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When to invest in carbon capture and storage technology in the presence of uncertainty: a mathematical model

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Abstract: We present a model for determining analytically the critical threshold for investment in carbon capture and storage technology in a region where carbon costs are volatile and assuming the cost of investment decreases. We first study a deterministic model with quite general dependence on carbon price and then analyse the effect of carbon price volatility on the optimal investment decision by solving a Bellman equation with an infinite planning horizon. We find that increasing the expected carbon price volatility increases the critical investment threshold and that adoption of this technology is not optimal at current prices, in agreement with other works. However, reducing carbon price volatility by switching from carbon permits to taxes or by introducing a carbon floor as in Great Britain would accelerate the optimal adoption of this technology. Our deterministic model provides a good description of this decision problem.

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1 Introduction

In 2005 the European Union introduced its Emission Trading Scheme (ETS), a system in which CO_2 emission permits are traded, as a key ingredient in its plan to adhere to the Kyoto Protocol on emission reduction. The idea was that by creating a market for emission permits cleaner technologies would be rewarded at the expense of heavy emitters. This measure was intended to accelerate investment in electricity generation from renewable sources and therefore move Europe towards becoming a low carbon emissions region. For more information on the ETS see Abadie and Chamorro (2008) for example.

However, renewable sources of generation tend to be intermittent so there is still a role for traditional fossil based generation to maintain system stability. The relative abundance of coal compared to other fossil fuels makes it an attractive option for electricity generation. However, it is amongst the largest producers of CO_2 per unit of electricity generated so that if emitters are to be be penalised through the need for ETS permits, coal loses some of its appeal if the cost of carbon dioxide emissions increases. One attractive approach, in theory, is to capture the carbon generated during combustion and store it permanently. There has been a huge research effort into this technique but at present there is still no commercially operating carbon capture and storage (CCS) storage unit anywhere in the world.

A number of authors have addressed the question of when it is optimal to invest in CCS given carbon price and electricity price uncertainty. In Fuss et al. (2008) both types of uncertainty are included in a numerical model with a finite planning horizon of 50 years. In their model the CCS unit may be switched on and off depending on which state is optimal. Their profit function is a linear function of electricity, heat and carbon price and other costs. They then solve numerically a Bellman equation to determine the optimal time to invest in CCS so that the sum of discounted expected future profits is maximised.

Another thorough numerical analysis of the problem is given in Abadie and Chamorro (2008). Again the electricity price and carbon price follow correlated stochastic processes (in both papers the carbon prices follow geometric Brownian motion) and there is a finite planning horizon. The problem is solved using a two-dimensional binomial lattice to obtain the optimal investment rule.

In Heydari et al. (2012) an analytical model was presented in which the authors solved a partial differential equation to determine the optimal investment boundary under fuel price and carbon price uncertainty (electricity price was found not to affect the option value of the retrofit of a coal fired power plant since the outputs of the plant pre- and post-retrofit were taken to be the same). The authors assumed that investment costs remain fixed.

In this work we present a model with an infinite planning horizon, as in Heydari et al. (2012), that allows us to obtain an analytical solution for the investment threshold that maximises the net present value of the asset. This complements numerical approaches, as analytic formulae allow greater clarity about the contribution of various factors to the investment decision. We consider ETS permit price uncertainty to be the dominant source of uncertainty (modelled by geometric Brownian motion as above). We first find a solution to the deterministic problem for quite general forms of the profit function and then add volatility with a profit function linear in the stochastic ETS permit price. Unlike the analytical solution in Heydari et al. (2012), we assume the investment costs decrease over time as the technology matures. Finally we present a numerical example of our solution for a baseload coal plant and find qualitative agreement to previous results using different parameters and methodologies.

2 When to invest in CCS - a free boundary problem

We are interested in determining analytically the optimal time for a new coal plant to retrofit a carbon capture and storage unit with and without ETS carbon price uncertainty. To do this we maximize the net present value (NPV) of the investment option.

Let P_o denote the profit function for the coal plant without the CCS unit upgrade and P_n denote the profit function for the upgraded plant, both depending on the carbon price C. If the time of investment in CCS is taken to be T (an unknown) then we can write the NPV of the asset as

$$W(C) = \int_0^T P_o(C(t))e^{-rt}dt + \int_T^\infty P_n(C(t))e^{-rt}dt - I(T)e^{-rT} \tag{2.1}$$

where $I(T)$ is the investment time dependent investment cost, and r is the discount rate. We are assuming that the option to retrofit the plant doesn't expire so that the upper limit in the integral above is ∞ though of course an investor will want to have time to recoup the investment cost before the plant is decommissioned - typically after 40 years.

2.1 Deterministic ETS permit price:

Assuming that C evolves deterministically, (2.1) may be differentiated with respect to T which yields

$$\frac{dW}{dT}(T) = \left(P_o(C(T)) - P_n(C(T)) + rI(T) - I'(T)\right)e^{-rT} \tag{2.2}$$

so that W is extremised when

$$P_n(C(T)) - P_o(C(T)) = rI(T) - I'(T). \tag{2.3}$$

To determine whether this extremal value is a maximum or a minimum we differentiate once again with respect to T

$$\frac{d^2W}{dT^2}(T) = -r\left(P_o(C(T)) - P_n(C(T)) + rI(T) - I'(T)\right)e^{-rT} \tag{2.4}$$
$$+\left(\left(\frac{dP_o}{dC} - \frac{dP_n}{dC}\right)\frac{dC}{dT}(T) + \left(-I''(T) + rI'(T)\right)\right)e^{-rT}. \tag{2.5}$$

The first term in brackets on the right hand side above vanishes at an extremal value (it is equal to $-r\frac{dW}{dT}$). Since we are assuming the profits of the plant that has not been upgraded, P_o, fall off faster with increasing carbon price C than the upgraded plant's profits, P_n, we have that

$$\left(\frac{dP_o}{dC} - \frac{dP_n}{dC}\right) < 0.$$

In the deterministic limit of an ETS price following geometric Brownian motion we have

$$dC = \mu C dt,$$

where μ is the constant drift rate taken to be positive to model an increasing ETS price, i.e.

$$\frac{dC}{dT} = \mu C > 0.$$

Furthermore, we assume that as the technology matures the investment costs will decrease so that for a convex decreasing investment cost function $I(T)$

$$\left(-I''(T) + rI'(T)\right) < 0.$$

Therefore, for quite general choices of $P_{o,n}$ and $I(T)$ we find

$$\frac{d^2W}{dT^2} < 0$$

at an extremal value and therefore the NPV is maximised at the value of T obtained from (2.3). We will find in the stochastic case below that our solution for the optimal investment boundary C^* reduces to (2.3) in the limit of zero volatility.

2.2 Stochastic ETS permit price:

Suppose now instead that C follows a geometric Brownian motion (GBM) process:

$$dC = \mu C dt + \sigma C dz$$

where μ is the constant drift rate, σ is the constant volatility and z describes a Wiener process.

We may no longer differentiate (2.1) to obtain the optimal T but rather we expand the integral using Ito's lemma. Our approach will be to solve a Bellman equation, sometimes called the Hamilton-Jacobi-Bellman equation, derived from (2.1) to obtain the critical threshold for investment, the "free-boundary" C^*, above which investment is optimal. This procedure has been carried out, for example, in Pindyck (2002).

As before we assume an infinite planning horizon so that the upper limit in the second integral in (2.1) becomes infinite. It is well known that in this case the resulting Bellman equation contains no time derivative, provided the integrand contains no explicit calendar time dependence (see Dixit and Pindyck (1994)). This is a standard approximation in analytical papers since the presence of a time derivative term turns the Bellman equation into a partial differential equation which usually must be solved numerically, losing the benefit of an analytic solution, see for example McDonald and Siegel (1986). Provided it is appropriate to take $r > \mu$, and P a linear decreasing function of C, we are guaranteed that the integral converges.

So, in the case where C follows GBM we have

$$W(C) = \mathcal{E}_0 \left(\int_0^T P_o(C(t)) e^{-rt} dt + \int_T^\infty P_n(C(t)) e^{-rt} dt - I(T) e^{-rT} \right) \tag{2.6}$$

where $\mathcal{E}_0$ denotes the expected value based on information available at time $t = 0$.

The presence of a T dependent investment cost $I(T)$ prevents us from simply applying a Bellman equation derived from the integral. However, this term may be taken inside the integral. Then we have

$$W(C) = \mathcal{E}_0 \left(\int_0^T P_o(C(t)) e^{-rt} dt + \int_T^\infty \left[P_n(C(t)) + I'(t) - rI(t) \right] e^{-rt} dt \right) \tag{2.7}$$

since

$$-I(T)e^{-rT} = \int_T^\infty \frac{d}{dt}(I(t)e^{-rt})dt = \int_T^\infty (I' - rI)e^{-rt}dt.$$

To avoid the explicit introduction of calendar time into the integral we define

$$\frac{d}{dt}I = -\xi I \tag{2.8}$$

where ξ measures the rate at which investment costs decrease, so now the problem depends on I and C only and not explicitly on t (i.e. $T = T(I, C)$). Now we can apply a standard Bellman equation to the regions before and after investment to determine the 'free-boundary' C^*, the trigger price above which it is optimal to invest. The general Bellman equation reads

$$rW(C) = \hat{P}(C) + \frac{1}{dt}E_0[dW(C)], \tag{2.9}$$

where $\hat{P}$ denotes the profit flow in the interval dt in the pre and post investment regions in (2.6) above, $E_0[dW(C]$ denotes the expected capital gain and r is the discount rate.

We assume that the profit function of the coal plant without CCS, P_o, may be written as

$$P_o = \alpha_o - q_oC(t)$$

and that the profit function of the coal plant with CCS retrofitted is given by

$$P_n = \alpha_n - q_nC(t),$$

where $\alpha_{o,n}$ and $q_{o,n}$ are constants throughout the lifetime of the plant.

Substituting this choice of profit function into the general Bellman equation (2.9) in the pre-investment region and expanding $\mathcal{E}_0[dW(C)]$ according to Ito's Lemma gives

$$rW^o = P_o + \frac{\sigma^2C^2}{2}W_{cc} + \mu CW_c \tag{2.10}$$

which, choosing $P_o = \alpha_o - q_oC$, has the solution

$$W^o = A_1C^m + A_2C^{m'} + \frac{\alpha_o}{r} - \frac{q_oC}{r-\mu},$$

where m and m' are the roots of $\hat{m}(\hat{m}-1)\frac{\sigma^2}{2} + \mu\hat{m} - r = 0$. If $r > \mu > 0$ then we know that one root is positive, m say, whilst the other, m', is negative. The first two terms in this solution represent the value of the option to wait before investing whilst the last two terms are particular solutions of the integral defining W (of course the integral must be a solution of the Bellman equation derived from it). Since we require $W^o(C = 0)$ to be finite we can set A_2=0.

In the region where it is optimal to invest ($C \geq C^*$) we have

$$rW^n = P_n - (\xi + r)I(t) + \frac{\sigma^2 C^2}{2} W_{cc} + \mu C W_c. \tag{2.11}$$

The solution of this equation is

$$W^n = B_1 C^m + B_2 C^{m'} + \frac{\alpha_n - \xi I(t)}{r} - I(t) - \frac{q_n C}{r - \mu}.$$

This time it is clear that there is no value to the option to delay, since we are in the investment optimal region. Thus we take $B_1 = B_2 = 0$.

The final two boundary conditions are the value matching condition on the free boundary

$$W^o(C^*) = W^n(C^*)$$

and the smooth pasting condition

$$W^o_c(C^*) = W^n_c(C^*).$$

Applying the value matching and smooth pasting boundary conditions we find that the free boundary is given by:

$$C^* = \frac{m}{m-1} \left(\frac{\alpha_o - \alpha_n - I'(t)}{r} + I(t) \right) \frac{r - \mu}{q_o - q_n} \tag{2.12}$$

after substituting $I'(t)$ for $-\xi I(t)$. This expression for C^* is the main result of this work. Note that we can already see a value to waiting to invest since $(-I'(t)) > 0$ behaves like extra revenue for the plant that has not yet been upgraded.

We now apply standard techniques of comparative statics to determine how C^* changes as its parameters vary.

We first study how this investment threshold changes as the carbon permit price volatility is varied, this standard argument may be found in more detail in (2), for example. First note that the only term in (2.12) that depends on the volatility σ is m, where recall that m is the positive root of the fundamental quadratic

$$Q(\hat{m}) = \hat{m}(\hat{m} - 1)\frac{\sigma^2}{2} + \mu \hat{m} - r = 0 \tag{2.13}$$

The coefficient of $\hat{m}$ in $Q(\hat{m})$ is positive so $Q(\hat{m})$ describes an upward pointing parabola tending to ∞ as $\hat{m} \to \pm\infty$. Now $Q(1) < 0$ since we are assuming $\mu < r$, and $Q(0) < 0$.

Therefore the graph of Q crosses the horizontal axis at one point to the right of 1 and at one point to the left of zero. Thus at the positive root $\hat{m} = m > 1$. We are interested in how m changes as the volatility is varied since m is the only parameter in (2.12)that depends on σ. For this we follow (2) and take the total derivative of (2.13) with respect to σ to find

$$\frac{\partial Q}{\partial \hat{m}} \frac{\partial \hat{m}}{\partial \sigma} + \frac{\partial Q}{\partial \hat{m}} = 0 \tag{2.14}$$

with all derivatives evaluated at the positive root m. Since $Q(\hat{m})$ is an upward-pointing parabola, at m we have $\frac{\partial Q}{\partial \hat{m}} > 0$. Furthermore

$$\frac{\partial Q}{\partial \hat{m}} = \sigma \hat{m}(\hat{m} - 1) > 0$$

at $m > 1$.

So we conclude that $\frac{\partial m}{\partial \sigma} < 0$ so that as σ increases, m decreases and in particular $\frac{m}{m-1}$ increases. So an increase in the volatility of the ETS permit price will push up the critical threshold for optimal investment C^*. Note that expanding the explicit formula for the positive root m in a power series in σ and taking the limit $\sigma \to 0$ we find that $m = \frac{r}{\mu}$. We thus obtain the correct form for the deterministic solution (2.3).

Now we define the difference in gross revenues of the plants $\triangle\alpha = \alpha_o - \alpha_n$ and the difference in the carbon coupling constants of the plants $\triangle q = q_o - q_n$. Using (2.12) it follows that

$$\frac{\partial C^*}{\partial \triangle \alpha} > 0 \tag{2.15}$$

and

$$\frac{\partial C^*}{\partial \triangle q} < 0. \tag{2.16}$$

Now (2.15) tells us that as we increase the difference between the gross revenues of the plants the optimal investment boundary increases, since in this case the plant without the upgrade has an increased relative advantage over the upgraded plant in terms of gross revenue. Likewise, (2.16) tells us that if the plant without the upgrade emits more CO_2 then the plant with the upgrade has a relative advantage and so the investment threshold decreases.

3 A numerical example

To illustrate the utility of our expression for C^* we will give a numerical example. We will assume we are dealing with a baseload coal plant throughout the lifetime of the plant.[1]

Suppose we have a Super Critical Pulverised Coal (SCPC) power plant with 500MW capacity, an 80% capacity factor and an average CO_2 emission rate of 800g/kWh (these characteristics are taken from Abadie and Chamorro (2008)). Assuming that 5% of the electricity output is consumed by ancillary units this gives a total annual output of 3, 328, 800MWh. Combining this with the CO_2 emission rate gives 2,663,040 ton/year of CO_2 emitted per year.

It is clear that the emissions cost to the plant is then 2, 663, 040 ton/year$\times$ Average ETS price €/ton=$q_o C$. Since 90% of the CO_2 is captured once the plant has been upgraded we have $q_n = q_o/10$. Following Abadie and Chamorro (2008) once more we take the cost of storage and transportation of the CO_2 to be €7.35/ton giving an annual cost of 2.663$\times 10^6$ton/year$\times 0.90 \times 7.35$€/ton=€17.62M/year.

Operation and maintenance cost of the CCS unit are taken to be 1.348 Euro/MWh giving a total annual cost of 4.49M €/year. So the total extra cost of running the CCS unit is approximately 22M €/year. This will provide a lower bound on $\triangle\alpha$ below since it ignores the revenue depletion from the reduction in output of the CCS unit (in Abadie and Chamorro (2008) it is assumed that there's a 20% loss of the plant's output due to the presence of the CCS unit). Finally we take our investment time dependent investment cost function $I(T)$ =€$214.5 \times 10^6 \exp(-0.0202T)$ so that $I(T)$ decreases by 2% per year, as in Abadie and Chamorro (2008).

We will choose the discount rate $r = 0.06$ and the carbon permit drift $\mu = 0.05$. In fact, as noted in Abadie and Chamorro (2008), some authors recommend using a much higher discount rate-as high as 14.8% in Rubin et al. (2007) to reflect the higher risk involved in CCS investments. For fixed $0 < \mu < r$, the higher the discount rate, the faster the convergence of the NPV integral and so our approach of using an infinite planning horizon becomes more similar to a finite horizon problem.

To consider the effects of carbon price volatility on the investment timing decision we plot the free boundary C^* with $\triangle q$ as above and with $\triangle\alpha$ =€$(22 + 50) \times 10^6$ i.e. assuming a revenue depletion of €50 M due to the reduced output of the upgraded plant (the comparative statics result (2.15) tells us that increasing $\triangle\alpha$ pushes up the investment boundary C^*). We plot C^* for $\sigma = 0$, the deterministic case, and for $\sigma = 0.3$, the stochastic case. In the deterministic case the intersection of the deterministic ETS permit price curve and the free boundary C^* gives the maximum of the NPV (not shown).

A summary of all the parameters used in this example is given in Table 1.

[1]For a high carbon price scenario this is unrealistic since coal plants without CCS are heavily penalised since they emit more carbon than gas plants and may not be dispatched as baseload.

Table 1: Parameters used in Figure 1 to plot the optimal investment boundary C^* (2.12)

Parameter	Value
Discount rate r	0.06
Drift rate μ	0.05
Volatility (Deterministic scenario) σ	0
Volatility (Stochastic scenario) σ	0.3
Initial Carbon Price $C(t = 0)$	€5/tCO_2
Investment Cost Function $I(T)$	€$214.5 \times 10^6 \exp(-0.0202T)$
Difference in Plant gross revenues $\triangle\alpha$	€$(22 + 50) \times 10^6/$y
Difference in emission coupling Constants $\triangle q$	2.397×10^6t$CO_2/$y

In the stochastic case the time of optimal investment depends on the sample path of our GBM. However we can still define the optimal 'switching time' as

$$T_s := \inf\{t > 0 : C(t) \geq C^*(t)\}$$

where inf stands for infimum or greatest lower bound, see Mosino (2012) for example. For presentation purposes we take the the deterministic path followed by C as our reference path, even in the stochastic case. Figure 1 clearly demonstrates the effect of volatility on the optimal decision choice. When $\sigma = 0$ we recover the deterministic solution and the intersection of C and C^* gives the maximum of the NPV. Adding volatility to the ETS price drives the free-boundary C^* upwards hence delaying the optimal decision to invest further, in agreement with the comparative statics of the previous section.

For the range of parameters chosen, investment in carbon capture technology is not optimal in the normal lifetime of an SCPC power plant which we take to be 40 years and assuming that the investor will not invest after the 35 year period as they will want want to recoup their investment (for the reference path chosen T_s is approximately 38 years for the deterministic scenario and approximately 50 years for the stochastic scenario. (Note that it is not uncommon for a coal fired power plant to have a lifetime of 60 years).

The significant difference between predicted investment timing in these two scenarios illustrates the sensitivity of investment to the expected volatility of carbon prices. This volatility assumption, in turn, depends upon the form of climate policy that is in place and the way the policy is operated. In particular, if climate policy relies on tradable carbon permits, as in the ETS, expected price volatility will likely be higher than if carbon taxes are used. Both mechanisms can give rise to some carbon price volatility, but taxes tend to change more slowly and predictably than the prices of permits. Permit systems are intended to guarantee a quantity of carbon abatement but must allow price variation to achieve this.

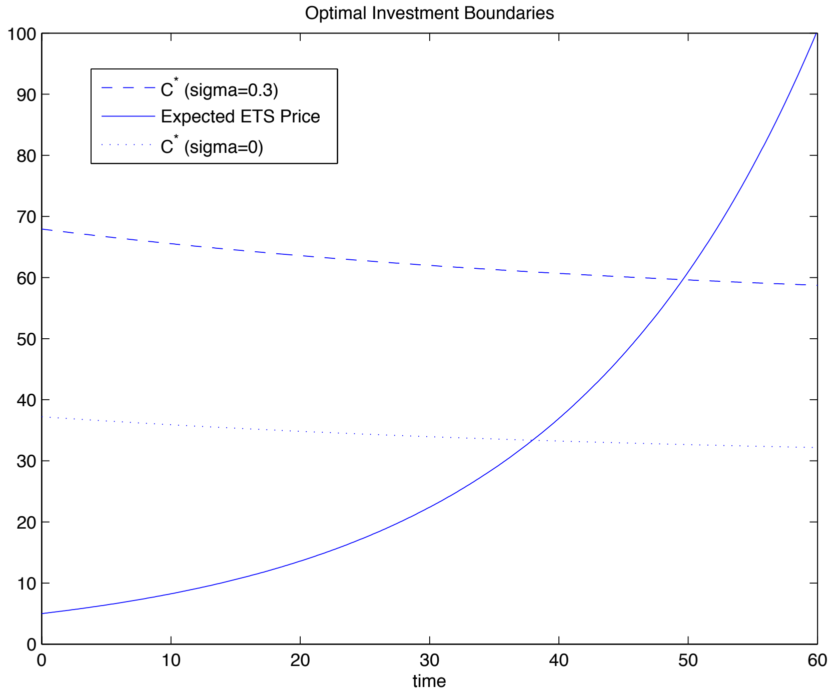

Figure 1: The intersection of the expected ETS price with the critical boundary curve C^* with and without ETS price volatility.

The current policy landscape in Europe offers a practical example of this difference. In Great Britain the newly introduced carbon price floor should substantially reduce the volatility in the carbon cost to producers. The current level of the floor, at £16/tCO2, approx €19/tCO2, is much higher than the current ETS price of approx €5/tCO2, so that this lower bound on the carbon price has effectively removed all volatility in the cost of carbon to generators for the foreseeable future (the floor price rises linearly to £30/tCO2 in 2020 and is set to reach £70/tCO2 by 2030). British generators will effectively face a carbon tax rather than a tradable permit system. With this higher starting point, planned linear growth and little volatility in the carbon floor price, it will be optimal to invest much sooner in Britain than in the rest of Europe in a technology such as CCS, all other things equal.

Figure 1 illustrates the point that putting structures in place that reduce the volatility from the ETS price (such as a carbon tax or binding carbon price floor) will lead to earlier investment in abatement technologies than maintaining volatile carbon prices.

4 Conclusion

We have shown that different investment timing decisions are optimal depending on the level of volatility in the ETS price. Carbon taxes and tax-type climate policy mechanisms such as the newly introduced carbon floor in Great Britain can substantially reduce the uncertainty in the carbon price and push the critical value of C for investment, C^*, lower. They are likely to be more effective than permit-based policies for encouraging investment in abatement technologies. Of course, their wider efficiency properties depend upon the tax/carbon price floor being set at an appropriate level and on the policy being harmonised across as many jurisdictions as possible.

As noted in Abadie and Chamorro (2008) different methodologies and parameters used in the existing literature will lead to different estimates of the optimal investment threshold. The main contribution of this paper is an analytic model of the CCS investment decision with decreasing investment costs. We reproduce the qualitative features of previous research, namely that volatility increases the investment threshold and that at current ETS permit prices it is not optimal to invest in CCS.

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