DEPARTMENT OF ECONOMICS
OxCarre (Oxford Centre for the Analysis of Resource Rich Economies)

Manor Road Building, Manor Road, Oxford OX1 3UQ
Tel: +44(0)1865 281281 Fax: +44(0)1865 281163
reception@economics.ox.ac.uk www.economics.ox.ac.uk

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Monopolistic Sequestration of European Carbon Emissions

Niko Jaakkola
OxCarre

Direct tel: +44(0) 1865 281281 E-mail: celia.kingham@economics.ox.ac.uk

Monopolistic sequestration of European carbon emissions

Niko Jaakkola[1]
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Abstract

Mitigating climate change by carbon capture and storage (CCS) will require vast infrastructure investments. These investments include pipeline networks for transporting carbon dioxide (CO_2) from industrial sites ('sources') to the storage sites ('sinks'). This paper considers the decentralised formation of trunk-line networks when geological storage space is exhaustible and demand is increasing. Monopolistic control of an exhaustible resource may lead to overinvestment and/or excessively early investment, as these allow the monopolist to increase her market power. The model is applied to CCS pipeline network formation in northwestern Europe. The features identified above are found to play a minor role. Should storage capacity be effectively inexhaustible, underinvestment due to the inability of the monopolist to capture the entire social surplus is likely to have substantial welfare impacts. Multilateral bargaining to coordinate international CCS policies is particularly important if storage capacity is plentiful.

Keywords: carbon capture and storage, exhaustible resources, network formation, spatial networks
JEL Classification: L50, Q31, Q58

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[1]Department of Economics, University of Oxford, and Oxford Centre for the Analysis of Resource Rich Economies (OxCarre). Email: niko.jaakkola@economics.ox.ac.uk
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1 Introduction

> Scotland-based companies and the government at Holyrood hope proximity to the rapidly-depleting oil and gas fields of the North Sea will put the country at the forefront of a potentially lucrative new industry storing carbon dioxide. (...) The development of CCS in Scotland including power stations and storage networks has the potential to support 10,000 jobs. (*Financial Times*, 16th Aug 2010)[2]

> [Norwegian] Statoil has dedicated a group of geologists to mapping the undersea region with the aim of one day providing carbon storage for power plants and manufacturers across Europe. "We want to build a business at Statoil as a carbon dioxide storage provider," says Kristofer Hetland, a Statoil executive. (*Financial Times*, 2nd Sep 2010)

Carbon capture and storage (CCS) is a technology intended to mitigate climate change.[3] CCS involves the capture of carbon dioxide (CO_2) from large point sources: typically coal- or gas-fired power plants or industrial installations. The gaseous pollutant is separated from other flue gases and compressed into either a liquid or a 'supercritical' ('dense') phase. Once transported to an appropriate location, the pollutant is then injected underground. Storage is conventionally considered to occur in suitable geological formations: depleted oil and gas reservoirs, or saline aquifers.[4] CO_2 will fill any vacant pore space in the rock, potentially displacing water or existing oil or gas in the formation.[5] Once underground, the storage site would be sealed (if necessary), with the carbon dioxide trapped by low-permeability layers above the formation, slowly

[2] A policy document from the Scottish government concurs:

> We want the North Sea to be seen as Europes principal CO2 storage hub (. . .) bringing new investment and a long term future for our offshore industries as hydrocarbon production eventually declines. (Scottish Government and Scottish Enterprise, 2010)

[3] IPCC (2005), although dated, remains the 'bible' on carbon capture and storage; see also Kheshgi et al. (2012).

[4] Storage in the deep ocean has also been suggested. See Lontzek and Rickels (2008) for an economic analysis of ocean sequestration.

[5] With large-scale CCS, large quantities of brine may be produced and would need to be disposed of adequately, e.g. by pumping it underground into a different formation or by desalination (Surdam et al., 2011; Bourcier et al., 2011). Not producing brine would imply a reduced overall storage capacity or higher pressures in the formation. The latter would increase the risk of fracturing the rock 'seal' overlying the storage formation, leading to CO_2 leakage or groundwater contamination; or of inducing seismic activity (Buscheck et al., 2011).

dissolving into the formation water and eventually mineralising into carbonate rock.

As the quotes above illustrate, the expectation of climate policies can transform subsurface storage capacity into a valuable asset. Two questions naturally arise: how *should* such assets be employed, and how *will* they be employed? The answer to the latter will depend on the regime of property rights and the relevant regulatory environment—that is, who controls the assets, and how they are allowed to utilise them. The two answers might well be different: under some regulatory environments, self-interested actors might utilise subsurface storage capacity in ways which are suboptimal from society's point of view. For example, a country such as Norway might want to ration storage capacity, in order to maximise the fees it can charge for storing the carbon emitted by German power plants. Such rationing would push up the costs of generating electricity in Germany; but such costs would not fall on Norway, and would hence not be taken into consideration.

As economy-scale CCS would almost certainly require storage in reservoirs which are not yet well understood, in particular saline aquifers, total available storage capacity remains an unknown quantity.[6] Storage in depleted oil and gas fields is fairly well understood; these could provide total capacity of up to 900 $GtCO_2$ worldwide. However, many such fields will not be located close to where the emissions are being generated; in Europe, such capacity is estimated to be only 20 $GtCO_2$ (Vangkilde-Pedersen et al., 2009b). Note that the potential emissions would well exceed this capacity: using projections by the International Energy Agency, European CO_2 emissions could be around 2-3 $GtCO_2$ per annum.[7] Storage in saline aquifers would at least double this capacity worldwide; in Europe, saline aquifers could provide 100 $GtCO_2$ additional capacity.

Several factors might limit the actual available storage capacities. Firstly, the expected abundance of storage capacity in saline aquifers might have been overestimated. The statistical methods used to assess regional storage capacities

[6]The component technologies of CCS are all relatively mature and have been commercially available for decades. However, to have a substantial impact of greenhouse gas concentrations, these technologies would have to be deployed at a vastly greater scale. For example, some 50 $MtCO_2$ is currently injected underground each year as part of enhanced oil recovery operations (ITFCCS, 2010). Integrated assessment models project storage rates of 10-20 $GtCO_2$ by 2100; an increase or two or three orders of magnitude.

[7]Note that while the original fossil fuel content partially corresponds to available capacity, CCS is *not* about 'putting back in' whatever was taken out: the CO_2 injected would be mostly sourced from coal-burning facilities, not oil or gas combustion. In some reservoirs, not the entire original hydrocarbon volume can be exploited as 'water-driven' reservoirs may have significant amounts of pore space invaded by water from the geological formation.

have been criticised as ignoring crucial geological and physico-chemical details (such as the migration of the CO_2 plume in the reservoir or the pressure and temperature profiles which affect CO_2 density). Detailed studies have shown that ignoring such detail may result in reported storage volumes exceeding actual potential by one or two orders of magnitude (Spencer et al., 2011).

Furthermore, restrictions on onshore storage may prove to be serious. At present, these seem most likely to stem from public health and safety concerns.[8] While such fears seem to be largely unfounded, they could severely constrict overall storage capacity and increase the overall cost of CCS. Hence, at this point, it seems prudent to take into account scenarios in which overall storage capacity is rather scarce.

Economy-scale CCS implies major investments: plants to separate CO_2 from a flue gas stream and to compress it, transport infrastructure (pipelines and/or ships and related facilities) to transport the pollutant to the injection site, and the injection plants. As an example, In Europe these investments could run into the tens and hundreds of billions of euros. The capture costs dominate overall costs. However, in the case of offshore storage, the cost of developing the transport infrastructure would gain more weight. Such investments are costly: a recent study estimated the cost of long offshore pipelines to be in excess of €2m/km (ZEP, 2011d), with fixed costs related to transportation and injection making up almost a third of the overall costs of CCS.[9] Major backbone infrastructure would require many pipelines of this capacity.[10]

This paper studies CCS under decentralised infrastructure investment and potentially exhaustible storage. Both features are novel in the study of optimal CCS infrastructure. I will use an exhaustible resources framework: the 'resource' being underground storage capacity, one can think of CO_2 injections as 'extraction' of storage capacity.

The main theoretical innovation of the paper is to consider the effect of set-up costs and market power in exhaustible resource markets. I will show

[8]People may be worried about a catastrophic release, such as the notorious incident of a release of naturally accumulated CO_2 in Lake Nyos, Cameroon, which led to thousand of fatalities by suffocation, or of induced earthquakes (Bradbury, 2012).

[9]According to ZEP (2011b) and the detailed sister reports, capturing a tonne of CO_2 post-combustion at a hard coal power plant, shipping it 1500 km offshore and injecting into a depleted gas field would cost roughly €53. Of this cost, the capture costs make up 59%, divided evenly between capital and operating costs. Pipeline and storage capital costs make up another 31%. The operating costs related to injection make up 8%, and the remaining 2% is due to transport operating costs.

[10]The 40" offshore pipeline used for the estimates can transport 20 Mt CO_2 per annum. Projected transport requirements run into the hundreds of megatonnes per annum.

that, under particular demand structures, a resource monopolist may build too much infrastructure, too early, compared to what is socially efficient. The conditions required for this to occur are rapidly increasing demand, an anticipated collapse in demand in the future (for example, due to technological innovation introducing a substitute for the resource) and the ability of the monopolist to appropriate an increasing fraction of the social value of resource use by cutting back demand.

With rapidly increasing demand, resource consumption would optimally be loaded towards the future, peaking at maximum capacity in the run-up to the termination of demand, when the excess value of consumption (net of any extraction costs) is the highest. This creates an incentive to postpone investment into opening the deposit. A monopolist will invest too early, and in too much capacity. The intuition is that the distorted investment decisions create market power for the monopolist. Investing early prolongs the remaining period until the technology revolution makes the resource worthless. High extraction capacity permits larger sales in the run-up to the technology revolution. Both factors allow the monopolist to increase prices immediately after investment, so capturing a larger share of the surplus due to the use of the resource, while still selling the entire stock.

These theoretical results may have implications for many capital-intensive resource markets. For example, the deposits of some rare earth elements—necessary for many high-tech applications, e.g. as permanent magnets used in computer hard drives, wind turbines and the engines of hybrid cars—are well-known to be concentrated in China. The exhaustibility of known deposits has been said to be a serious issue. The industry is very capital intensive, due to the complicated supply chain required to extract and refine these metals.[11]

In the second half of the paper, I apply the model to the European CCS market under decentralised pipeline network formation. I find that the above questions of overinvestment or early investment are not very important from a welfare perspective: if the exhaustibility of storage capacity truly bites, then the monopolist is likely to behave in ways which come close to the efficient outcome. However, the more important case is that in which storage capacity is plentiful.

[11] Other particularly capital-intensive resource industries, such as supply of liquefied natural gas or exploitation of unconventional oil reserves, may feature a lower degree of market power on part of the owner of the capital-intensive deposit. In oil markets, the market power is instead held by OPEC, who sell mainly conventional oil; although even extraction of conventional oil is rather capital intensive. In LNG markets, on the other hand, market power is less likely to be an issue in the near future due to the rapidly increasing shale gas supply from the United States, and potentially elsewhere.

In this case, while the potential social benefits of CCS are higher, so are the potential losses due to lack of coordination between the countries which emit CO_2 and the countries with the possibility to store these emissions.

The existing literature on CCS economics is not very extensive.[12,13] One strand of literature uses stylised, long-run, macro-scale analytical models to consider the optimal timing of CO_2 sequestration. Lafforgue et al. (2008) consider the efficient timing of CCS when multiple storage sinks exist, under the constraint of atmospheric CO_2 concentrations not exceeding a given ceiling. The sinks are assumed to have finite capacity. They are only used once the atmospheric ceiling becomes binding. Before this is the case, 'storage in the atmosphere' is preferred as this is not only cheaper, but also has the added benefit of natural decay proportional to the stock. Once the economy hits the ceiling, resource use continues over and above the maximum rate of natural decay rate at the ceiling, with the excess emissions stored in sinks, and the cheapest sinks used first. Amigues et al. (2010) and Coulomb and Henriet (2011) point out that if noncapturable emissions, such as the diffuse emissions resulting from transport fuel consumption, are very large, then the entire flow of capturable emissions might be stored while at the ceiling. With late capture constrained and so unable to fully substitute for early capture, CCS begins before the atmospheric ceiling is reached. Amigues et al. (2012) consolidate and extend this line of inquiry further by studying the optimal timing of CCS when the costs are affected by the cumulative capture (due to either learning-by-doing or scarcity of storage capacity) or purely by the flow rate of capture.

Grimaud et al. (2008) consider an endogenous growth model, with an exhaustible resource, the use of which produces a stock pollutant. They allow for a carbon capture process which uses labour to remove a fraction of the carbon emissions. It is found that the optimal carbon tax, while increasing, can be interpreted as a decreasing ad valorem tax on resource use. This is result consistent with the 'Green Paradox' literature (Sinclair, 1994): resource owners seek to postpone extraction in response to a lower ad valorem tax rate in the future.[14] Importantly, the level of the tax becomes important (alongside the rate of change) as this incentivises optimal CCS efforts.

[12] I am omitting the voluminous engineering-economic literature considering the costs of various detailed processes in the CCS chain.

[13] I will cover the theoretical literature on set-up costs in Section 2.

[14] The 'Green Paradox' states that any policy constricting future demand, as perceived by the resource owner, relative to current demand will tend to accelerate extraction (and, presumably, pollution) as resource owners reoptimise their extraction schedules.

None of the above papers take into account the 'energy penalty' related to CCS. Part of the cost of CCS results from need to burn more fuel to drive the energy-intensive capture process. Thus, to avoid a given amount of emissions, a larger amount has to be captured; in addition to the avoided emissions, the CO_2 emitted during production of energy used in capture itself has to be captured. This of course increases the demand for fuel, in particular coal. Hoel and Jensen (2012) point out that, if CCS is feasible, an expected carbon tax in the future may in fact *increase* future demand for coal, because of this energy penalty. This effect may eliminate the Green Paradox, as a tightening climate policy leads to increasing demand for coal, thus incentivising conservation of the resource.

At the other end of the spatial scale, Leach et al. (2011) study how a profit-maximising firm optimally schedules oil extraction by CO_2-enhanced oil recovery (EOR), thereby sequestering carbon in the process. Their model departs from commonly used models of resource extraction by being founded more closely on models employed by reservoir engineers and oil industry practitioners. These models typically feature falling oil extraction due to falling pressure in the reservoir (the 'production decline curve') (Adelman, 1990; Cairns and Davis, 2001). CO_2 injections are found to decrease over time, driven by exhaustibility of storage capacity and a fall in the marginal product of injected CO_2 (in terms of produced oil) as reservoir pressure falls. Carbon sequestration is found to be much more sensitive to the oil price than to the carbon price. Other authors have pointed out that the timing of EOR-related CO_2 demand, among other factors, imply that while enhanced oil recovery is likely to be important in terms of higher oil production, it may play a rather small role in sequestering meaningful amounts of carbon (Davidson et al., 2011; Dooley et al., 2010).

Recently, a number of studies (some of these funded or conducted by the European Commission) have studied optimal CO_2 pipeline networks using geographically detailed economic models (Middleton and Bielicki, 2009; Morbee et al., 2012; Neele et al., 2010). These studies, all of which have an operations research flavour, consider minimisation of overall system-wide costs required to meet exogenous goals; such as sequestering a given amount of carbon per year, or complying with a carbon tax. The implicit assumption is that there exists a regulator with the incentives and legal powers to mandate the construction of the cost-minimising network. The studies are either static or use a relatively coarse temporal resolution.

All of the above papers (except Leach et al., 2011) thus focus on the centrally planned, socially optimal or social cost-minimising outcome. Such central planning may not be feasible. There may not exist the political will or desire to regulate the industry (this could well be the case in the United States). Alternatively, a regulator with sovereignty over the various actors might not exist; say, were CO_2 pipelines to cross international borders, a situation seen as unavoidable in the EU.[15] With multiple self-interested decisionmakers, game-theoretic methods are required.

The application in the present paper falls somewhere between the models considering the optimal timing of CCS and those focusing on infrastructure network formation. I strip down the geographical detail in order to focus on the large-scale features of transport networks; in particular, the timing of 'backbone' pipelines transporting large quantities of CO_2. I do this in order to focus on the dynamics of sequestration when coordination fails, in the sense that the backbone is unilaterally constructed by the owner of a major storage site, in order to profit from CCS storage.

The present paper does not consider issues such as regulation of monopolies or network industries (Armstrong et al., 1994). These would be natural questions to consider when focusing on appropriate incentives for a pipeline network located under a single jurisdiction. By assumption, in the present paper, no regulator with the required powers exists. As I only focus on a major 'backbone' component of the pipeline network, the problem is really one of fixed costs for a single investment: network externalities do not play any role in the model. I also abstract from questions of long-term leakage rates of stored carbon (Ha-Duong and Keith, 2003). The question of optimal carbon taxes is ignored; this paper focuses on regional mitigation efforts so that the carbon tax can be taken as exogenous. Similarly, the availability and optimal use of fossil fuel resources is ignored; coal reserves are, in any case, estimated to be plentiful for the foreseeable future.

The paper is divided into two halves. Section 2 introduces a simple model of set-up costs with exhaustible resources, focusing on monopolistic extraction and investment timing. Section 3 applies the model to CCS, taking storage capacity as the resource. Section 4 summarises the findings, considers future research directions and concludes.

[15] Heitmann et al. (2012) argue that failures to subordinate local and/or national decisionmakers to EU-wide CCS policies may hinder the development of European CCS projects.

2 Exhaustible resources and set-up costs

Opening a deposit of an exhaustible resource may involve set-up costs to develop the associated infrastructure. The interaction between such costs and market power has received surprisingly little attention. Stiglitz (1976) showed that, faced with isoelastic demand and a given period of extraction, a monopolistic resource owner is unable to use market power to her advantage. An attempt to hike up prices in one period will require more of the resource to be sold in other periods, depressing prices, for the resource stock to be fully used up. This increases overall profits if prices are raised precisely when demand is less elastic, and decreased when demand is more elastic. With isoelastic demand profits cannot be increased.

Hartwick et al. (1986) show that this result breaks down when set-up costs are introduced: a monopolist who owns two deposits plans to open the second deposit too late, delaying the infrastructure investment. Fischer and Laxminarayan (2005), on the other hand, show that there are two different effects at play. The monopolist, deciding when to open a second (and final) deposit, is faced with a choice between hiking up prices, thus stretching out the period of extraction from the penultimate deposit; or depressing prices and opening the terminal deposit sooner. In the case of isoelastic demand, the latter effect outweighs the former and the monopolist will always invest excessively early.

Gaudet and Lasserre (1988) model upfront exploration investment, which determines the size of the initial resoure stock. They find that, under isoelastic demand, the monopolist will not invest enough in exploration. This is because the monopolist does not capture the entire surplus from consuming the resource. Both the planner and the monopolist will set the marginal cost of developing a resource deposit to the marginal benefit, i.e. the scarcity rent; this will be lower for the latter, as the marginal social value of the stock exceeds the marginal private value. The monopolist cuts back *cumulative* supply, analogously to the static case.[16]

I will below present related results. Suppose that demand is such that lowering the quantity sold increases the share of revenue in gross surplus.[17] If demand is increasing over time, until some date T at which a substitute enters and makes the resource obsolete, the monopolist will tend to invest too early

[16] Without extraction costs, the scarcity rent for the social planner is just the resource price at the time of opening the deposit, while for the monopolist it is the marginal revenue.

[17] Linear demand satisfies this, while for isoelastic demand, of course, the share is constant.

into opening a deposit. Furthermore, if investment costs are not fixed but associated with an expansion of maximum capacity, the monopolist will also have an incentive to invest in too much capacity.

These results are, in some ways, the mirror image of those in Gaudet and Lasserre (1988). In their paper, the period of extraction and the capacity were fixed (indeed, with capacity not binding), while stock was endogenous. In the present paper, the stock is fixed, but both the period of extraction and the capacity are endogenous. These quantities determine the degree of market power the monopolist has. The date of investment determines the effective length of the period of extraction. As the quantity of the resource is fixed, a longer period implies a lower average rate of extraction. Further, increasing demand causes extraction to be postponed, so that any capacity constraints are hit at the very end of the extraction period. Higher capacities allow more to be extracted late in the deposit's lifetime, hence allowing extraction to be constrained early on.

For ease of exposition, I will focus on the special case of time-varying linear demand and a finite and given terminal date. This choice is motivated by the application to CO_2 storage in Section 3. I will briefly comment on the isoelastic and infinite horizon cases as well.

2.1 Single exhaustible deposit and set-up costs

Suppose that, at any moment $t \in [0, T]$, demand for an exhaustible resource is linear:[18]

$$p(q, t) = \overline{p}(t) - \xi q$$

with corresponding gross consumer's surplus

$$CS(q) = \overline{p}q - \frac{\xi}{2}q^2 \tag{1}$$

Let the choke price $\overline{p}(t)$ grow at some rate $\gamma \in \mathbb{R}$ until the given terminal date T, following which it is zero forever:

$$\overline{p}(t) = \begin{cases} \overline{p}(0)e^{\gamma t} & \text{for } t \leq T \\ 0 & \text{for } t > T \end{cases}$$

The justification for this effectively finite time horizon is the arrival of some cheaper substitute which makes the resource unnecessary. This drastic assump-

[18]The results up to the characterisation of the optimal investment date (equation (6)) in fact hold for any downward-sloping demand curve.

tion is made for simplicity. The results would not change qualitatively if the demand were assumed to die off e.g. smoothly yet rapidly; a peaking demand (over time) is the essential feature.[19] The increase in the choke price might reflect exogenous economic growth driving up demand.[20]

The decisionmaker (either the social planner or a monopolist) initially has a fixed stock of the resource S(0), which can be extracted costlessly. Before extraction begins, a fixed investment cost I has to be paid. For now, this investment allows the extraction and sale of the resource at any rate.[21] The decisionmaker discounts the future at rate ρ.

2.1.1 Social planner

The social planner maximises the discounted stream of total surplus; as resource extraction is costless, this equals gross consumer's surplus less investment costs:[22]

$$\max_{q(t),t^*} \int_{t^*}^{T} e^{-\rho t} \left(CS \left(q(t) \right) \right) \mathrm{d}t - e^{-\rho t^*} I$$

subject to $\dot{S} = -q$, $S \geq 0$; $q(t) = 0, \forall t < t^*$.

The problem is solved in two stages: by first optimising for a given investment date t^*; second, by choosing the investment date t^* which maximises profits. The plan has to yield a positive net surplus for the investment to be undertaken at all.

Given t^*, the Hamiltonian for this problem is

$$\mathcal{H} = \overline{p}(t)q(t) - \frac{\xi}{2}q(t)^2 - \lambda_S(t)q(t)$$

and an optimal path has to satisfy the necessary conditions

$$\begin{aligned} \lambda(t) &= \overline{p}(t) - \xi q(t) \\ \lambda(t) &= \lambda(t^*) e^{\rho(t-t^*)} \\ \lambda(T)S(T) &= 0 \end{aligned} \tag{2}$$

with $\lambda(t)$ denoting the scarcity rent of the resource. The interpretation of the

[19] Of course, technology revolutions are very uncertain *a priori*. It might be more satisfying to interpret T as reflecting the resource owner's subjective expectation of such a revolution.

[20] In the application in Section 3, the choke price will reflect an exogenously increasing carbon price.

[21] Capacity constraints are introduced in 2.4.

[22] In other words, firms do not play a role in the social optimum; the resource is simply allocated to consumers.

above conditions is straightforward. The first states that the marginal benefit of selling the resource has to, at all times, equal the scarcity cost of not being able to sell the same unit at some other moment. The second implies that the present value of the scarcity rent is constant, so that profits cannot be increased by shifting extraction between any two points in time. The final condition just requires that either the resource be fully used by up by the terminal date; or, if otherwise, that the resource is not scarce to begin with, so that demand will be fully satisfied at all times following t^*.

I will, for now, focus on situations in which scarcity bites, i.e. $\lambda(t) > 0$, $\forall t$. Denoting the final date on which extraction takes place by $\tilde{T} \leq T$, this implies

$$\int_{t^*}^{\tilde{T}} q(s)\,\mathrm{d}s = S(0) \tag{3}$$

It should be noted that, differentiating this with respect to the investment date t^*, one obtains

$$q(t^*) = \int_{t^*}^{\tilde{T}} \frac{\partial q(s)}{\partial t^*}\,\mathrm{d}t + q(\tilde{T})\frac{\partial \tilde{T}}{\partial t^*} \tag{4}$$

This just implies that a small delay in investment date requires the amount extracted in the initial period to be reallocated along the extraction schedule, with the final date of extraction potentially adjusted. Clearly any delay in investment can only be optimal is $\gamma > 0$. If demand is not increasing, the social planner can do no better by delaying, but in fact will end up worse off: any profits are delayed and restrictions imposed by the terminal date (if binding) will get worse.

From the necessary conditions, following investment the optimal extraction path is given by

$$q(t) = \xi^{-1}\left(\overline{p}e^{\gamma(t-t^*)} - \lambda(t^*)e^{\rho(t-t^*)}\right) \tag{5}$$

with $q(t) \geq 0$ required. For a given investment date t^*, the optimal extraction path can be obtained from (3) and (5). The path is continuous; if extraction ever falls to zero, it will stop forever. Hence, paths such that the time horizon does not bind ($\tilde{T} < T$) are characterised by $q(\tilde{T}) = 0$. This implies that the last term in (4) drops out, as either the extraction flow at $t = \tilde{T}$ is zero, or the terminal date is fixed ($\tilde{T} = T$).

Optimal date of investment is obtained by differentiating profits, given optimal extraction, with respect to t^*:

$$\frac{\mathrm{d}\pi(t^*, q(t))}{\mathrm{d}t^*} = \int_{t^*}^{\tilde{T}} e^{-\rho t} \frac{\partial CS(t, q(t))}{\partial q(t)} \frac{\partial q(t)}{\partial t^*} \,\mathrm{d}t + e^{-\rho \tilde{T}} CS(\tilde{T}, q(\tilde{T})) \frac{\mathrm{d}\tilde{T}}{\mathrm{d}t^*} \\ - e^{-\rho t^*} CS(t^*, q(t^*)) + \rho e^{-\rho t^*} I = 0$$

By using (4), the fact that the first derivative of consumer's surplus yields $\frac{\partial CS(t,q(t))}{\partial q(t)} = \lambda(t)$, and the fact that either $q(\tilde{T}) = 0$ or $\frac{\mathrm{d}\tilde{T}}{\mathrm{d}t^*} = 0$, this gives the first-order condition for investment:

$$q(t^*) \left(\frac{CS(t^*, q(t^*))}{q(t^*)} - \lambda(t^*) \right) \geq \rho I, \quad t^* \geq 0, \quad \text{C.S.} \tag{6}$$

The second-order condition becomes, after some manipulation,

$$\xi \int_{t^*}^{\tilde{T}} e^{-\rho(t-t^*)} \left(\frac{\partial q(t)}{\partial t^*} \right)^2 \mathrm{d}t \geq -\rho \lambda(t^*) q(t^*)$$

which is clearly always satisfied.

The first-order condition (6) is very similar to the result obtained by Fischer and Laxminarayan (2005) in a slightly different setting. The right-hand side is the benefit obtained by a short delay in investment: the avoided opportunity cost of the investment outlay. The left-hand side is the cost of delaying. The small amount of resource not extracted during this delay has to be reallocated along the planned extraction schedule. Doing this, the per-unit return is just the marginal surplus $\lambda(t)$; or, discounted back to t^*, $\lambda(t^*)$. Had these units been extracted in the initial period, they would have instead earned the average surplus $\frac{CS(q(t^*))}{q(t^*)}$. Of course, the foregone average surplus exceeds the marginal surplus, and so delaying has a cost.

For the linear demand curve, the optimal investment date is characterised by

$$q(t^*) = \sqrt{\frac{2\rho I}{\xi}} \tag{7}$$

Thus, the 'day-one' extraction rate, assuming an interior solution for the investment date, does not depend on the level or rate of increase of the demand curve (Figure 1).[23] An increase in ρI raises the opportunity cost of investment, that is, the benefit of delaying. Hence investment occurs later; as there is a shorter

[23] For the linear demand curve, the difference between the price and (gross) consumer's surplus does not depend of the level of the demand curve, only on the slope (Figure 1).

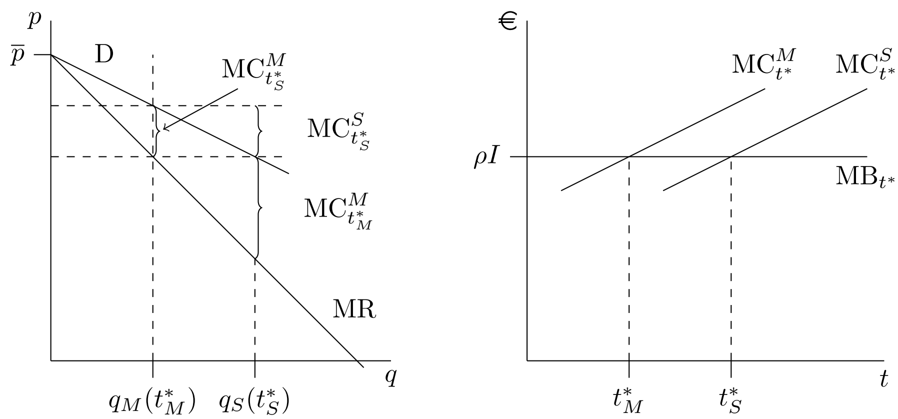

Figure 1: (*left*) The cost of a marginal delay in investment for the social planner is average surplus less price: $\mathrm{MC}^S_{t^*} = \frac{CS(q(t^*))}{q(t^*)} - p(q^*)$. With linear demand, this depends only on the slope of demand, not the level $\overline{p}$. The cost for the monopolist is price less marginal revenue: $\mathrm{MC}^M_{t^*} = p(q^*) - \mathrm{MR}(q^*) = 2\mathrm{MC}_{t^*}$. As the marginal benefit of delaying is the same for both, the monopolist's 'day one' extraction rate will be half that of the social planner. (*right*) For any given t, the monopolist's marginal cost of delay is higher than the social planner's; the marginal benefit is, for both, the opportunity cost of funds ρI.

period of extraction, the extraction rate has to also increase. An increase in ξ raises, for any $q(t^*)$, the difference between average surplus and price—thus increasing the marginal cost of delaying. Investment occurs earlier and extraction rates fall.

For brevity's sake, I will focus on the case in which resource depletion continues until the terminal date: $\tilde{T} = T$. With two unknowns, $t_S \equiv t^*$ and $\lambda_S(t_S)$, the social planner's optimum (with linear demand) is uniquely described by

$$\overline{p}(t_S)\frac{e^{\gamma(T-t_{\mathrm{S}})}-1}{\xi\gamma} - \lambda_S(t)\frac{e^{\rho(T-t_{\mathrm{S}})}-1}{\xi\rho} = S(0) \tag{8a}$$

$$\frac{\overline{p}(t_S)-\lambda_S(t_S)}{\xi} = \sqrt{\frac{2I\rho}{\xi}} \tag{8b}$$

where the first equation is the resource constraint, and the second the first-order condition for investment.

2.2 Monopolistic extraction

Consider now the case in which a monopolist owns the stock of the resource. The monopolist maximises the stream of discounted revenues, less the investment cost:

$$\max_{q(t),t^*} \int_{t^*}^{T} e^{-\rho t} \left(p(q(t),t)q(t)\right) \,\mathrm{d}t - e^{-\rho t^*} I$$

subject to the same conditions as the social planner. The solution method proceeds exactly as above; I will only state the differences here. The FOC for maximising the Hamiltonian becomes

$$\lambda(t) = \overline{p}(t) - 2\xi q(t)$$

so that the optimal extraction path is

$$q(t) = (2\xi)^{-1} \left(p(t^*)e^{\gamma(t-t^*)} - \lambda(t^*)e^{\rho(t-t^*)}\right) \tag{9}$$

The first-order condition for investment becomes

$$q(t^*) \left(p(q(t^*)) - \lambda(t^*)\right) \geq \rho I \tag{10}$$

where the intuition is as before: delaying investment leads the need to extract at a higher rate following investment. For a monopolist, this depresses prices on the inframarginal units at all future dates; the discounted scarcity rent $\lambda(t^*)$ just equals marginal revenue, which is of course below the price $p(t^*)$. The monopolist also has a constant 'day one' extraction rate, lower than the social planner's:

$$q(t^*) = \sqrt{\frac{\rho I}{\xi}} \tag{11}$$

The intuition for the relationship between the two day-one extraction rates is shown in Figure 1 (left panel).

For extraction continuing until the terminal date, the monopolist's optimal solution is implicitly given by

$$\overline{p}(t_M)\frac{e^{\gamma(T-t_{\mathrm{M}})}-1}{\xi\gamma} - \lambda_M(t)\frac{e^{\rho(T-t_{\mathrm{M}})}-1}{\xi\rho} = 2S(0) \tag{12a}$$

$$\frac{\overline{p}(t_M) - \lambda_M(t_M)}{\xi} = 2\sqrt{\frac{I\rho}{\xi}} \tag{12b}$$

Note that the entire plan in conditional on the monopolist actually achieving positive profits following it. Otherwise the monopolist will simply remain inactive and make zero profits.

2.2.1 Comparison of monopolistic and optimal outcomes

If the choke price rises at the discount rate ρ, the elasticity of demand is constant along the optimal path (although clearly not, in general, for the demand curve) for both social planner and monopolist. Hence:

Lemma 1. For $\gamma = \rho$, both the monopolist and the social planner will follow the same Hotelling Rule:

$$\frac{\dot{p}_M}{p_M} = \frac{u'(q_S)\dot{q}_S}{u'(q_S)} = \rho, \forall t > t_i$$

for $i \in \{S, M\}$. Hence, for a given investment date $t_S^* = t_M^* = t^*$, the time profiles of extraction will be identical: $q_S(t) = q_M(t), \forall t > t^*$.

Proof. Immediate from (5) and (9), and from combining these with the resource constraint (3). □

Proposition 1. As long as the choke price grows at some rate sufficiently close to ρ, the monopolist will invest earlier than socially optimal:

$$\exists \epsilon > 0 : \text{for } \gamma \in (\rho - \epsilon, \rho], t_M^* < t_S^*$$

Proof. For $\gamma = \rho$, obtained by explicitly solving (8) and (12). As the systems defining the two equilibria are continuous, this will also hold for some $\gamma < \rho$. □

Under the given demand curve, as long as demand increases sufficiently quickly, the monopolist will find it profitable to invest excessively early. The motivation for this is to increase the length of the period over which the resource is extracted, in order to push up the resource price. If there is a terminal date which is binding for the social planner, the monopolist can only extend the extraction interval by investing too early.[24]

[24] Suppose that demand is linear but the time horizon is not binding or infinite. It can be shown that the monopolist will spread out extraction over a longer time interval, but the extension of the interval is partially absorbed by delaying the terminal date of extraction $\tilde{T}$. The effect on the investment date is ambiguous.

Consider the case $\gamma = \rho$.[25] Constant elasticity of demand along the optimal path means that the monopolist does not 'frontload' or 'backload' extraction, relative to the social planner. The optimal investment date is the point at which the cost, to the decisionmaker, of deferring investment (delaying getting the surplus, plus any decreases in the current value surplus) just equals the benefit (delaying payment of the set-up costs) (Figure 1, right panel).

The monopolist captures a share $\frac{pq}{CS}$ of the total surplus as revenues. For the particular case we are considering, as both price and extraction rate increase at the rate ρ, this is constant given an investment date:

$$\frac{pq}{CS} = \frac{\overline{p}_0 - \xi q_0}{\overline{p}_0 - \frac{\xi}{2} q_0}$$

where it is understood that q_0 only indexes the level of the extraction schedule; of course extraction is only positive after the investment date. Notice that the fraction of surplus captured decreases with q_0. Earlier investment implies a lower extraction schedule, and thus a higher fraction of total surplus captured (Figure 2, left panel).

For the planner, the cost of a short delay is given by

$$\begin{aligned}\mathrm{COST}^{\mathrm{SP}}(t^*) &= -\frac{\mathrm{d}}{\mathrm{d}t^*}\left(\int_{t^*}^{T} e^{-\rho t} CS \,\mathrm{d}t\right) \\ &= -\int_{t^*}^{T} e^{-\rho t} \frac{\mathrm{d}CS}{\mathrm{d}q(t)} \frac{\mathrm{d}q(t)}{\mathrm{d}t^*} \,\mathrm{d}t + e^{-\rho t^*} \left. CS \right|_{t=t^*}\end{aligned}$$

which is positive for the particular demand curve we are considering.

With a constant $\frac{pq}{CS}$, the same cost for the monopolist can be written[26]

$$\begin{aligned}\mathrm{COST}^{\mathrm{MON}}(t^*) &= -\frac{\mathrm{d}}{\mathrm{d}t^*}\left(\int_{t^*}^{T} e^{-\rho t} \frac{pq}{CS} CS \,\mathrm{d}t\right) \\ &= \frac{pq}{CS}\mathrm{COST}^{\mathrm{SP}}(t^*) - \int_{t^*}^{T} e^{-\rho t} \frac{\mathrm{d}(pq/CS)}{\mathrm{d}q_0} \frac{\mathrm{d}q_0}{\mathrm{d}t^*} CS \,\mathrm{d}t\end{aligned} \tag{13}$$

for any given t^*. Suppose the monopolist considers investing at the socially optimal date t^*_{SP}. The cost of delay is smaller due to the monopolist capturing a smaller fraction of the total surplus (first term). This effect is very similar to

[25] For lower γ, the intuition is complicated by the fact that demand is no longer isoelastic along the optimal paths, and so the monopolist will load extraction, over time, differently compared to the social planner.

[26] Write revenues $pq = \frac{pq}{CS} CS$, differentiate, and use the expression for $\mathrm{COST}^{\mathrm{SP}}$.

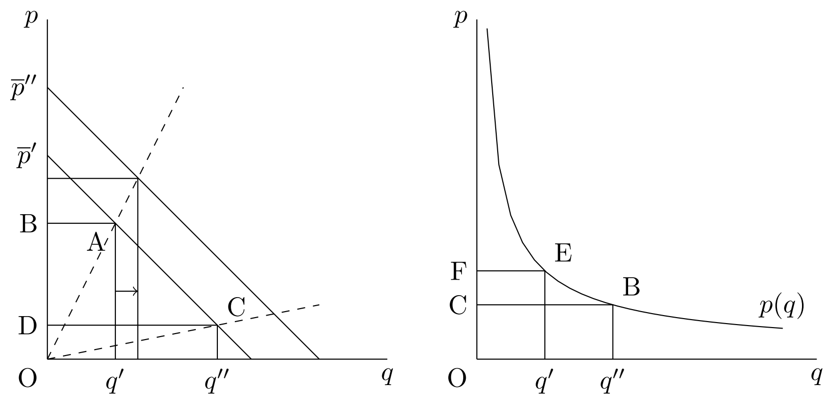

Figure 2: Surplus, revenue streams. (*left*) Linear demand, with $\gamma = \rho$. The extraction rate and price increase proportionally along a ray (through A) from the origin. An optimal plan just exhausts the stock by time T. The ratio of revenues to total surplus $\frac{\text{Oq'AB}}{\text{Oq'A}\overline{p}}$ remains constant, for a given initial rate of extraction. Delaying investment, however, increases initial $q(t^*)$ and so reduces this ratio to $\frac{\text{Oq''CD}}{\text{Oq''C}\overline{p}'}$. (*right*) With isoelastic demand, the monopolist's share of total surplus is unaffected by $q(t^*)$: $\frac{Oq''BC}{\int_O^{q''} p(q)} = \frac{Oq'EF}{\int_O^{q'} p(q)}$.

that investigated by Gaudet and Lasserre (1988). However, it is larger due to the delay leading to this fraction falling (second term). With linear demand, the latter effect outweighs the former and the monopolist faces a higher cost of delaying than the social planner does. The benefit of delay, the opportunity cost of investment funds, is the same for both the social planner and the monopolist. The monopolist will hence want to bring investment forward.

Consider briefly the case of isoelastic demand with a finite terminal date (Figure 2, right panel). In this case, for a given investment date, the monopolist and planner again follow the very same extraction paths. Further, $\frac{pq}{CS}$ is again constant; it is constant along the entire demand curve! Equation (13) still holds, but the second term of the right-hand side is zero. In this case, the cost of a marginal delay, for a given day one extraction rate, is smaller for the monopolist than for the social planner. The monopolist thus chooses to invest later. These two polar cases illustrate the mechanism leading to the monopolist investing early in the case of rising linear demand.

Finally, consider the case in which the resource is plentiful: $\lambda_S = \lambda_M = 0$. It is straightforward to observe from (7) and (11) that this implies $\overline{p}(t_S^*) < \overline{p}(t_M^*)$, i.e. $t_S^* < t_M^*$. This is obvious: when scarcity does not play a role, a change in the investment date does not affect the day one extraction rate nor, hence, the share of surplus the monopolist appropriates. The only effect at play is the monopolist's appropriating a lower share of the rents, and thus the monopolist optimally delays investment.

2.3 Optimal policy with commitment

I will now consider the ability of the regulator to achieve the socially optimal outcome by committing to taxes on resource sales and on set-up investment. An ad valorem tax on the resource, $\theta(t)$, has to motivate an efficient extraction path following investment.[27] A unit tax on investment, τ_I, can be used to ensure that the resource stock is opened up at an optimal date. Negative taxes imply subsidies.

Following investment, the monopolist now faces the same inverse demand curve but only gets a share $1-\theta(t)$ of the revenue flow. The cost of investment inclusive of taxes is $I+\tau_I$. The taxes can be characterised further:

Proposition 2. If the social optimum satisfies $p(t^*)S_0 \geq 2I$, the regulator can obtain the efficient outcome with the monopolist's profits being at any weakly positive level. If the condition does not hold, full nationalisation is the only way to obtain the efficient outcome.

If the rate of change of the choke price is strictly less than (equal to) the discount rate ρ, the efficiency-inducing ad valorem resource tax rises (does not change) over time:

$$\gamma < \rho \Rightarrow \dot{\theta} > 0$$
$$\gamma = \rho \Rightarrow \dot{\theta} = 0$$

The level of this tax can be freely chosen, as long as $\theta(t) \leq 1$ for all t. The optimal investment tax depends on this level, and is characterised by

$$\tau_I = \big(1 - 2\theta(t^*)\big)I$$

Proof. In Appendix 5. □

If resource sales are not taxed, the tax on investment should just equal the investment cost again; this increases the opportunity cost of the funds required

[27] The solution is different if the regulator sets a time-varying unit tax on resource sales.

for investment, and encourages the monopolist to delay investment. If the initial resource tax is at 50%, investment should be neither subsidised nor taxed. As θ tends to one, i.e. as the regulator appropriates almost all of the potential resource revenues, investment should be subsidised at a rate approaching 100%; this would be equivalent to a 'nationalisation' of the sector. These tax (or subsidy) instruments allow any distributional outcomes to be satisfied; the regulator can effectively choose any level of (weakly positive) profits it allows the monopolist to obtain.

2.4 Set-up costs with capacity constraints

In the previous section, set-up costs have been assumed independent of the quantity of the resource sold. I will now relax this assumption and consider the case in which an investment gives the resource owner the ability to extract and sell the resource up to a chosen capacity constraint. The resource owner thus has an extra choice variable. Furthermore, there may be an incentive to make several investments: if there is increasing demand for the resource, it may be optimal to invest first in a small amount of capacity and then increment this later with additional investments. These investments could describe investment into rigs and infrastructure, or, as in the next section, into transport pipelines.

For simplicity, consider the case $\gamma = \rho$ and linear demand. Suppose the resource owner makes n investments. These are described by the set of investment times and capacities $\{(t_1^*, \overline{q}_1), \ldots, (t_n^*, \overline{q}_n)\}$. The capacity constraint at time t is now given by

$$q(t) \leq Q(t) \equiv \sum_{\{j : t_j^* \leq t\}} \overline{q}_j$$

To focus on interesting cases, I will assume that there are some fixed costs to investment.[28] I will also assume costs are weakly convex in capacity. Thus, in current value terms, the investment cost is given by $C(\overline{q}), C(0) > 0, C' > 0, C'' \geq 0$. Thus, the social planner's problem is to solve

$$\max_{q(t), \{(t_i^*, \overline{q}_i)\}} \int_{t^*}^{T} e^{-\rho t} \left(CS\left(q(t)\right)\right) \mathrm{d}t - \sum_i e^{-\rho t_i^*} C(\overline{q}_i)$$

subject to the resource and capacity constraints.

For a given investment schedule, the social planner's first-order condition for

[28] Otherwise it would be optimal to make an infinite number of infinitely small investments.

extraction now becomes

$$p(q) \geq \lambda, \quad q \leq \overline{q}, \quad \text{C.S.} \tag{14}$$

coupled, of course, with the associated non-negativity constraint (given my assumptions, these will never hold). Other first-order conditions and the resource constraint remain unchanged. The resulting optimal extraction path will have a discontinuous shape, with capacity caps clipping off a part of the curve (Figure 3).

Proposition 3. For ease of notation, denote $t^*_{n+1} \equiv T$. Starting with $t = t^*_1$, the optimal path consists of $2n$ stages, divided by the dates of investment, and in between these dates, the dates at which the current quantity gap starts binding $\{\tilde{t}_i\} \equiv \{\min t : \xi^{-1}(\overline{p}(t) - \lambda(t)) = Q(t^*_i)\}$. These latter dates satisfy $\tilde{t}_i \in [t^*_i, t^*_{i+1})$.

The social planner's optimal investment schedule is characterised by

$$\Delta_{t^*_i}\Big[CS(q) - p(t^*_i)q\Big] = \rho C(\overline{q}_i), \quad t^*_i \geq 0, \quad \text{C.S.} \tag{15a}$$

$$\sum_{j\in[i,n]} \int_{\tilde{t}_j}^{t^*_{j+1}} e^{-\rho t}\left(p(Q(t)) - \lambda(t)\right) \mathrm{d}t = e^{-\rho t^*_i} C'(\overline{q}_i) \tag{15b}$$

in which $\Delta_t[X(s)] \equiv \lim_{s\downarrow t} X(s) - \lim_{s\uparrow t} X(s)$, i.e. the upward discontinuous jump in variable X at time t. The optimal number of investments $n \in \{0, 1, 2 \dots\}$ is chosen so that welfare is maximised.

Proof. In Appendix 4. □

In words, investment at t^*_i is followed by two stages: first, the new quantity cap may not be binding, but from $\tilde{t}_i$, it will. The first stage may be degenerate, but the second always exists: the next investment will not be made until the capacity constraint becomes binding—otherwise the investment could have been profitably delayed. The intuition for the optimal dates is as before: a marginal delay in investing has the benefit of saving the opportunity cost of investment, but extends the period of capped sales, which has a cost in terms of revenues (net of the scarcity rent, i.e. taking into account that the resource can be sold in other periods; equation (15a)). As the quantity will only ever jump up, this cost will be positive (Figure 4). The marginal benefit of investment quantity is just given by the cumulative marginal welfare due to being able to sell more

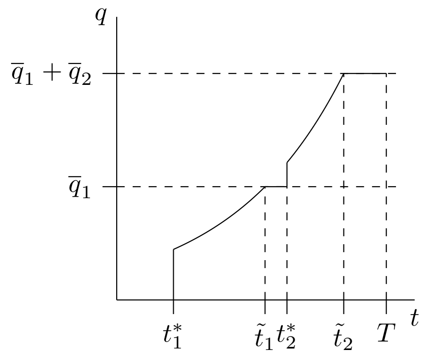

Figure 3: The optimal path consists of a series of investments. After an investment, the quantity sold may be below the cap; it will reach the cap before the next investment.

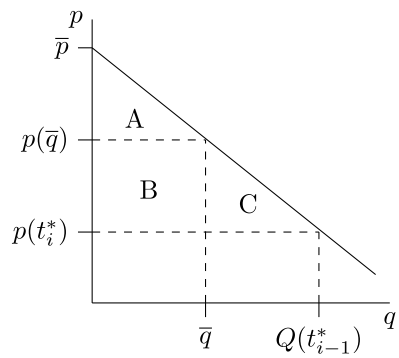

Figure 4: The gross marginal cost of extending the next investment is ABC, but A can be recouped by reallocating sales. Net marginal cost is BC > 0.

resource in all future periods when the quantity cap binds, net of the scarcity rent (as these units can be reallocated to be sold in periods in which the cap is not binding) (equation (15b)). This marginal benefit is always positive (by (14)), and has to equal the marginal cost of capacity.

For the monopolist, the problem changes in an analogous manner. The outcome is similar, with the FOC (14) changing to

$$MR(q) \geq \lambda, \quad q \leq \overline{q}, \quad \text{C.S.} \tag{16}$$

The FOCs for investment date and quantity become, respectively,

$$\Delta_{t_i^*}\Big[(p(q) - \lambda(t_i^*))q\Big] = \rho e^{-\rho t_i^*} C(\overline{q}_i) \tag{17a}$$

$$\sum_{j \in [i,n]} \int_{\tilde{t}_j}^{t_{j+1}^*} e^{-\rho t} \left(MR(Q(t)) - \lambda(t)\right) \mathrm{d}t = e^{-\rho t_i^*} C'(\overline{q}_i) \tag{17b}$$

where the LHS are positive, by positivity of marginal revenue and equation (16), respectively.

Proposition 4. Suppose demand is linear, investment costs are weakly convex in capacity ($C'' \geq 0$), that a single investment is optimal for both the monopolist and the social planner ($n_M = n_S = 1$), and that the resource is scarce for both ($\lambda_S, \lambda_M > 0$). Then the monopolist either invests too early ($t^*_{1,\mathrm{M}} < t^*_{1,\mathrm{M}}$), or invests in too much capacity ($\overline{q}_{1,\mathrm{M}} > \overline{q}_{1,\mathrm{S}}$), or both.

Proof. In Appendix 4. □

Thus, the counterintuitive result obtained in the absence of capacity constraints may still hold when such constraints are included. A further counterintuitive result is added: with linear demand, there is a tendency for the monopolist to also invest too much. At least one of these effects will always be observed. The intuition for the latter effect is that, when only a single investment is made, higher capacity allows the monopolist to sell more when the cap is reached. This occurs close to T, allowing the monopolist to raise prices early in the extraction period, yet still sell the entire stock. As in the case with unlimited capacity, the monopolist's share of early surplus increases . With multiple investments, the entire extraction path changes and it is difficult to make claims at this level of generality. In the next section, I will show numerically that, with multiple investments, the monopolist will tend to overinvest; and will tend to make at least some investments excessively early.

3 Investment in CCS infrastructure

I will now sketch out an application of the above model to carbon capture and storage. I will consider the particular scenario of transporting CO_2 emissions from northwestern Europe to the North Sea by large pipelines. Such a scenario has been widely discussed in the policy literature on CCS (Haszeldine, 2009; Neele et al., 2010; Morbee et al., 2012). The dominant players would be Norway and the UK, particularly were the storage led by EOR projects; in the long term, should projections of potential storage in saline aquifers be borne true, Norway in particular might hold 25% of European storage capacity (Neele et al., 2011b; Vangkilde-Pedersen et al., 2009b).[29]

There is a potential need to construct large trunk line networks out to the North Sea, in particular if onshore storage is ruled out (for whatever reason). The detailed routing of such networks varies between existing studies; Haszeldine (2009) and Neele et al. (2010) envision a connected network for the entire region, while Morbee et al. (2012) find the optimal trunk lines to be more fragmented. It is apparent the debate over the spatial structure of such a backbone

[29] However, the Netherlands might play a non-negligible role given its share of depleted gas fields in the southern North Sea.

network is not settled, and that the existence of a single connected network for the entire region cannot be ruled out.

I will focus on a very simplified spatial structure in order to consider decentralised network formation and the dynamic effects of market power. Quite clearly, the various actors (the storage sites and the emitting firms) are under separate, sovereign jurisdictions. Under a single jurisdiction, a regulator could implement the first-best solution. Here, as such a regulator does not exist, the game-theoretic approach is appropriate.[30] Moreover, as the emissions are produced by a large number of firms, the assumption of ruling out bilateral contracts is also appropriate. Of course, the results are contingent on the assumption that cooperation between various countries fails. The only other study to consider imperfect coordination is Morbee (2012), who adopts a cooperative game theoretic approach in a static framework.

At the heart of the climate change problem lies a market failure—the absence of markets for the public bad of climate change. Hence, in the decentralised problem, appropriate incentives (e.g. carbon taxes or a cap-and-trade scheme) are required for the agents to undertake CCS at all. I take climate policy as exogenous as northwestern Europe cannot substantially affect the path of atmospheric CO_2 concentrations.

The assumption of exogenous climate policy implies that there exists a regulator with the desire to implement such incentives, and the power to enforce them. This contrasts with the absence of a regulator for CCS policy. Such asymmetry is plausible, however. There might exist sufficient political pressure to get an overall climate policy regime in place, but not enough to implement detailed regulation on how it should be complied with (for which the regulator would also require better information). Climate policy also turns subsurface storage sites into valuable assets, and there could be organised lobbying against the regulator interfering with the management of such assets. I assume full compliance with the climate policy, and will not consider whether the agents might want to withdraw from such a policy regime.

The North Sea has major storage potential, with UK and Norwegian depleted oil and gas fields providing capacity for up to 10.5 $GtCO_2$ and large saline aquifers potentially multiplying this capacity several times over (Vangkilde-Pedersen et al., 2009a).[31] Some of the oil and gas fields have legacy infras-

[30] Of course, the exporting country, or countries, could try to cartelise CO_2 supply.

[31] Some CCS experts have pointed out that commonly used statistical methods to assess regional storage capacities tend to overestimate actual, final capacities by one or two orders

tructure in place; others are still producing, and CO_2 injections could begin as enhanced oil recovery operations.[32] The geology of the oil and gas fields is also already well understood.

Major clusters of emission sources lie relatively close, both in the UK and in the Rhine valley. Onshore storage of these emissions would be cheaper, assuming saline aquifer storage turns out to be feasible. Were this assumption to fail, onshore geological storage capacity would fall substantially. Moreover, public concerns over health and safety, possibly the most important obstacle to CCS (House of Commons Science and Technology Committee, 2012), may rule out onshore storage. As an example, a major pilot storage project in Barendrecht in the Netherlands was cancelled in 2010 due to public outcry (Feenstra et al., 2010), and an exploration project in Beeskow is Germany has met similar public opposition (Dütschke, 2011).

I will now map the model of the previous section into a scenario of carbon storage in the North Sea. It should be emphasised that the assumptions (no onshore storage, and no saline aquifer storage capacity offshore) tend to err on the pessimistic side, and the exercise below is entirely conditional on these assumptions holding. Offshore storage in saline aquifers would substantially reduce the threat of scarcity of storage, with the conclusions reported below for cases without scarce storage holding. Were onshore saline aquifer storage feasible, the resulting network structure, and the decentralised pipeline investment problem, would be very different: in particular, the onshore network structure would be more fragmented, consisting of many individual, small pipelines. This alternative problem would have to be analysed using a much more complicated model.

Spatial structure. Consider an industrial cluster emitting CO_2 ('Source') and a site suitable for geological storage of the pollutant ('Sink'). Considering the Sink to be Norway and the Source to be the industrial agglomeration in northwestern Europe, I will assume the sites are separated by a distance of roughly 1200 km. This corresponds to the pipeline from the Ruhr to the Utsira formation in Haszeldine (2009).

Timing. I take the base year to be 2020. Emissions will continue for $T = 50$

of magnitude (Spencer et al., 2011). These issues affect storage in saline aquifers; the geology of the hydrocarbon fields has been mapped in detail as part of the oil and gas extraction operations, and estimates of overall storage capacity can be estimated fairly accurately.

[32] Dooley et al. (2010) argue that while EOR projects may help advance the relevant technologies, in the US they are unlikely to be important in terms of actually storing meaningful quantities of carbon.

years, after which there is an overnight transition to clean energy, resulting in capturable carbon emissions falling to zero. An alternative case considers a longer time horizon with $T = 80$. All agents discount the future at the common rate $\rho = .03$.

Carbon pricing. An exogenous climate policy governs both nodes, mandating a carbon tax $\overline{p}(t)$ per unit of carbon emitted. The carbon price rises at the rate $\gamma = \rho$. The fact that the rate of increase equals the discount rate implies that the cumulative amount of carbon emitted is capped, as suggested, for example, by Allen et al. (2009). The carbon price is not paid for stored emissions as these do not contribute to climate change.

This policy is assumed to be optimal, in the sense that the carbon tax corresponds to the social cost of carbon emissions, allowing direct comparisons of social welfare versus private profits: attention can then be focused on the efficiency of the CCS process itself. I consider two cases: one with a low initial (2020) carbon price (€73/tCO_2) and one with a high initial carbon price (€146/tCO_2).[33]

CO_2 capture. Instead of being emitted to the atmosphere, carbon emissions can be captured, transported and buried underground up to the capacity of the pipeline linking the Source to the Sink.[34] Capture costs are incurred in this process. Provided the carbon price is higher than the marginal capture costs, capturing and storing carbon is (weakly) welfare-improving (after any pipeline costs have been sunk).

The Source is a representative polluter, composed of a large number of small actors, all faced with different capture cost curves. The aggregate capture cost curve $C(q(t))$ is strictly convex, and for convenience specified quadratic: $C(q) = \frac{\xi}{2}q^2$. The representative firm faces a choice between emitting the marginal unit and paying the carbon tax $\overline{p}(t)$, or capturing the marginal unit at marginal cost $\xi q(t)$ and paying the Sink the asking price $p(t)$ to dispose of it. Equalising these for optimality yields the inverse demand curve for carbon storage:

$$p(t) = \overline{p}(t) - \xi q(t)$$

The key assumption here is that of increasing marginal cost. This could result from a combination of marginal costs varying across firms and marginal

[33] By the year 2030, the prices are fairly close to the projections in the two scenarios in IEA (2008). The initial values may seen implausibly high for 2020.

[34] I abstract from questions of pipeline and reservoir leakage.

costs varying within firms. Variation across firms exists, particularly if industrial plants are included as sources alongside power-generating facilities.[35] It is more difficult to ascertain the degree to which individual installations are able to adjust at the intensive margin (the capture rate), and how costs would vary with respect to this. Most engineering-economic studies assume a fixed capture rate and report costs given this. A few studies do consider variation in the capture rate, either in terms of switching off capture and instead venting the carbon into the atmosphere (Chalmers et al., 2009), or in terms of altering the fraction of CO_2 captured (Wiley et al., 2011; Ziaii et al., 2009; Brunetti et al., 2010). These studies indicate that there does, indeed, exist an intensive margin for captured CO_2, even if they provide no information on costs or elasticities of supply. As the present paper is concerned with margins aggregated at the level of a large industrial cluster, I will assume that the linear marginal cost curve is a reasonable first step.[36]

I am implicitly assuming that there is no fixed investment into capture equipment: instead, these costs are subsumed into the operating costs. This is a major assumption, made in order to simplify the model. Incorporating capture investment would introduce investment hold-up issues, as a marginal plants might face the risk of not recouping investment costs.

Putting actual numbers to the cost curve is a fraught exercise, involving projections of economic growth, the change in the composition of energy infrastructure, and so on. I will take the shortcut of using projections from IEA (2008). In particular, they provide projections of CCS-equipped infrastructure in the OECD power-generating sector in 2030 at two different carbon price levels: 78 GW (all coal-fired) at a carbon price of \$90/tCO_2, and 170 GW (120 GW coal-fired, the rest gas turbines) at a carbon price of \$180/tCO_2. To obtain the equivalent figure for the region in question, I assume the generating capacity is divided between countries in proportion to their 2010 electricity generation (OECD, 2012). I pick the countries in the region; for UK, Germany and France I scale emissions in proportion to the total quantity of CO_2 emissions originat-

[35] See e.g. Damen et al. (2009), who provide an aggregate CO_2 supply curve for the Netherlands.

[36] Note that I have not explicitly considered the energy penalty. This is because the storage demand curve aggregates the intensive and extensive margins in a stylised fashion. Were all adjustment to happen at the intensive margin, the penalty could be interpreted as follows. Suppose that the additional energy required is linear in the captured quantity q, so that emissions are $E(q) = E_0 + \nu q$, where E_0 are the emissions when fully vented (CCS switched off). Suppose also that emissions are linear in fuel consumption, and that the fuel price c is rising at the discount rate. Then the model holds as is, but we must interpret $\overline{p} = p_{CO_2}(1-\nu) - c$; that is, the carbon price is expressed net of the energy penalty and fuel price.

ing broadly in the relevant region (using the European Pollutant Release and Transfer Register database). 96% of German, 84% of UK and 55% of French power generation CO_2 emissions fall in the relevant region; with northwestern Europe accounting for roughly 14% of total OECD electricity generation. This implies that, at the lower carbon price, the region would contain 14 hard coal power plants with CCS (800 MW each). At the higher carbon price, there would be an additional 7 hard coal power plants and 14 combined-cycle gas turbines (500 MW each). I calculate the carbon captured for both price levels (ZEP, 2011a)[37] to obtain $\xi = 1.6$ and I assume CCS demand is stationary at this level for the entire time period.

$\mathbf{CO_2}$ transport and storage. The sink's upfront capital costs are just the pipeline capital costs. Pipeline investment cost is given by the formula $C(\overline{q}) = \alpha_1 + \alpha_2 \overline{q}$ per kilometer, a linear relationship as estimated from a number of previous studies by Morbee et al. (2012) (with $\alpha_1 = 1.066$, $\alpha_2 = .038$ after adjusting by the terrain factor for offshore) This implies that a 20 Mtpa pipeline would cost €1.9m per kilometer. This is slightly higher than the cost estimated by ZEP (2011d). The capital costs of storage facilities (\$6 per tCO_2) are calculated for the volume stored between two consecutive pipeline investment dates. ZEP (2011c) uses a central assumption of 66 Mt capacity per field, with a 5 $MtCO_2$ per annum injection rate. This would imply field lifetime of 13 years, which is mostly of similar order of magnitude as the optimal investment intervals given in the present model.

I include constant, fixed operating costs incorporating the operating costs of transport and storage (\$1 and \$4 per tCO_2, respectively). Note that I am implicitly assuming a very long pipeline lifetime, as there is no depreciation of installed capacity. This assumption might be contested in the context of the longer time horizon.[38]

It should be noted that operational considerations impose minimum and maximum bounds on the volume transported through a pipeline at a given moment: sufficient pressure is required to force CO_2 into the supercritical phase for transport. Hence, the underutilisation of capacity may imply that CO_2 is temporarily stored at source until sufficient a quantity has been accumulated for transportation. Alternatively, as the results imply transport links of magnitude

[37] Note that the carbon emissions avoided needs to be transformed into carbon captured; due to the energy penalty imposed by capturing carbon, i.e. the need to burn additional fuel to power the capture process, these two quantities are not equal.

[38] ZEP (2011d) assumes capital costs are depreciated over a 40-year period.

which cannot be constructed as a single pipeline, but rather as several lines running side by side, it may be that initially some of these component pipelines are not used at all times.

Storage capacity. The sink initially has a fixed stock of storage space $S_0 =$ 3200 $GtCO_2$, corresponding to the depleted oil and gas fields in the Norwegian sector in the North Sea (Vangkilde-Pedersen et al., 2009a). As an alternative scenario, I consider storage by the UK, with a larger capacity $S_0 = 7300$.

3.1 Results

I will compare outcomes under monopolistic supply of CCS and the socially optimal case. In the base case (Figure 5, top panel), a monopolistically behaving Sink does not find scarcity biting for either level of initial capacity; hence there is no difference between the two countries. Investment occurs immediately, with three further capacity expansions. The social planner invests earlier and in more capacity; the Norwegian monopolist's initial capacity is 20% lower than efficient, and the UK monopolist's 45%. The welfare costs are substantial, leading to present value monetary losses of 14% and 24% of the total value of CCS operations, respectively. These differences in investment are driven by the inability of the monopolist to capture the entire social surplus. In other words, the monopolist cuts back cumulative supply, analogously to monopolistic behaviour in a static model. Scarcity bites for the social planner when storage occurs in Norway, but not if it occurs in UK. Note that the fixed cost of laying pipelines induces both the social planner and the monopolist to practice 'oversizing' (as reported by Morbee et al., 2012): the constraints on the capacity are never binding immediately after investment. In fact, they only bind for roughly half of the entire time horizon in the base case, and even less under the alternative scenarios.

Suppose now that the technology revolution is perceived to occur much later, in 2100 instead of 2070. With storage in saline aquifers proving to be infeasible, capacity becomes scarce for all agents. A Norwegian monopolist would now invest inefficiently early, building the first pipeline (of five) in 2023 whereas efficient investment would be postponed until 2036 (Figure 5, bottom panel). Following investment, as both types of agent will want to fill the entire capacity, the social planner must capture slightly more. The differences are relatively small, and the welfare impact of monopolistic storage is only .3% of total CCS value. In the case of the UK, both the monopolist and the planner follow very similar paths. The larger storage capacity requires more transport capacity, construction of which is spread over seven investments. The paths are nearly identical and welfare differences are essentially zero. These results indicate that, if storage capacity is scarce even for the monopolist, then market power is not worth worrying about. However, note that in the base case, when the monopolist finds it optimal to cut back supply and leave some storage unutilised, the welfare impacts are substantial.

These are very basic points. Consider a static context, with a quantity cap which binds even for a monopolist. Then the monopolist will sell as much as she can, as will the social planner. This result holds also in the dynamic context examined here, with the cap being analogous to the cumulative quantity of resource available.

Note that either outcome results in substantially lower total sequestration rates than projections consistent with the stated long-term climate goals of the European Union. Neele et al. (2010), as an example, project total sequestration rates of up to 750 $MtCO_2$ per year by 2050, should onshore storage be ruled out. These compare with 20–100 Mt per year (depending on the case considered) by the same date in the present model.[39] This partly reflects the assumption of much more limited storage capacity: Neele et al. assume offshore saline aquifer storage to be feasible.

High carbon prices (starting at \$146/tCO_2 in 2020) motivate more storage, ensuring that even with a short time horizon the entire capacity is used up except by a monopolistic UK (Figure 6). A Norwegian monopolist overinvests but by very little; the welfare impacts are vanishing. In the case of the UK, the inability to capture the entire surplus leads to underinvestment by the monopolist, with substantial effects on welfare (18% of the total present value of CCS operations).

The model projects cost shares which are consistent with those obtained from engineering-economic studies, despite explicit optimisation of investment timing and capture rates and the rather abstract calibration of the storage demand curve. The share of total discounted capture costs is between 65% and 82% of total costs, with higher costs resulting from higher carbon prices or from having more storage capacity and a longer time horizon. Of course, both factors lead to higher overall stocks of sequestered carbon. These compare with engineering-economic benchmarks of 59% (for a hard coal post-combustion capture plant) and 84% (for natural gas combined cycle plant with post-combustion capture)

[39] It should be mentioned that Neele et al. (2011a) also consider such large volumes 'unrealistic'.

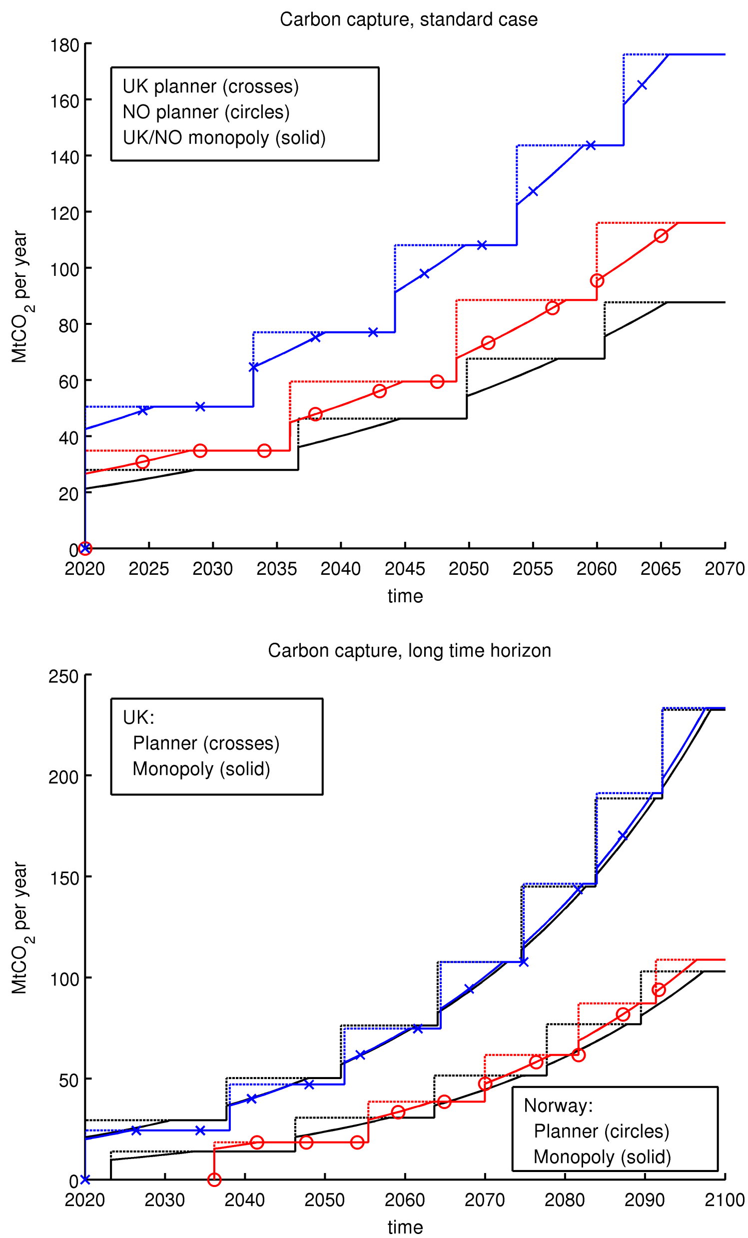

Figure 5: (*top*) Comparison of the socially optimal schedule (*red with cirles*: Norway / low capacity, *blue with crosses*: UK / high capacity), with the monopolistic outcome, identical for both capacities (*solid*). (*bottom*) The same comparison when clean energy arrives in 2100. Now scarcity bites in all cases. To utilise the entire UK capacity, a larger volume must be transported and it is efficient to build up to total capacity gradually. Note that in the Norwegian case the monopolist would invest 13 years earlier than efficient.

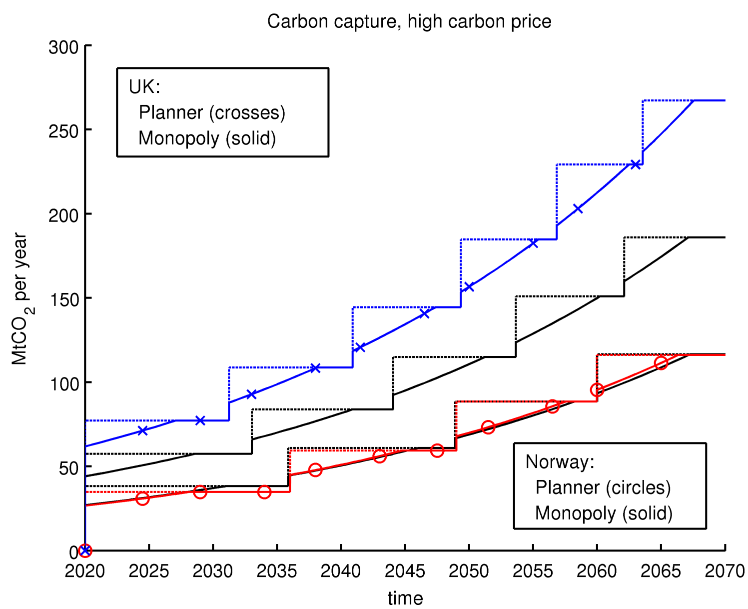

Figure 6: (*top*) Comparison of the socially optimal schedule (*red with cirles*: Norway / low capacity, *blue with crosses*: UK / high capacity), with the monopolistic outcome (*solid*), when the initial carbon price is high. Higher capture rates make capacity investment more profitable, so that the resource is scarce for all except the UK monopolist. Overinvestment by the monopolist is barely visible in the Norwegian case, and has negligible welfare impacts. The inability of the monopolist to capture the entire surplus leads to substantial underinvestment, with a welfare cost of 17%.

(ZEP, 2011b).[40] Pipeline and storage capital costs are projected to comprise between 11% and 25% of total costs; the actual costs are correlated with capture costs, but the latter respond more so that the cost shares are inversely correlated with capture costs. These compare with benchmark shares of 26% and 12% for the hard coal and natural gas combustion, respectively.

4 Conclusions

Poor infrastructure investments may drive up the total, lifetime, system-wide costs of large-scale CCS. Studies to date have considered CO_2 pipelines from a social planner's perspective, seeking to minimise CCS system costs. However, these studies assume the existence of a regulator with the powers to mandate or incentivise the construction of the optimal network. These studies also ignore the possible exhaustibility of geological storage capacity.

I have studied the interaction between set-up costs and market power in a market for an exhaustible resource. A well-known result is that, facing isoelastic demand, a monopolist is unable to use market power. Wanting to sell the entire resource stock, profits cannot be increased by reordering extraction over time. This changes when the monopolist gets to choose the date and magnitude of investment, and when demand is such that the monopolist is able to affect the share of overall surplus she captures by her extraction choices. A monopolist can then create market power by extending the period over which she extracts the resource, or by committing to high future extraction by overinvesting. I have shown this effect to hold for linear demand rising sufficiently quickly, but the feature will hold for other types of 'similar' demand functions.

I have applied the above model to CCS pipeline investment for the case of a single sink, single source. In principle, a monopolistic carbon sink may invest excessively early into CCS infrastructure, or invest in too much infrastructure. These results hold when storage capacity is effectively exhaustible, as it might be if, for example, the overall capacity of saline aquifers happened to be systematically overestimated. However, I have shown that these effects are not very substantial.

A much more important concern arises when storage capacity is plentiful, as would be the case were the massive saline aquifers under the North Sea brought online for CCS. While this would of course be good news overall, it increases the

[40] Assuming a 1500 km offshore spine with storage in depleted oil and gas fields without legacy technology; in the present study, the pipeline is 300 km shorter.

potential losses due to unilateral action by monopolistic suppliers. Specifically, there is a risk that the monopolist will underinvest as she is unable to capture the entire social surplus due to CCS. Such concerns may have very large welfare effects and it seems appropriate that the nations concerned coordinate their policies.

One could also consider the case of duopolistic storage, with Norway and the UK both building their own trunk lines and competing in supplying storage to a single connected market. This would have the effect of making storage capacity more abundant, as well as reducing the monopoly rents available to either supplier. The problems of early investment would be even less likely to hold, and the underinvestment resulting from the suppliers not capturing the entire surplus would become even more important. This holds a fortiori were storage capacity to become truly plentiful, as in the less pessimistic case of North Sea saline aquifers becoming available for storing CO_2.

These considerations emphasise the need to draw up contracts which ensure the entire surplus due to carbon storage is captured and shared among the parties. These parties should include all countries which either have major storage reservoirs and/or large domestic emissions. Countries without North Sea coast should be included, as several previous studies have shown that, were onshore storage not possible, even long-distance transport of captured CO_2 would be welfare-improving. The obvious question is how the surplus should be divided among the various parties. Morbee (2012) is a first comment on this question. A more detailed, dynamic treatment, taking into account the capacities of the various available reservoirs, would be a more satisfying way to assess how the surplus from CCS would be shared. However, this would be a substantially more difficult problem to tackle.

Multilateral bargaining between the countries responsible for emitting CO_2 and the providers of storage capacity is essential to ensure the entire value of potential CO_2 storage capacity is used. This paper thus presents further arguments for multilateral coordination of CCS policies (Heitmann et al., 2012). On the other hand, if there are grounds to believe that storage owners behave as if storage capacity were exhaustible, then the potential losses arising from lack of coordination may not be very high.

5 Proofs

Proof of Proposition 2. The socially optimal Hotelling Rule is

$$\dot{q} - \rho q = \frac{\gamma - \rho}{\xi}\overline{p} \tag{18}$$

For a given capture tax path, the Hotelling Rule the monopolist follows is given by

$$\dot{q} - \rho q = \frac{1}{2\xi}\left((\gamma - \rho)\overline{p} - \frac{\dot{\theta}}{(1-\theta)^2}\lambda\right) \tag{19}$$

where λ is determined by the resource constraint $\int_{t^*}^{T} q(t)\,\mathrm{d}t \leq S(0)$ and the monopolist's first-order condition

$$q(t) = \frac{\overline{p} - \frac{1}{1-\theta(t)}\lambda}{2\xi}$$

For any $\lambda(t) = \lambda(0)e^{\rho t} \geq 0$, equating (18) and (19) implies that the socially optimal capture tax path satisfies

$$-\frac{\dot{\theta}}{(1-\theta)^2} = \frac{\overline{p}(0)}{\lambda(0)}(\gamma - \rho)e^{(\gamma-\rho)t} \leq 0$$

which establishes the sign of $\dot{\theta}$. This can also be solved to get

$$1 - \theta = \frac{\lambda}{\overline{p} + K\lambda}, \qquad K > 0$$

with K an arbitrary constant.

For any given path $\theta(t)$, the monopolist's profits are

$$\pi^M = \int_{t^*}^{T} e^{-\rho t}(1-\theta)pq\,\mathrm{d}t - e^{-\rho t^*}(I + \tau_I) \tag{20}$$

and optimal investment date is given by

$$
\begin{aligned}
\frac{\mathrm{d}\pi^M}{\mathrm{d}t^*} &= \int_{t^*}^{T} e^{-\rho t}(1-\theta)(\overline{p}-2\xi q)\frac{\mathrm{d}q(t)}{\mathrm{d}t^*}\,\mathrm{d}t \\
&\qquad - \big(1-\theta(t^*)\big)e^{-\rho t^*}\, pq\big|_{t=t^*} + \rho e^{-\rho t^*}(I+\tau_I) \\
&= e^{-\rho t^*}\left(\lambda(t^*)\int_{t^*}^{T}\frac{\mathrm{d}q(t)}{\mathrm{d}t^*}\,\mathrm{d}t - \big(1-\theta(t^*)\big)\, pq\big|_{t=t^*} + \rho(I+\tau_I)\right) \\
&= e^{-\rho t^*}\left(-\xi q(t^*)^2\big(1-\theta(t^*)\big) + \rho(I+\tau_I)\right) \\
&= 0
\end{aligned}
$$

assuming an interior solution, and where I have used the monopolist's FOC and the derivative (with respect to t^*) of the resource constraint. This yields the $q(t^*)$; setting this to be equal to that chosen by the social planner determines the optimal tax on investment.

Finally, using the socially optimal values in (20), the optimised profits are

$$\pi^M_{\mathrm{OPT}} = (1-\theta)(\overline{p}S_0 - 2I)$$

which is positive as long as $\theta \leq 0$ and the bracketed term is positive. Provided this is the case, any positive profits can be given to the monopolist by setting *theta* sufficiently low. □

Proof of Proposition 3. With n investments, there are at most $2n$ stages: following each investment there may be a stage in which the cap does not bind, after which there is a stage in which the cap is binding. Given an investment schedule $\{(t_i^*, \overline{q}_i\}$, from (14) and the equation of motion $\dot{\lambda} = \rho\lambda$ it is apparent that, given a series of investments, the extraction rate increases monotonically until it hits the cap; and, after hitting the cap, it will remain constant until the next investment (after the last investment, the terminal time T). Clearly the next investment will never be made until the current cap has become binding; were this to be the case, profits could be increased by postponing the investment in question.

Denote the times at which the cap becomes binding by $\{\tilde{t}_i\}$ and let $t^*_{n+1} \equiv T$. With $q^*(t)$ denoting the optimal extraction quantity given the sequence of investments, I can write the profits as

$$W(\{t_i^*, \overline{q}_i\}) = \sum_{j\in\{1,\dots,n\}} \int_{t_j^*}^{\tilde{t}_j} e^{-\rho t} p(q^*(t))q^*(t)\,\mathrm{d}t + \int_{\tilde{t}_j}^{t_{j+1}^*} e^{-\rho t} p(Q(t))Q(t)\,\mathrm{d}t \tag{21}$$

and the resource constraint as

$$\sum_{j\in\{1,\dots,n\}} \int_{t_j^*}^{\tilde{t}_j} q^*(t)\,\mathrm{d}t + \int_{\tilde{t}_j}^{t_{j+1}^*} Q(t)\,\mathrm{d}t \leq S_0 \tag{22}$$

Differentiating the latter with respect to t_i^* ad using Leibniz's Rule, we get

$$\sum_{j\in\{1,\dots,n\}} \int_{t_j^*}^{\tilde{t}_j} \frac{\mathrm{d}q(t)}{\mathrm{d}t_i^*}\,\mathrm{d}t = \Delta_{t_i^*}\left[q(t)\right]$$

as the quantity sold in the capped periods does not change, as the quantity path is continuous at times $\tilde{t}_j$, and as for $j \neq i$, $\frac{\mathrm{d}t_j^*}{\mathrm{d}t_i^*} = 0$. In words, a marginal delay in investment means the units not sold during this delay (proportional to the upward jump in quantity) have to be reallocated to the periods in which extraction is not capped. On the other hand, differentiating the resource constraint with respect to $\overline{q}_i$ gives

$$\sum_{j\in\{1,\dots,n\}} \int_{t_j^*}^{\tilde{t}_j} \frac{\mathrm{d}q(t)}{\mathrm{d}t_i^*}\,\mathrm{d}t = -\sum_{j\in\{i,\dots,n\}} \int_{\tilde{t}_j}^{t_{j+1}^*} 1\,\mathrm{d}t$$

The RHS shows how a marginal increase in the magnitude of investment i increases the extraction rate during all future periods in which extraction is capped. For the resource constraint to hold, the extraction rate has to fall during all time periods when extraction is capped.

Differentiating (21) with respect to t_i^*, and understanding that $q(t)$ refers to the optimal value $q^*\left(t; \left\{(t_j^*, \overline{q}_j)\right\}\right)$ and that the sums are taken over $j \in$

$\{1, \ldots, n\}$,

$$
\begin{aligned}
\frac{\mathrm{d}W}{\mathrm{d}t_i^*} &= \sum_j \int_{t_j^*}^{\tilde{t}_j} e^{-\rho t_i^*} \frac{\mathrm{d}CS(t)}{\mathrm{d}q(t)} \frac{\mathrm{d}q(t)}{\mathrm{d}t_i^*} \,\mathrm{d}t - \Delta_{t_i^*} e^{-\rho t} CS(t) + \rho e^{-\rho t_i^*} C(\overline{q}_i) \\
&= e^{-\rho t_i^*} \left(p(t_i^*) \sum_j \int_{t_j^*}^{\tilde{t}_j} \frac{\mathrm{d}q(t)}{\mathrm{d}t_i^*} \,\mathrm{d}t - \overline{p}(t_i^*) \Delta_{t_i^*} [q(t)] + \frac{\xi}{2} \Delta_{t_i^*} \left[q(t)^2 \right] + \rho C(\overline{q}_i) \right) \\
&= e^{-\rho t_i^*} \left(p(t_i^*) \Delta_{t_i^*} [q(t)] - \overline{p}(t_i^*) \Delta_{t_i^*} [q(t)] + \frac{\xi}{2} \Delta_{t_i^*} \left[q(t)^2 \right] + \rho C(\overline{q}_i) \right) \\
&= e^{-\rho t_i^*} \left(-\frac{\xi}{2} \left(\Delta_{t_i^*} [q(t)] \right)^2 + C(\overline{q}_i) \right) \\
&= e^{-\rho t_i^*} \left(-\Delta_{t_i^*} [CS(q(t)) - p(q(t_i^*) q(t)] + C(\overline{q}_i) \right)
\end{aligned}
$$

where I have used the fact that, given the assumptions, the resource price grows at rate ρ; the derivative of the resource constraint with respect to t_i^*; the last line is straightforward to verify by calculation. Setting this equal to zero, for optimality, yields (15a). To check second-order conditions, differentiate again and use the FOC to get

$$
\begin{aligned}
\frac{\mathrm{d}^2 W}{\mathrm{d}t_i^{*2}} &= -e^{-\rho t_i^*} \frac{\mathrm{d}}{\mathrm{d}t_i^*} \left(\Delta_{t_i^*} [CS(q(t)) - p(t_i^*) q(t)] \right) \\
&= -e^{-\rho t_i^*} \frac{\mathrm{d}}{\mathrm{d}t_i^*} \left(\frac{\xi}{2} \left(\Delta_{t_i^*} [q(t)]^2 \right) \right) \\
&= -e^{-\rho t_i^*} \frac{\xi}{2} 2 \Delta_{t_i^*} [q(t)] \frac{\mathrm{d}}{\mathrm{d}t_i^*} \Delta_{t_i^*} [q(t)] \\
&< 0
\end{aligned}
$$

as delaying investment will increase the uncapped extraction rate, and holding the cap constant, thus increase the upward jump in the extraction rate.

To obtain the FOC for $\overline{q}_i$, note that

$$
\begin{aligned}
\frac{\mathrm{d}W}{\mathrm{d}\overline{q}_i} &= \sum_j \int_{t_j^*}^{\tilde{t}_j} e^{-\rho t} \frac{\mathrm{d}CS(t)}{\mathrm{d}\overline{q}_i} \,\mathrm{d}t + \sum_{j \geq i} \int_{\tilde{t}_j}^{t_{j+1}^*} e^{-\rho t} \frac{\mathrm{d}CS(Q(t))}{\mathrm{d}Q} \,\mathrm{d}t - e^{-\rho t_i^*} C'(\overline{q}_i) \\
&= \lambda(0) \sum_j \int_{t_j^*}^{\tilde{t}_j} \frac{\mathrm{d}q(t)}{\mathrm{d}\overline{q}_i} \,\mathrm{d}t + \sum_{j \geq i} \int_{\tilde{t}_j}^{t_{j+1}^*} e^{-\rho t} p(Q(t)) \,\mathrm{d}t - e^{-\rho t_i^*} C'(\overline{q}_i) \\
&= \sum_{j \geq i} \int_{\tilde{t}_j}^{t_{j+1}^*} e^{-\rho t} \left(p(Q(t)) - \lambda(t) \right) \,\mathrm{d}t - e^{-\rho t_i^*} C'(\overline{q}_i)
\end{aligned}
$$

where $\lambda(t) = p(t)$ at all times such that resource sales are positive and the cap is non-binding; and using the derivative of the resource constraint with respect to $\overline{q}_i$. Setting the last line equal to zero yields (15b). Differentiating again to get the second-order condition,

$$\begin{aligned}
\frac{\mathrm{d}W^2}{\mathrm{d}^2\overline{q}_i} &= \sum_{j \geq i} \int_{t_j^*}^{\tilde{t}_j} e^{-\rho t} \left(p'(Q) - \frac{\mathrm{d}\lambda}{\mathrm{d}\overline{q}_i} \right) \mathrm{d}t + e^{-\rho t_{j+1}^*} (p(Q) - \lambda(t_{j+1}^*)) \frac{\mathrm{d}t_{j+1}^*}{\mathrm{d}\overline{q}_i} \\
&\quad - e^{-\rho \tilde{t}_j} (p(Q) - \lambda(\tilde{t}_j)) \frac{\mathrm{d}\tilde{t}_j}{\mathrm{d}\overline{q}_i} - e^{-\rho t_i^*} C''(\overline{q}_i) \\
&= \sum_{j \geq i} \int_{t_j^*}^{\tilde{t}_j} e^{-\rho t} \left(-\xi Q - \frac{\mathrm{d}\lambda}{\mathrm{d}\overline{q}_i} \right) \mathrm{d}t - e^{-\rho t_i^*} C''(\overline{q}_i) \\
&< 0
\end{aligned}$$

where the second equality follows from the fact that either $\frac{\mathrm{d}t_j^*}{\mathrm{d}\overline{q}_i} = 0$ and that $p(Q(\tilde{t}_j)) = \lambda(\tilde{t}_j))$. Increasing $\overline{q}_i$ increases extraction at all times $t \geq t_i^*$ such that demand is capped; to meet the resource constraint, extraction has to fall when demand is not capped, i.e. $\frac{\mathrm{d}\lambda(t)}{\mathrm{d}\overline{q}_i} > 0$.

The formulae for the monopolist are derived similarly. □

Proof of Proposition 4. From the analysis of second-order conditions in the previous proof it becomes apparent that, in present value terms, the marginal benefit of delaying investment is constant with respect to t^*, while the marginal cost is increasing (Figure 7). Assuming $\overline{q}_M = \overline{q}_S$, it is straightforward to show that the monopolist's marginal cost is higher for any t_* and she will thus invest earlier. Suppose the monopolist invests less than the planner: $\overline{q}_M < \overline{q}_S$. We have

$$\begin{aligned}
\frac{\partial \mathrm{MB}}{\partial \overline{q}} &= \rho C'(\overline{q}) > 0 \\
\frac{\partial \mathrm{MC}_M}{\partial \overline{q}} &= (p(t^*) - CS'(q(t^*)) \frac{\mathrm{d}q(t^*)}{\mathrm{d}\overline{q}} + q(t^*) \frac{\mathrm{d}p(t^*)}{\mathrm{d}\overline{q}} \\
&= q(t^*) \frac{\mathrm{d}p(t^*)}{\mathrm{d}\overline{q}} < 0
\end{aligned}$$

where the first term in the second equation vanishes as either the term in the brackets is zero (cap not binding) or the derivative is (with binding cap); the remaining term has to be negative for the resource constraint to be met. This is illustrated graphically in Figure 7 and it is apparent that the monopolist will

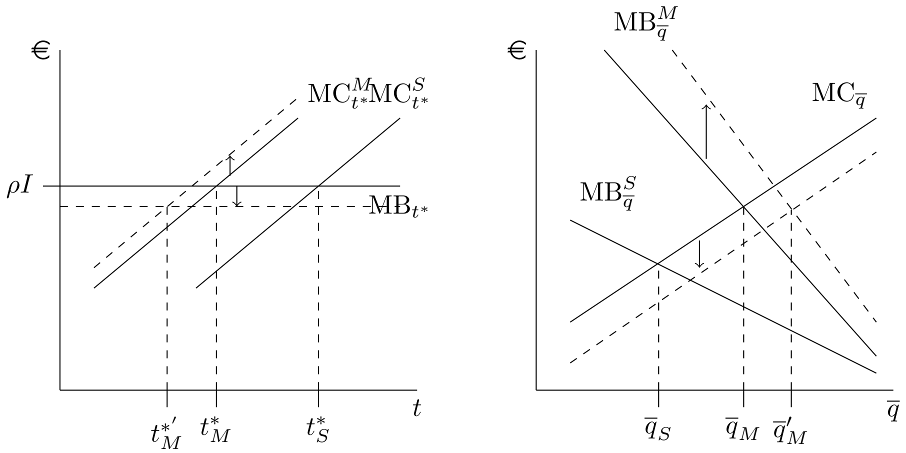

Figure 7: (*left*) The marginal costs and benefits of delaying investment. Given $\overline{q}$, the monopolist will invest earlier: $t^*_M < t^*_S$. Supposing the monopolist invests in less capacity, these curves shift (*dashed lines*) so that the result holds *a fortiori* ($t^{*'}_M$). (*right*) Marginal benefit and cost of pipeline capacity (*solid lines*). Supposing the planner and the monopolist invest at the same time, the monopolist invests more: $\overline{q}_M > \overline{q}_S$. Supposing the monopolist invests earlier, the marginal costs and benefits shift (*dashed lines*) and the monopolist invests in even more capacity $\overline{q}'_M$.

certainly invest even earlier.

A similar argument holds shows that, were the monopolist to invest later than the planner, then she would for sure invest in higher capacity. Firstly, for the same t^*, the monopolist's marginal benefit of capacity is higher than the planner's. It is straightforward to show that the marginal cost of capacity falls at t^* increases. Above we showed that the marginal cost of delay decreases with capacity, i.e. that the cross-partial derivative of the monopolist's operating profit is positive. Hence, the marginal benefit of capacity increases as t^* increases.

Thus the monopolist will always invest earlier and/or in more capacity than the social planner. □

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