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Pricing Contracts Under Uncertainty in a Carbon Capture and Storage Framework

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ABSTRACT

Carbon capture and storage (CCS) has been demonstrated as a viable option for reducing carbon emissions to the atmosphere. We consider a situation where a tax on emissions is imposed on carbon dioxide (CO_2) producers to encourage their participation in CCS. Operators of CO_2 transportation pipelines and storage sites enter into individual contracts with emissions producers to store CO_2. We study the problem of selecting the optimal price and volume of these contracts under both cost and emissions uncertainty to optimize the storage operator's expected profit.

1. Introduction

Most low-carbon energy technologies require well-designed policy incentives and business models to encourage widespread deployment of the necessary infrastructure. For carbon capture and storage (CCS), large networks of capture plants, transportation pipelines, and storage reservoirs will be necessary. In parallel, a market-based incentive structure is required to encourage emitters to reduce emissions by participating in a CCS infrastructure.

The potential impacts of CO_2 emissions to the atmosphere are well known and have triggered significant work on low-carbon energy technologies. In order to reduce atmospheric concentrations of greenhouse gases over the long term, multiple solutions are needed to reduce the total emissions volume. Given the magnitude of global dependence on carbon-intensive fuels, no single technology has been identified that is sufficient to meet the challenge alone. However, most major studies on practical strategies to reduce global emissions have included CCS on the list of technologies that can have a significant impact on emissions by 2050 (International Energy Agency, 2010; Pacala and Socolow, 2004). The basic idea behind CCS is to identify major point sources, like coal-fired power plants or cement production facilities, and then capture the produced CO_2 before it is released to the atmosphere. The captured gas can then be compressed and piped to special storage sites where it is injected into deep subsurface reservoirs. The sequestered CO_2 is stored indefinitely and therefore does not increase atmospheric concentrations.

Currently, there are eight industrial scale CO_2 capture and storage projects operating around the world, with dozens more in the construction or planning stages (Global CCS Institute, 2012). The longest running project, Sleipner, has been injecting CO_2 since 1996 and so far has stored 16 Mt ($1\text{ Mt} = 10^6$ metric tonnes $= 10^9$ kg) in a deep reservoir beneath the Norwegian North Sea (Arts et al., 2008; Chadwick et al., 2012). Sleipner was developed in response to the passage of a Norwegian CO_2 tax in 1991, and the avoided tax burden quickly paid for the development costs.

Several business models are available to deal with the capture, transportation, and storage of CO_2, including "self build and operate", "joint venture" and "pay at the gate" (Esposito et al., 2010). The first model takes a vertically-integrated approach in which the emissions producer handles the entire chain of capture, transportation, and storage. This means that the emissions producer needs to acquire and obtain permits for reservoirs, build injection wells and pipeline networks, and assemble a team of internal staff to operate and maintain these facilities. The latter two models involve either partnering or contracting with one or more companies to handle the transportation and disposition of CO_2. Thus, the emissions producers only need to invest in the CO_2 capturing technology. Most studies in the existing literature (Keating et al., 2011; Kemp and Kasim, 2010; Klokk et al., 2010; Middleton and Bielicki, 2009; Middleton et al., 2012a) focus on the design of an optimal

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vertically-integrated CCS infrastructure that minimizes the total cost of capturing, transportation and storing CO_2. Our work considers the “pay at the gate” approach, in which we assume that the emissions producers are responsible for capturing CO_2 emissions while the operator provides the transportation and the storage as a single service. Certainly, these services could be handled separately as well.

In the US, a modest market for CO_2 already exists in Enhanced Oil Recovery (EOR) operations, in which CO_2 is used to release residual oil trapped in depleted fields. Currently, the primary sources of CO_2 are from natural deposits and from certain industrial processes. The CO_2 is sold, at a profit, to oil and gas companies for their EOR operations. In many ways, the current CO_2 market therefore already reflects a “pay at the gate” model. For CCS to have a significant mitigation effect on global greenhouse gas emissions, however, simply expanding the EOR market is insufficient. CO_2 capture from power plants and dedicated geologic storage will be required. Nevertheless, a similar market structure may be adopted.

The “pay at the gate” model provides a number of advantages. The most significant one is that emissions producers do not need to develop in-house expertise and staffing in CO_2 transportation and storage, which are far outside their traditional knowledge area. Secondly, there are significant risk and liability issues associated with subsurface CO_2 storage. A dedicated CO_2 storage provider may be able to better manage these risks by developing the necessary technical capabilities. Thus, having a dedicated company to provide the service and free the emissions producers from these concerns can be attractive to the emissions producers. Thirdly, by providing the service to multiple emissions producers, the service company can reduce the risks associated with uncertainty and become cost efficient.

We design contracts between two individual players: a CO_2 emissions producer and a transportation and storage provider. We refer to these players as the “emitter” and the “storage operator” respectively. An emitter can be any large point-source of CO_2: a coal- or natural-gas-fired power plant, a steel maker, or a cement manufacturer. Both energy service companies and oil and gas companies can be good candidates to play the role of storage operators. We study how a storage operator should design a contract that specifies the amount of captured CO_2 to be transported via pipeline at a fixed service price (per Mt). We consider the storage operator's costs, his expectations of both the emissions quantity and the emitter's capture cost, and an external tax rate on emissions faced by the emitter. While we do not model negotiations between the players, results from our models can help the storage operator choose an initial offer.

Our work is based on three premises: (1) all participants are utility maximizers, (2) a fixed carbon tax has been established, and (3) some of the inputs needed to design the contract, namely the capture cost and the emissions quantity, are uncertain. While the first premise enables us to establish an economic model of how participants make their decisions, the second premise is essential since emitters will have little financial incentive to participate in CCS if they can emit CO_2 into the atmosphere for free. A carbon tax is generally considered as an effective economic incentive to reduce CO_2 emissions. To date, many countries and municipalities have adopted some form of carbon taxation, including: Finland (1990); Netherlands (1990); Norway (1991); Sweden (1991); Denmark (1992); United Kingdom (2001); Boulder, Colorado (2007); Quebec (2007); British Columbia (2008); and the Bay Area Air Quality Management District, California (2008) (Sumner et al., 2011). A number of other countries have carbon tax proposals under consideration.

The third premise allows us to construct an optimal contract for the storage operator while allowing for uncertain information. Due to the novelty of CO_2-capture technology and the one-of-a-kind nature of new capture plants, the true cost to install and operate the capture facility can only be known to the emitter, who may want to conceal its value to keep the storage contract price low. Additionally, the emissions quantity is not constant. In the case of a power plant, the uncertainty in emissions quantity is a result of fluctuations in electricity demand and plant downtime for maintenance. As demonstrated by Middleton and Eccles (2013), emissions profiles at different plants are heterogeneous and therefore greatly impact the emitters' decisions on the amount of CO_2 captured. Thus, such uncertainty also affects the optimal contract the storage operator offers to the emitter in our analysis. Optimizing the price and volume of the contract together can further increase the profit of the storage operator, especially when the distributions of the capture cost and emissions quantity are correlated. While Middleton et al. (2012b) demonstrate that the geologic reservoir uncertainty has large cost implications on building a CCS infrastructure, our analysis shows uncertainty in capture cost and emissions quantity also have significant impacts on the optimal contractual agreement between the emitters and the storage operator.

The models proposed in this paper encompass the unique aspects of the contract design problem. The emitter compares the cost of paying the emissions tax against the cost of engaging a storage operator to store their CO_2. Meanwhile, a storage operator has limited capacity and incurs costs for transporting and storing captured CO_2. Neither player will participate if a negative utility is obtained. We construct a newsvendor model and derive the optimal contract terms that maximizes the expected profit of the storage operator, while incentivizing the emitter to participate. Our results provide guidance in determining how much CO_2 should be expected to be transported and stored, and at what cost. We also provide analysis on the effect of information accuracy on the optimal contracts.

The rest of our paper is organized as follows: Section 2 provides the modeling details and the structure of the contract. In Section 3 we introduce the first model, in which we choose the optimal contract volume given uncertainty in the emissions quantity and a pre-determined service price. We extend the basic model to select the optimal price considering both uncertainty in the capture cost and emissions quantity in Section 4. In Section 5 we present numerical results for realistic input values, and study the effect of correlation between the capture cost and emissions quantity on the optimal profit. Section 6 draws conclusions and details avenues for further research. All proofs appear in Appendix A.

2. Model details

In this section we describe the components of our model, which are summarized in Table 1. Let K denote the fixed monthly cost associated with setting up the site, which includes the costs of drilling the injection wells, monitoring the site, insurance, etc. Note that both the number of wells and the depth of each well are determined by the geology of the reservoir, and the number of wells often determines the storage cost. The limiting factor in determining capacity is often the maximum storage rate (Mt/yr) rather than the maximum volume (total Mt). In our model, we focus on a single-period setting which corresponds to monthly injection and storage. Thus we assume that the contracted amount of CO_2 will

Table 1
List of terms and variables.

Data [units]	
K	Monthly fixed cost [\$] for site
α_1	Marginal cost [\$/Mt] incurred by the storage operator for transporting and storing CO_2 via pipelines
α_2	Marginal cost [\$/Mt] incurred by the storage operator for transporting and storing CO_2 via other means
cap	Maximum capacity for site [Mt]
tax	Fixed tax [\$/Mt] that the emitter pays for CO_2 vented
Random variables [units]	
em	Amount of CO_2 [Mt] emitted by the emitter, has a p.d.f., $f(\cdot)$ and a c.d.f., $F(\cdot)$
cc	Cost [\$/Mt] incurred by the emitter for CO_2 captured, has a p.d.f., $g(\cdot)$ and a c.d.f., $G(\cdot)$
Decision variables [units]	
prc	Service price [\$/Mt] that the storage operator charges the emitter for CO_2 stored at site
con	Contract amount of CO_2 [Mt] transported via pipeline and stored at the operator's site

be injected at a rate below the physical limit, and let *cap* denote the maximum monthly capacity that the storage operator can take.

The storage operator also incurs a unit cost α_1 (per Mt) for transporting and storing CO_2 up to the contract amount, and a marginal cost α_2 (per Mt) to transport and store any excess CO_2 above the contract amount. Note that this is a simplified cost model that masks many of the financing details associated with large capital planning projects. More complex cost structures, however, can be converted to equivalent fixed and unit costs. Additionally, there is a *tax* (per Mt) imposed on the emitter for any CO_2 that is released to the atmosphere.

The power plant has an emissions volume *em* (in Mt) during the single period which is a random variable from a known distribution. Additionally, the capture cost *cc* is the (per Mt) cost of employing capture technology to prevent CO_2 from being emitted. This cost is privately known to the emitter, but the storage operator can estimate a distribution on *cc* to help decide what price to charge the emitter.

We divide the decision process into two stages. In the contracting stage, the storage operator maximizes his expected profit over two decision variables. The first is the service price, *prc*, to charge the emitter per Mt of CO_2 transported and stored. The second is the contract amount, *con* (in Mt) that is the amount the emitter can store at a given value of *prc*. Once such decisions are made, the storage operator presents a contract that specifies both the price and the contract amount. The emitter decides whether to accept the contract by comparing *prc* against the difference between the tax and the capture cost. If the emitter finds it is cheaper to capture and store the carbon than to pay the emissions tax, he accepts the contract, and the storage operator commits to build the pipeline capacity so that the contracted amount of CO_2 (*con*) can be transported via pipeline and stored. The storage operator only builds the pipeline between the emitter and the storage site after the contract is accepted and prior to the beginning of transporting CO_2.

In the execution stage, the emitter observes the actual emissions quantity and has the right (but not the obligation) to store *con* Mt of CO_2 at the operator's site. If the emitter wants to store more CO_2 than the contracted amount, the storage operator may choose not to accept the excess based on either the cost of transportation or the capacity of the site. However, the storage operator is not able to charge a higher price for the additional amount of CO_2.

Under the framework described above, we construct two linked models for the storage operator to determine the optimal contract volume and the optimal price in Sections 3 and 4, respectively.

3. Stochastic emissions quantity

First, we determine the optimal contract amount in the presence of a stochastic emissions quantity. Because there is uncertainty in the capture process, the demand for power varies, and the plant may need to shut down for unexpected maintenance, neither the emitter nor the storage operator can definitively predict the volume of CO_2 emissions available for storage. To address this uncertainty, we treat the emissions volume (*em*) as a random variable with a known distribution. Let *f*(em) denote the probability density function (p.d.f.) of the emissions quantity, and *F*(*em*) denote its cumulative density function (c.d.f.). Since the emissions quantity needs to be positive and can be potentially quite large, we further assume that the density function has a non-negative and continuous support. The storage operator's goal is to optimize the contract given a pre-determined *prc*, which, for now, we assume is known.

Because the storage operator needs to build the pipelines for transporting CO_2 from the emitter to the site after the contract has been accepted but prior to any CO_2 being transported, the optimal contract amount is an important decision. For simplicity, we assume that the emitter builds the capacity of the pipelines to match the contract amount. If the emitter asks to store more than the contract amount, the storage operator can use another method (truck, train or ship) to transport the excess CO_2 at a higher marginal cost, α_2 ($>\alpha_1$). In general, building a pipeline is the most efficient way of transporting large volumes of CO_2, and other options such as trucking are more expensive in the long run (Herzog and Golomb, 2004).

Because our model assumes that the storage operator can only charge a single price for all CO_2 stored, the profit function for the storage operator varies depending on *em*. Recall that *cap* denotes the maximum capacity at the site the operator makes the injection. If emissions amount is less than *cap*, the storage operator receives revenue $prc{\cdot}em$; otherwise, he receives $prc{\cdot}cap$. On the cost side, the operator incurs a cost of $K + \alpha_1{\cdot}con$ (where K is the fixed setup cost and α_1 is the marginal cost of operating the transport and storage system) regardless of the emissions quantity. When *em* is above *con*, the storage operator incurs an additional cost of $\alpha_2{\cdot}(\min(em, cap) - con)$ for transporting and storing the additional CO_2. The following equation summarizes the profit function for the three cases:

$$\Pi(con, prc) = \begin{cases} prc \cdot em - \alpha_1 \cdot con - K & \text{if } em \le con \\ prc \cdot em - \alpha_1 \cdot con - \alpha_2 \cdot (em - con) - K & \text{if } con < em < cap \\ prc \cdot cap - \alpha_1 \cdot con - \alpha_2 \cdot (cap - con) - K & \text{if } em \ge cap. \end{cases}$$

The storage operator's expected profit is:

$$\begin{aligned} E[\Pi(con, prc)] = & -K - \alpha_1 \cdot con + \int_{em=0}^{con} [prc \cdot em] f(em) dem \\ & + \int_{em=con}^{cap} [prc \cdot em - \alpha_2 \cdot (em - con)] f(em) dem \\ & + \int_{em=cap}^{\infty} [prc \cdot cap - \alpha_2 \cdot (cap - con)] f(em) dem. \end{aligned} \tag{1}$$

Eq. (1) shows the calculation of the expected profit by performing a probability-weighting over the possible profits the storage operator would receive under different values of *em*. Since the storage operator's goal is to maximize his expected profit, we can formulate an optimization problem as

$$\max_{con} \{E[\Pi(con, prc)] | \text{s.t. } con \le cap\}. \tag{2}$$

The optimal solution to the problem is summarized in the proposition below, and the proof is provided in Appendix A.

Proposition 1. *Given a pre-determined service price, the optimal contract that maximizes the storage operator's expected profit is*

$$con^* = \min\left\{F^{-1}\left(\frac{\alpha_2 - \alpha_1}{\alpha_2}\right), cap\right\},$$

where F^{-1} is the inverse of the c.d.f. F.

Proposition 1 suggests that the optimal contract amount is independent of the pre-determined service price (*prc*) charged for the contract (as long as the price is high enough for the storage operator to make a profit). Instead, it depends on the marginal costs (α_1 and α_2) of transporting and storing CO_2 as well as the distribution function of the emissions quantity. The optimal contract amount (con^*) increases in α_2 but decreases in α_1. Since the storage operator commits himself to transport and store the contract amount via pipelines, he is thus incentivized to build a bigger pipeline capacity when the marginal cost of pipeline is cheaper or when the other transportation methods are costly.

Suppose the emissions level follows a uniform distribution $U[\mu_{em} - \delta_{em}, \mu_{em} + \delta_{em}]$, where μ_{em} is the mean of the distribution and δ_{em} is the half-width of the support. If the emissions distribution has a lower bound above zero, the storage operator's optimal contract amount is $con^* = \min\{\mu_{em} + (1 - 2\alpha_1 / \alpha_2)_{em}, cap\}$. In the extreme case where the marginal cost of transporting and storing carbon is the same using pipelines as other transportation methods (i.e., $\alpha_1 = \alpha_2$), the storage operator should build pipeline capacity equivalent to the lower bound ($\mu_{em} - \delta_{em}$). In the other extreme case where another transportation method is not available (i.e., α_2 is infinity), the storage operator should set the contract amount to be the minimum of the upper bound ($\mu_{em} + \delta_{em}$) and the total capacity (cap). In the scenario where the emissions distribution has a positive density at zero, the storage operator should not build any pipeline when the marginal costs of the two types of transportation are not significantly different. We provide some numerical examples showing the optimal contract amount under different distributional settings in Section 5.

4. Stochastic capture cost

Next, we model the decision for how much the storage operator should charge the emitter per Mt of CO_2 stored given uncertainty in both the capture cost *cc* and the emissions quantity *em*. Because the emitter's capture cost varies depending on the technology used, it is private information and the emitter does not have any incentive to report the cost truthfully. To address this information asymmetry, the storage operator needs to form rational expectations of the distribution of the emitter's capture cost. We allow *cc* to be a random variable with a known distribution. The storage operator's objective is to find the optimal price for the contract to maximize his profit while still incentivizing the emitter to participate (as long as the emitter is sufficiently efficient in capturing CO_2 and *cc* is low enough).

For a given price, the emitter will either accept or reject the contract based on his capture cost. If the price is set too high, the storage operator bears the risk of being turned down because the emitter is better off emitting to the atmosphere and paying the tax. On the other hand, if the price is set too low, the storage operator leaves "information rent" to the emitter which in turn lowers his profit.

Given a contract (*prc*, *con*) specified by the storage operator, the emitter determines whether he should accept the contract or vent the CO_2 and pay the tax. Since the cost to the emitter is the price to store the CO_2 plus the cost of capturing it, he will accept the contract only if $ptc + cc \leq tax$. If the actual emissions quantity is less than the contracted amount ($em < con$), then both parties agree to only transport and store *em* Mt of CO_2 at the price of *prc*. On the other hand, if the emitter produces more CO_2 than the contract amount ($em > con$), the emitter can either pay tax on the excess amount or can request the storage operator to transport more to his site. For simplicity, we assume that the storage operator is unable to charge a higher price for the additional CO_2. However, he may choose not to fulfill the request if there is a lack of capacity.

Though the capture cost is the emitter's private information, it is natural for us to assume that the storage operator can learn the distribution of the emitter's capture cost through estimation. Let $g(cc)$ and $G(cc)$ denote the probability and cumulative distribution function of the capture cost (per Mt of CO_2) of the emitter, respectively. Since the capture cost should be positive and can be very high, we assume that the density function g has a non-negative and continuous support. Recall from Section 3 that the optimal contract amount does not depend on the price or the distribution of *cc*, and we can thus use the contract amount (con^*) as given.

If the price is set such that the emitter is willing to accept the contract, the storage operator will receive revenue from the contract. The storage operator also pays the cost of operating the site as well as the cost of transporting and storing the contracted (or requested) amount of CO_2. Otherwise, the emitter rejects the contract and the storage operator builds neither the storage site nor the pipeline connecting the emitter and the storage site, and consequently incurs no costs.

Consider the problem of designing a contract from the storage operator's point of view given the uncertainty in *cc* and *em*. For a given price *prc*, the storage operator's profit can be written as:

$$\Pi'(con, prc) = \begin{cases} 0 & \text{if } cc > tax - prc \\ prc \cdot em - \alpha_1 \cdot con - K & \text{otherwise } \& \ em \leq con \\ prc \cdot em - \alpha_1 \cdot con - \alpha_2 \cdot (em - con) - K & \text{otherwise } \& \ con < em < cap \\ prc \cdot cap - \alpha_1 \cdot con - \alpha_2 \cdot (cap - con) - K & \text{otherwise } \& \ em \geq cap \end{cases}$$

We can thus calculate the storage operator's expected profit while allowing the contract to be rejected. This is the same as the expected profit given the contract is accepted times the probability that the contract is accepted. Since we assume that the emitter is rational, we conclude that he would accept the contract if the sum of his capture cost and the service price charged by the storage operator is lower than *tax*, i.e.,

$$cc + prc \leq tax \Rightarrow cc \leq tax - prc.$$

Thus, $G(tax - prc)$ is the probability that the emitter will participate in CCS with the storage operator, and we can write the storage operator's expected profit as follows:

$$E\left[\Pi'(con, prc)\right] = E[\Pi(con, prc)] \cdot G(tax - prc). \tag{3}$$

To maximize the storage operator's expected profit, we solve the following unconstrained optimization problem by determining the optimal price:

$$\max_{prc}\left\{E\left[\Pi'(con^*, prc)\right]\right\}.$$

Proposition 2. *Given the optimal contract amount (con^*), the optimal service price, prc^*, that maximizes the storage operator's expected profit solves the following implicit equation:*

$$G(tax - prc) \cdot \left(cap - \int_0^{cap} F(em)dem\right) = g(tax - prc) \cdot E\left[\Pi(con^*, prc)\right]. \tag{4}$$

In addition, the following conditions must hold at prc^*:

$$(i) E[\Pi(con^*, prc^*)] \geq 0, \text{and} (ii) g'(tax - prc^*) \cdot E[\Pi(con^*, prc^*)] - 2g(tax - prc^*) \cdot \left(cap - \int_0^{cap} F(em)dem\right) < 0.$$

Proposition 2 suggests that the optimal price depends on $G(tax - prc)$, which is the cumulative probability that the capture cost is lower than the difference between tax and price. As mentioned before, the storage operator wants to set the service price to be as high as possible to maximize his expected profit, but also ensures that the service price is low enough to induce efficient emitters (i.e., with low capture costs) to accept the contract. This tradeoff is thus incorporated by having the distribution of *cc* in the optimal solution in the terms $G(tax - prc)$ and $g(tax - prc)$.

The discontinuity of the profit function at $cc = tax - prc$ results in the reliance on the density function $g(tax - prc)$. While such reliance makes a closed form solution for prc^* intractable for general distribution functions, simple line search methods can be used to find the optimal solution numerically for any arbitrary distribution of g. Condition (i) stated in Proposition 2 ensures that the optimal price guarantees a non-negative profit for the storage operator. He should choose not to provide the service if this condition does not hold. Condition (ii) checked the second order condition. These conditions may further restrict the value of prc^*, the allowable range of *tax* to motivate a CCS infrastructure, as well as the allowed shape of the density distribution $g(cc)$.

To provide more intuition for our result, let us consider uniform distributions for both the capture cost and emissions quantity. Let $f(\cdot) \sim U[\mu_{em} - \delta_{em}, \mu_{em} + \delta_{em}]$ and $g(\cdot) \sim U[\mu_{cc} - \delta_{cc}, \mu_{cc} + \delta_{cc}]$ where μ_{cc} and δ_{cc} are defined similarly for the capture cost distribution. Further, the upper limit of the emissions quantity is below the total capacity and the lower limit is non-negative, i.e., $\mu_{em} + ta_{em} < cap$ and $\mu_{em} - \delta_{em} \geq 0$. Recall that the optimal contract amount is $con^* = \mu_{em} + (1 - 2\alpha_1 / \alpha_2)\delta_{em}$, and the storage operator's expected profit given the acceptance of the contract is

$$E[\Pi(con^*, prc)] = prc \cdot \mu_{em} - \alpha_1 \cdot (\mu_{em} + (1 - \alpha_1/\alpha_2)\delta_{em}) - K. \quad (5)$$

Solving Eq. (4), we obtain the optimal price as follows:

$$prc^* = \frac{\alpha_1 \cdot (\mu_{em} + (1-\alpha_1/\alpha_2)\delta_{em}) + K}{2\mu_{em}} + \frac{tax - (\mu_{cc} - \delta_{cc})}{2}. \quad (6)$$

Note that since the distribution of capture cost is bounded, prc^* must be within the range of $[\mu_{cc} - \delta_{cc}, \mu_{cc} + \delta_{cc}]$. Otherwise, setting the optimal service price to the lower limit of the distribution is optimal. This means that all emitters would accept the contract. Since $g(cc)$ is uniform, $g'(tax - prc^*) = 0$. Condition (ii) becomes $-1/\delta_{cc} \cdot (cap - \int_0^{cap} F(em)dem) < 0$, and is thus satisfied. Condition (i) holds as long as the marginal tax is large enough, i.e.,

$$tax \geq \mu_{cc} - \delta_{cc} + \frac{\alpha_1 \cdot (\mu_{em} + (1-\alpha_1/\alpha_2)\delta_{em}) + K}{\mu_{em}}.$$

Because $\partial prc^*/\partial\alpha_1 = (\mu_{em} + (1 - 2\alpha_1/\alpha_2)\delta_{em})/(2\mu_{em}) \geq 0$, and $\partial prc^*/\partial\alpha_2 = (\alpha_1/\alpha_2)^2\delta_{em}/(2\mu_{em}) > 0$, the optimal service price increases when either of the transportation costs increases. Similarly, a higher set-up cost also drives up the service price. Moreover, a higher tax rate not only allows the storage operator to charge a higher price, but also increases the emitter's willingness to participate in CCS. Consequently, the storage operator's overall expected profit increases.

5. Experimental results

In this section, we provide numerical examples to assess the effect of the distributions of the capture cost (cc) and the emissions quantity (em) on the optimal policies. The contract decisions are computed in two stages. In the first stage, the optimal contract amount is calculated independently of the service price. In the second stage, we set the optimal service price. While the optimal values can be calculated numerically for given distributions of cc and em, we can also use simulation to choose the contract values. Simulation is an easy way to generate expected profit values for different contract options. We demonstrate that a higher accuracy of information about cc and em (i.e., lower variance in their distributions) can lead to higher expected profit for the storage operator.

We use the parameter values given in Table 2. These values are taken to be representative of realistic costs based on current experience (Herzog and Golomb, 2004; Rubin et al., 2007; Sumner et al., 2011). Due to the immaturity of the CCS industry and the site-specific nature of all costs, however, estimated values for each of these parameters can cover very broad ranges and are the subject of some debate.

Table 2
Parameter values used in numerical solution.

Parameter	Value
K	\$500,000 per month
α_1	\$6 per tonne
α_2	\$15 per tonne
cap	1 Mt per month
tax	\$100 per tonne
Mean of em	0.5 Mt per month
Mean of cc	\$50 per tonne

5.1. Uniform distributions

Simulation optimization has recently become a very popular method for finding optimal solutions when objective functions can be evaluated via simulation (see Fu et al. (2008) for an overview). In order to estimate the optimal solution, we simulate many possible values of cc and em according to their distributions g and f, and determine the optimal values of the service price (prc) and contract amount (con) that would provide the highest average profit using those simulated values. As a first example, we consider uniform distributions for em and cc. Specifically, we use a distribution of the form $U[\mu - k\sigma, \mu + k\sigma]$, where μ is the mean of the distribution and σ is some level of variation in the distribution. We vary k (using the same k for both cc and em) to show the effect on the optimal solution when the ranges of the distributions vary.

Table 3 suggests that with lower levels of uncertainty, the expected profit and expected amount of CO_2 stored are higher. When $k = 0$, we have the deterministic case where the optimal contract amount and price can be calculated exactly given the exact information. As uncertainty increases, the optimal contract amount increases to allow for potentially higher emissions, but the price decreases to allow for uncertainty in capture costs that might lead to rejection of the contract. Because there is an increased chance of rejection or low emissions, the expected value of CO_2 stored decreases. However, for high levels of uncertainty, we notice an increase in the optimal price to compensate for the extreme risk to the storage operator.

5.2. Normal distributions

We now consider normal distributions for cc and em as $\mathcal{N}(\mu_{cc}, \sigma_{cc})$ and $\mathcal{N}(\mu_{em}, \sigma_{em})$, respectively. The μ parameters are the sample means of the distributions, while the σ values are the standard deviations. We modify the coefficient of variation (CoV), which is defined to be σ/μ for the normal distribution, and represents the relative level of dispersion given the mean. Keeping the mean constant, we modify the CoV through the standard deviation (using the same CoV for both cc and em). Table 4 displays the optimal solutions, and we again see that a higher optimal price can be obtained when the uncertainty in the distribution is either very low or very high.

The results for the normal distribution in Table 4 are similar to those of the uniform case. The deterministic case (CoV = 0) yields the same results, and as uncertainty increases, con^* increases, while the expected profit and expected amount stored decrease. The optimal price decreases originally, but increases when uncertainty is large. The results provide lower bounds on the optimal contract amounts and price that should be offered, and provide benchmarks on the profit that can be expected. The similarity in scale between the uniform and normal values implies that our model may be robust to incorrect distribution selections, and we would recommend that the user try many distributions to check model sensitivity. While the ideal situation is low or zero uncertainty, the storage operator may want to use a high-variance distribution in order to obtain a conservative estimate of their expected profit.

Table 3
Optimal solutions for different values of k when the distributions of em and cc take the form $U[\mu - k\sigma, \mu + k\sigma]$ with $\mu_{em} = 0.5$ Mt, $\sigma_{em} = 0.1$ Mt, $\mu_{cc} = \$50$/tonne, and $\sigma_{cc} = \$10$/tonne.

k	con^* (Mt)	prc^* (\$/tonne)	E[profit] (millions)	E[CO_2 stored] (Mt)
0	0.50	\$50.00	\$21.50	0.50
0.5	0.51	\$45.00	\$18.82	0.50
1	0.52	\$40.00	\$16.14	0.50
2	0.54	\$39.61	\$11.85	0.38
3	0.56	\$44.44	\$10.48	0.30
4	0.58	\$49.66	\$9.97	0.25

Table 4
Expected optimal solutions for different values of σ / μ for $\mathcal{N}(\mu, \sigma)$ with $\mu_{em} = 0.5$ Mt and $\mu_{cc} = \$50$/tonne.

CoV	con^* (Mt)	prc^* (\$/tonne)	E[profit] (millions)	E[CO_2 stored] (Mt)
0	0.50	$50.00	$21.50	0.50
1/6	0.52	$40.93	$14.13	0.42
1/5	0.53	$40.37	$13.45	0.42
1/4	0.53	$40.20	$12.26	0.39
1/3	0.54	$40.40	$11.21	0.36
1/2	0.57	$45.58	$10.04	0.28

To better view the profit function over choices of price and contract amount, we plot the expected profit over both dimensions. Fig. 1 shows a contour plot of the expected profit under the different options of (prc, con). We see that for many solutions, the expected profit to the storage operator is negative. This reinforces our belief that the decision of the amount of CO_2 to store, and the best price to charge the emitter, are important for making this venture Profitable.

5.3. Correlated distributions

Lastly, we use the simulation optimization to estimate optimal solutions for cases where the distributions of the emissions quantity and capture cost are correlated. For example, economies of scale in CO_2 emissions capturing may lead to a lower capture cost, suggesting that *em* and *cc* might be negatively correlated.

By jointly simulating *cc* and *em* according to correlated distributions, we can capture the potential dependence in the randomness and estimate the appropriate optimal solution. As an example, we simulate *em* and *cc* from the same normal distributions as used in the previous section with CoV values of 1/6 as in Fig. 1, but with correlations of −0.7 and 0.7. Fig. 2 shows the contour plots of the expected profit function for the correlated cases.

Our simulation results demonstrate that correlation between the emissions quantity and capture cost has no effect on the optimal contract amount. However, the left plot of Fig. 2 shows that a higher expected profit can be obtained by the storage operator when the emissions quantity and capture cost are negatively correlated. This is because larger plants that emit more tend to have lower capture costs and so are more likely to accept the contract for a given price, leading to a higher expected revenue for the storage operator. When the emissions quantity and the capture cost are positively correlated, however, larger plants tend to have very high costs and are thus less likely to accept the contract. As a result, the storage operator's expected profit is lowered. This intuition is supported by the right plot of Fig. 2.

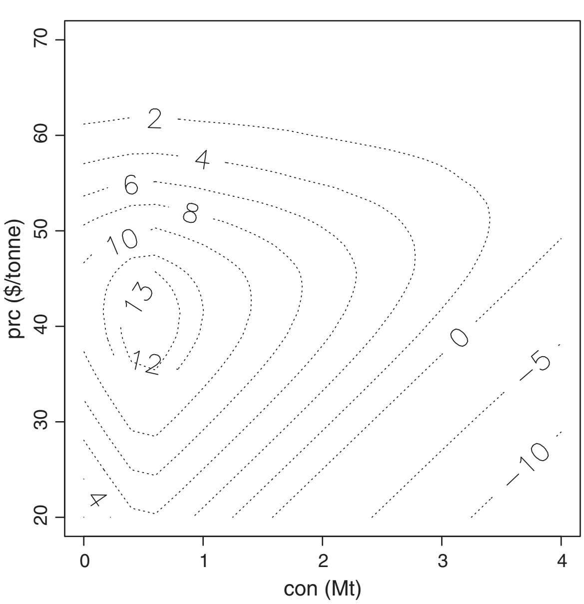

Fig. 1. Contour plot of E[Π] over *prc* and *con* using normal distributions with a CoV of 1/6.

6. Conclusions

We propose a stylized model to address the problem of incentivizing both the storage operator and the emitters to participate in CCS. While a tax on emissions would encourage power plants and other emitters to reduce the level of CO_2 released into the atmosphere, in order for CCS to contribute to this reduction it must be profitable for an independent party to invest in the transportation and storage infrastructure. Our paper shows that profit maximization policies not only facilitate the storage operator to decide the optimal contract volume to commit to and the optimal service price to charge, but also provide estimation of the likely amount of CO_2 that could be stored if such a party was to take advantage of a carbon tax. Given the relative newness of such contracts and CCS technology, uncertainty in our models allow for both parties to better deal with the risk associated with the "pay at the gate" business model.

The methodology used in this paper for designing optimal contracts between the storage operator and the emitter can be extended in several directions. A natural extension is to study the optimal contract design between one storage operator and multiple emitters, each of whom has a different profile in terms of emissions quantity, capture cost, and distance from the storage site. We can then examine whether a risk-pooling effect exists; that is, whether the storage operator could increase the expected amount of CO_2 stored and consequently achieve a higher expected profit when compared to serving each emitter independently. Another direction is to incorporate in our model other costs or revenues, whether deterministic or stochastic, of both the storage operator and the emitters. As an example, because CO_2 is currently used to improve oil recovery from oil and gas reservoirs, both the storage operator and the emitters can make profits (or offset costs) by selling a portion of captured CO_2 to oil and gas companies. It is thus worth evaluating the impact of this option on the emitters' willingness to participate in CCS as well as on the storage operator's expected amount of CO_2 stored and the associated profit. In addition, we can consider competition among multiple storage operators who are willing to serve multiple emitters, and evaluate whether a shared pipeline network could be beneficial for all parties over dedicated pipelines.

Appendix A

Proof of Proposition 1. To find the optimal value of *con* that maximizes the storage operator's expected profit, we first solve the unconstrained problem and maximize the objective function (1). We take the derivative of the expected profit function with respect to *con* and set it equal to 0. Applying Leibniz rule, we obtain the following equation:

$$\begin{aligned}\frac{\partial E[\Pi(con, prc)]}{\partial con} &= (prc \cdot con)f(con) + \int_{con}^{cap} \alpha_2 \cdot f(em)dem \\ &\quad -(prc \cdot con)f(con) + \int_{cap}^{\infty} \alpha_2 \cdot f(em)dem - \alpha_1 \\ &= \int_{con}^{cap} \alpha_2 f(em)dem + \int_{cap}^{\infty} \alpha_2 f(em)dem - \alpha_1 \\ &= \alpha_2(1-F(con)) - \alpha_1 = 0.\end{aligned} \tag{7}$$

We thus find the stationary point as

$$con^* = F^{-1}\left(\frac{\alpha_2 - \alpha_1}{\alpha_2}\right).$$

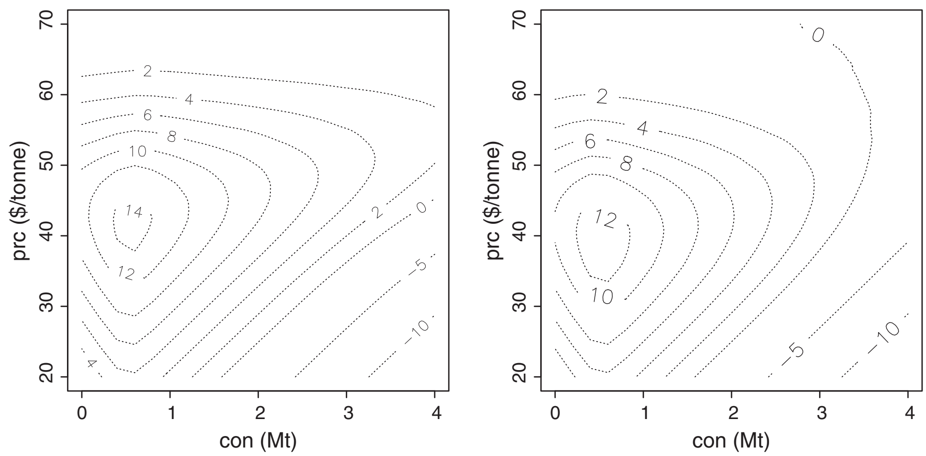

Fig. 2. Contour plot of E[Π] over *prc* and *con* using normal distributions with a CoV of 1/6, and a correlation of −0. 7 (left) and 0. 7 (right) between *em* and *cc*.

We now verify that the second order condition is satisfied at con^*, i.e.,

$$\frac{\partial^2 E[\Pi(con, prc)]}{\partial con^2}\Big|_{con^*} = -\alpha_2 \cdot f(con)\big|_{con^*} = -\alpha_2 \cdot f(con^*) < 0.$$

Thus, con^* is the optimal solution that maximizes the storage operator's expected profit. Since the storage operator cannot set the contract amount to exceed the maximum capacity of the operator, and the expected profit function is concave for all values of *con* for which $f(con) > 0$, we set the optimal contract amount to be $con^* = \min\left\{F^{-1}\left(\frac{\alpha_2-\alpha_1}{\alpha_2}\right), cap\right\}$. □

Proof of Proposition 2. First we re-write $E[\Pi(con^*, prc)]$ as

$$\begin{aligned} E[\Pi(con^*, prc)] &= -K - \alpha_1 \cdot con^* + prc \cdot \int_0^{cap} em \cdot f(em)dem \\ &\quad + prc \cdot \int_{cap}^{\infty} cap \cdot f(em)dem - \alpha_2 \cdot \int_{con^*}^{cap} (em - con^*) f(em)dem \\ &\quad - \alpha_2 \cdot \int_{cap}^{\infty} (cap - con^*) f(em)dem \\ &= -K - \alpha_1 \cdot con^* + prc \cdot \left(em \cdot F(em)\big|_0^{cap} - \int_0^{cap} F(em)dem\right) \\ &\quad - \alpha_2 \cdot \left((em - con^*) \cdot F(em)\big|_{con^*}^{cap} - \int_{con^*}^{cap} F(em)dem\right) \\ &\quad + prc \cdot cap \cdot (1 - F(cap)) - \alpha_2 \cdot (cap - con^*) \cdot (1 - F(cap)) \\ &= -K - \alpha_1 \cdot con^* + prc \cdot \left(cap - \int_0^{cap} F(em)dem\right) \\ &\quad - \alpha_2 \cdot \int_{con^*}^{cap} \overline{F}(em)dem, \end{aligned}$$

where $\overline{F}(em)$ is $1 - F(em)$.

Thus, $\frac{\partial E[\Pi(con^*, prc)]}{\partial prc} = cap - \int_0^{cap} F(em)dem$. To find the optimal value of *prc* that maximizes the storage operator's expected profit, take the derivative of the expected profit function $E[\Pi']$ with respect to *prc* and set it equal to 0:

$$\begin{aligned} \frac{\partial E\left[\Pi'(con^*, prc)\right]}{\partial prc} &= \frac{\partial (E[\Pi(con^*, prc)] \cdot G(tax - prc)])}{\partial prc} \\ &= \frac{\partial E[\Pi(con^*, prc)]}{\partial prc} \cdot G(tax - prc) \\ &\quad - E\left[\Pi(con^*, prc)\right] \cdot g(tax - prc) \\ &= G(tax - prc) \cdot \left(cap - \int_0^{cap} F(em)dem\right) \\ &\quad - g(tax - prc) \cdot E\left[\Pi(con^*, prc)\right] = 0. \end{aligned}$$

The stationary point (prc^*) solves the above equation.

Next, we check second order condition at prc^*:

$$\begin{aligned} \frac{\partial^2 E\left[\Pi'\right]}{\partial prc^2}\Big|_{prc^*} &= g'(tac - prc) \cdot E\left[\Pi(con^*, prc)\right] \\ &\quad - 2g(tax - prc^*) \cdot \left(cap - \int_0^{cap} F(em)dem\right). \end{aligned}$$

When the value of the second derivative is less than 0, prc^* is the optimal solution that maximizes the storage operator's expected profit. In addition, to ensure the operator's expected profit is non-negative, we further restrict $E[\Pi(con^*, prc^*)] \geq 0$. □

Appendix B. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.eneco.2014.02.003.

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