Long-Term Dynamics in CO_2 Allowance Prices and Carbon Capture Investments

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Abstract

In this paper we analyse the behaviour of the EU market for CO2 emission allowances; specifically, we focus on the contracts maturing in the Kyoto Protocol's second period of application (2008 to 2012). We calibrate the underlying parameters for the allowance price in the long run and we also calibrate those from the Spanish wholesale electricity market. This information is then used to assess the option to install a carbon capture and storage (CCS) unit in a coal-fired power plant.

We use a two-dimensional binomial lattice where costs and profits are valued and the optimal investment time is determined. In other words, we study the trigger allowance prices above which it is optimal to install the capture unit immediately. We further analyse the impact of several variables on the critical prices, among them allowance price volatility and a hypothetical government subsidy.

We conclude that, at current permit prices, from a financial point of view, immediate installation does not seem justified. This need not be the case, though, if carbon market parameters change dramatically and/or a specific policy to promote these units is adopted.

Keywords: power plants, European Trading Scheme, Kalman filter, carbon capture and storage, real options.

JEL Codes:

1 Introduction

Combustion of fossil fuels and other human activities are causing an increase in the atmospheric concentration of greenhouse gases (GHG). This in turn induces climate change with its sequel of a rise in global average temperature. According to Kyoto Protocol, the European Union must reduce its emissions by 8% below the 1990 levels during 2008 to 2012. In order to ease the fulfilment of this commitment, several instruments have been developed. Two of them are the so-called Joint Implementation and Clean Development Mechanisms. The third instrument is the European Trading Scheme (ETS), a system whereby CO2 emission permits are traded.[1]

The ETS envisages several time phases. The first one goes from 2005 to 2007 and can be considered as a trial or "warm-up" period. It was preceded by an allocation of permits to the installations by the EU Member States; this took place within each country's National Allocation Plan (NAP). The second allocation phase is planned for the period 2008-2012, which coincides with the Kyoto commitment period. From then on, succeeding five-year periods will span the potential post-Kyoto commitment periods.

The trading system started officially to operate on January 1st 2005. It involves some 4,000 facilities in the EU covering approximately 45% of CO2 emissions.[2] In its initial stage, according to Böhringer et al. [1], free allowance allocation has been a necessary condition for the ETS to be accepted by carbon-intensive industries with political clout. In spite of this, as Buchner et al. [3] point out, the world's largest ever market in emissions has been established, and EU firms now face a carbon-constrained reality in form of legally binding emission targets.[3]

European companies thus face the choice between investing in projects that help them reduce GHG emissions (so as to incur in lower carbon payments or get some revenue from spare permits), or purchasing allowances to release GHG emissions. In this scenario, managers have a pressing need of project selection methodologies that allow them to sharpen decision making. Some of the issues concerned may be suitably analyzed by means of standard finance theory or cost/benefit analysis. Occasionally, when managers deal with (significantly) irreversible investments, the returns on which are (highly) uncertain, and have (non-negligible) flexibility to defer investment, real options analysis can prove beneficial.

Insley [7] addresses the decision faced by an electric power company

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[1] Directive 2003/87/EC establishing a scheme for GHG emission allowance trading within the Community and amending Council Directive 96/61/EC.

[2] Transport and households, among other sectors, are not covered by the ETS.

[3] As Laurikka and Koljonen [9] point out, emissions trading is likely to impact cash flows in a given period through four mechanisms: existing cost categories (fuel costs), new costs (value of surrendered allowances), energy outputs (price of power and heat), additional revenues (free allowances).

regarding its abatement strategy to comply with the Clean Air Act (the US Acid Rain Program). In particular, the firm has the option to install a scrubber to limit sulphur dioxide emissions; if the option is exercised, the need to purchase emissions permits is eliminated. Obviously, the perceived benefit of a scrubber depends on the firm's expectations concerning future allowance prices. The paper considers the effect of uncertainty in the price of emissions permits on the decision to install the scrubber. This is a problem of investment under uncertainty.[4] Specifically, the firm must solve for the dollar value of the investment option as well as for the optimal exercise time, i.e. the optimal time to invest. This takes the form of a "critical" or "trigger" permits price above which the scrubber must be installed immediately; otherwise, it is better to wait and keep the option alive. The paper further examines whether US firms' actual behaviour is consistent with optimal behaviour as predicted by the real options model.

Sarkis and Tamarkin [12] consider a project of carbon dioxide re-injection. Sometimes gas extracted from a new field contains high CO2 levels that must be removed to comply with pipeline transmission specifications. Standard practice is to vent this removed CO2 into the atmosphere. The firm's project involves re-injection and long-term underground storage of CO2 in the reservoir from which the gas was extracted. Again, the firm has flexibility to defer installation of the unit until some future date. This option to delay has a value; indeed the firm must exploit it in such a way that flexibility attains its highest value if the firm is to maximize its own value. Consequently, as before, the firm must determine the optimal time to install the equipment. They use internal estimates from British Petroleum-Amoco (BP) for average carbon price in the coming future and expected annual growth rate in price. Their conclusion is that, unless carbon prices have a dramatic upturn, the installation of this equipment should be delayed for an indeterminate time.

Our paper considers the case of an EU-based power company which may purchase carbon allowances in the ETS in order to release CO2 or may alternatively install a long-lived carbon capture and storage (CCS) unit. As usual, the cost of this unit is well known, whereas the future price of the permits is uncertain. The firm we have in mind finds itself in May 2007 but looks to the future while trying to exploit any source of information about it. The ETS plays a crucial role in this respect.

Section 2 provides some background on the market for carbon allowances. Then in Section 3 we propose a stochastic model for the allowance price and calibrate its parameters from actual ETS data. In particular, we assume a standard geometric Brownian motion and apply Kalman filter

[4] Dixit and Pindyck [5] and Trigeorgis [17] provide thorough analyses of the topic. Numerous examples can be found in Brennan and Trigeorgis [2] and Schwarz and Trigeorgis [14].

to the price series in order to come up with the underlying dynamics. Concerning electricity price, we assume a mean-reverting stochastic process. Now, though, parameters are calibrated using monthly average prices from the Spanish wholesale electricity market (OMEL). Section 4 presents basic parameter values for a Supercritical Pulverized Coal-fired power plant. This is the long-lived facility where the potential installation of the CCS unit would take place. Section 5 shows numerical results. Specifically, the option to install the CCS unit is analyzed alongside the optimal time to invest; a sensitivity analysis is also performed. We further consider the possibility of a government subsidy to promote early adoption of the CCS unit by utilities. Section 6 concludes; under current conditions, it will take many years before investing in this technology looks financially sound.

2 An overview of carbon and electricity markets

2.1 The futures market for emission allowances

In order to accomplish cost-efficient emission reductions, the implementation of the Directive has brought about a regulated market. Contracts on these emission allowances are traded on different platforms (in addition to over-the-counter markets). Due to its volume of operations and liquidity, the European Climate Exchange (ECX) stands apart. It manages the European Climate Exchange Financial Instruments (ECX CFI), which are traded in the International Petroleum Exchange (IPE). The information on quotes from the futures market for emission permits gathered at IPE has been used here.

The IPE ECX CPI futures contract is a deliverable contract where each Clearing Member with a position open at cessation of trading for a contract month is obliged to make or take delivery of emission allowances to or from National Registries in accordance with IPE regulations. Contracts with maturities spanning the next 12 months have been introduced of late. However, except for those maturing in December, trading is sparse.[5] Additionally, 5 December contracts are listed from December 2008 to 2012. Contract size is 1,000 metric ton of carbon dioxide equivalent gas. Price units are euros/metric ton. Finally, as usual in futures markets, trading takes place continuously and all open contracts are marked-to-market daily.

As this paper was developed, there were futures contracts for both the first period (2005-2007) and the second one (2008-2012). Figure 1 shows the lower volatility of long-term futures contracts relative to short-term contracts. As can be seen, the closest-to-maturity carbon allowances (Dec-06

[5] Because of their lower liquidity and shorter life span, they do not seem suitable for valuing long-lived assets and have not been used in this paper. Moreover, they fall within the first period.

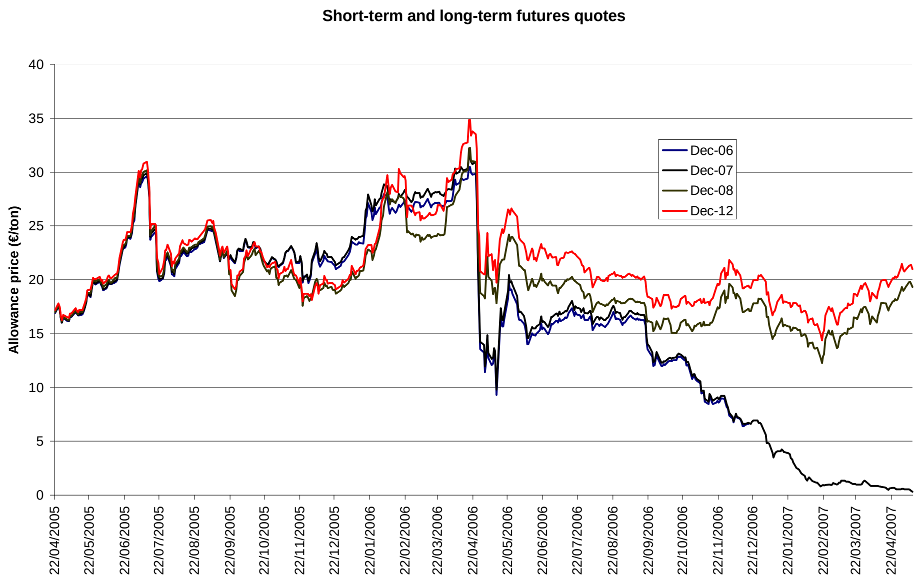

Figure 1: Short- and long-term futures prices (22-April-2005 to 10-May-2007).

and Dec-07) describe wider swings, whereas those with maturity furthest into the future (Dec-12) evolve more closely around their average value.

Typically, cold winters in Europe bring about an increase in the price of emission permits. Over 2005 the rise in natural gas prices and the greater stability in coal prices implied a swell in allowance prices. On November 23rd 2005 the decision by the European Court to authorize 20 million additional permits to the British NAP is reflected. The Figure also shows the decline that started in late April 2006 when an excess of emission allowances was confirmed. It can be observed that, after this adjustment, the price for the longest-term futures contract has been systematically above that for the contract with closest maturity. On the last sample day (May 10th 2007), the Dec-07 contract fetched 0.30 €/ton CO2. Nonetheless, second-phase contracts show a more stable profile. Lately, they reflect the approval (sometimes conditioned) by the EU of NAPs for the second phase.

Table 1 shows basic statistics from futures price series. Contracts are sorted either by their remaining time to maturity or period of expiration.

The first two subsets of contracts (by time to expiration) correspond to years 2006 and 2007. The five remaining subsets, though, go from 2008

Table 1. Summary statistics for CO_2 emission allowances (2006-2012). Daily data from 01-05-2006 to 10-05-2007

		Price (€/ton)		Maturity (years)	
Futures Contracts	Observations	Mean	Std. Deviation	Mean	Std. Deviation
	1,755	16.80	4.80	3.31	1.92
Grouped by time to maturity					
1. Dec-06	165	13.67	3.29	0.32	0.18
2. Dec-07	265	9.58	6.56	1.12	0.30
3. Dec-08	265	17.49	2.19	2.12	0.30
4. Dec-09	265	18.06	2.21	3.11	0.30
5. Dec-10	265	18.63	2,23	4.13	0.30
6. Dec-11	265	19.20	2.26	5.13	0.30
7. Dec-12	265	19.77	2.28	6.12	0.30
Grouped by period					
2006-2007	430	11.15	5.88	0.81	0.47
2008-2012	1,325	18.63	2.37	4.12	1.45

to 2012. It can be seen that the average futures price increases mildly with time to maturity. Concerning price volatility, it rises within each of the two implementation subperiods as the term of the contracts lengthens. This pattern is hardly consistent with mean reversion in prices. [6] Also, volatility drops significantly from the first subperiod to the second, being much lower for futures contracts expiring from 2008 to 2012. One possible explanation is that short-term behaviour is mainly driven by current NAPs which are known for certain, while there is greater scope for uncertainty in the post-2008 scenario.[7]

Yet it is the second period (2008-2012) which seems to be more suitable to assess long-run dynamics in allowance prices, given that we deal with the valuation of long-lived assets. Also, the structural change shown in Figure 1 suggests the convenience to use exclusively the second period for long-run estimations and only from May 2006 onwards. Thus Table 1 shows basic statistics for the futures price series starting on May 1st 2006. We thus have 1,325 daily obervations for 5 futures contracts maturing from Dec-08 to Dec-12. As already mentioned, the increasing relation between volatility and maturity advances the geometric Brownian motion as a suitable model for allowance price.

[6] Indeed, it is the opposite of observed patterns in many commodities futures markets which display the 'Samuelson effect', a sign of mean reversion.

[7] Under the ETS, utilities have received at least 95% of the allocated permits for 2005-2007 free of charge. For 2008-2012, this percentage drops to 90%.

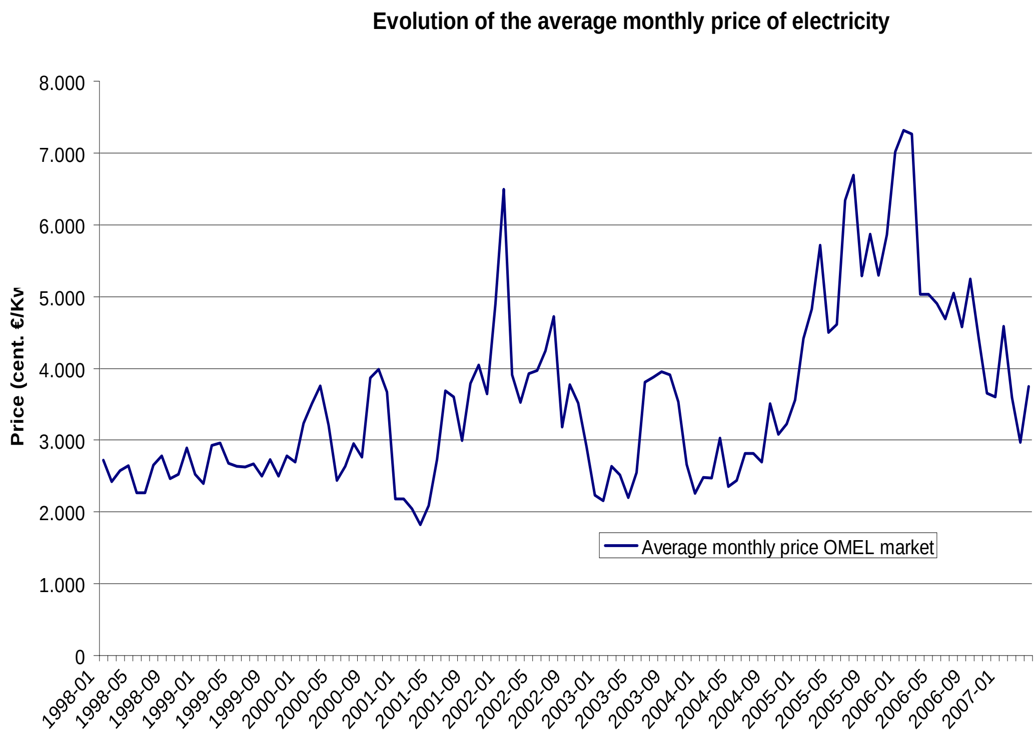

Figure 2: Evolution of the average monthly price of electricity (OMEL Market)

2.2 The Spanish electricity market

Since the aim of the paper concerns long-lived base load plants, monthly average prices have been chosen.The data set comprises 112 monthly average electricity prices (in cents €/kWh) from the Spanish wholesale spot market (OMEL). The time span goes from January 1998 to April 2007, as shown in Figure 2.

Table 2 displays some basic statistics from the monthly price series.

In this case, a price process showing mean reversion seems plausible.

Table 2. Statistics from OMEL market.	
Mean (cts €/kWh)	3.5504
Median	3.2165
Minimum	1.8250
Maximum	7.3140
Standard deviation	1.2351
Coeff. Variation	0.34788
Skewness	1.1447
Excess Kurtosis	0.84177

3 Stochastic models and parameter values

3.1 The model for emission allowance price

We assume that the CO_2 allowance price follows a non-stationary stochastic process. Specifically, following Insley [7], it is governed by a Geometric Brownian Motion (GBM):[8]

$$dC_t = \alpha_c C_t dt + \sigma_c C_t dW_t^c, \tag{1}$$

where C_t denotes the time-t (spot) price of the allowance to emit 1 tonne of CO2, and $E(C_t) = C_0 e^{\alpha_c t}$. Adopting the transformation $X_t \equiv \ln C_t$ and applying Ito's Lemma yields:

$$dX_t = (\alpha_c - \frac{\sigma_c^2}{2})dt + \sigma_c dW_t^c. \tag{2}$$

The risk-neutral version of this equation is:

$$d\hat{X}_t = (\alpha_c - \frac{\sigma_c^2}{2} - \lambda)dt + \sigma_c dW_t^c, \tag{3}$$

where λ stands for the risk premium.

Now, the futures price $F(\cdot)$ (in euros/ton CO2), i.e. the value of the delivery price at time t such that the current value of the futures contract equals zero, is the expected spot price in a risk-neutral context. Besides, by the properties of the log-normal distribution (X) we know that:

$$F(C_{0,}t) = e^{(E(X)+\frac{1}{2}Var(X))} = e^{(\ln C_0+(\alpha_c-\frac{\sigma_c^2}{2}-\lambda)t+\frac{\sigma_c^2}{2}t)} = C_0 e^{(\alpha_c-\lambda)t}. \tag{4}$$

Stating the equation in logarithmic form we get:

$$\ln F(C_{0,}t) = \ln C_0 + (\alpha_c - \lambda)t. \tag{5}$$

[8] Instead, Laurikka [8] assumes a one-factor mean-reverting process, namely the Ornstein-Uhlenbeck process.

We are going to estimate the parameters of this process by applying Kalman filter. The measure equation is deduced from equation (4) since we observe futures quotes, whereas the unobservable spot price is the state variable. Therefore, using Harvey's [6] notation, for the measure equation:

$$\mathbf{y}_t = \mathbf{Z}_t \alpha_t + \mathbf{d}_t + \boldsymbol{\varepsilon}_t, \;\; t = 1, 2, ..., T$$

where:

a) $y_t = [\ln F(t_t^N)]$, $N = 1, 2, ..., 5$, vector of observations (contract price series).

b) $\mathbf{Z}_t$ is an $N \times m$ matrix, N being the number of futures prices available for each day, and $m = 1$ being the number of state variables (just one in this case, namely the spot price). We thus have $\mathbf{Z}_t = [1\ 1\ 1\ 1\ 1]'$.

c) $\alpha_t \equiv X_t$ is the non-observable state variable on each day.

d) $\mathbf{d}_t$ is a 5×1 matrix of the form:

$$\mathbf{d}_t \equiv \begin{pmatrix} (\alpha_c - \lambda) t_t^1 \\ ... \\ (\alpha_c - \lambda) t_t^5 \end{pmatrix},$$

where t_t^1 is the time to maturity of the closest futures contract at time t_t. See Figure 3. This is therefore a Kalman-filter case in which vector $\mathbf{d}_t$ varies over time, since the remaining time until the expiration of futures contracts changes from one day to the next.

e) $\boldsymbol{\varepsilon}_t$ is a 5×1 matrix of serially incorrelated errors. They are assumed to have zero mean and covariance matrix $\mathbf{H}_t$:

$$E(\boldsymbol{\varepsilon}_t) = \mathbf{0}\ ,\ Var(\boldsymbol{\varepsilon}_t) = \mathbf{H}_t\ ;$$

in our case $\mathbf{H}_t = \sigma_\epsilon \mathbf{I}$ is chosen, where $\mathbf{I}$ denotes the 5×5 identity matrix.

Discretizing equation (2) it is possible to get the transition equation:

$$X_{t+1} - X_t \approx (\alpha_c - \frac{\sigma_c^2}{2})\Delta t + \sigma_c dW_t^c.$$

In Harvey's notation:

$$\alpha_{t+1} = T_t \alpha_t + c_t + \eta_t \quad (6)$$

where $\alpha_t \equiv X_t$, $T_t = 1$, $c_t = (\alpha_c - \frac{\sigma_c^2}{2})\Delta t$, $E(\eta_t) = 0$, $Var(\eta_t) = \sigma_c^2 \Delta t$. [9]

Parameter values are derived from maximization of the log-likelihood function; see Table 3.

[9] Note that an equation of the type $dX_t = \mu_c dt + \sigma_c dW_t^c$ has as a solution a centered second moment: $[X_t - E(X_t)]^2 = \sigma_c^2 \int_0^t ds = \sigma_c^2 \Delta t$.

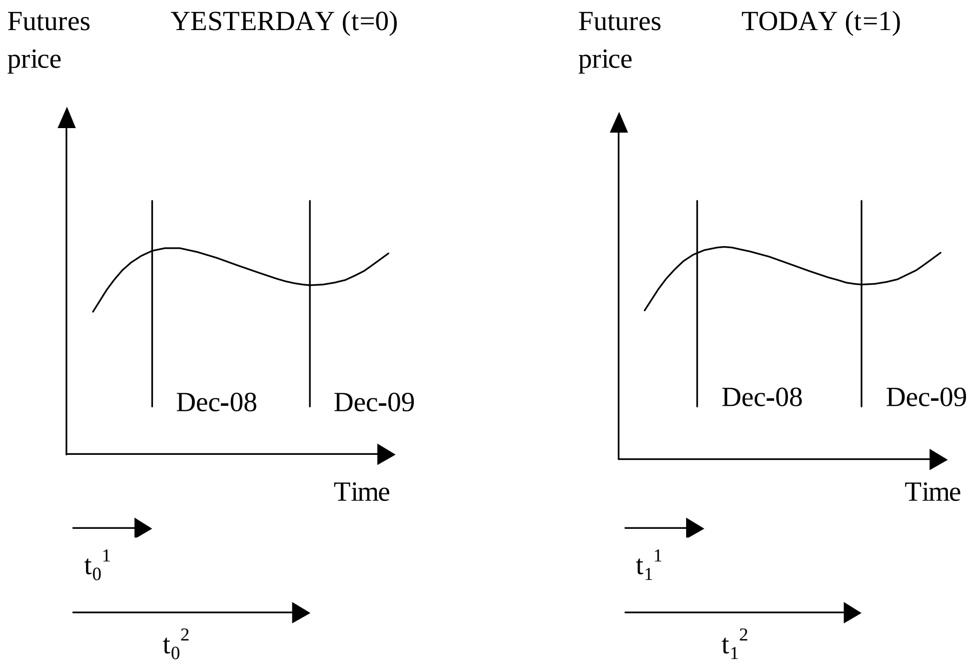

Figure 3: Times to maturity of two futures contracts.

Table 3. Parameter values for CO_2 allowance prices.	
Sample period: 01-05-06 to 10-05-07.	
No. observations	1,325
α_c	0.0690
λ	0.0382
σ_c	0.4683
σ_ϵ	0.0056
Log-likelihood function	4,324.3

Table 4. Estimated futures carbon prices.	
Term (years)	€/ton CO_2
0	18.01
5	21.01
10	24.51
15	28.59
20	33.75
25	38.91
30	45.39
35	52.94
40	61.76

Hence, $(\alpha_c - \lambda) = 0.0690 - 0.0382 = 0.0308$, which allows to compute easily the estimate of the futures value from the estimate of the value for the state variable (the spot price). For instance, on May 10th 2007 the estimate for the log spot was 2.8912, equivalent to 18.01 €/ton (using equation (5)). See Table 4. According to this, it is expected that emission allowances will get dearer over time.

3.2 Calibration of the model for electricity price

The following model is assumed:

$$dE_t = k_e(L_e - E_t)dt + \sigma_e E_t dW_t^E, \tag{7}$$

where L_e denotes the long run equilibrium value. E_t is the electricity price at time t, while σ_t stands for the instantaneous volatility. This is an Inhomogeneous Geometric Brownian Motion (IGBM), with $dW_t^E dW_t^c = \rho dt$, which corresponds to an autorregresive model of order 1, or AR(1). There is currently a futures market for electricity in Spain. However, contract maturities do not go beyond one year. As a consequence, this market is not very appropriate for estimating a risk premium. We assume that the electricity price return is not correlated with the capital market return so the risk premium is zero.

Estimation proceeds as shown in Appendix 1. The results appear in Table 5.

4 Basic data and preliminary computations

We consider a Super Critical Pulverized Fuel black coal (SCPF) power plant. We assume it has a size of 500 megawatts (MW); ancillary units consume a

Table 5. Parameters from OMEL market.	
k_e	0.9604
L_e	3.7852
σ_e	0.4968
ρ	0.2738

Table 6. Investment Costs (M€).		
Time (years)	SCPF power plant	CO_2 capture unit
0	337.0	214.5
1	334.5	210.2
5	324.6	193.9
10	312.6	175.3
15	301.0	158.4
20	289.9	143.2
25	279.2	129.4
30	268.9	117.0
35	258.9	105.8
40	249.4	95.6

5% of the output electricity, and capacity factor is 80%. From these figures, electricity production amounts to:

$$Ouput = 500MW \times 1,000 \frac{kW}{MW} \times 0.80 \times 8,760 \frac{hours}{year} \times (1-0.05) = 3,328,800,000 \ kWh \quad (8)$$

per year. The disbursement required to invest in this plant is assumed to drop by 0,75% each year owing to technological improvements:

$$I_t = I_0 e^{-0.007528t}. \quad (9)$$

Taking a capital cost of 674, 000 €/MW, investment at the initial time would involve a cost of 337 M€.

A complementary unit for capturing CO_2 is assumed to cost initially 214.5 M€, henceforth decreasing by 2% per year:

$$CA_t = CA_0 e^{-0.02020t}. \quad (10)$$

We further assume that this capture unit takes one year to build, disbursement must be done at the outset, and it has a residual value at expiration of zero.

The time path of the expected costs of these investments is shown in Table 6.

The evolution in the third column favours the option to wait before installing a carbon capture unit in an operating power plant. Nonetheless, the unit would operate over a shorter period and it would not be economically profitable to build it during the last years of the plant's useful life. See Figure 4.

The plant's efficiency is assumed to be 41%. Therefore the heat rate is:

$$HR = 3,600 \frac{kJ}{kWh} \times \frac{1}{0.41} \times \frac{1}{1,000,000} \frac{GJ}{kJ} = 0.008,780,488 \ GJ/kWh \quad (11)$$

This implies that annual fuel needs are:

$$B = 500,000kW \times 0.8 \times 8,760 \frac{hours}{year} \times HR = 30,766,829GJ/year.$$

Typically, this kind of plant has an average CO2 emission of 800 g/kWh, so it emits annually:

$$EM = 800 \frac{g}{kWh} \times 3,328,800,000 \frac{kWh}{year} \times \frac{1}{1,000,000} \frac{ton}{g} = 2,663,040 \ ton/year. \quad (12)$$

With a proper unit, 90 % of these emissions can be captured, i.e. 2,396,736 CO2 ton/year; the remaining 10%, though, is not captured.[10]

Operation of the capture unit brings about a reduction in the plant's output. Instead of assuming a 5% loss, now this is assumed to be a 20% (Coombes et al. [4]), or 525,600,000 Kwh less a year. The cost to transport and storage of CO2 is 7.35 €/ton; this average cost times 2,396,736 tons captured per year gives a total of 17.62 M€/year. Operation and maintenance costs of the capture unit are assumed to be 1.348 €/MWh; this figure must be multiplied by the plant's initial output (3,328,800 MWh) to get the cost in euros: 4.49 M€.

Finally, we allocate the investment outlay linearly over the unit's life of 40 years, i.e. 214.5 M€ / 40 = 5.36 M€ per year, and assume an average electricity price of 3.7852 cents €/kWh (for the revenue lost to the capture unit, see Table 5). With the above data, we get a preliminary estimation of 19.76 €/ton CO2 as shown in Table 7.

[10] A particular feature of carbon sequestration is that the CO2 stored is always at risk of leaking back to the atmosphere. Teng and Tondeur [16] address this issue and the overall efficiency of CCS from both a phisical and economic point of view. Instead, we leave it aside.

Table 7. Preliminary estimation of annual costs to CCS unit.	
Item	M€/year
Transport and storage	17.62
Operation and maintenance	4.49
Investment/40	5.36
Electricity revenue loss	19.90
TOTAL COST/year	47.37
Total cost /ton CO_2 captured	19.76 €/ton

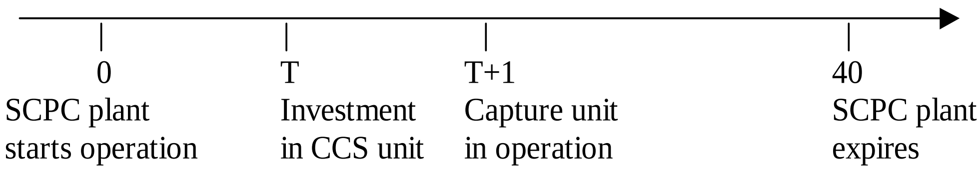

Figure 4: Time schedule of investments.

Compensation from the capture unit would derive from the avoided cost (at market prices) of CO_2 emission permits. Before we have estimated an initial spot price of 18.01 €/ton which is lower than the average cost of 19.76 €/ton. Yet, according to quotes from futures markets, carbon prices are expected to rise significantly over time; to the extent that they are well below the trigger price (see next section), this pushes in favour of the option to wait.

Now let us consider a power plant in operation. If we invest at time t=τ_1, the capture unit will be working in $\tau_1 + 1$ and remain so until the end of the plany's useful life in τ_2.[11]

Under these conditions, the net present value (NPV) of the capture unit would be:

$$NPV_{CCS} = PV_{EMI} - PV_{T\&S} - PV_{O\&M} - PV_{CA} - PV_E. \quad (13)$$

That is, the present value of the emission allowances minus that of transport and storage costs, operation and maintenance costs, investment outlay in the capture unit, minus the present value of foregone revenues from electricity.

The corresponding values are computed at time τ_1 in the following way:

[11] If one considers a SCPF power plant from its inception, then $\tau_2 = 40$. More generally, though, τ_2 will be the remaining useful life at the moment of the valuation analysis. Obviously, since the capture unit takes a year to build and start operations, there is no point in investing when $\tau_2 - \tau_1 \leq 1$.

$$PV_{EMI} = EM_0 \frac{e^{\tau_2(\alpha_c - \lambda_c - r)} - e^{(\tau_1+1)(\alpha_c - \lambda_c - r)}}{(\alpha_c - \lambda_c - r)}, \quad (14)$$

where $EM_0 = 2,396,736$ $ton/year \times 18.01$ €$/ton = 43.165$ M€.

$$PV_{T\&S} = TA_0 \frac{e^{-r(\tau_1+1)} - e^{-\tau_2 r}}{r}, \quad (15)$$

where $TA_0 = 17.62$ M€.

$$PV_{O\&M} = OM_0 \frac{e^{-r(\tau_1+1)} - e^{-\tau_2 r}}{r}, \quad (16)$$

where $OM_0 = 4.49$ M€.

$$PV_{CA} = CA_0 e^{-0.02020T},$$

where $CA_0 = 214.5$ M€.

$$PV_E = PA_0[\frac{L_e}{r}(e^{-r(T+1)} - e^{-40r}) + (\frac{E_0}{k_e + r} - \frac{L_e}{k_e + r})(e^{-(k_e+r)(T+1)} - e^{-40(k_e+r)})] \quad (17)$$

where $PA_0 = 525,600,000$ kWh/year lost, $L_e = 0.037852$ €/kWh, $E_0 = 0.04083$ €/kWh (as of April 2007, deseasonalised), $k_e = 0.9604$ and $r = 0.05$.

With these values, initially, if the decision to install a capture unit were taken (which would operate in one years's time), the NPV would be:

$$\begin{aligned} NPV_{CCS} &= 1,162.40 - 287.45 - 73.21 - 214.50 - 325.20 = \\ &= 262.04 \text{ M€}. \end{aligned}$$

Thus, following the NPV criterion investment at that time would be accomplished.[12]

Table 8 shows these results as a function of the subsidy level to enhance adoption of the CCS unit. Given the sensitivity of the results to the expected growth rate of carbon price in a risk neutral world ($\alpha_c - \lambda = 0.0308$ or 3%, Table 3), the NPV of the capture unit is also computed for different values of this parameter.

We will show below that, when the possibility to decide the optimal time to invest is considered, a positive NPV is not sufficient to undertake this type of investment.

[12] An allowance spot price equal to or higher than 13.95 €$/ton$ at that time would be necessary to accept the investment under this criterion. Note that NPV does not include the value of the option to defer the investment in the CO_2 capture unit.

Table 8. NPV of the capture unit (M€) with varying subsidies			
(Investment outlay = 214.5 M€)			
Subsidy (%)	$\alpha_c - \lambda = 0.01$	$\alpha_c - \lambda = 0.02$	$\alpha_c - \lambda = 0.0308$
0	-81.43	62.57	262.04
10	-59.98	84.02	283.49
20	-38.53	105.47	304.94
30	-17.08	126.92	326.39
40	4.37	148.37	347.84
50	25.82	169.82	369.29
60	47.27	191.27	390.74
70	68.72	212.72	412.19
80	90.17	234.17	433.64
90	111.62	255.62	455.09
100	133.07	277.07	476.54

5 Numerical results

5.1 Binomial Lattice for the risk-neutral GBM and IGBM processes

We have two risk-neutral stochastic processes. For the carbon allowance price:

$$d\hat{X}_t = (\alpha_c - \frac{\sigma_c^2}{2} - \lambda)dt + \sigma_c dW_t^c = \hat{\mu}_1 dt + \sigma_c dW_t^c.$$

For the electricity price, defining $\hat{Y}_t = \ln E_t$:

$$d\hat{Y}_t = (\frac{k_e(L_e - E_t)}{E_t} - \frac{\sigma_e^2}{2})dt + \sigma_e dW_t^E = \hat{\mu}_2 dt + \sigma_e dW_t^E,$$

with:

$$dW_t^c dW_t^E = \rho dt.$$

In order to solve this two-dimensional binomial tree there are four probabilities and, if we want the branches to recombine, two increment values (ΔX and ΔY). Since probabilities must add to one and also be consistent with means, variances and correlations, there are six restrictions to be satisfied. It can be shown that the solution is:

$$\Delta X = \sigma_c \sqrt{\Delta t}, \tag{18}$$

$$\Delta Y = \sigma_e \sqrt{\Delta t}, \tag{19}$$

$$p_{uu} = \frac{\Delta X \Delta Y + \Delta Y \hat{\mu}_1 \Delta t + \Delta X \hat{\mu}_2 \Delta t + \rho \sigma_c \sigma_e \Delta t}{4 \Delta X \Delta Y}, \tag{20}$$

$$p_{ud} = \frac{\Delta X \Delta Y + \Delta Y \hat{\mu}_1 \Delta t - \Delta X \hat{\mu}_2 \Delta t - \rho \sigma_c \sigma_e \Delta t}{4 \Delta X \Delta Y}, \quad (21)$$

$$p_{du} = \frac{\Delta X \Delta Y - \Delta Y \hat{\mu}_1 \Delta t + \Delta X \hat{\mu}_2 \Delta t - \rho \sigma_c \sigma_e \Delta t}{4 \Delta X \Delta Y}, \quad (22)$$

$$p_{dd} = \frac{\Delta X \Delta Y - \Delta Y \hat{\mu}_1 \Delta t - \Delta X \hat{\mu}_2 \Delta t + \rho \sigma_c \sigma_e \Delta t}{4 \Delta X \Delta Y}. \quad (23)$$

At any time the four probabilities must take on values between zero and one.

A two-dimensional binomial tree is arranged with 6 time steps per year ($\Delta t = 1/6$). This amounts to 6×39 =234 steps for the case of 40 years (the last nodes would occur at time 39, where a null value would arise as the maximum between building the capture unit in exchange for nothing and zero):

$$W = \max(NPV_{CCS}, 0) = 0 \quad (24)$$

At earlier moments, in each node the best option is chosen, be it whether to invest or continue:

$$W = \max(NPV_{CCS}, (p_{uu}W^{++} + p_{ud}W^{+-} + p_{du}W^{-+} + p_{dd}W^{--})e^{-r\Delta t}). \quad (25)$$

Investing yields the NPV_{CCS}, whereas continuing allows to wait and get the future value discounted at the risk-free rate. The future value of the next step is the sum of the values in the four nodes weighted by the risk-neutral probabilities of reaching each of these values.

At time $t = 0$, the value of the option to wait is just the difference between the value of postponing the investment and that of investing immediately. With 6 steps per year, the difference between the option value and the NPV turns out to be 344.49 M€. These results are shown in Figure 5 and Table 9.

Convergence towards the solution as the number of steps increases can be observed. This profile justifies the choice of six steps per year, since no significant improvement is gained with a higher number of steps while the time elapsed in computations rises dramatically. [13] There is a difference of order 5 per thousand between the solution with 6 steps per year and that with 20 steps.

[13] When working with 40 years, the tree is built for 39 years. Using 6 steps per year implies that, in the final moment of the analysis at the step 234, there are 54,756 nodes. The choice of a number of time steps that combines reliable results and reasonable computing time is justified in this work by the need to estimate the optimal value and timing of exercise through the two-dimensional tree.

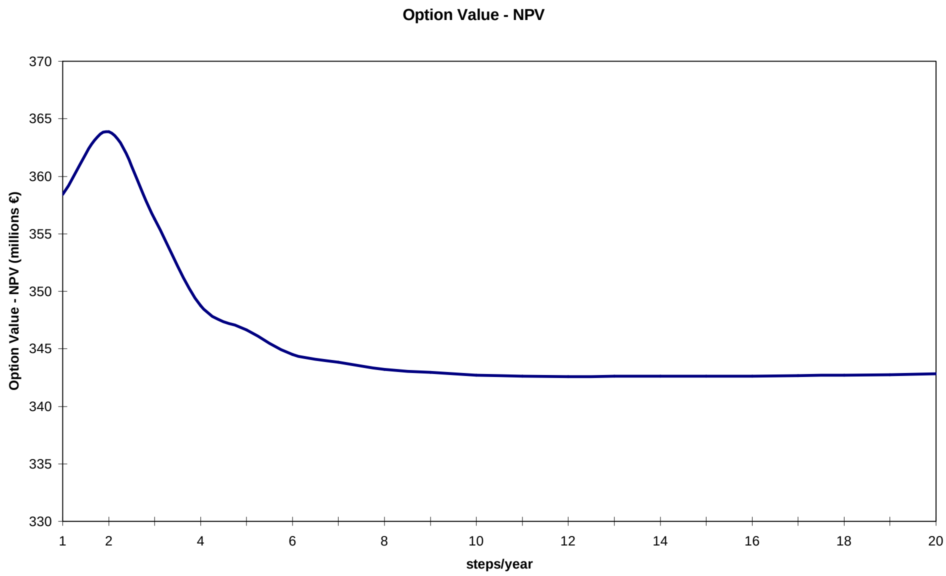

Figure 5: Option Value - NPV as a function of the number of time steps.

Table 9. Value of the option to wait.		
Sensitivity to the number of time steps		
Steps per year	Total steps	Option Value - NPV
1	39	358.42
2	78	363.86
4	156	348.76
6	234	344.49
8	312	343.19
10	390	342.70
12	468	342.58
14	546	342.64
16	624	342.63
18	702	342.12
20	780	342.81

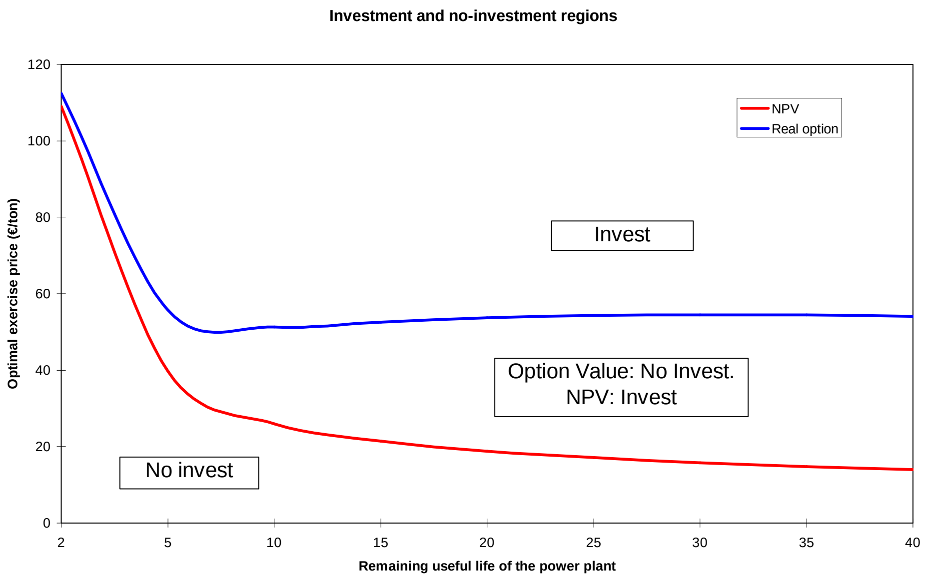

Figure 6: Investment and no-investment regions with 30 years of useful life.

5.2 Case study: The option to install a CCS unit in a coal-fired power plant

We consider several situations.

5.2.1 The allowance trigger price for the capture unit

First, we analyze the price of CO_2 allowances above which it will be optimal to invest depending on the power plant's remaining useful life (remember that by assumption the capture unit's residual value is zero when the plant to which it is attached expires).

Figure 6 shows that, taking into account the value of the option to invest at the optimal time, for useful lives above 8 years, investment will only take place generally for allowance prices above 55 €/ton. However, if it is only possible to invest immediately or never, i.e. when the NPV criterion prevails, the threshold price to overcome ranges between 13.95 €/ton with 40 years and 25.97 €/ton with 10 years of useful life.

The shape of the curve is determined among other factors by:

a) The recovery period of the investment, which implies a higher permit price for lives shorter than 8 years.

b) The expected rise in the allowance price.

c) The expected drop in the investment cost of the CCS unit.

Table 10 shows some of the numerical values in Figure 6. They suggest

Table 10. Carbon trigger price as a function of plant's life.		
Useful life (years)	Real Option	NPV
2	112.38	109.00
5	55.66	39.75
10	51.35	25.97
15	52.58	21.39
20	53.68	18.84
25	54.31	17.11
30	54.51	15.81
35	54.40	14.79
40	54.09	13.95

that the current situation is not favourable, from a financial point of view, for the firms to decide to install CCS units right now. Everything pushes for deferring this type of investments and seeing what happens in the meantime.

One of the most influential parameters upon valuation is the allowance price volatility. As long as This is high, it is more likely that these investments will be postponed. In the base case we have used an allowance price volatility of 46,83% (see Table 3). With 30 years of remaining useful life, this implies an optimal exercise price of 54.51 €/ton.

5.2.2 Sensitivity analysis

Now we undertake a sensitivity analysis of the critical price for the carbon permits (which triggers the decision to invest immediately in a CCS unit), assuming 30 years of remaining useful life (thus with $6 \times 29 = 174$ time steps).

Figure 7 shows that allowance price volatility is a key factor in the decision to invest in a CCS unit. A significant reduction in volatility would diminish the value of the option to wait and would render a wide deployment of these investments much more likely. Whereas for a volatility value of 50% the trigger price is 57.86 €/ton, if the former drops to 20% the optimal price reduces to 32.19 €/ton. Some of the results in Figure 7 are shown in Table 11.

With 30 years of remaining useful life, the critical carbon price is 54.51 €/ton. Since the expected spot price evolves along $E(C_t) = C_0 e^{\alpha_c t}$, given $C_0 = 18.01$ €/ton and $\alpha_c = 0.069$, it will take 16.04 years to reach that level under current conditions. From a strictly financial point of view, the firm

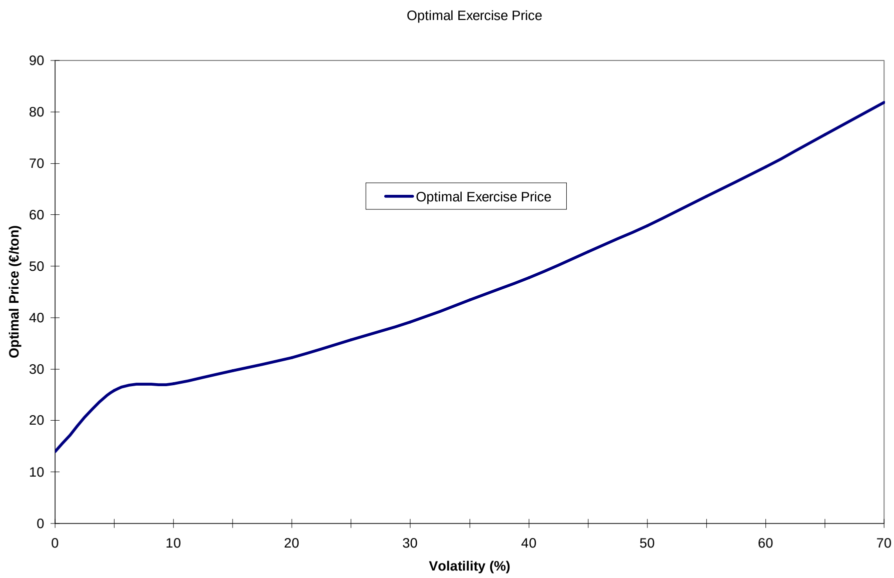

Figure 7: Trigger price as function of volatility with 30 years of remaining useful life.

Table 11. Optimal exercise price.	
Sensitivity to changes in volatility	
Volatility (%)	Trigger price (€/ton)
0	13.95
0.1	17.81
1	22.46
5	25.87
10	27.19
20	32.19
30	39.19
40	47.79
46.83	54.51
50	57.86
60	69.29
70	81.82

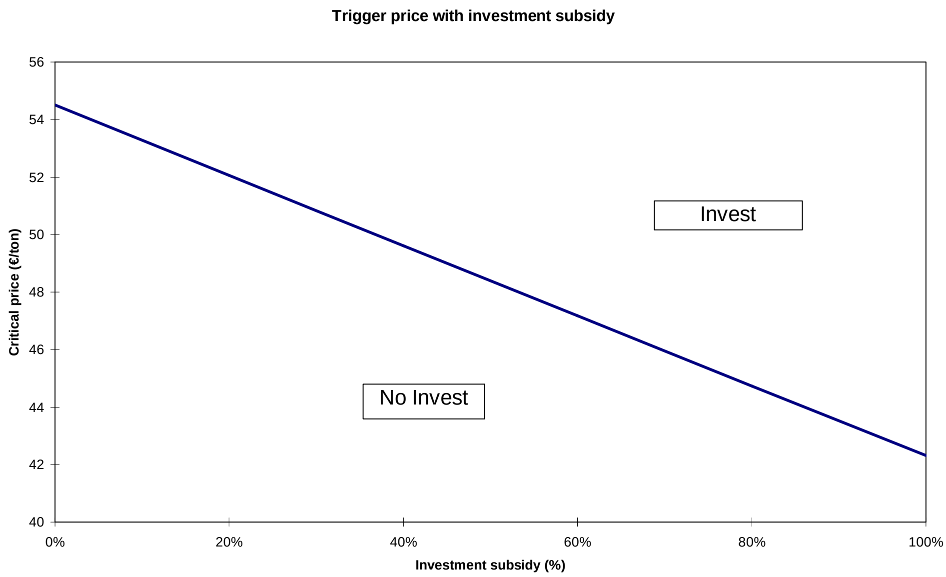

Figure 8: Trigger price with 30 years of remaining useful life and investment subsidy.

would not invest in the CCS unit until year 2023; this could be unacceptable if a faster emissions reduction is pursued. In case volatility dropped to 30%, though, the trigger price would fall to 39.19 €/ton; this could be reached in 11.26 years and installation would speed up to year 2018.

5.2.3 A government subsidy to CCS unit adoption

Another factor that can affect the investment decision is the potential existence of a government subsidy for some fraction of the unit's total disbursement.[14] See Figure 8.

In this case, the optimal exercise price falls between 54.51 €/ton without subsidy and 42.31 €/ton with a 100% subsidy. These prices show that, at current allowance price levels, not even a total subsidy is enough to induce an immediate building of these units.[15]

[14] Given that we have assumed a time decreasing investment cost as technology develops, the absolute subsidy could be lower in periods further into the future.

[15] Even though, with a 100% subsidy, the NPV amounts to 476.54 M€ (see Table 8).

6 Conclusions

In this paper we have analyzed the option to invest in a CCS unit using standard parameter values for it. Two correlated stochastic processes have been considered, one for the allowance price and the other one for electricity price. Parameter values for these price processes have been calibrated from the European Trading Scheme (ETS) and the Spanish wholesale electricity market (OMEL).

Our results show that current permit prices do not provide an incentive to the quick adoption of this technology, the more so when the option to choose the optimal time to invest is considered. Immediate construction by coal-fired power plants would be justified for carbon prices close to 55 €/ton. This figure is significantly higher than 13.95 €/ton which would result from a simple NPV analysis. Plants with less than eight years of remaining useful life would hardly adopt this technology at all, since there would not be enough time to recover the investment. For all other terms of useful life, a carbon price close to 55 €/ton is rather stable and almost independent of the remaining life.

The high value of the trigger price is mainly driven by the high allowance price volatility (close to 47%). An structural market change bringing about a sizeable drop in volatility would imply a significant decrease in the optimal price and, consequently, earlier adoption of this technology by utilities. For example, for a carbon price volatility of 20%, the trigger price falls to 32 €/ton.

We have also considered the possibility to promote these units by means of a subsidy. When this is maximum (100 % of the unit's initial cost), the optimal price approaches 42 €/ton; this represents a drop of more than 12 €/ton from that without subsidy (or 22.38 %). All in all, the current framework does not seem to encourage an early adoption of the CCS technology.

A better estimation of the stochastic model for the allowance price would be feasible as long as we approach the second application phase of the Kyoto Protocol (2008-2012), there are more futures prices for this period and current uncertainties unfold (though new ones could appear).

The model may be applied to other types of power technologies, like natural gas-fired combined cycle (NGCC) plants or integrated gasification combined cycle (IGCC) plants. In the first case, carbon emissions are significantly lower, [16] and in the second they are also lower but just because of the higher efficiency of this facility.

The model can be extended in several ways. For instance, the possibility to build a somewhat more expensive power plant but designed from the outset to be "capture-ready"; that is, to disburse today a higher sum of

[16] About 350 g/kWh, depending on the plant's efficiency.

money in exchange for the option to incur less costs in the future should the case for installing a CCS unit become compelling.

A Appendix

The following stochastic model is estimated for the electricity price:

$$dE_t = k_e(L_e - E_t)dt + \sigma_e E_t dW_t^E, \tag{26}$$

with a time series consisting of 112 average monthly prices (from February 1998 to April 2007).

Note that:

$$E(E_{t+1}) = L_e + (E_t - L_e)e^{-k_e \Delta t}. \tag{27}$$

After discretization and rearranging this equation becomes:

$$\frac{E_{t+1} - E_t}{E_t} = (e^{-k_e \Delta t} - 1) + L_e(1 - e^{-k_e \Delta t})\frac{1}{E_t} + \sigma_e \sqrt{\Delta t}\epsilon_t^E. \tag{28}$$

where $\epsilon_t^E \sim N(0,1)$

Expressed as $Y_t = \beta_1 + \beta_2 X_{2t} + u_t$, we get the following OLS estimates (adjusted for heteroskedasticity) for $\hat{\beta}_1$ and $\hat{\beta}_2$:

Coefficient	**Estimate**	**Standard dev.**	$t-$**statistic**	$p-$**value**
$\hat{\beta}_1$	-0.0769185	0.0535881	-1.435	0.15405
$\hat{\beta}_2$	0.291154	0.169468	1.718	0.08863

$$\hat{\beta}_1 = \text{-0.0769185} = e^{-k_e \Delta t} - 1 \ , \ k_e = -\frac{1}{\Delta t}\ln(\hat{\beta}_1 + 1) \tag{29}$$

$$\hat{\beta}_2 = 0.291154 = L_e(1 - e^{-k_e \Delta t}) \ = \ -\hat{\beta}_1 L_e. \tag{30}$$

The standard deviation of the residuals is 0.143416. Hence σ_e =0.143416 $\sqrt{\Delta t} = 0.4968 = 49.68\%$. It follows that:

Parameter	**Value**
k_e	0.9604
L_e	3.7852
σ_e	0.4968
ρ	0.2738

In our computations we will assume $\lambda_e = 0$. Durbin-Watson's statistic takes on a value of 1.77963.

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