contracts, a plant can deliver as much CO_2 it wants to the storage, and it will be charged a pre-determined price per unit of received CO_2. Furthermore, we assume that a storage actor has to charge the same price to all its clients; price discrimination is not allowed by the government. We will relax this assumption later.

To capture the game with its key characteristics, we set up a model with three stages of decisions. In stage one, each storage actor sets a price to receive captured CO_2 from plants. In stage two, plants decide whether to invest in captured facilities and to which storage site they will transport their captured CO_2. Finally, in stage three the storage firms develop their storages for captured CO_2. 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 τ. 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_2 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

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

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 costs (x), storage costs at *A* (z_A) and a verage transportation costs 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:

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

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

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 hat 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

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

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

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

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

$$z_B - z_A < tL \tag{6}$$

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 The market outcome

In the subsequent sections, we consider three possible market outcomes. The first outcome, *no competition*, is the outcome with a "low" carbon tax. More precisely, the carbon tax 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 tax. More precisely, the tax 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 tax. 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 site).

In all three outcomes, plants decide in stage two of the game whether to invest in capture facilities and if so, to which storage site to transport their captured CO_2 – subject to the prices for storage services agreed upon and committed to in stage one of the game. Hence, the demand for storage services is determined prior to stage three. Therefore, in stage three of the game each storage firm develops its storage site according to the pre-determined demand for storage services.

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_2, $i = A, B.$ Let d_A be the location of the plant that is indifferent between paying the carbon tax τ and investing in capture facilities that will be delivered to storage site A, i.e.,

$$\tau = x + td_A + p_A \tag{7}$$

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

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

where we have used (7). Notice in particular that

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

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

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

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., $d_A\left(p_A\right)$ decreases. Maximizing profit with respect to the price p_A and using (9) we obtain

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

giving

$$p_A = \frac{\tau + z_A - x}{2} \tag{12}$$

Then using (7) we obtain

$$d_A = \frac{\tau - z_A - x}{2t} \tag{13}$$

To ensure a positive net price, $p_A - z_A > 0,$ we need $\tau > x + z_A,$ i.e., the sum of (i) the unit cost of investment in capture facilities and (ii) 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_2 to storage firm *A*, see (13).

Profit of storage firm *B* is $\pi_B = (p_B - z_B)\left(L - d_B(p_B)\right)E / L$ 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

$$p_B = \frac{\tau + z_B - x}{2} \tag{14}$$

and

$$d_B = L - \frac{\tau - z_B - x}{2t} \tag{15}$$

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

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

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

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

and

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

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

$$\overline{p}^* = \frac{p_A^* + p_B^*}{2} = \frac{z_A + z_B}{2} + \frac{tL}{2} \tag{19}$$

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 tax 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 $p_A + t\overline{d} = p_B + t(L - \overline{d})$, which implies:

$$d_A = \overline{d} = \frac{p_B - p_A + tL}{2t} \tag{20}$$

and $d_B = L - \bar{d}$. Profits of firm A and B are now given by $\pi_A = (p_A - z_A) d_A(p_A, p_B) E / L$ and $\pi_B = (p_B - z_B)(L - d_B(p_A, p_B)) E / L$. Firm A chooses p_A so that its profits are maximized for the given value of p_B. Using (20) this gives us[13]

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

Similarly, maximizing firm B's profits gives

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

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

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

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

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

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 $p_B^{**} > p_B^{*}$

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

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

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

$$z_B - z_A < 3tL \tag{27}$$

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[13] 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 ½.

Comparing with (6), it is clear that this inequality will hold if it is socially optimal to use two store 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* looses market shares is that initially, the marginal plant (at $\bar{d}$) transports its captured CO_2 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 tax 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

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

Inserting from (23)-(26) we obtain

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

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

8 Partial competition

We have found the equilibrium for $\tau < \tau^{*}$ and for $\tau > \tau^{**}$. We now turn to the case where the carbon tax 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 costs are, the larger is this interval. For these values of τ 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

$$x + p_A + t\bar{d} = \tau \tag{30}$$

and

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

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)):

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

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

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

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

$$\Delta = p_B - p_A \tag{34}$$

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

$$p_A = \tau - x - \frac{tL}{2} - \frac{\Delta}{2} \tag{35}$$

$$p_B = \tau - x - \frac{tL}{2} + \frac{\Delta}{2} \tag{36}$$

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

$$\bar{d} = \frac{L}{2} + \frac{\Delta}{2t} \tag{38}$$

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.,

$$\pi_A'(p_A^+) \le 0 \tag{39}$$

The condition for not being able to increase π_A by *reducing* p_A is

$$\pi_A'(p_A^-) \ge 0 \tag{40}$$

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 Δ 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 taxes there is a range of Δ-values satisfying the inequalities above. Hence, the equilibrium values of the prices are not unique.[14] However, it is clear from (37) that there is a unique *average* price, and this average price is higher the higher is the carbon tax. 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 tax τ.

Figure 1 illustrates how p_A depends on the carbon tax τ. The shaded area for $\tau \in (\tau^*, \tau^{**})$ shows the range of equilibrium values of p_A for these tax rates. 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 taxes giving no competition or partial competition will be relatively narrow.

[14] 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 $z_A \neq z_B$.

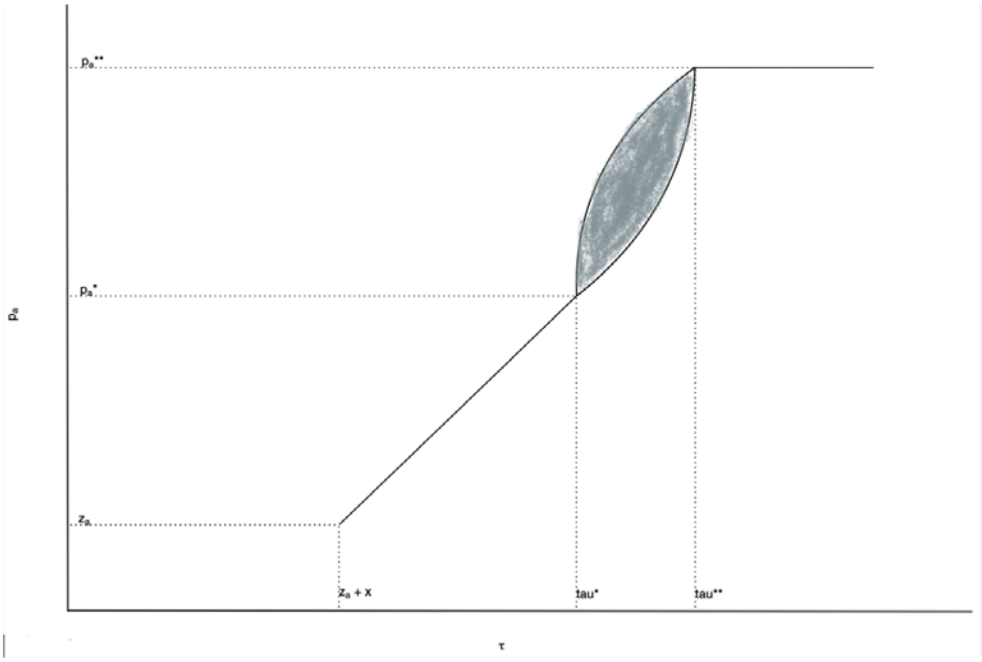

Figure 1 *Effect of price on emissions (τ) on price of storage charged by firm A* (p_A) *when cost of storage may differ across firms* $(z_A \leq z_B)$.

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

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

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

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

Inserting from (35) and (38) gives

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

In the Appendix A it is shown that $\pi_A\,'(\Delta) > 0$, so that the best value of Δ for storage firm *A* is the highest value that is consistent with the inequalities (39) and (40). From the definition of Δ 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

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

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

$$\Delta = \frac{z_B - z_A}{2} \tag{45}$$

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).

Some 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 $\tau \le \tau^*$ there exists a unique no-competition equilibrium, and for each $\tau \ge \tau^{**}$ 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.*

Finally, the solutions to the outcomes in sections 6-8 may alternatively be illustrated using price response curves for the two storage firms, see the Appendix B.

9 Monopoly versus competition vs. social optimum

We now consider the equilibrium price in more detail for the case of $z_A = z_B = z$ and with a symmetric equilibrium for the case of 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)

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

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

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

Note that $\lim_{\tau \to \tau^*} p^{NC} = p^{PC}(\tau^*)$ and $p^{PC}(\tau^{**}) = p^{FC}$, so that the equilibrium price is a continuous function of τ. Furthermore, as τ increases from $x + z$ to τ^{**}, 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 τ is twice as high for medium values of τ (partial competition) as it is for low values of τ (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 τ, 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

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

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

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

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

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

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

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, but the demand effect is smaller than under monopoly (the demand curve is steeper) because the potential new buyers have an alternative supplier; they can buy from firm *B*. Hence, the incentives to choose a low price is *lower* under partial competition and full competition than under monopoly. This explains why the price is lowest 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 2. With two identical firms, the firms do not compete if $\tau \le \tau^*$. However, the common price, as well as the market share of each firm, are increasing in τ. 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 τ 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 $\tau \ge \tau^{**}$, there is full competition. However, in this regime the common price is not dependent on the level of τ, see (48).

Turning to monopoly, the monopoly price is always increasing in τ, and at a higher rate once the monopolist covers the entire market ($\tau \ge \tau^M$), 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 $\tau < \tau^M$.

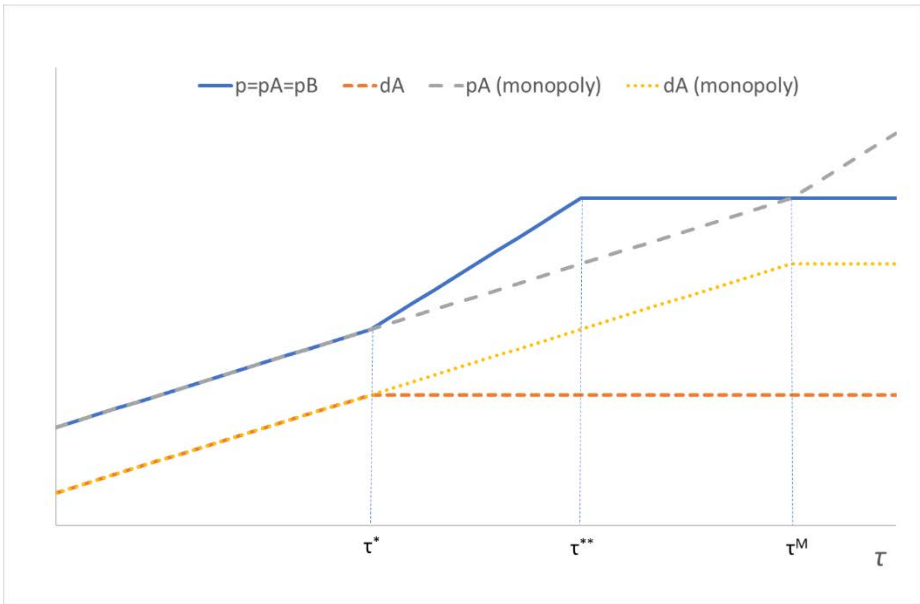

Figure 2. *Effect of price on emissions (τ) on price of storage (p) and market size of firm A (d_A) when cost of storage does not differ across firms* $(z_A = z_B)$.

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* $(\tau^* < \tau \le \tau^{**})$ *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 Extensions

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

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

10.1 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.

Proposition 3. *Assume the parameters ensure full competition with two identical storage firms* $(\tau > \tau^{**} = x + z + \frac{3}{2}tL)$, *i.e., each firms 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^{**}.

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 $\tau > \tau^{**}$.

10.2 Price discrimination

Above we analyzed the game under the assumption that each storage firm has 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.[15] Below, we first examine cases where $\tau > z_B + x + tL$ and $z_B \geq z_A$, i.e., it is socially beneficial that all plants invest in capture facilities.

Assume first that there is only one storage firm (*m*onopoly), namely *A*. For each plant, the emission price τ represents an upper limit of its cost; this is the cost if the plant does not invest in carbon capture facilities. For the plant located at point *d*, the monopolist therefore sets the price $p_{A,d}^m$ such that total cost of abatement of this plant $(p_{A,d}^m + x + td)$ is equal to (or actually marginally below) the emission price τ. Hence,

$$p_{A,d}^m = \tau - x - td \tag{54}$$

[15] For a discussion on price discrimination by buyers along a line in space, see, for example, Thisse and Vives (1988) and also Graubner et al. (2021) for an overview.

Hence, the closer the plant is located to storage site A, the more it pays for deposit services. Under our assumption $\tau > z_B + x + tL$, the monopoly firm will cover the entire Hotelling line.

Next, assume there are two storage firms, *A* and *B* (full *c*ompetition). Assume first that $z_B > z_A$. Through Bertrand competition with identical products, the two competitors will bid down the price for each potential client. However, the lowest price for deposit services that storage firm *i* can offer is z_i.

For a plant located closer to *A* than *B*, firm *A* has both a location advantage and a cost advantage in serving this plant, whereas for a plant located closer to *B* than *A*, firm *A* has a cost advantage and firm *B* has a location advantage. We want to find the distance from site *A* where the cost advantage of firm *A* equals (in monetary terms) the location advantage of firm *B*. The plant located at this point will be indifferent between accepting the offer from *A* and from *B*. Hence, $z_A + x + td = z_B + x + t(L-d)$, which implies that $d = \tilde{d}$, where $\tilde{d}$ is the social efficient division between the two storage firms, see (5).

Plants located closer to site *A* than $\tilde{d}$ will be served by storage firm *A* if it offers a price $p^c_{A,d}$ such that the total cost of the plant $(p^c_{A,d} + x + td)$ is equal to (or actually marginally lower than) the total cost of the plant if it accepts the price offer from B, which is $z_B + x + t(L-d)$. Hence, storage firm *A* must offer

$$p^c_{A,d} = z_B + t(L-2d) \quad d \le \tilde{d} \tag{55}$$

Also, storage firm *A* cannot offer a price which exceeds the reservation price of a plant; $\tau - x - td$. Under our assumptions $\tau > z_B + x + tL$ and $z_B \ge z_A$, the reservation price of the plant will be higher than $p^c_{A,d}$. Hence, firm *A* offers the price $p^c_{A,d}$ and thus all plants being served by *A* pays a lower price than under monopoly. Thus competition between storage firms *A* and *B* drives down the price below the reservation price, which is the price charged in the case of monopoly. Using (5) and (55), we find that $p^c_{A,0} = z_B + tL$ and $p^c_{A,\tilde{d}} = z_A$.

Plants located closer to site *B* than $L - \tilde{d}$ will be served by storage firm *B* if it offers a price $p^c_{B,d}$ that makes the total cost of the plant $(p^c_{B,d} + x + t(L-d))$ equal to (or actually slightly lower than) the total cost of the plant if it accepts the price offer from *A* $(z_A + x + td)$. Hence, storage firm *B* must offer the price

$$p_{B,d}^{c} = z_A + t(2d - L) \quad \tilde{d} < d \le L \tag{56}$$

Note that under our assumptions $\tau > z_B + x + tL$ and $z_B \ge z_A$, the reservation price of the plant will be higher than $p_{B,d}^{c}$. Hence, firm *B* offers the price $p_{B,d}^{c}$ and thus all plants being served by *B* pays a lower price than under monopoly.

The plant located at $\tilde{d}$ will receive offers from both firm *A* and *B* and these offers are equally good. Because this plant is better off accepting one of these offers than to pay the price of emissions, there is no partial competition under perfect price discrimination.

As explained above, under monopoly each plant is charged its reservation price. This means that under monopoly, the entire social surplus is captured by the monopolist; this corresponds to the standard text-book result of a perfectly price-discriminating monopolist. In contrast, under full competition each plant is charged a lower price than its reservation price, and therefore the storage firms do not capture the entire social surplus. Hence, each plant is better off under competition than under monopoly.

Our discussion is summarized by Propositions 4:

Proposition 4. *Assume that there is perfect price discrimination when storage firm A is a monopolist and also when there is competition between storage firms A and B ($z_B \ge z_A$). Moreover, assume that 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.*

We close this section by examining the case where the emission price is so low that there is no competition between two perfectly price discriminating monopolists, each located at each end of the Hoteling line.

From (54) we know that when firm *A* is a monopolist, it will offer a plant-specific price of its services until the price of storage equals its unit cost. Hence, the marginal plant being served by firm *A*, $\hat{d}_A^m$, is determined from $\tau - x - t\hat{d}_A^m = z_A$, i.e., $\hat{d}_A^m = (\tau - x - z_A)/t$. Similarly, the marginal plant being served by the local monopoly *B* is determined from $\tau - x - t(L - \hat{d}_B^m) = z_B$, i.e., $\hat{d}_B^m = L + (z_B + x - \tau)/t.$ The requirement to have two local monopolists is $\hat{d}_A^m + (L - \hat{d}_B^m) < L,$ i.e., $\hat{d}_A^m < \hat{d}_B^m.$ This requires that the emission price is sufficiently low:

$$\tau < x + \frac{z_A + z_B}{2} + \frac{tL}{2} \equiv \hat{\tau} < \tau^*. \tag{57}$$

Consider a price of emission $\tau < \hat{\tau}$ and assume that this price is used also in the case where each storage firm has to offer all its clients the same price. Using (13), we find that firm *A* will cover a shorter segment of plants when it is committed to impose the same price for all its client than when it is a perfectly, price discriminating, local monopolist $(d_A < \hat{d}_A^m)$:

$$d_A = \frac{\tau - z_A - x}{2t} < \frac{\tau - z_A - x}{t} = \hat{d}_A^m \tag{58}$$

The result that the local monopolist will cover a shorter segment of plants when it is committed to impose the same price for all its client than when it is a perfectly, price discriminating, local monopolist, resembles a well-known text-book result: output under a perfectly price discriminating monopoly is greater than under a monopoly charging all its clients the same price. Under price discrimination, there is no link between the prices offered to the various clients—a price discriminating monopolist charges each client a unique price—and therefore the monopolist expands on the Hotelling line beyond the standard monopoly quantity. Finally, our result that with perfect price discrimination by sellers the market size is maximized, is similar to the result in Holahan (1975) that price discriminating *buyers* leads to maximization of the market area.

10.3 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 one 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 optima 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 gives 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 tax 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

$$F < \frac{tLE}{4} \tag{59}$$

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 π (i.e., profit before subtracting the fixed cost) for each storage site is increasing in the carbon tax for carbon taxes up to $\tau^{**} > \tau^{*} > \tau^{0}$. For the borderline case between no competition and partial competition, this profit follows from (10) and (17):

$$\pi^* = (p^* - z)\frac{L}{2}\frac{E}{L} = \frac{tL}{2}\frac{L}{2}\frac{E}{L} = \frac{tLE}{4} \tag{60}$$

We immediately see that for gross profits equal to or larger than π^*, gross profits will exceed the fixed cost *F* if the inequality (59) holds. In other words, if the carbon tax is at least τ^*, both storage firms will be used in the market outcome if this is socially optimal. Since the gross profit π of a storage firm is increasing in τ, we may have $\pi - F > 0$ even if (59) 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 tax lies between τ^0 and τ^*, the gross profit π is lower than π^* given by (60). In this case we may have $\pi - F < 0$ even if (59) 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.

10.4 Sequential moves

In this subsection, we examine the case where firm *A* sets the price before firm *B*. 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 explore whether there is a first-mover advantage, and how this will affect the profit of the second mover.

Note that 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.

In the Appendix C, we examine in detail the cases of full competition and partial competition when there is no learning from the first mover to the second mover. We mainly examine the games under the assumption that the two storage firms have equal storage cost, i.e., $z_A = z_B = z$.

We show in the Appendix C that the carbon tax must be higher to get an equilibrium with *full competition* with sequential moves than in the case of simultaneous moves. The reason is that both storage actors charge a higher price than with simultaneous moves.

This gives the following Proposition:

Proposition 5. *When firms have equal storage costs, the carbon tax must be higher in the sequential move game than in the simultaneous move game in order to have an equilibrium with full competition.*

We also show that by changing the sequence of moves from simultaneous moves to sequential moves, the price charged by the leader increases more than the price charged by the follower, see also Pindyck and Rubinstein (2018).

This has implication with respect to the split of the market between *A* and *B*: with identical cost of storage, the market share of the leader is $3/8$, whereas the market is split equally under simultaneous moves. 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.

In the Appendix C, we also examine the case of *partial competition* under the assumption of equal cost of storage. From the analysis above, we first note the tax interval that gives partial competition has increased with sequential moves compared to simultaneous moves as the outcome with no competition is the same, and the tax necessary to have full competition, τ^{***}, is higher with sequential moves ($\tau^{***} > \tau^{**}$). As in Section 8, the equilibrium with partial competition must satisfy the equations (35)-(38). Since firm *A* now moves first, it can choose the value of Δ, 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* (see the Appendix B for a discussion on response curves).

In the Appendix C, we show the following proposition:

Proposition 6. *When firms have equal storage costs and there is partial competition with firm A moving first,* $p_A < p_B$ *for* $\tau \in \left(\tau^{*}, \tau^{**}\right)$ *and* $p_A > p_B$ *for* $\tau \in \left(\tau^{**}, \tau^{***}\right)$ *where* $\tau^{***} = \frac{15}{8} tL + x + z > \tau^{**}$.

In the simultaneous move game, there was a continuum of equilibria for $\tau \in \left(\tau^{*}, \tau^{**}\right)$. In the sequential move game the equilibrium is unique, and for $\tau \in \left(\tau^{*}, \tau^{**}\right)$ 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 τ between τ^{**} and τ^{***}, 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.

Some of the results from the analysis above can be summarized in the following proposition:

Proposition 7. *When firms have equal storage costs and* $\tau \le \tau^{**}$ *, firm A's profits in the sequential move game are equal to or higher than they are in the simultaneous move game, while B's profits in the sequential move game are equal to or lower than they are in the* *simultaneous move game. When firms have equal storage costs and* $\tau > \tau^{**}$ *, both firms have higher profits in the sequential move game than in the simultaneous move game.*

From the discussion above, we know that there is an advantage of being the second mover compared to being a first mover with full competition. Further, who benefits most under partial competition depends on the carbon price. If we introduce *learning* from *A* to *B* in this model, so that the storage costs 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 a market situation with no competition with simultaneous moves could end up with competition with sequential moves and learning as the market that B covers $(L - d_B)$ expands. With competition, *B*'s response curve will shift with learning as its costs will be reduced, and it can easily be shown that p_B will be lower for a fall in z_B for every price p_A. As *B* has the possibility to choose the same price as with no learning, the shift in the response curve reflects that it benefits from the new price. Thus, again *B* will benefit more from sequential moves with learning than with no learning.

Based on this, the advantage of being the second mover in the storage site game can be one possible explanation why investments in CCS have been small. A possible storage site investor may wait for other storage sites to develop first. With few storage sites, the transport costs of several firms will be higher and fewer firms will invest in capture facilities compared to the case with more storage sites. Note that this is in contrast to the result found in subsection 10.3 where economies of scale could lead to a market outcome where only one storage firm would enter.

10.5 Heterogeneous plants

Above, we have assumed that the cost of investment is the same for plants. In the Appendix D we analyze the case where the 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 Numerical simulations

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

11.1 Data and reference parameter values

The Hotelling line

We apply our model under the assumption that all emitting plants are located i) in Norway, the UK, Belgium and the Netherlands, and ii) all plants are situated either at the coast or close to the coast and their cost of transport to a CO2 storage site differs. Clearly, these plants are not situated along a straight line. In the Appendix E, 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

Carbon limits (2022) provides estimates of unit capital cost, unit non-energy cost and cost of energy (20 years lifetime). Hence, we can calculate total unit cost for investment in carbon capture (EUR 95/tCO_2). Using information from National Petroleum Council (2019), we also find cost intervals (€77/tCO2 to €114/tCO_2). For other sources of cost of capture, see part II in the Appendix E.

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_2 transport. However, transport by ships is the cheapest option for small CO_2 quantities (IEA, 2020).

According to IEA (2020), cost of offshore pipeline transport ranges from approximately 2 to 16 USD/tCO_2 for a distance of 250 km (for quantities between 3 and 30 Mtpa), which corresponds to 0.0075 – 0.06 EUR/tCO_2/km. For transport by ship, cost ranges from 20 to 30

USD/tCO_2 for distances between 100 to 1000 km. This corresponds to 0.028 - 0.19 EUR/tCO_2/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_2 km.

<u>Cost of storage</u>

According to the Norwegian Ministry of Petroleum and Energy (2019), the estimated cost of storage for the Northern Lights project amounts to 18 EUR/tCO_2. 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 £/tCO2). 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_2. For more information on costs of CCS, see part II in the Appendix E. Table 1 shows the reference parameter values.

Parameter	Value	Unit	Data Source
Cost of investment in capture facilities x	95.00	Eur/tCO2	Carbon Limits (2022)
Unit cost of storage z	18.00	Eur/tCO2	Pale Blue Dot (2015) Norwegian Ministry of Petroleum and Energy (2019)
Cost of transport t	0.04	Eur/tCO2/km	Carbon Limits (2022)
Hotelling line length L	2000.00	km	Google Maps API

Table 1. *The reference parameter values.*

11.2 Simultaneous moves

We now present the numerical simulations for the cases of simultaneous moves, using the reference parameter values, see Table 1. Figure 3 shows the intervals for how high the cost of carbon - the carbon price (τ) - should be for the three equilibrium regimes to occur, when we use the reference parameter values. As seen from Figure 3, if the carbon price is below 113 EUR/tCO_2, there is no equilibrium as the carbon price is too low to trigger investment. For carbon prices between 113 and 193 EUR/tCO_2 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 τ and independent of the transport cost, t, see eq. (46).

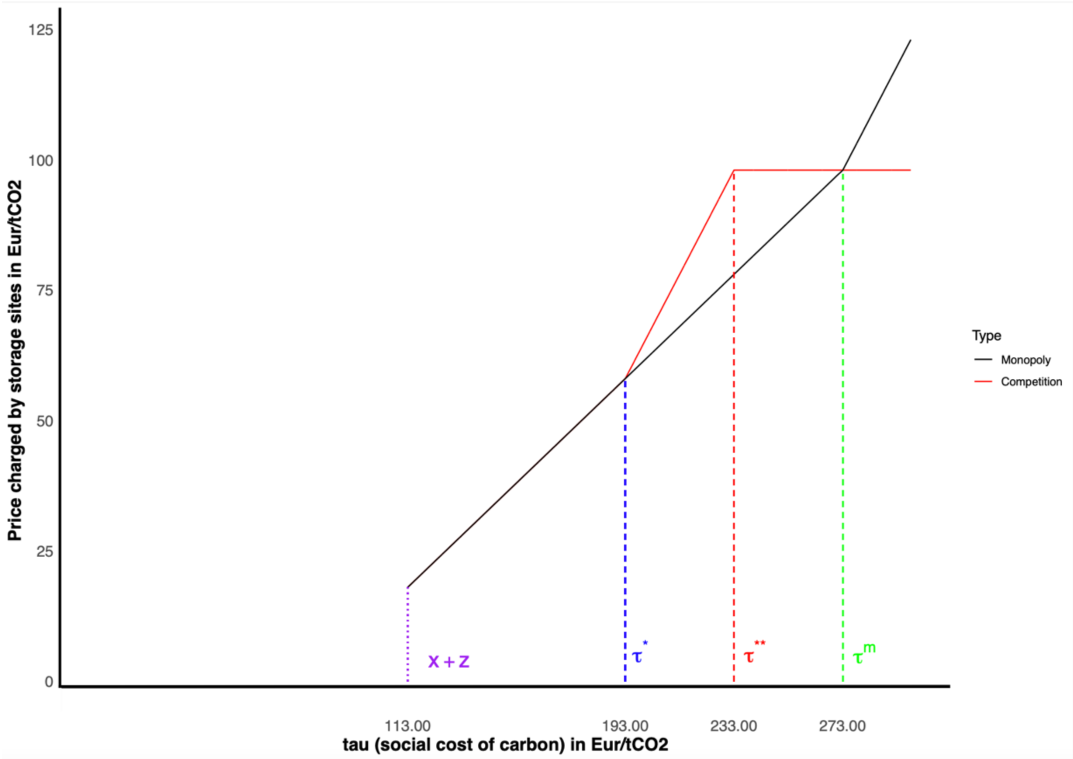

Figure 3. *Competition regimes and carbon prices, τ, in EUR/tCO2. No competition ($113 < \tau < 193$), partial competition ($193 < \tau < 233$) and full competition ($\tau > 233$).*

For a carbon price between $\tau^* = 193$ EUR/tCO2 and $\tau^{**} = 233$ EUR/tCO2, 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/tCO2 (at $\tau^* = 193$) and $p^{**} = 98$ EUR/tCO2 (at $\tau^{**} = 233$), see the red curve in Figure 4. Under partial competition, the price of storage service is increasing in the carbon price, τ, but decreasing in the cost of transport, see eq. (47).

The black curve in Figure 3 shows the price of storage charged by the storage firm when it is a monopolist. As seen from Figure 3, the monopoly price is always lower than the price under partial competition.

For carbon prices exceeding 233 EUR/tCO_2, there is full competition. As explained in section 7, the carbon price is so high that all plants on the Hotelling line invest in capture facilities. Therefore, the second segment of the red curve depicted in Fig. 3, which shows the price of storage under full competition, is flat: the price charged by the storage firms does not depend on τ when the price of carbon exceeds 233 EUR/tCO_2. 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 Fig. 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 tax is so high that the monopolist charges the highest possible price consistent with serving the entire market. For sensitivity analysis of the case with simultaneous moves, as well as simulations of the cases of sequential moves and economies of scale, see Part I in the Appendix E.

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_2, emitting plants demand storage if they choose to capture their CO_2 emissions (CCS). Using a combination of theoretical analysis (through applying the Hotelling line model) 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. 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 that the marginal plant is *not* indifferent between investing in CCS or not, but only 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, this depends crucially on the assumed transport costs and the length of the Hotelling line.

A critical assumption in our analysis is the use of the Hotelling line. In reality, emitting plants are rather scattered around. Still, the transport costs to different storage sites will differ among the plants, with some plants being much closer to one storage site than another. Hence, we believe the Hotelling line captures an important element of the competition between sites located at different places. However, the numerical results should of course be interpreted with caution.

Another simplifying assumption is that we mostly consider homogeneous emitting plants, with identical capture costs. In one of the extensions, we consider heterogeneous plants, but assume a continuum of plants with uniform distribution of capture costs, in which case we have a unique Nash equilibrium also under partial competition. In reality, however, we have a discrete number of firms, with a discrete distribution of capture costs. Hence, multiple equilibria cannot be ruled out even if capture costs are heterogeneous.

An important issue only vaguely touched upon in our analysis is technological improvements and learning. Moreover, except for the different stages and possibly sequential moves, our model is static. Both capture and storage are relatively immature technologies and operations, and hence learning and cost reductions are expected. Considering 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 possible reasons for a regulator to support early investments in storage sites.

One concern though is that different storage sites (and emitting plants considering CCS) are often located in different countries, and hence the regulator in one country would not like to spend money that in the end gain foreign competitors (or foreign emitting plants). This might be easier at the EU level, as support may then come from the EU, not from a single country. However, two of the major countries in the North Sea area are not EU members.

Carbon capture and storage will likely be an important element of future abatement of CO_2 emissions, both in Europe and elsewhere (IPCC, 2022), but it is still in an early stage. Increased understanding of this market is vital, especially because it has some special characteristics such as different types of infrastructure (transport and storage), economies of scale, network effects, and a high potential for technological improvements. Improved understanding of this market will make it easier to design proper policies and regulations.

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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

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

i.e.,

$$p_A \geq z_A + t\bar{d} \tag{61}$$

Inserting (35) and (38) in (61), and rearranging we find

$$\Delta \leq \tau - x - z_A - tL \tag{62}$$

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

$$\bar{d} + (p_A - z_A)\left(-\frac{1}{2t}\right) \geq 0 \tag{63}$$

i.e.,

$$p_A \leq z_A + 2t\bar{d} \tag{64}$$

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

$$\Delta \geq \frac{2}{3}(\tau - x - z_A) - tL \tag{65}$$

Combining (62) and (65) gives us

$$\frac{2}{3}(\tau - x - z_A) - tL \leq \Delta \leq (\tau - x - z_A) - tL \tag{66}$$

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

$$\frac{2}{3}(\tau - x - z_B) - tL \leq -\Delta \leq (\tau - x - z_B) - tL \tag{67}$$

For $\tau = \tau^*$, inserting (16) into the right inequalities in (66) and (67) gives

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

and

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

implying

$$\Delta = \frac{z_B - z_A}{2} \tag{68}$$

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

$$p_A = z_A + \frac{tL}{2} + \frac{z_B - z_A}{4} \equiv p_A^* \tag{69}$$

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 (66) and (67) gives

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

and

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

implying

$$\Delta = \frac{z_B - z_A}{3} \tag{70}$$

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

$$p_A = z_A + tL + \frac{z_B - z_A}{3} \equiv p_A^{**} \tag{71}$$

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 (67), the right inequalities in (66) and (67) give

$$\Delta \leq \frac{z_B - z_A}{2} + k \tag{72}$$

and

$$\Delta \geq \frac{z_B - z_A}{2} - k \tag{73}$$

Using $\tau = \tau^* + k = \tau^{**} - [(\tau^{**} - \tau^*) - k]$, the left inequalities in (66) and (67) give

$$\Delta \geq \frac{z_B - z_A}{3} - \frac{2}{3}[(\tau^{**} - \tau^*) - k] \tag{74}$$

and

$$\Delta \leq \frac{z_B - z_A}{3} + \frac{2}{3}[(\tau^{**} - \tau^*) - k] \tag{75}$$

Clearly, there is a range of Δ-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 (66) we have

$$p_A \geq \tau - x - \frac{tL}{2} - \frac{1}{2}(\tau - x - z_A - tL) = \frac{1}{2}(\tau - x + z_A) \tag{76}$$

From (35) and the left inequality in (67) we have

$$p_A \geq \tau - x - \frac{tL}{2} + \frac{1}{2}[\frac{2}{3}(\tau - x - z_B) - tL] = \frac{4(\tau - x) - z_B}{3} - tL \tag{77}$$

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

$$\ell^A(\tau) = Max\left[\frac{\tau - x + z_A}{2}, \frac{4(\tau - x) - z_B}{3} - tL\right] \tag{78}$$

We now turn to the upper bound $u^A(\tau)$ for p_A. From (35) and the right inequality in (67) we have

$$p_A \le \tau - x - \frac{tL}{2} + \frac{1}{2}(\tau - x - z_B - tL) = \frac{3(\tau - x) - z_B}{2} - tL \tag{79}$$

From (35) and the left inequality in (66) we have

$$p_A \le \tau - x - \frac{tL}{2} - \frac{1}{2}\left[\frac{2}{3}(\tau - x - z_A) - tL\right] = \frac{2(\tau - x) + z_A}{3} \tag{80}$$

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

$$u^A(\tau) = Min\left[\frac{2(\tau - x) + z_A}{3}, \frac{3(\tau - x) - z_B}{2} - tL\right] \tag{81}$$

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 tax τ.

Consider next the profit of storage site A, given by (41). It immediately follows from (43) and the right inequality in (66) that $\pi_A(\Delta)$ is maximized when Δ is at the highest level that is consistent with the inequalities (66) and (67).

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: Response curves

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 $p_B(p_A)$. Panel (i) in Figure 1 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 ½, cf. footnote 13. 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 for firm *A* is independent of firm *B*'s price, and hence the price response curve is constant.[16]

[16] In the figure, we have assumed that the response curve consists of all three segments. This obviously depends on the parameters of the model, not at least τ.

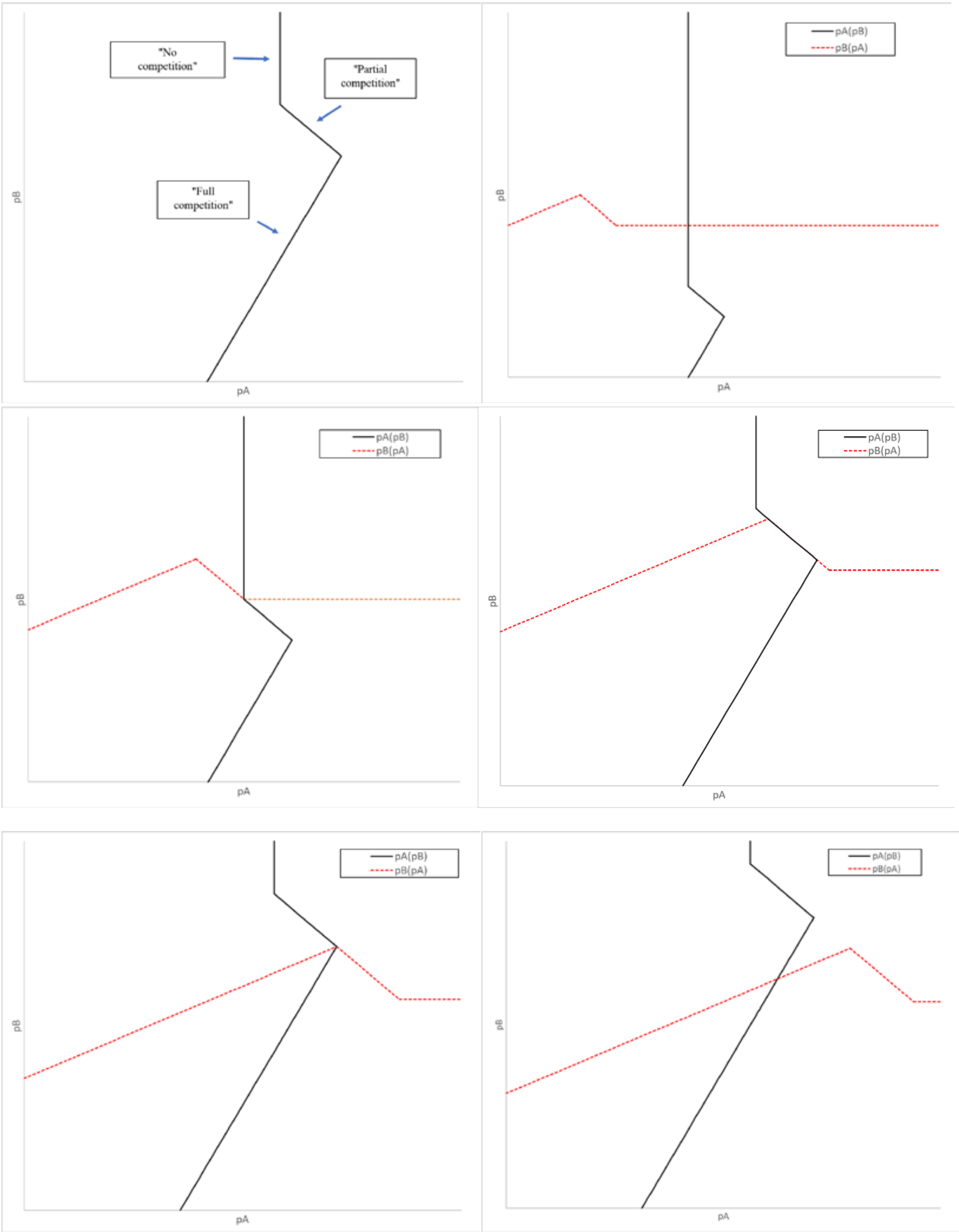

Figure 1. *Price response curves and Nash equilibria for different levels of the price of emission, τ. From top left: (i) price response curve for firm A, (ii) equilibrium under no competition ($\tau < \tau^*$), iii) equilibrium in the limiting case of $\tau = \tau^*$, (iv) equilibrium under partial competition ($\tau^* < \tau < \tau^{**}$), (v) equilibrium in the limiting case of $\tau = \tau^{**}$, (vi) equilibrium under full competition ($\tau > \tau^{**}$).*

The other panels in Figure 1 shows the Nash equilibria under different assumptions about τ relative to τ^* and τ^{**}, 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 $\tau = \tau^{**}$.

Appendix C: 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 tax 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. Will firm *A* behave as a monopolist also in this case? Not necessarily. The reason is the following. As before, we assume that plants are forward-looking, rational actors. 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 tax. 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.[17] 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 $\overline{d}$ as functions of p_A. In particular, we find

[17] 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 tax. The reason is that they need to pay the carbon tax 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.

$$\bar{d} = \frac{3}{4}L + \frac{1}{4t}(z_B - p_A) \tag{82}$$

implying

$$\frac{\partial \bar{d}}{\partial p_A} = -\frac{1}{4t} \tag{83}$$

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

$$\bar{d} + (p_A - z_A)\frac{\partial \bar{d}}{\partial p_A} = 0 \tag{84}$$

Inserting from (82) and (83) gives

$$p_A = \frac{3}{2}tL + \frac{z_A + z_B}{2} \equiv p_A^{***} \tag{85}$$

Inserting this equation and (82) into (20) gives

$$p_B = \frac{5}{4}tL + \frac{z_A + 3z_B}{4} \equiv p_B^{***} \tag{86}$$

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 (82) and (85) into (28) (with $z_A = z_B = z$) we obtain

$$\tau > \frac{15}{8}tL + x + z \equiv \tau^{***} \tag{87}$$

With simultaneous moves, the corresponding limit for τ was (from (29))

$$\tau > \tau^{**} = \frac{3}{2}tL + x + z = \frac{12}{8}tL + x + z \tag{88}$$

We immediately see that $\tau^{***} > \tau^{**}$. This gives us Proposition 5.

The reason that the carbon tax must be higher to get 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 (85) and (86) and get

$$p_A^{***} = \frac{3}{2}tL + z \tag{89}$$

and

$$p_B^{***} = \frac{5}{4}tL + z \tag{90}$$

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

$$p_A^{**} = p_B^{**} = tL + z \tag{91}$$

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 (89) into (82) and find

$$\bar{d} = \frac{3}{8}L\,. \tag{92}$$

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 (91) and $\bar{d} = L/2$ into the profit functions:

$$\pi_A^{**} = \pi_B^{**} = \frac{1}{2}tLE \tag{93}$$

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 (89), (90) and (92).:

$$\pi_A^{***} = \frac{9}{16}tLE \tag{94}$$

$$\pi_B^{***} = \frac{25}{32}tLE \tag{95}$$

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 (93), (94) and (95), 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 tax interval that gives partial competition has increased with sequential moves compared to simultaneous moves as the outcome with no competition is the same, and the tax 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 Δ, 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 Δ that satisfy the best response conditions for *B* are the values that satisfy the inequalities (67), 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 Δ for firm *A* is $\Delta = \tau - x - z - tL$. This value satisfies the left inequality in (66) for "small" values of τ. But for "large" values of τ the optimal feasible value of Δ for firm *A* is the upper limit of Δ given by the right inequality in (66). More precisely, it is straightforward to derive the following:

$$\begin{aligned} &\Delta = \tau - x - z - tL \quad \textit{for} \quad \tau \in \left[\tau^{*}, x + z + \frac{6}{5}tL\right] \\ &\Delta = tL + x + z - \frac{2}{3}\tau \quad \textit{for} \quad \tau \in \left[x + z + \frac{6}{5}tL, \tau^{***}\right] \end{aligned} \tag{96}$$

Notice that Δ increases from 0 as τ increases from τ^{*}, but declines once τ reaches $x + z + 6tL/5$, and passes 0 as τ passes τ^{**}. This gives us proposition 6.

Appendix D: 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.[18] Let $\hat{x}_d$ denote the unit cost of investment of a plant located at *d* which is indifferent between paying the carbon tax τ 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., $\hat{x}_{d'} \geq \overline{x}$, 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 tax is below τ^*. As in our previous case, τ^* 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 tax above τ^{**}. As in our previous case, τ^{**} 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 taxes between τ^* and τ^{**} we have partial competition. Note that the difference between τ^{**} and τ^* is now greater than in Section 8. In an equilibrium with partial competition, there will as before be a marginal location $\overline{d}$ where any plants investing will be indifferent between storage sites *A* and *B*. Also, at the location $\overline{d}$ there will be a plant with

[18] 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 tax will affect the total amount of carbon capture, while in Section 8 the carbon tax 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.[19]

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.

[19] 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 E: cost elements of CCS

Part I: Additional simulation results

E.1 The Hotelling line

We have constructed three, alternative (piece-wise) lines to represent the fact that cost of transport of CO_2 to a storage site differs across plants, see Figure E.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 E.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.

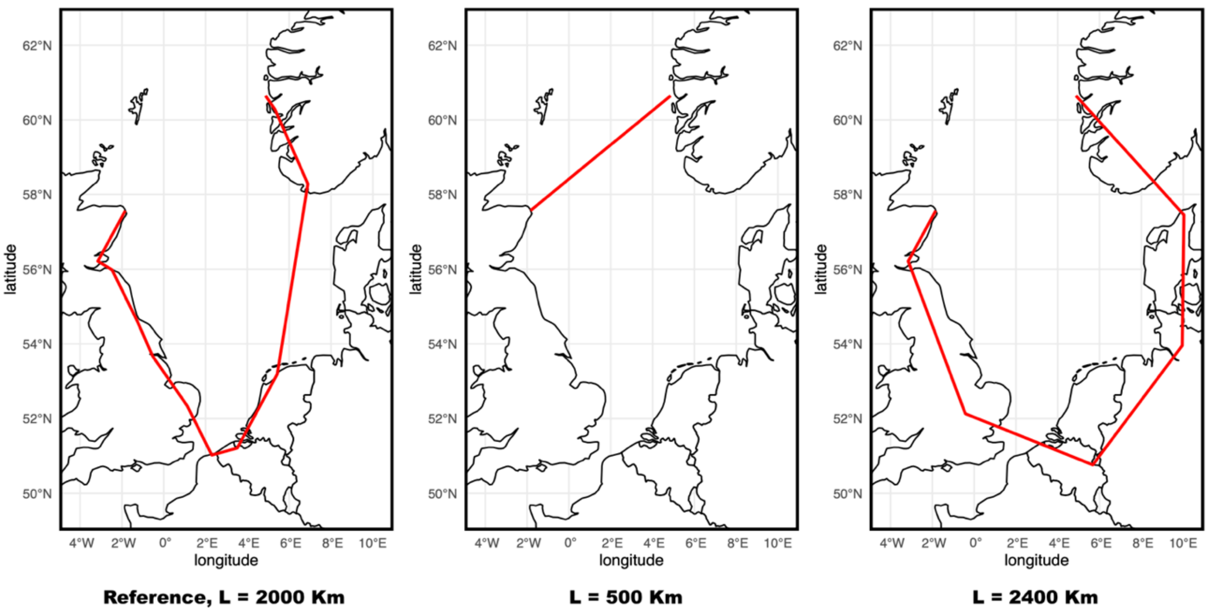

Figure E.1 *Three approximations of the Hotelling line.*

E.2 Simultaneous moves - sensitivity analysis

In this subsection we examine how alternative values of the parameters and the length of the Hotelling line impact the outcomes under simultaneous moves. We investigate a number of cases:

a) Parameters are increased by fifty percent 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. This allows us to examine the effect of cost variations on the carbon price, τ ,required to trigger the different competition regimes and the price, p ,charged by the storage firms. The results are shown in Table E.1.

	x+z (Eur/tCO_2)	τ^* (Eur/tCO_2)	τ^{**} (Eur/tCO_2)	τ^m (Eur/tCO_2)	p^* (Eur/tCO_2)	p^{**} (Eur/tCO_2)
Reference	113.00	193.00	233.00	273.00	58	98
Cost of investment in capture (x) increased by 50%	160.50	240.50	280.50	320.50	58	98
Unit cost of storage (z) increased by 50%	122.00	202.00	242.00	282.00	67	107
Cost of transport (t) increased by 50%	113.00	233.00	293.00	353.00	78	138
Cost of investment in capture (x) decreased by one third	81.33	161.33	201.33	241.33	58	98
Unit cost of storage (z) decreased by one third	107.00	187.00	227.00	267.00	52	92
Cost of transport (t) decreased by one third	113.00	165.00	191.00	217.00	44	70
Hotelling line L = 500 km	113.00	133.00	143.00	153.00	28	38
Hotelling line L = 2400 km	113.00	209.00	257.00	305.00	66	114

Table E.1 *Sensitivity analysis of the case with simultaneous moves. Lowest price of carbon that triggers investment* $(x+z)$, *lowest price of carbon sustaining partial competition* (τ^*) *and the associated price of storage* (p^*), *lowest price of carbon sustaining full competition* (τ^{**}) *and the associated price of storage* (p^{**}), *and price of carbon sustaining the same price of storage under full competition and monopoly* (τ^M).

As shown in the table, an increase by 50% in the cost of investment in capture facilities x changes the interval of carbon prices that sustain partial competition from 193-233 EUR/tCO_2 (prior to the increase) to 241-281 EUR/tCO_2. Remember that from the discussion above, we know that these intervals are equally long; $tL/2$. The lowest price of carbon under partial competition, p^*, does not change; this follows from equations (47) and the definition of τ^*. Also, the price under full competition does not change; this follows from equation (48).

A higher cost of storage and a higher cost of transport change the interval of carbon prices sustaining partial competition from 193-233 EUR/tCO_2 (prior to the increase) to 202-242 EUR/tCO2 (higher cost of storage) and 233-293 EUR/tCO_2 (higher cost of transport). With these shifts, also the prices of storage increases under partial competition and full competition.

If the length of the Hoteling curve is reduced from 2000 km (reference value) to 500 km, the lowest carbon price sustaining partial competition decreases from 193 to 133 EUR/tCO_2. For this border value (τ^*), the corresponding price p^* decreases substantially; from 58 EUR/tCO_2 to 28 EUR/tCO_2.

E.3 Sequential moves

We now simulate the sequential move game when storage firm A is the first mover and thus sets the price first. 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 E.2. 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_2 and $p_B^{***} = 118$ EUR/tCO_2, respectively. From the discussion in Section 10.4 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_2, which exceed the corresponding carbon price under simultaneous moves ($\tau^{**} = 233$). From Section 10.4, we also know that under sequential moves, 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 E.2 also offers results form 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 and carbon prices necessary to sustain a full competition equilibrium in the two cases.

	Sequential Moves				Simultaneous Moves	
	p^{***}_a (Eur/tCO_2)	p^{***}_b (Eur/tCO_2)	$\bar{d}$ (km)	τ^{***} (Eur/tCO_2)	$p^{**}_a = p^{**}_b$ (Eur/tCO_2)	τ^{**} (Eur/tCO_2)
Reference	138	118	750.0	263.00	98	233.00
Cost of investment in capture (x) increased by 50%	138	118	750.0	310.50	98	280.50
Unit cost of storage (z) increased by 50%	147	127	750.0	272.00	107	242.00
Cost of transport (t) increased by 50%	198	168	750.0	338.00	138	293.00
Cost of investment in capture (x) decreased by one third	138	118	750.0	231.33	98	201.33
Unit cost of storage (z) decreased by one third	132	112	750.0	257.00	92	227.00
Cost of transport (t) decreased by one third	96	83	750.0	210.50	70	191.00
Hotelling line L = 500 km	48	43	187.5	150.50	38	143.00
Hotelling line L = 2400 km	162	138	900.0	293.00	114	257.00

Table E.2 *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* τ^{***} (τ^{**}) *in order to sustain full competition under sequential (simultaneous) moves.*

E.4 Economies of scale

In Section 7, we discussed under what condition it is socially optimal to use both storage sites. We also derived a condition for when only one storage site will be used under full competition although it is socially optimal to use both sites. Furthermore, in Section 10.3 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 (59).

To estimate the parameter F, we need to identify how much of the total costs 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 four countries on our Hotelling "line", namely Norway, United Kingdom, Belgium, and The Netherlands. Next, we multiply this amount of emissions (117

$mtCO_2$) with the reference unit cost of storage (18 EUR/tCO_2), to obtain total costs of storage (1800 million EUR). Hence, with to 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 E.3. With a Capex share of 50%, we find that the fixed cost of a storage site amounts to 450 million EUR. Hence, $F < \frac{tLE}{4} = 2340$ million EUR.[20] Hence, it is optimal to use both storage sites.

	Viking A	Captain X	Forties 5, Site	Bunter CL36	Goldeneye	Hewett	Endurance
Pre-FID	28	31	103	52	38	24	30
CAPEX	429	201	922	617	277	623	777
OPEX	639	385	1446	751	110	988	1085
ABEX	94	96	205	148	110	130	315
MMV	14	92	293	40	33	81	78
TOT CAPEX	551	328	1230	817	425	777	1122
TOT OPEX	653	477	1739	791	143	1069	1163
TOT CAP+OP	1204	804	2968	1609	629	1846	2285
SHARE CAPEX	45.76%	40.80%	41.44%	50.78%	67.57%	42.09%	49.10%
SHARE OPEX	54.24%	59.33%	58.59%	49.16%	22.73%	57.91%	50.90%

Table E.3 *Capex and Opex for different storage sites in the UK in million £$_{2015}$. Source: Pale Blu Dot (2015).*

Part II: More information on cost of storage

E.5 Cost of capture

Cost of capture in industrial processes depends on the concentration of CO_2 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),

[20] 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.

provides estimates for different types of cost of capture and how these differ by emission source, see Table E.4.

Capture Costs

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

Source: Clean Air Task Force (CATF)

Table E.4 Cost of capture

In Norway, there are currently two CCS projects underway: Norcem and Fortum Oslo Varme (Fov). 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 tonne of CO_2 captured, see Table E.5.

Costs per tonne of CO2 captured

	Norcem	Fov
Capex P50 (Eur/ton)	85.61	113.27
Opex P50 (Eur/ton)	25.42	47.64
Total cost of 1 ton of CO2 captured (P50)	111.03	160.91
Capex P85 (Eur/ton)	100.10	131.70
Opex P85 (Eur/ton)	29.27	54.27
Total cost of 1 ton of CO2 captured (P85)	129.36	185.97

Capex and Opex tot in milion June 2021 Kroner, ex. VAT: NORCEM - CAPEX P50 = 3250 , OPEX P50 = 119, CAPEX P85 = 3800, OPEX P85 = 137; FOV - CAPEX P50 = 4300, OPEX P50 = 223, CAPEX P85 = 5000, OPEX P85 = 254 . Period: 10 years, discount rate r = 4%, CO2 captured per year in million tonnes: 0.4. Prices per tonne are adjusted at current May 2023 Kr/Eur rates.

Table E.5 Cost of capture for the two Norwegian projects Norcem and Fov.

As seen from Table E.5, with a probability of 50%, total cost of capture is lower than 111 EUR/tCO_2, and, with a probability of 85%, lower than 129 EUR/tCO_2 for the Norcem project.

These numbers are higher than the weighted average of the cost estimates in Table E.4; 95 EUR/tCO_2. In the present study, the latter estimate is used.

E.6 Cost of transport

CO_2 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_2, see Carbon Limits (2021). Table D.4 provides cost of transport of captured carbon by different means of transport. In the present study, we use 0.04 EUR/tCO_2 km, which is almost the cost of using ship to transport captured carbon in Table E.6.

Transportation Costs

Transport type	Cost (EUR/t/km)
New Pipeline Onshore	0.019093
New Pipeline Offshore	0.043072
Reuse Onshore	0.006110
Reuse Offshore	0.013783
Ship	0.047766
Rail	0.149094
Truck	0.150691

Source: Clean Air Task Force (CATF)

Table E.6 Cost of transport of captured CO_2.

E.7 Cost of storage

The International Energy Agency (IEA, 2011) identifies three main types of storage for captured CO_2: 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 process, CO_2 is permanently stored (IEA, 2020). Storage in saline formations has a high technology readiness level (TRL), and projects have shown that CO_2 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.

Norway has 42 storage sites, primarily located in the Norwegian North Sea. For the United Kingdom, a theoretical CO_2 storage capacity of 78 Gigatons was identified in Bentham et al. (2014). The majority of the storage capacity is located in saline formations in the North Sea. Whereas the Netherlands has significant onshore storage capacity, most companies emitting CO_2 are located near ports, making offshore storage the most convenient solution.

Table E.7 shows cost estimates and storage characteristics for some storage sites located in the North Sea:

Storage costs and characteristics

Storage Site	Storage Type	Storage Size (Mt)	Injection rate (Mt/yr)	Levelised Unit Cost Of Storage	Unit Technical Cost (Eur/t)
Viking	Depleted Oil/Gas Feld	130	5	12 £/t	-
Captain X (Acorn)	Saline Formation	60	3	16.50 £/t	-
Forties 5	Saline Formation	300	6-8	13.88 £/t	-
Bunter Closure 36	Saline Formation	280	7	9.12 £/t	-
Goldeneye	Depleted Oil/Gas Field	30	3	27.45 £/t	-
Hewett	Depleted Oil/Gas Field	200	5	12.50 £/t	-
Endurance	Saline Formation	520	13	7.81 £/t	-
Northern Lights	Geological Formation	t.b.d.	1.5-5	18 Eur/t	-
P15/P18	Depleted Gas Field	82	0.45	-	4.6
L10	Depleted Gas Field	103.4	0.45	-	5.9
K7/K8	Depleted Gas Field	104	0.45	-	2.1-5
K14/K15	Depleted Gas Field	171.2	0.45	-	4.4-9.4
Q1/Q4	Saline Aquifer/Depleted Gas Field	123.6	0.45	-	4.9
P6	Depleted Gas Field	33	0.45	-	5.3
K12	Depleted Gas Field	37	0.45	-	2.9-10.4

[a] Source: Pale Blue Dot, Norwegian Ministry of Petroleum and Energy, Gausnie and EBN

Table E.7 Cost of storage for North Sea sites.

Reported cost of CO_2 storage ranges from \$5/tonne for depleted onshore oil and gas fields, via \$6/tonne for onshore saline reservoirs, to \$18/tonne for offshore saline reservoirs[21] (Bassett et al., 2020), and even higher. The Clean Air Task force assumes that cost of CCS in Europe amounts to 18 EUR per tonne of CO_2 (Carbon Limits, 2022), which is the estimate we use in the present study.

[21] Costs are reported in USD 2018.