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Economic Incentives for Carbon Dioxide Storage under Uncertainty: A Real Options Analysis

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Abstract:
Carbon dioxide capture and storage (CCS) is considered to be an important option for reducing carbon dioxide (CO2) emissions. However, there are still concerns about its economic viability, especially if the risk of leakage in the storage site is taken into account. We use a real options approach for assessing the impact of uncertainty on the timing and the profitability of CO2 storage projects. We model an investment decision for a storage site under uncertainty about CO2 leaking from the storage site, about the development of carbon prices, and about the cost of investment. The numerical model results show that investment under these uncertainties requires a much larger price for carbon credits for storage than an investment plan ignoring uncertainty would suggest. We also show under reasonable parameter assumptions that the risk for investing in CO2 storage is dominated by the uncertain development of carbon prices, whereas the risk of carbon leakage has little influence on the investment decision.

Keywords: Carbon dioxide capture and storage (CCS), real options analysis, climate policy

JEL classification: D81, Q49, Q54

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1. Introduction

Carbon dioxide capture and storage (CCS) has gained wide recognition in recent years as a potentially major option for climate change mitigation. Although the CCS technology is in the process of being tested in large scale projects, prospects of its feasibility and costs critically condition the commercial viability of CCS projects and thus strongly influence the long-term paths of global climate policy. For example, recent assessments by both IEA (2014) and IPCC (2014) regard CCS as a critical option to achieve the control of climate change in the long run. In this regard, examination of CCS's technical viability and potential costs offer important implications for the formulation of climate policy options.

CCS has long been subject to research regarding its technological feasibility. Recently the risks in terms of ecologic and climate effects of storing carbon dioxide (CO_2) in sub-seabed formations have been investigated (http://www.eco2-project.eu/). Economic assessments of CCS begin to play an essential role for the debate about the role of CCS in future climate policy. Economic dimensions of CCS have been investigated so far mainly by using integrated assessment models (IAMs), and there is already a fairly large accumulation of literature (Ha-Duong and Keith, 2003; Herzog et al., 2003; Riahi et al., 2004; Smekens and van der Zwaan, 2006; Gilotte and Bosetti, 2007; MIT, 2007; Keller et al., 2008; van der Zwaan and Gerlagh, 2008; Gerlagh and van der Zwaan, 2011). A central issue for economic studies of CCS is risk and uncertainty associated especially with the storage of CO_2. Most of those studies incorporate uncertainty of CCS in the form of long-run CO_2 leakage from the storage reservoirs. By modeling cost-effectiveness of CCS being inclusive of long-run CO_2 release from leakage, they examine the long-term emission reduction pathways at global, regional or national levels as a function of leakage risks and abatement costs.

Those macro-level studies, however, do not address some important aspects of uncertainty and leakage associated with CCS that would become apparent when its operation is seen as a problem of private decision making. It is most likely that large scale CCS activities will need to be conducted by the private sector, both because of its technological knowledge and the sheer scale of the operations.

For the operators of storage sites, profitability of the facility is a fundamental factor. It depends on a number of factors, among which leakage could be one particular risk. Leakage risks can take on multiple forms with diverse economic implications. It could be a loss in carbon credits resulting from a re-entry of stored CO_2 into the atmosphere. It could also be the ecologic damage to the marine environment if the CO_2 is resolved in the vicinity of a sub-seabed storage site. In particular, as only one single leakage event normally gives sufficient reason for at least a temporal termination of a storage operation, the possibility of leakage may significantly affect operators' decisions even if the eventual release of CO_2 into the atmosphere after the event is negligible.

Meanwhile, leakage is not the only type of uncertainty that operators of a storage facility face. They decide to start storage by anticipating policy incentives in the future, and uncertainty about those incentives is an integral element for their decision making. Indeed, a prevailing perception in the business community is that uncertainty in net economic benefit of CCS overall discourages or at least delays investment in CCS.

We examine these economic incentive problems of CO_2 storage under uncertainty based on a real options framework. Several studies have conducted real options analysis of CCS highlighting economic returns from CO_2 capture operation without the factor of CO_2 leakage (Abadie and Chamorro, 2008; Fleten and Näsäkkälä, 2010; Abadie et al., 2014, Walsh et al., 2014). Here we focus on the last step of CCS, the storage of the CO_2 which is currently the most controversial step in the whole process of CCS. We also focus on sub-seabed storage since on-shore storage is currently unlikely to be implemented in Europe. In comparison to IAM studies, the advantages of our approach are a consistent representation of potential leakage with the current scientific understanding and an explicit consideration of uncertain returns to investment in CO_2 storage due to an uncertain future of carbon price levels. Also, our choice of using an analytical model allows for a transparent evaluation of the effects of various parameters.

With a rising trend of the carbon prices, our results show that an investor for a storage facility generally has an incentive to wait until the carbon price reaches a level well beyond a break-even point of costs and benefits. This is essentially due to the fact that the maximum capacity of a storage facility for which the investment is to be spent limits the time at which returns can be obtained. This creates the incentives – even without uncertainty – to delay the operation since the price increase in the carbon price raises the returns on storage.

In addition to this, uncertainty of the carbon price significantly favors a further delay in the beginning of operation. This feature supports arguments that favor a carbon tax over a cap-and-trade scheme (e.g., Nordhaus, 2008) because a carbon tax scheme is less likely to be subjected to price volatility than a cap-and-trade scheme is. Our results also show that with realistic levels of parameters – in contrast to the uncertainty about carbon prices – the uncertainty about leakage of CO_2 has little influence on the firm's decision to start sub-seabed storage although the possibility of leakage evidently reduces the expected return to the sub-seabed storage project. In addition, uncertainty about future investment costs – in other words, the slope of the learning curve – delays investment decisions even further.

The rest of this paper is organized as follows. Section 2 describes general issues that arise in storage operations and thus need to be dealt with by assessment of CCS. Section 3 discusses a real options model. Section 4 presents a simple numerical example by using representative values of parameters and discusses implications of this model for general CCS policy. Section 5 summarizes and concludes the findings.

2. Note on General Issues Regarding the Assessment of Sub-seabed Storage[1]

This section summarizes general issues being interest of current carbon storage operations and assessment, especially with regard to the potential mechanisms of leakage. Various issues regarding leakage are discussed in IPCC (2005), and knowledge is supplemented by more recent studies on actual sub-seabed storage operations or natural CO_2 seepage analogues to CO_2 leakage from human-made CO_2 storage reservoirs (e.g., Arts et al., 2008; Chadwick et al., 2009; McGinnis et al., 2011).

The first operations of sub-seabed storage are taking place on a relatively small scale. They have shown that sub-seabed storage on land as well as in sub-seabed storage sites is technically feasible. However, the issue of leakage has not been well understood. First research projects assessing the fate of CO_2 in storage sites and potential leakage have started and yield first results (e.g. Phelps et al. 2014). These activities have already identified a more differentiated view on leakage that may occur in the course of a CCS activity. Without going into many of the details of leakage possibilities there seem to be three types of leakage that one should be concerned with and which may have different economic aspects. Leakage may occur in the early phase of a sub-seabed storage project, it may occur in a period where the capacity of the storage sites approaches its limit, and leakage may occur after the sub-seabed storage activity on a particular site has been terminated and there may still be a liability for long-term leakage.

The first type of leakage is one which the researchers from the natural and engineering sciences have been most concerned about. Leakage in the early phase is believed to be the most likely event. This is so because there may be geological aspects such as cracks in the storage formation that may not have been identified in the exploratory phase of the project. Such surprises may happen and the probability for such events can be influenced by the amount of resources devoted to a proper investigation of the storage site. It can also happen that due to human errors the operation of the project fails and a CO_2 blow out may take place. Such an event, on the other hand can be influenced by the care that is taken first in the selection process of a storage site and, secondly, in the operation of the storage facility which translates into the cost of running the storage facility.

Second, there is a positive probability that - even after the sequestration on a storage site has ended – CO_2 may leak into onto the surface or into higher geological layers. Although this is not a very likely event according to current knowledge, it raises questions with respect to the long-term cost of leakage and their impact on current incentives for performing storage projects. Issues that will need to be addressed are the role of long-term liability of the operator versus societal liability, intergenerational justice with respect to future leakage, or the role of a social discount rate for influencing the profitability of current CCS projects.

[1] For the discussion of this section, we greatly benefited from a conversation with Matthias Haeckel at the Helmholtz Center for Ocean Research Kiel.

A common feature of leakage threats is their probabilistic nature. In order to keep the model simple we start with the assumption that there is a positive but most likely very small probability of leakage during the CO_2 storage operation that is constant and independent of the amount CO_2 stored or the pre-project investment into the exploration of the site. There are several modifications possible. The leakage probability could be influenced by the degree to which the storage site is investigated before the start of the project. Hence, the leakage probability is a function of some initial sunk investment.

Leakage of CO_2 from sub-seabed storage sites will first enter the water column and will partly be dissolved there. As a consequence the surrounding waters will acidify. It may eventually enter the atmosphere and thus counter the intended effect of avoiding carbon emissions into the atmosphere. Several studies indicate that the fate of leaked CO_2 depends strongly on the environmental and geological conditions in which the leakage takes place. In general, long-term leakage in shallow waters with little water perturbation has a higher probability of creating local ecologic damages and of being released into the atmosphere. Deep water releases with only one blowout are rather unlikely to have much of an effect. They also show that the impact of leaked CO_2 is almost impossible to predict in general (e.g. Phelps et al. 2014 or Blackford et al. 2008). In addition, current preparations of test sites and the experiences with advanced monitoring suggest that it is extremely unlikely that leakages will happen in the first place if the storage site is well assessed beforehand.

3. Model

We construct a simple analytical model of investment decisions for a CO_2 storage project by taking explicitly into account the possibility of future leakage of CO_2, uncertainty about the cost of the project, and uncertain future carbon prices, i.e. the return for the project. The key idea for the model is that since a decision to start CO_2 storage is an irreversible choice, the storage operator considering the start of a CO_2 storage project weighs the (time-discounted net) benefit of storage operation and the benefit of waiting and starting it later. As we will see below, the benefit of waiting is generally significant, and under certain conditions the firm has incentive not to begin CO_2 storage even when the net present value of storage operation is positive.

The model builds on the real options framework, whose comprehensive exposition is made by Dixit and Pindyck (1994). The real options framework is essentially an application of the concept of financial options to decision problems of “real” investment. A key idea for the real options concept is the combined effect of uncertainty and irreversibility of decisions: with irreversibility of initial investment, uncertainty in future return induces the operator of a sub-seabed storage facility to delay the start of operation and to wait until the carbon price goes sufficiently high to compensate potential price decreases in the future. In the context of sub-seabed storage, the effect becomes more complex when uncertainty about leakage is added to the uncertain profitability. A real options model can capture these features. A common insight that has emerged from the real options studies is that a real options analysis and an analysis based on the standard net present value (NPV) evaluation yield significantly different results and implications for a wide range of cases (Dixit and Pindyck, 1994).

We discuss a real options model à la Dixit-Pindyck and evaluate the effects of project risks by finding the changes in the threshold carbon price beyond which a project is worth starting immediately. The uncertainty about the carbon price or about investment costs provides an incentive for the operator to wait and see, i.e., observe the development of the price and choose the best timing to start a project. This affects the timing of, and in turn also the threshold carbon price for, the start of CO_2 storage project. Meanwhile, the leakage risk affects the threshold carbon price by reducing the net benefit of running a project. By calibrating the model with realistic parameter values and then presenting numerical results, we show the relative importance of the effects originating from these two types of risk.

For the model setting, we consider a firm that owns a CO_2 storage reservoir (maximum capacity $S^{max} > 0$) and faces a choice between initiating CO_2 storage operation immediately and delaying the start of operation. Figure 1 illustrates the modeling problem. Once storage operation starts, the firm processes CO_2 by a flow E (>0, constant) and sells the credits at the (exogenous) market price for carbon P, i.e., the revenue flow for the firm is $P*E$.[2] Note that while we discuss below the model in the context of an independent CCS operator without its own CO_2 sources, the decision problem is essentially identical for a CO_2 emitter (e.g., the owner of a fossil-fuel power plant) facing a choice between buying external carbon credits and initiating CCS by herself.

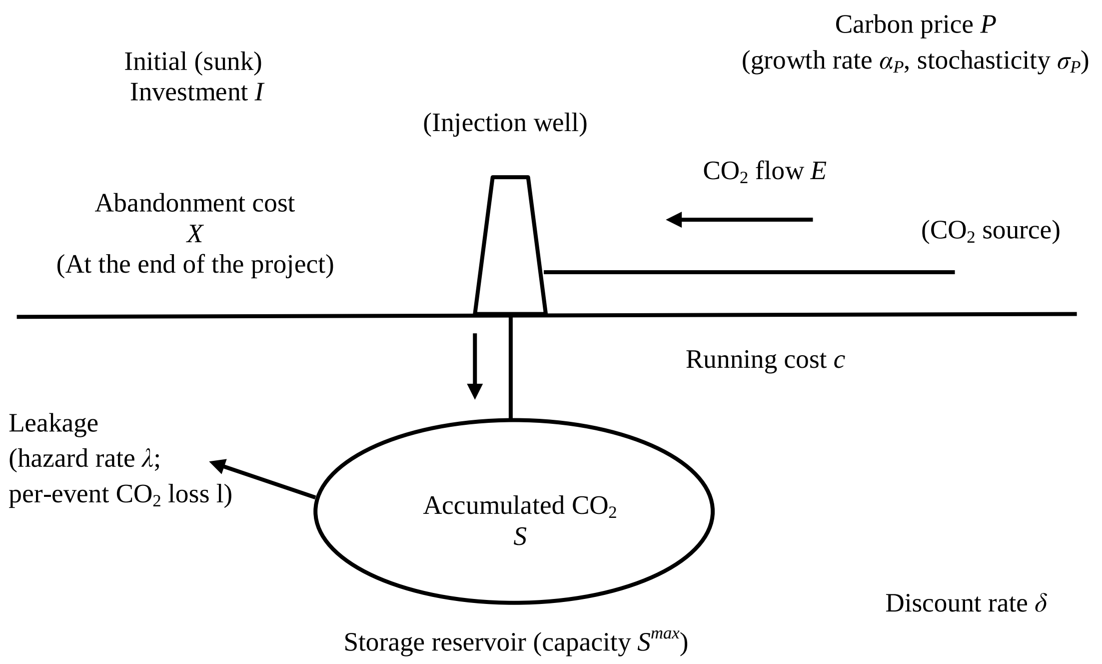
As the CO_2 storage operation proceeds, the stock of CO_2, S, increases in the CO_2 reservoir and eventually reaches S^{max} at the end of operation. The storage project incurs an initial sunk investment I (>0), the operational cost c (≥0) during the years of operation, and an abandonment cost X (≥0) at the end of the project. Below, we primarily interpret X as a private cost, but it could also be seen as a public cost if one assesses the social optimality of a storage operation.

Leakage of CO_2 from the storage reservoir during the project period occurs as probabilistic event according to a hazard rate. In the basic case, we set the hazard rate λ as constant ($0 < \lambda << 1$), i.e., independent of the accumulated CO_2 stock S. The probability of leakage during a time interval dt is expressed as λdt. When a leakage event occurs, the operation is immediately terminated, and the firm abandons the site. The leakage event entails a (value) loss of CO_2 $l*P$ where P is the current carbon price. We assume $E > \lambda * l$ (the expected loss rate from leakage is less than the injection rate). Note that the characterization of leakage in this model has some qualitative difference from that of other economic studies examining CO_2 leakage. While other studies consider that economic costs of leakage only come from release of CO_2 into the atmosphere, our model reflects the economic loss for the firm from not

[2] Note that this formulation implies that the CCS operator owns not only the injection facilities but also the CO_2 capture facilities adjacent to CO_2 sources. If the CCS operator only conducts storage and transport, the revenue flow would be $(P - P^{cap})*E$ where P^{cap} is the exogenous price of CO_2 capture.

being able to continue the storage project as well as the loss from the atmospheric release of CO_2 through leakage.

Figure 1. Schematic diagram of the modeling framework



The condition for initiating a CO_2 storage project is that the net present value of an operation exceeds the initial investment cost plus the value of keeping (i.e. delaying) the CO_2 storage option intact. The last factor represents the expected value of an inactive storage project to be exercised in the future in anticipation of an increase in profitability (carbon price) in later periods. Defining the net present value of a sub-seabed storage site operation as V^o and the value to keep the storage opportunity (option value) as V^w, this means that $V^o - I > V^w$ (>0). Considering that the firm evaluates an investment at time 0 prior to the time of investment t, the present values $\tilde{V}^o$, $\tilde{V}^w$, and $\tilde{I}$ are expressed as $\tilde{V}^o = V^o e^{-\delta t}$, $\tilde{V}^w = V^w e^{-\delta t}$, and $\tilde{I} = Ie^{-\delta t}$ by using the current values V^o, V^w, and I at time t. Below, we first find solutions for the current value formulations.

Introducing future uncertainty in the return to investment in a sub-seabed storage facility combined with the irreversibility of sunk investment, the evaluation departs from the standard net present value framework and necessitates a real options framework. In this model, as a representation of profit uncertainty regarding sub-seabed storage, we adopt a simple characterization of the carbon price P evolving in a Brownian motion: P has a baseline that exponentially grows at the (exogenous) rate α_P (i.e., $P_0 e^{\alpha_P}$ where P_0 is the carbon price at time

0) and also has a random drift with a drift parameter σ_P, i.e. $dP = \alpha_P Pdt + \sigma_P PdZ$. The assumption of an exogenous carbon price trend is quite reasonable since most estimates predict that the share of CCS to the total CO_2 emission reduction measures remains small globally in the next few decades (e.g., IEA, 2010). We assume that α_P is less than the discount rate δ ($\alpha_P < \delta$): the growth rate of the optimal carbon tax less than the discount rate because of exogenous technological improvement, etc.[3] The Brownian motion of *P* corresponds to a very simplified representation of unpredictable future incentives for the adoption of CCS with sub-seabed storage.

We find the solution of the model by using a similar method as that of Dixit and Pindyck (1994). V^o is a function of *P* (*P* as the state variable) subject to the above-described formulation of *dP*. In making use of Ito's Lemma, the Bellman equation for V^o is given by:

(1) $$\delta V^o dt = (PE - c)dt + E[dV] = (PE - c)dt + \alpha_P PV_P^o dt + \frac{1}{2}\sigma_P{}^2 P^2 V_{PP}^o dt - \lambda V dt - \lambda(lP + X)dt$$

The solution to the above equation is obtained heuristically. The solution of V^o contains a general term A^*P^β (*A*, β are constants) corresponding to the homogenous part of the equation and a particular solution for the non-homogenous part. Plugging P^β into the above equation yields the following condition for the exponent β:

(2) $$\alpha_P \beta + \frac{1}{2}\sigma_P{}^2 \beta(\beta - 1) - \delta = 0$$

The solution of Equation (2) is:

(3) $$\beta = \frac{1}{2} - \frac{\alpha_P}{\sigma_P{}^2} \pm \sqrt{\left[\frac{\alpha_P}{\sigma_P{}^2} - \frac{1}{2}\right]^2 + \frac{2\delta}{\sigma_P{}^2}}$$

The above means β has a positive and a negative root. Denote the positive root by β_1 and the negative root by β_2. Note that the above form implies $\beta_1 > 1$ as $\delta > \alpha_P$.

The general term of V^o (V^{og}) is expressed as the following form of linear combination:

(4) $$V^{og} = A_1 P^{\beta 1} + A_2 P^{\beta 2}$$

[3] Note that in this model's context, the discount rate δ is the discount rate for investment, which internalizes the effect of future economic growth and the society's aversion to riskiness of investments, and not the pure time preference, which, as some argue, may need to be near-zero (Stern, 2006).

Meanwhile, the particular solution (V^{op}) is given by:

$$(5)\qquad V^{op} = P(E-\lambda l)\left(\frac{1-e^{-(\delta-\alpha_P+\lambda)T}}{\delta-\alpha+\lambda}\right) - (c+\lambda X)\left(\frac{1-e^{-(\delta+\lambda)T}}{\delta+\lambda}\right) - Xe^{-(\delta+\lambda)T}$$

where $T = S^{max}/E$.

The complete solution of V^o is given by $V^o = V^{og} + V^{op}$.

Some additional logical conditions can be applied to V^{og}. First, V^{og} should be 0 if $P = 0$ (because if $P = 0$, *P remains* zero in the future as well), and this means that $A_2 = 0$. Second, if the risk market is perfect and future risk in return to the storage investment is thus fully incorporated into the discount rate (i.e., if the discounted rate = the risk-adjusted interest rate), the $P^{\beta 1}$ term of V^{og} is also zero, i.e., $A_1 = 0$. In other words, volatility of P alone does not generate any additional value for the storage project if the project risk is already reflected in the (relatively high) level of the discount rate.

Hence,

$$(6)\qquad V^o = V^{op}$$

V^w is a function of P. Similar to the above case of V^o, the Bellman equation for V^w is given by:

$$(7)\qquad \delta V^w dt = \alpha_P P V_P^w dt + \frac{1}{2}\sigma_P{}^2 P^2 V_{PP}^w$$

Note that the equation does not have a non-homogenous part because holding the option does not generate any profit flow or economic loss from leakage. The solution of V^o contains a general term $B{*}P^{\beta}$ (B is a constant). β satisfies the same condition as for V^o, hence takes the same values of β_1 and β_2.

Similarly to V^o, V^w is expressed as:

$$(8)\qquad V^w = B_1 P^{\beta 1} + B_2 P^{\beta 2}$$

Similar to the case of V^o, B_2 should be zero as V^w should be zero if $P = 0$.

Hence,

$$(9)\qquad V^w = B_1 P^{\beta 1}$$

Note that $B_1 > 0$ since V^w is positive.

B_1 is determined by boundary conditions. Given the nature of V^w (the value of waiting in anticipation of future increase in P), V^w should outweigh V^o at lower P's, and there should be a threshold $P = P^*$ where V^o and V^w equal (beyond that level of P, there is no point of waiting further, and the firm simply runs carbon storage). At P^*, V^o and V^w should equal (the value-matching condition) while the slopes of V^o and V^w as functions of P should also equal (the smooth-pasting condition).

$$(10) \qquad V^w\left(P^*\right) = V^o\left(P^*\right) - I$$

$$(11) \qquad \frac{dV^w}{dP}\left(P^*\right) = \frac{dV^o}{dP}\left(P^*\right)$$

Those conditions yield the following P^* and B_1:

$$(12) \qquad P^* = \beta_1\left[I + (c + \lambda X)\left(\frac{1 - e^{-(\delta+\lambda)T}}{\delta + \lambda}\right) + Xe^{-(\delta+\lambda)T}\right] \cdot \left[(\beta_1 - 1)(E - \lambda l)\left(\frac{1 - e^{-(\delta-\alpha+\lambda)T}}{\delta - \alpha_P + \lambda}\right)\right]^{-1}$$

$$(13) \qquad B_1 = (\beta_1 - 1)^{\beta 1 - 1}\beta_1^{-\beta 1}\left[I + (c + \lambda X)\left(\frac{1 - e^{-(\delta+\lambda)T}}{\delta + \lambda}\right) + Xe^{-(\delta+\lambda)T}\right]^{-(\beta 1 - 1)} \cdot \left[(E - \lambda l)\left(\frac{1 - e^{-(\delta-\alpha+\lambda)T}}{\delta - \alpha_P + \lambda}\right)\right]^{\beta 1}$$

Carbon Price and Investment Cost Uncertainty with Technological Advancement

A key question in CCS debates is the role of declining technology costs which are determined by learning and also subject to uncertainty of their own. We extend the model to incorporate the uncertainty of investment costs which have some baseline change of decline. This represents the expected learning effects once a larger number of storage sites have been developed as currently only a few – and often small scale - demonstration sites are running. It is not possible to derive general analytical solutions for this problem, but the problem is analytically solvable for a special case with c=0 and X=0 (operational and abandonment costs are zero). In fact, the running costs are normally small compared to the initial investment and CAPEX costs in storage operations.

We follow the solution approach of Section 6.5 of Dixit and Pindyck (1994) by using the following function of $p = P/I$.

(14) $V^w(P,I) = If(P/I) = If(p)$

Assuming c=0 and X=0, V^o now becomes:

(15) $V^o = P(E - \lambda l)\left(\frac{1 - e^{-(\delta_P - \alpha_P + \lambda)T}}{\delta_P - \alpha_P + \lambda}\right)$

The exponent of the option value is now given by the following quadratic equation:

(16) $\frac{1}{2}\left(\sigma_P{}^2 - 2\rho\sigma_P\sigma_I + \sigma_I{}^2\right)\beta(\beta - 1) + \left(\delta_I - \alpha_I - \delta_P + \alpha_P\right)\beta - \left(\delta_I - \alpha_I\right) = 0$

where α_I, σ_I, and ρ are the trend growth rate and stochasticity of I and the correlation of σ_P and σ_I, respectively, and whose positive solution is:

(17) $\beta_1 = \frac{1}{2} - \frac{\delta_I - \alpha_I - \delta_P + \alpha_P}{\sigma_P{}^2 - 2\rho\sigma_P\sigma_I + \sigma_I{}^2} + \sqrt{\left[\frac{\delta_I - \alpha_I - \delta_P + \alpha_P}{\sigma_P{}^2 - 2\rho\sigma_P\sigma_I + \sigma_I{}^2} - \frac{1}{2}\right]^2 + \frac{2(\delta_I - \alpha_I)}{\sigma_P{}^2 - 2\rho\sigma_P\sigma_I + \sigma_I{}^2}}$

From the following value-matching and smooth-pasting conditions:

(18) $f(p) = p(E - \lambda l)\left(\frac{1 - e^{-(\delta_P - \alpha_P + \lambda)T}}{\delta_P - \alpha_P + \lambda}\right) - 1$

(19) $f'(p) = (E - \lambda l)\left(\frac{1 - e^{-(\delta_P - \alpha_P + \lambda)T}}{\delta_P - \alpha_P + \lambda}\right)$

(20) $f(p) - pf'(p) = -1$

we obtain the following for the threshold *P* and *I*.

(21) $\frac{P^*}{I^*} = p^* = \frac{\beta_1}{\beta_1 - 1} \cdot \frac{\delta_P - \alpha_P + \lambda}{\left(1 - e^{-(\delta_P - \alpha_P + \lambda)T}\right)(E - \lambda l)}$

4. A Numerical Example and Implications of the Model

We illustrate the model results with a numerical calculation of the main variables by using representative parameter values. Table 1 summarizes the default choices of the parameter values. The numbers are only indicative but are within realistic ranges of real world cases. With those choices, the annualized costs of CO_2 storage with these settings correspond to around $75 per ton of CO_2.

Table 1. Default parameter levels for the numerical example

Parameter	Level	Note
E	2	CO_2 flow rate (Mt/yr)
I	1700	Initial investment costs (million $)
c	20	Operational costs (million $/yr) *Together with *I*, the levels are set to match the return under the carbon price of roughly $75 per ton[4]
X (X^f, m)	0	Abandonment costs
T (S^{max}/E)	20	Lifetime of operation (yrs)
δ	0.05	Discount rate (/yr)
α_P	0.02	Growth rate of the carbon price (/yr) *This roughly follows the DICE optimal run's
σ_P	0.1	Stochasticity (uncertainty) of the carbon price
λ	0.01	Leakage hazard rate (/yr)
l	2	Amount of CO_2 release at a leakage event (Mt)

Additional parameters for simulations with investment cost uncertainty (see Figure 6)

Parameter	Level	Note
δ_I	0.05	Discount rate for investment (/yr)
α_I	-0.02	Growth rate (reduction rate) of the initial investment cost (2% decline per year – a typical rate for energy technologies)
σ_I	0.05	Stochasticity (uncertainty) of the price of initial investment
ρ	0	Correlation of σ_P and σ_I (i.e., the two are independent)

[4] $I \cdot \left[\left\{ 1 - \left(\frac{1}{1+\delta} \right)^T \right\} \Big/ \left\{ 1 - \left(\frac{1}{1+\delta} \right) \right\} \right]^{-1} + c = 1700 \cdot (0.05/1.05) \cdot (1 - 1.05^{-20}) + 20 = 74.9$

Currently there is a plan for a project where from the Peterhead Power Station in Aberdeenshire, Scotland, up to 10 million tons of CO_2 emissions could be captured, and then transported by pipeline and stored, approximately 100km offshore in the depleted Goldeneye gas reservoir, at a depth of more than 2km under the floor of the North Sea (www.shell.co.uk/peterheadccs). However, whether this project will eventually start is not decided yet, apparently due to a lack of commercial viability. Scientific evidence suggests that the leakage risk of such storage is very small. Therefore, our assumption of a leakage hazard rate λ=0.01, i.e. an unrecoverable failure happens with 1% probability every year is extremely high. We model here most likely a worst case scenario with respect to leakage probabilities, although - as mentioned above - the hazard rate for CO2 re-entering the atmosphere is almost impossible to predict.

Figure 2. V^o - I (the net present value of the storage operation minus the investment cost) and V^w (the value of waiting) as functions of P. All parameter values are set according to Table 1.

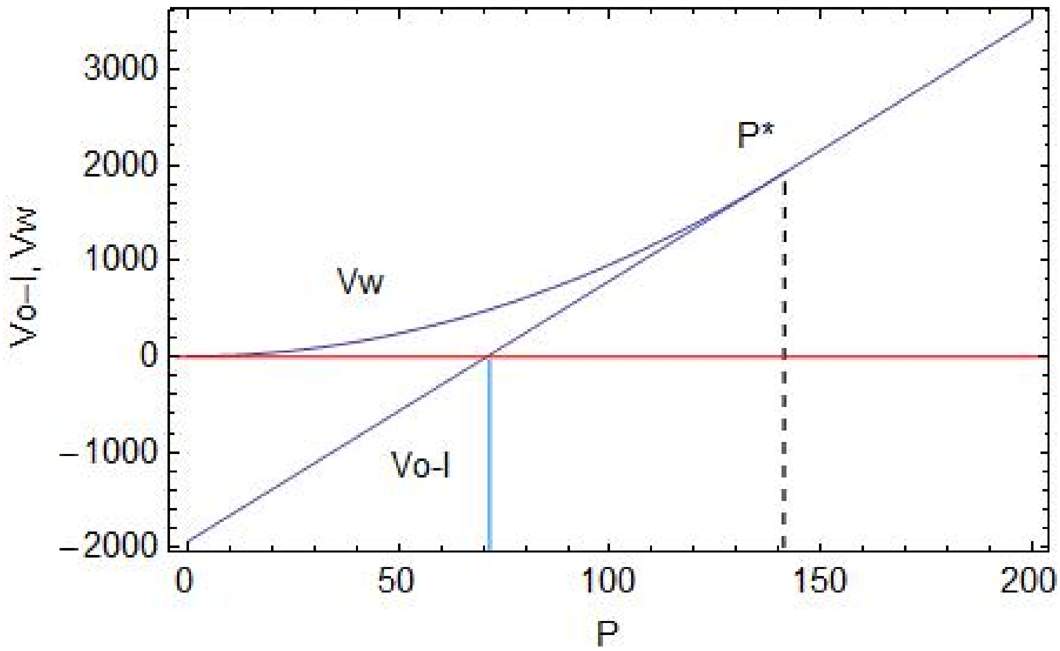


Figure 2 illustrates the basic relationship between the net present value of a storage project and its option value. It shows the value of delaying the option to run a storage site, V^w, and the net present value of operating the storage site, V^o-I , as a function of the threshold carbon price P^*. At low carbon price levels V^w outweighs V^o-I indicating that at carbon prices between zero and \$75/tCO_2 it is neither profitable nor profit maximizing to run a storage site. If the current carbon price is in the range between \$75/tCO_2 and \$142/tCO_2, the storage site would yield a positive net present value, i.e. would be profitable. However, it would be rational from the point of view of an owner of a site to delay the start of operation because the profit to be obtained by starting the operation at some later period is larger than the profit of starting immediately. V^w and V^o-I meet at around $142 per ton ($P*$ on the graph). This means that it is favorable for the firm to wait until the carbon price reaches $142/t$CO_2$, and beyond that level, it should start investing in and operating the storage site immediately rather than postponing it.

As mentioned above, the investment and operational costs are set to reproduce annualized costs of roughly $75 per ton of CO_2. This would in a normal cost calculation indicate that at $75/t$CO_2$ carbon storage would become profitable and would be likely to start. But, the combined effect of uncertainties with respect to the development of carbon prices, the threat of leakage as well as the limited capacity of a storage site make it more profitable to wait with the investment in a storage site until its profitability has increased sufficiently to compensate for the uncertainty involved in the investment.

The parameters influencing this pattern are the following: The carbon price is growing over time reflecting the increased scarcity of the atmosphere to take up carbon emissions. This by itself creates an incentive to delay the start of a storage project as further returns for storage services will be higher than current ones. Only discounting leads to the decision to start the project at a carbon price of $ 75/tCO_2 in this model. With the presence of stochasticity, σ_P, of the carbon price which continues to grow but at a stochastic path a second incentive is introduced. The uncertainty of the carbon price will induce the investor to require a higher return on her investment.

This feature is largely ignored by the existing macro-level IAM studies and puts into perspective the chances for creating incentives for a quick development of carbon storage through CCS policies. In the following we illustrate the impact of the different uncertainties on the timing of investments in carbon storage. First, the impact of uncertainty of carbon prices will be assessed. Then we look at the impact of potential leakage on investment decisions for carbon storage. Finally, we look at the interaction of investment decisions with investment costs and the size as well as the length of the storage project.

Figure 3 shows the impact of uncertainty (stochasticity) about future carbon prices on the threshold price P* for which an investment becomes profitable. Conforming to intuition, uncertainty about future returns on investment raises the threshold P*. In other words, the higher the uncertainty about the development of carbon prices the higher will be the carbon price at which the firm is willing to invest. This also means that the higher the uncertainty, the longer it will take before carbon storage will be supplied by operators. For example, the threshold price P* is $ 193/tCO_2 at σ_P=0.2, whereas it is only $ 125/tCO_2 at the lower stochasticity of σ_P =0.05. This difference of threshold prices can be translated into years by which investment would be delayed given the parameters in Table 1. The increase in σ from 0.05 to 0.2 would delay the investment by roughly 22 years. This is the more surprising as the difference in the 95% confidence intervals between σ_P=0.2 and σ_P=0.05 at a price of $ 125/tCO_2 is only about $ 8 ($ 154/tCO_2 and $ 96/tCO_2 versus $ 150/tCO_2 and $ 100/tCO_2). It seems that, although the threshold price does not change much with different degrees of uncertainty about the carbon price, the time by which the project would be delayed is strongly influenced by the degree of uncertainty.

Figure 3 also illustrates how the discount rate of the investors influences the threshold price at which investment will take place. At a high discount rate and under a high stochasticity the threshold price will be lower than under a lower discount rate, under low stochasticity it will just the opposite. The rationale behind this is the following: At high discount rates the investor values near term profits higher than long term profits. This creates an incentive to wait until the near term profits are sufficiently high, i.e. the threshold price needs to be high. Under high stochasticity the value of waiting becomes prominent, and the threshold price is higher for a low time-discounting case than for a high time-discounting case, as long-term profits are valued higher in the former than in the latter. Hence, beyond a certain point the uncertainty about the development of carbon prices dominates the higher valuation of short term profits, and the investor is already satisfied with a lower short run profit.

Figure 3. Effect of stochasticity (σ) on the threshold carbon price P^*. For the solid line, the parameter levels besides that of σ are as in Table 1, including δ=0.05. The dashed line is for δ=0.1 (i.e., the discount rate is 10% per year: the levels of the other parameters are the same as for the solid line).

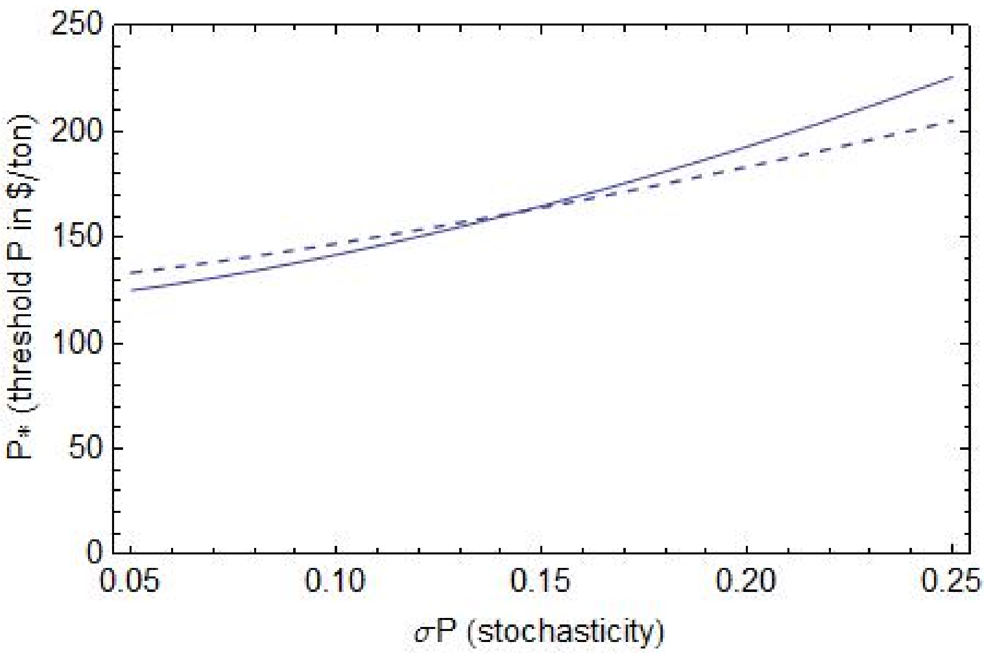
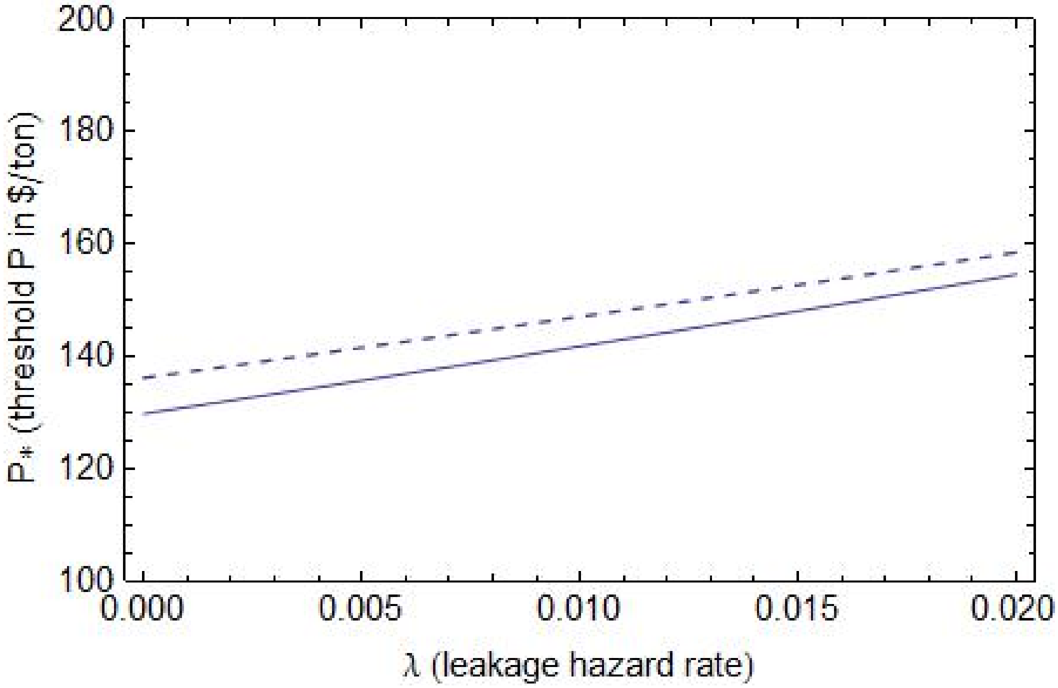


Figure 4 illustrates the impact of the leakage hazard rate on the threshold price and thus the timing of investment decisions. As mentioned above the likelihood of the leakage of CO_2 into the oceans can be very low depending on the storage site as well as the depth of the sub-seabed storage. The likelihood of CO_2 from a leaking site entering the atmosphere is even lower. Since we model leakage as an event where the operation is immediately stopped, it is essentially profits lost that determine the influence of leakage hazard on the threshold price.

Figure 4. Effects of the leakage hazard rate (λ) on the threshold carbon price *P**. For the solid line, the parameter levels besides that of λ are as in Table 1. The dashed line is for δ=0.1 (i.e., the discount rate is 10% per year: the levels of the other parameters are the same as for the solid line).

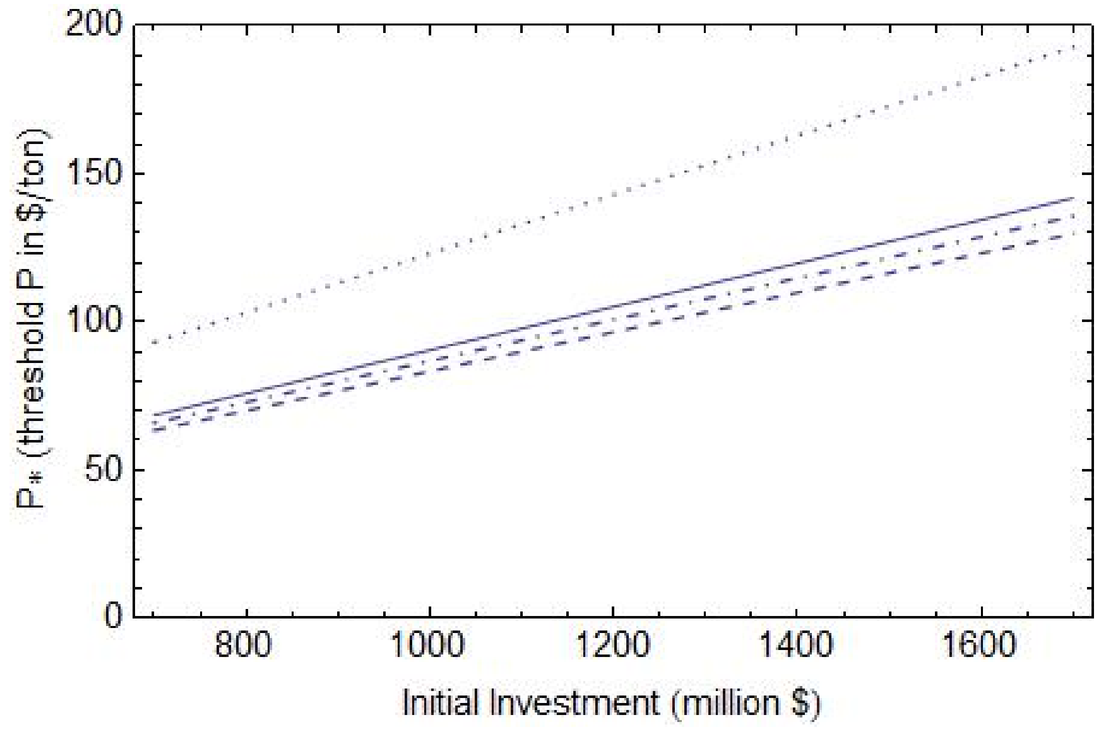


In our numerical parameter set from Table 1, a zero leakage probability will lead to investment if the carbon price reaches \$ 130/tCO_2. It would increase to \$ 142/tCO_2 if the leakage hazard rate is 0.01. Even a high leakage hazard of 0.01 will therefore have only a minor influence on the threshold price that would induce the investment for developing and running a storage site. As a consequence, higher leakage hazards would delay investment only by little, in fact, in our numerical example by approximately 4 years. Reducing the hazard rate to zero would also only speed up investment by 4 years. Figure 4 also shows that leakage is in fact of little concern for the incentives for investing in storage operations. The mark-up over the annualized cost of a storage operation from \$ 75/tCO_2 to \$ 130/tCO_2 is due to the uncertainty of carbon prices and the limited storage capacity. Only the increase from \$ 130/tCO_2 (zero leakage risk) to \$ 142/tCO_2 (high leakage risk) represents the leakage premium.

A higher discount rate will require a higher threshold price because the higher carbon prices in the future will count less in the present value of the investment project. However, this effect is also small compared to the uncertainty premium for the carbon price path. The higher threshold price does not change much with increases in the leakage hazard. At very high leakage hazards the threshold price reacts even less to a high discount rate. Although very small, this effect is due to the fact that the risk of losing future income after a leakage event is discounted more strongly.

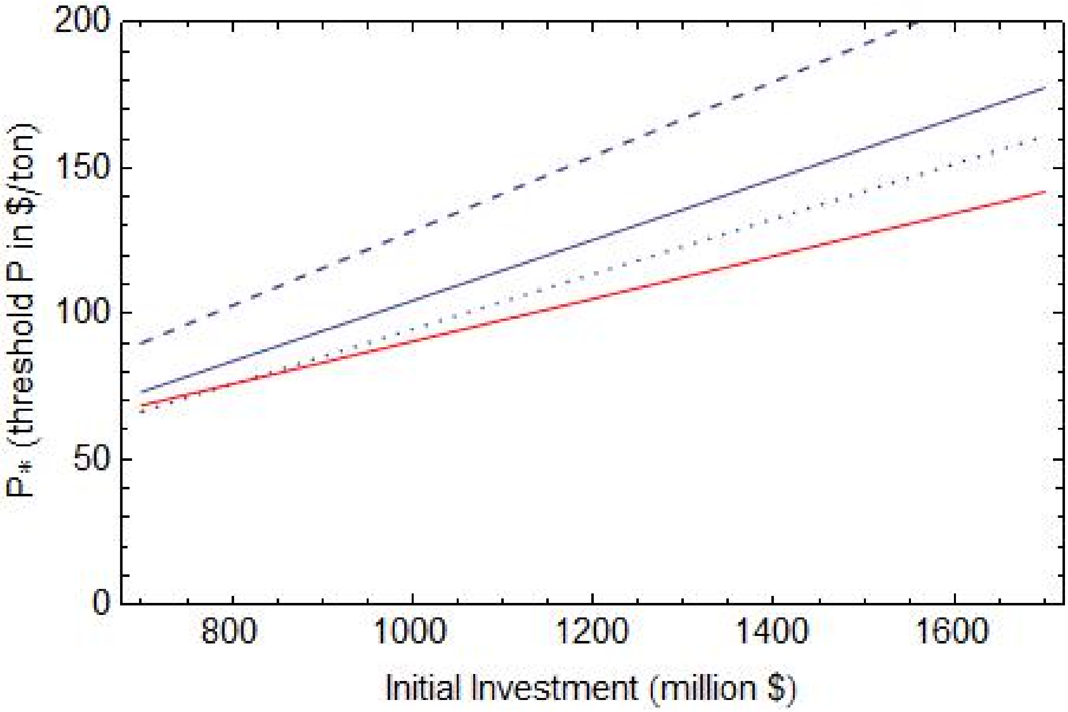
Figure 5 presents the results of the simulation for different investment levels for a storage facility. It is not yet clear how much the setup of a storage facility will actually cost. This is likely to depend on the availability of an already existing infrastructure, such as an abandoned platform for extracting oil or natural gas. Compared to the standard investment cost of $1.7 bn (Table 1) that have been reported lowering these cost has an almost linear effect, i.e. investment costs dominate the threshold price necessary to induce investment. Again, varying the hazard rate (dash-dot and dashed lines) has a very small effect. However, the uncertainty with respect to the carbon price is the main factor influencing the threshold price at all investment costs.

Figure 5. The threshold carbon price *P** as a function of the initial investment cost (*I*). The solid line is for the parameter levels as given in Table 1, and the dash-dot and dashed lines are for hazard rate λ=0.005 and 0, respectively. The dotted line is for stochasticity $\sigma_P = 0.2$.



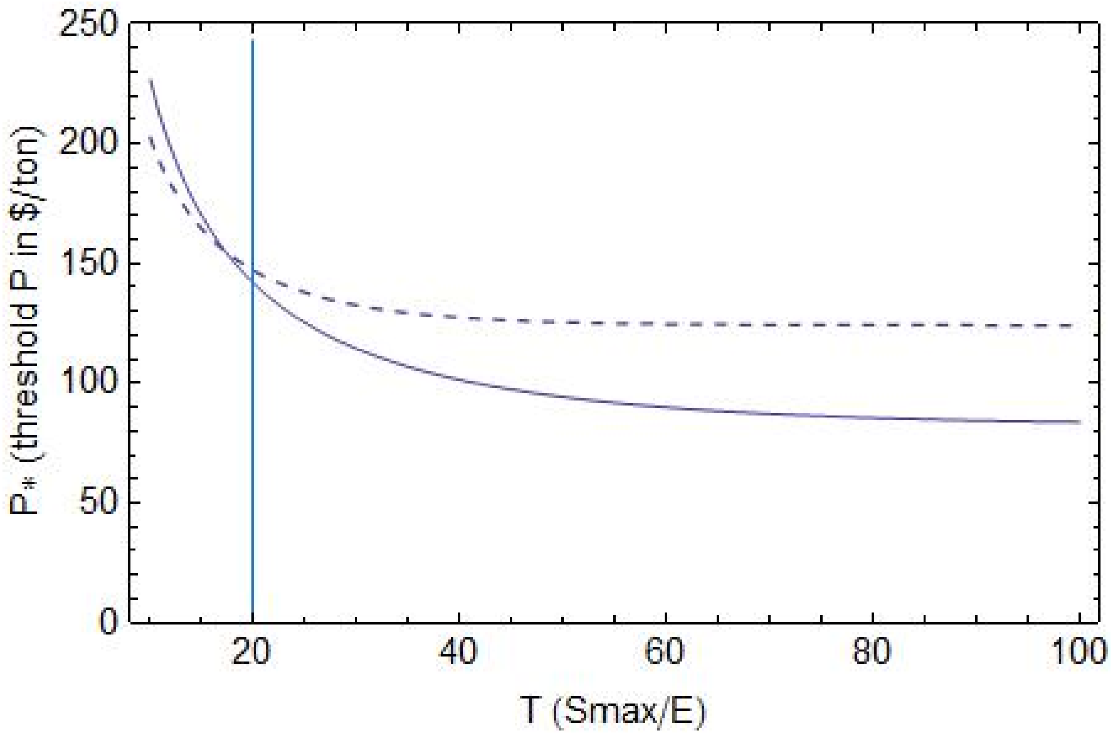
Whereas Figure 5 looks at different but known investment levels, Figure 6 shows the result of the extended model where - on top of the other uncertainties - there is uncertainty about the investment cost of a storage facility. The figure shows that the stochasticity of investment costs has a higher impact on the threshold price P* than even high leakage risks.

Figure 6. The threshold carbon price P^* as a function of the initial investment cost (I) for the extended model including investment cost uncertainty. The solid blue line is for the parameter levels as given in Table 1, and the dotted line is for hazard rate λ=0. The dashed line is for stochasticity of investment cost σ_I = 0.2. The red line represents the case without uncertainty about investment costs



It is not clear how large a certain storage facility will be, in other words, how long it will be able to store additional amounts of carbon. Fig. 7 shows how the size of the storage facility influences the carbon price. It turns out that the relationship is not linear. The solid line reflects the decreasing influence of the option value of waiting combined with the uncertainty about the carbon price. The larger the capacity and the longer time of operation the less important become the factors that require a mark-up for starting to invest in a storage site. Theoretically the solid line in Fig. 7 converges to the \$75/tCO_2 price at which the project becomes profitable under certainty conditions.

Figure 7. Effects of the project length (*T*, which is determined by the storage capacity S_{max}) on the threshold carbon price *P**. For the solid line, the parameter levels besides that of *T* are as in Table 1. The dashed line is for δ=0.1 (i.e., the discount rate is 10% per year: the levels of the other parameters are the same as for the solid line).



The dashed line corresponds to a higher discount rate. The solid and dashed lines cross in the graph. This is because both the option value and the value of project operation decrease with the discount rate, and the threshold carbon price is determined by the balance of the two. For a large T, which corresponds to a large storage capacity (Smax), the effect of the option value becomes minor (i.e., storage could be operated nearly indefinitely anyway, so the pure value of waiting diminishes), and P* is primarily determined by the value of project operation. Since the future returns under high carbon prices are discounted strongly (dashed line), the threshold price for large T is higher than that under a lower discount rate (solid line). The option value for small T is low because the value of waiting is discounted more strongly whereas the impact of the discounted returns is not so strong. As a consequence, for low capacity sites with a short time horizon of usage the threshold price is lower under a high discount rate.

5. Summary and Conclusions

This paper has addressed the economic impact of different dimensions of uncertainty about the storing of CO_2 in sub-seabed formations. We have developed a real options model which introduces a decision model for investing in a storage site for CO_2 by taking explicitly into account several uncertainties. Three investment risks are included in the model: (i) leakage of CO_2 back into the sea or the atmosphere, (ii) the development of carbon prices which provides the income for the storage services, and (iii) the development of investment costs for a storage site. These risks usually lead to a delay in the investment decision until more information has been acquired or the economic conditions for such a project have improved.

Several numerical analyses of a typical storage project are performed. The stylized data are comparable to a currently planned project. We calibrate the numerical model to approximate investment figures which leads to a risk free threshold price for investing in a storage site of around \$75/tCO_2. Based on this we investigate the threshold price under which an investment will be profitable given the above mentioned uncertainties. We show that the much discussed leakage risk will increase the threshold price by relatively little. This is essentially due to the fact that the hazard rates for leakage and the resulting damage are very small compared to the size and length of the project.

When we compare the impact of the uncertainty about different leakage hazards with the uncertainty about future returns for storage services it is obvious that the dominating factor for a lack of profitability of a storage site is the uncertainty about future carbon prices. They completely determine the income side of a project and thus have a strong impact on the cost-income balance. Two factors drive up the option value of a storage investment. Since a site has only a limited capacity and carbon prices will increase over time, the option to wait will automatically increase the income that can be generated since each ton of CO_2 stored will receive a higher price. The other effect is due to the uncertainty of the carbon prices. The range of possible carbon prices increases over time such that at low discount rates the project requires larger carbon prices to become profitable.

We have also computed the approximate delay of CO_2-storage due to the different uncertainties. Again the dominating factor is the carbon price development. Translating the threshold price necessary for starting a project and the expected development of carbon prices into years by which the start of a project would be delayed, we find that an increase of the threshold price from \$125/tCO_2 at a low stochasticity of the carbon price to \$193/tCO_2 at a higher stochasticity would translate into a delay of the project start by 22 years.

The role of uncertainty about future investment costs, or in other words, of technical development in storage technologies influences the threshold price substantially as well. At a large stochasticity of future investment costs the carbon prices necessary to get to a break even situation almost double when compared to certainty about investments costs. Since only a few pilot plants are planned or in operation the investment uncertainty may significantly influence the commercial introduction of a storage operation. Since investment costs are stochastic due to learning which lowers cost or due to unforeseen complications in developing, monitoring, and running a storage site thus raising project costs, reducing this uncertainty through research and through demonstration projects could lower option values and thus speed up the realization of storage projects.

The real options model and the stylized numerical example reveal some important policy consequences for the evaluation of the economic viability of a carbon storage site from the perspective of a commercial investor. Different risks can arise from investing in carbon storage, such as the economic loss of closing a storage site after leakage has occurred, uncertainty about future returns from receiving carbon credits for storing CO_2, or uncertainty about the final investments costs. It turns out that the much discussed leakage risk has little influence on the investment decision.

However, since a storage facility is expected to receive its income from carbon credits the uncertainty about future returns in the form of carbon prices for these credits is the major obstacle for investing in a storage facility. Reducing this uncertainty would make carbon storage profitable at much lower carbon prices and therefore induce investment much earlier. The currently discussed option to integrate CCS into existing emission trading schemes such as the European Emission Trading Scheme (EU-ETS) would only create a market which can only theoretically support CCS activities. A power plant which captures CO_2 and uses the services of a storage site would avoid the purchase of emission rights at the EU-ETS market. Instead, the storage services would receive up to the EU-ETS allowance price for any ton of CO_2 stored. The current EU-ETS has market prices at which no CCS activity could recover its cost, even if learning effects have lowered CCS costs. The proposed reform of the EU-ETS would raise allowance prices thus increasing the incentives to CCS. The question remains, however, by how much allowance prices need to rise. Even a reformed EU-ETS would not entirely eliminate the stochasticity of carbon prices which are inherent to an emission trading scheme which fixes the amount of emissions and lets the market define the accompanying prices.

There are several possibilities by which the stochasticity of carbon prices could be reduced. One option, consistent with the logic of emission trading, would be to further develop the carbon markets by introducing futures markets that could smoothen out the price path of allowances and provide longer term security about carbon prices and thus provide a secure income for CCS activities. Another possibility that could be used in the introductory face of CCS development is to guarantee a certain carbon price for a CCS operation for a pre-specified length of time. Instead of confronting an investor with the uncertainties of future carbon markets, this policy would make investment into a storage facility profitable at a much lower carbon price since it would remove the variability of income from avoiding carbon allowances. A floor price for carbon credits such as it has been introduced in the UK could also serve such a purpose.

Acknowledgments

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