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When to invest in carbon capture and storage technology: A mathematical model

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ABSTRACT

We present two models of the optimal investment decision in carbon capture and storage technology (CCS)—one where the carbon price is deterministic (based on the newly introduced carbon floor price in Great Britain) and one where the carbon price is stochastic (based on the ETS permit price in the rest of Europe). A novel feature of this work is that in both models investment costs are time dependent which adds an extra dimension to the decision problem. Our deterministic model allows for quite general dependence on carbon price and consideration of time to build and simple calculus techniques determine the optimal time to invest. We 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 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 adoption of carbon abatement technologies such as CCS.

1. Introduction

The European Union introduced its Emission Trading Scheme (ETS), a system in which CO_2 emission permits are traded, in 2005 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 emission 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 penalised through the need for ETS permits, coal loses some of its appeal. One attractive approach, in theory, is to capture the carbon released 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) unit anywhere in the world.

The goal of this paper is to analyse the investment decision in CCS, and determine analytically the optimal time to invest, in a region with volatile emission costs (such as a permit-based system like the ETS) and also the decision facing the investor in a region where the cost of emissions evolves deterministically (such as in a tax-based system). We will explicitly take into account decreasing investment costs as the technology matures.

The carbon floor mechanism introduced in Great Britain (GB) in April 2013 means that electricity producers in GB are effectively subject to a deterministically evolving tax rather than a stochastically evolving allowance price such as the ETS. The current level of the ETS is approx. €5/ton CO_2. The lower bound on carbon to be paid by generators in GB is currently £16/ton CO_2 rising linearly to £30/ton CO_2 in 2020 and rising again to £70/ton CO_2 by 2030. Since the ETS permit price is significantly less than the carbon floor price and the fact that reforms of the ETS aimed at raising its level are slow, the price of carbon emissions by fossil fuel based electricity generators in GB will be effectively deterministic. For more information on the carbon floor mechanism in GB see (Curtis et al., 2013) for example.

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As noted above, the carbon floor price has introduced an effectively deterministic carbon price into GB. Without a carbon price floor mechanism in place, power plants in the rest of Europe are subject to the stochastically evolving ETS permit price. Despite the current low ETS price, a number of proposals have been put forward to raise the ETS price and penalise heavy polluters. One such mechanism, called "back-loading", involves the withdrawal of a large proportion of the ETS permits in the hope that this will increase the price of the permits in the short term before they are reintroduced at a later date. However, the ETS permit price will still be volatile so to model the investment decision facing non-GB European power plants more sophisticated techniques of stochastic calculus will need to be employed.

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 and 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). They also (numerically) value the option to invest in full CCS (approx. 85–95% of carbon emissions captured) and partial CCS (approx. 45–65% of carbon emissions captured) and find that if price volatilities are low enough the investment region is dichotomous so that for a given fuel price investment is optimal in full CCS (partial CCS) if the carbon price increases (decreases) sufficiently. It was assumed in this work that investment costs remain fixed.

The literature on CCS has identified the lowering of investment costs as crucial to the large-scale deployment of CCS technology. In Herzog (2011), it was noted that the first several CCS plants would likely be more expensive, typical of the introduction of a new technology. In Riahi et al. (2004), the situation was compared to the past experience of installing scrubbers to control sulfur dioxide emissions from power plants. A 'learning curve' for CCS was quantified in comparison with the sulfur dioxide case with investment costs greatly reduced as the technology matures. The importance of including time dependent investment costs in any model of CCS uptake is further illustrated in the two-period model in Hoel and Jensen (2012), where it was concluded that cost reductions in CCS may be more desirable than cost reductions associated with renewable energy, from a welfare perspective.

The decision the investor faces today, based on estimates of total investment cost, will be different to the decision faced in the future if investment costs have fallen. Since quantifying the value of waiting for more favourable conditions before investing is one of the key strengths of the real options approach, we believe that incorporating time dependent costs is an important advancement on other approaches that ignore this issue and use fixed costs (see Heydari et al. (2012) for example).

We are not aware of any other research comparing the optimal investment decisions for CCS retrofitting using a carbon price process that models the deterministic carbon floor in GB and another that models the stochastic ETS permit price. This work is timely as reform of the ETS is needed if it is to meet its goal of driving Europe towards becoming a low carbon emission region and the newly introduced carbon floor mechanism in GB promises to provide guaranteed incentives to generators to reduce emissions.

We expect to find it optimal to invest in CCS much sooner in GB than in the rest of Europe, which has obvious policy implications if policy makers still see a role for coal-based electricity generation in Europe. The reason for this expectation is two-fold. Firstly, the current ETS price is much lower than the current value of the carbon floor price. Secondly, we expect to find that increasing the volatility of the ETS price will increase the critical investment threshold. Modelling uncertainty is thus fundamental to this problem.

As in all the works mentioned above, we will model the ETS permit price as geometric Brownian motion. The volatility of the process takes into account the inherent uncertainty of a tradable allowance permit and also the uncertainty in expectations over future emission policies.

In this work we first model the investment decision facing the investor in GB. We model this as a deterministic problem for the reasons outlined above in connection to the carbon floor. We obtain the optimal time to invest that maximises the net present value (NPV) of the option taking into account a time to build of one year and assuming that no revenue is received during this year. A numerical example for a hypothetical baseload coal plant illustrates this result in Section 2.2. We then model the decision facing an investor in the rest of Europe subject to a stochastically evolving ETS permit price in Section 2.3 and find the critical investment threshold of the ETS price above which it is optimal to invest (assuming that the CCS unit may be built instantaneously). A numerical example for a hypothetical baseload plant in Europe (excluding GB) follows in Section 2.4. We conclude this work with a summary and discussion of our results in Section 3.

In both of our models our investment cost function varies with time and in this respect provides a valuable addition to the literature on this topic. Our models are analytic and compliment numerical approaches, as analytic formulae allow greater clarity about the contribution of various factors to the investment decision.

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 carbon price uncertainty. To do this we maximize the net present value (NPV) of the investment option.

2.1. The CCS investment decision in GB: deterministic case

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

$$W(C) = \int_0^T P_o(C(t))e^{-rt}dt + \int_{T+1}^{40} P_n(C(t))e^{-rt}dt - I(T)e^{-rT}, \qquad (2.1)$$

where $I(T)$ is the investment cost function, and r is the discount rate. We have assumed that it takes one year to build the CCS unit and that during this time there is no profit flow (hence the lower bound in the second integral is $T + 1$ rather than T). Also we are assuming that the lifetime of the plant is 40 years.

We assume that the investment cost is irreversible since, as noted in (Abadie and Chamorro, 2008), the CCS unit has a limited range of uses and cannot be installed at another power plant so that, as noted by Pindyck (2007) and Abadie and Chamorro (2008), there is an opportunity cost associated with the investment. We model the investment cost as a once-off payment. For a discussion of the case of a multi-stage investment see Dixit and Pindyck (1994).