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Optimal Abandonment of Coal-Fired Stations in the EU

Luis M. Abadie[1], Mikel Gonzalez-Eguino[2], José M. Chamorro[3]

Carbon-fired power plants could face some difficulties in a carbon-constrained world. The traditional advantage of coal as a cheaper fuel may decrease in the future if CO2 allowance prices start to increase. This paper seeks to answer empirically the most drastic question that an operating coal-fired power plant may ask itself: under what conditions would it be optimal to abandon the plant and obtain its salvage value? We try to assess this question from a financial viewpoint following a real option approach at firm level so as to attract the interest of utilities and the broader investment community. We consider the specific case of a coal-fired power plant that operates under restrictions on carbon dioxide emissions in an electricity market where gas-fired plants are considered as marginal units. We also consider three sources of uncertainty or stochastic variables: the coal price, the gas price and the emission allowance price. These parameters are derived from future markets and are used in a three-dimensional binomial lattice to assess the value of the option to abandon. Our results (and sensitivity analysis) show the conditions that have to be met for the abandonment option to be exercised. This option to abandon coal-fired plants is, however, hardly likely to be exercised if plants can operate as peaking plants. However, the decision may go differently in different circumstances, such as high CO2 allowance prices, very low volatility of allowance price or a decrease in the price of gas. The decision is also influenced by the remaining lifetime of the plant and its thermal efficiency. In any case the price of CO2 will work to bring forward the decision to abandon in older and less efficient coal-fired plants, which are less likely to be retrofitted in the future.

Keywords: power plants, coal, natural gas, emission allowances, futures markets, stochastic processes, abandonment, real options

JEL Classification: Q4, Q5, C6

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1 INTRODUCTION

The mitigation of anthropogenic greenhouse gas emissions is a key issue in the international agenda. A post-Kyoto agreement is still being negotiated [A PRINCIPIOS DEL AÑO 2010], but developed countries have already presented national reduction plans up to 2020. For that year the EU has set the objective of reducing its emissions by 20-30% (below 1990 levels), Japan is committed to a reduction of 25% and, according to the Markey-Waxman law, the US has committed to at least a 4% decrease. Therefore, it is reasonable to expect that emissions of CO_2 will start to be increasingly scrutinized, regulated and priced (Schelling [24]).

In the European Union many firms are already subject to the EU Emissions-Trading Scheme (ETS), the largest multi-national emissions trading scheme in the world and a major pillar of EU climate policy. The ETS was established in 2005 and currently covers over 10,000 installations, responsible for some 45% of CO_2 emissions. In the near future other sectors, like aviation, and other greenhouse gases are planned to be incorporated to ETS. Similar systems have already been discussed in the United States, Australia and Japan and are expected to be implemented in the near future. It could even be the case that some national cap and trade systems may join together.

At the same time as prices for CO_2 are coming in, subsidies on fossil fuel are on their way out. In one of the latest meetings of the G20 (Pittsburgh, September 2009) it was agreed to "phase out inefficient subsidies for fossil fuels". If these subsidies are finally withdrawn the impact will be significant, as they amount to nearly $300 billion globally. These subsidies are particularly important in the coal industry and for those countries that maintain them for energy security reasons.

The role of coal-fired power plants in a new, carbon-constraining world has yet to be determined. In developing countries more than four fifths of all the coal consumed is normally used in the power industry (IEA [13]). Updated versions of traditional pulverized coal technology still offer one of the cheapest sources of power (total levelized, IEA [10]), especially when crude oil and natural gas prices have been high. However, increasing prices for carbon emissions may change this situation, and profitability could be substantially reduced.

Although many utilities are not facing high CO_2 prices, the mere prospect of them in the future is already altering utilities' decision-making and resource choices (Barbose et al. [5]). This may be why in the US construction of around one hundred projected coal-fired power plants has been cancelled or delayed since 2000 (NETL [18]). The number of coal-fired plants planned across America has plummeted from 150 to 60 in the past five years. Moreover, in 2008 5.4 gigawatts (GW) of new electricity capacity were announced, but instead only 1.2 GW were completed because of cancellations or delays. In Europe, in spite of plans to construct at least 38 new plants with a capacity of over 300 MW in 2006-2012, from 2000-2005 only 4 projects of this type were completed, adding up just 3.5 GW in total, which means around 0.7 GW/year. In fact, new coal plants are not keeping up with closures and, in a context of growing demand, many utilities are switching new investments from coal to natural gas.

Another explanation for the decline in investment in coal plants can be found in environmental requirements. The European Union's Large combustion Plant Directive (LCPD) has set new emission standards for Member States for nitrogen oxides (NO_x), sulfur dioxide (SO_2) and dust particulate matter (PM) from all power stations with an installed capacity greater than 50 megawatts (EU [8]). Under this directive those power stations that do not meet the specified emission standards must either retrofit appropriate pollution control equipment or close down. Plants that 'opt out' of meeting the new standards can operate for a maximum of 20,000 hours after January 2008 and must shut down by 2015 at the latest. The opt-out decision could be optimal in the case of plants that operate at significantly lower load factors and for which investment in new equipment does not make much commercial sense. In any case, plants will have to face CO_2 prices.

In the medium/long term coal plants will depend greatly on regulations, on the availability of carbon capture and storage (CCS) technology and on cost. In Britain any coal plants must now deploy the possibility of adding a CCS unit on at least 400 megawatts of their output. Also significant, for example, is the decision taken in 2008 by the banks Citigroup, JP Morgan Chase, and Morgan Stanley. In view of the real possibility that a system might be introduced to limit emissions in the US in the coming years, they have developed a new system for environmental standards with tougher financial conditions for coal plants in the US (as they believe that there is increased risk in investment with higher emissions). These banks require anyone who invests in coal plants to have discussed other options first, such as improvements in energy efficiency and renewables, and require proof that those choices are not viable. If coal plant is financed, it must be "capture-ready", i.e. must have flexibility in its design to allow for emission capture when the relevant technology becomes commercially available.

CCS technology could put a maximum price on the cost of producing electricity with coal. In 2003 a study carried out at MIT (Ansolabehere et al. [4]) came to the conclusion that coal use could increase in the future but would be highly dependant in the developing world on the development and cost of CCS technology. According to this study the best technology options will increase the cost per kW from 32% (Pre-combustion in an Integrated coal Gasification combined Cycle or ICGC) to 62% (Post-combustion in supercritical pulverized coal or SCPC). Newer technologies such as IGCC offer the prospect of more affordable carbon capture and other potential advantages, but these technologies have higher up-front investment costs and there are few plants of this type up and running. According to the studies carried out, CCS could be ready on a commercial scale by 2020-2030 in a range of $14-91 per ton of emissions avoided (IPCC [15]). In one of its latest reports (IEA [12]) the International Energy Agency estimates that the price (per tCO_2 avoided) for the first big plants would be $40-90 and McKinsey, a consultancy, has arrived at an estimate of $75-115. Although CCS could be a solution for coal-fired power plants in the future it will need time to become financially viable.

The current economic downturn, with lower demand for emission allowances and lower prices, has temporarily delayed the decline in coal-fired stations' profit margins. A change in the macroeconomic outlook, with higher electricity demand and a strong push in allowance prices, could reverse the situation and jeopardize plants' profits. This could be the case for a large proportion of coal-plants, which are too old or too inefficient to wait for the possibility to install a CSS facility in the future an remain competitive. According to the IEA, CCS will not be viable for plants with low electric efficiency due to the increase in cost per kWh of electricity. Therefore, "investing in high efficiency power plants is a first step in a CCS strategy" (IEA [11]). In the US around 75% of the total installed coal-fired capacity (around 250GW) are plants older than 35 years. In Europe the average age of the coal-fired plants currently operating is 26 years, but 9% of the total units are more than 40 years old (Tzimas et al. [26]). Plants more than 35-40 years old generally have net efficiency levels of between 25 and 30% (IEA [14])

To date, several papers have analyzed the prospects for coal in a carbon-constraint situation, using different approaches and techniques. There are a number of studies that have examined the economics of coal, with and without carbon capture. Many of these papers use computable general equilibrium models to analyze how competing technologies, input prices and general equilibrium effects can influence coal plants and CCS adoption. For example, McFarland et al. [22] [21] use the MIT-EPPA model in a study that shows that carbon price, dispatch and the gap between coal and gas prices have the most significant effects on coal consumption. With carbon prices approaching 400 $/\mathrm{t}C$ or 109$/\mathrm{t}CO_2$ (reference scenario) in the period after 2050, coal capture technologies will quickly start to dominate electricity production and conventional coal will be phased out.

Other papers follow different but complementary perspectives as they focus more on analyzing firms' decisions. Laurikka and Koljonen [19]) study quantitative investment appraisal of fossil fuel-fired power plants following a real option approach. Using Monte Carlo simulation and the prices of electricity and emission allowances as stochastic variables, they extend standard discounted cash flow analysis to take into account the value of two real options: the option to wait and the option to alter the scale of operation. The case study shows that the uncertainty regarding the allocation of emission allowances is critical in a quantitative investment appraisal of fossil fuel-fired power plants.

Abadie and Chamorro [2] value the income risk facing coal plants assuming separate dynamics for alternative input (coal, natural gas) and output (electricity, carbon dioxide) prices in a liberalized market. The prices of inputs are governed by stochastic processes and Monte Carlo simulation is used to compute the expected value and risk profile of earnings by coal-fired plants. According to this study the margins remain positive over the Kyoto Protocol's commitment period, but may drop significantly immediately afterwards. Expected margins may turn negative or remain slightly positive but with a high risk of becoming negative in many cases. In such scenarios, this would lead to the temporary shutdown of coal-fired plants, thus reducing the chances of recovering investment costs.

This paper goes one step further and analyzes the conditions under which a coal-fired power plant could take its most drastic decision: to abandon the plant and obtain its residual value. We assess this question from the perspective of firms and finances (following a real option approach), so as attract the interest of utilities and the investment community. We consider the specific case of a coal-fired power plant that operates under restrictions on carbon dioxide emissions in an electricity market. In our model we consider that gas-fired plants are the marginal units that set the price of electricity. In this sense the margin between the price obtained for electricity and the cost of natural gas and emissions allowances can be estimated as a fixed value. We also consider three sources of uncertainty or stochastic variables: the coal price, the gas price and the emission allowance price. The underlying parameters are derived from futures markets and are used in a three-dimensional binomial lattice to assess the value of the option to abandon.

The contribution of this paper takes several directions. Firstly, it complements current research into the prospects for coal using a firm-level approach, as most of the studies that analyze the future of coal use partial or general equilibrium models applied at energy-system or macroeconomic level (Paltsev et al. [23]). Secondly, most models assume scenarios for energy prices and do not capture the intrinsic uncertainty of these variables. Our study considers the price of coal, carbon and gas as stochastic variables that are estimated from actual futures prices. Finally, it adds new knowledge to the growing literature on the application of financial economics instruments to the energy investment decisions of firms. One of the innovations of our approach is to use numerical estimates in a three-dimensional binomial lattice to assess the value of the option to abandon. The methodology is similar to that in Boyle et al. [6] and Gamba and Trigeorgis [9]. However, our procedure allows for mean-reverting stochastic processes (as opposed to standard geometric Brownian motions), and is later used to value American-type options (as opposed to European-type options). Finally, another aspect of this paper is the inclusion of a methodology to estimate seasonality underlying futures gas prices for non homogeneous periods (months, quarters, seasons and years).

Our results show that (strong) conditions have to be satisfied for coal-fired plants to decide to abandon. However, this decision may be made due to high CO_2 allowance prices, very low allowance volatility or a decrease in the price of gas. The remaining life of the plant and its thermal efficiency are also important variables. We show that the price of CO_2 can bring forward the decision to abandon and that older, less efficient coal-fired plants are most likely to be abandoned. We also show that the possibility of coal-fired plants working as peak load units is one of the key reasons for not abandoning plants.

The rest of the paper is organized as follows. Section 2 briefly introduces the topic and provides some market background. Section 3 sets the theoretical framework. The particular stochastic processes for the three uncertain variables are presented. We also derive the formula for the value of a stochastic annuity and the margins for gas- and coal-fired plants. Section 4 outlines the estimation procedure and shows the numerical values of the underlying parameters and Section 5 describes the margin for coal-fired power plant. Section 6 explains the three-dimensional binomial lattice method used. Section 7 gives the general results and the sensitivity analysis, and Section 8 concludes.

2 SOME PRELIMINARIES

2.1 Coal-fired power plants: background

Coal is the world's most abundant fossil fuel. The coal sector accounted in 2008 for nearly 32% of all global fossil fuel consumption and 38% of all emissions. The electricity generated from coal accounted for 80% of the total in Australia, 50% in the US and 30% in Europe (EU-27). Most of the coal-fired electricity-generating plants installed are conventional pulverized plants (PC), with efficiencies of about 35% for the more modern units. New supercritical steam plants can reach about 40%, but are more costly.

According to the IEA, if no restriction or technology transfer is implemented, around five hundred new 500MW coal-fired power plants will be built up to 2030 in developing countries to meet electricity demand there (IEA [12]). This picture contrasts with the prospect for new coal investments in developed countries. coal investment in these countries is highly dependent on carbon prices, environmental regulations and energy prices. The future of capture and storage (CCS) availability and costs are determinant variables for the future of coal in the long term (Abadie and Chamorro [1]).

The average age of the existing power plant stock differs from country to country depending on the historical electricity demand and supply mix. Figure 1 shows the coal-fired plant construction profile for Europe and the USA. The figure shows a clear peak around 1970 followed by a sharp decrease. New constructions of power plants have being declining, with other options such as gas-fired power plant and renewable being used instead. Between 2000 and 2005 few new coal plants were built in Europe and the Unites States. This means that the net capacity of this technology is decreasing, as is its contribution to the energy mix.

The coal plant fleet is getting old quickly. In Europe the average age in 2005 for this type of plant was 26 years, and 10% of the stock was more than 40 years old. In the US at least 10% of the total stock has an average age of 35 years. Given a lifespan of 40 years many plants on both sides of the Atlantic will need to be replaced around 2010-2020, and in this time frame CCS will probably not yet be available on the market at reasonable prices. Moreover these old plants are the less likely to be retrofitted with CCS facilities as their net efficiency is between 25 and 30%.

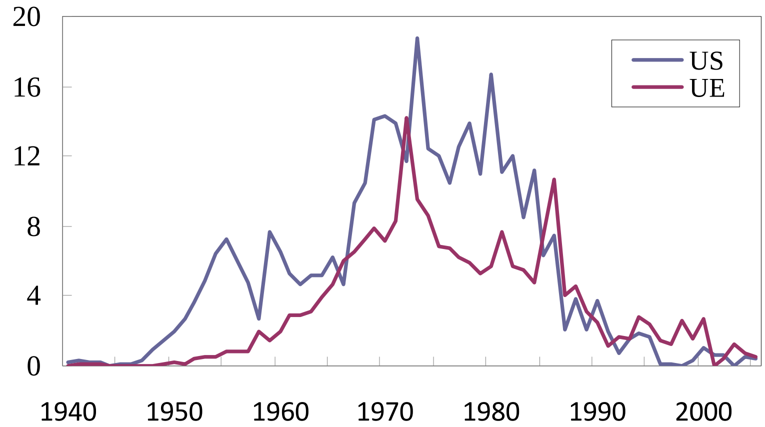

Figure 1: New coal-fired power plant capacity addition (GW/year).

2.2 The dark spread and the clean dark spread

The electricity industry has traditionally been organized as a regulated monopoly, where the electricity price was set such that investors received adequate returns on investments and a desirable mix of technologies was assured. Today, many countries have switched to a deregulated market, where utilities provide electricity at a variable price that is determined on the market and where margins are determined largely by technology choice and fuel price volatility.

Only units for which there is a positive difference between the price of electricity and the price of a particular fuel are operated. It is this spread that determines the economic value of a generation asset that can be used to transform input fuel into electricity output. Therefore, power operators pay close attention to the so called "dark" and "spark" spreads. The "dark spread" is the theoretical gross margin of a coal-fired power plant from selling a unit of electricity; having bought the fuel required to produce that unit of electricity. All other costs (operation and maintenance, capital and other financial costs) must be covered from the dark spread. The term "spark spread" is similar but refers to gas-fired power plants. Dark and spark spreads can provide a good reference concerning the profits of a plant. They can also be used as a proxy to assess the loss of revenue if a power station is switched from a normal running scenario to one where it is held in reserve or is unable to generate.

In countries where there is a price for carbon, generators also have to consider the cost of carbon dioxide emission allowances. Therefore, it is useful to refer to the Clean Dark Spread (CDS), the result of subtracting carbon allowance costs from the dark spread and, similarly, to the Clean Spark Spread (CSS). A positive CDS or a positive CSS would mean that it is profitable to generate electricity in that period, while a negative spread means that generation would be a loss-making activity. A positive dark spread with a negative CDS means that production becomes non profitable when carbon costs are included [1].

Finally, the difference between the CDS and CSS, is sometimes known as the "Climate Spread" (CS). In a carbon-constrained economy where gas is the marginal technology that normally sets the electricity price and coal-fired plants operate as baseload plants, coal may eventually encounter a negative CS if carbon credit prices rise given its higher emission factors per kWh. A logical response to this would be to operate the coal plant as peak unit or to switch from coal to gas. In many cases the transformation from coal to gas means practically having to build a completely new plant, though some elements of the old one may be used (land, transport infrastructures, etc.).

2.3 Sample data

The sample used in this work consists of weekly averages of electricity prices (PowerNext, France), natural gas prices (at Zeebrugge, Belgium, as provided by Bloomberg), spot carbon prices (on ETS, as provided by BlueNext), and ARA coal one-month futures prices (EEX, Leipzig, Germany). Thus, the sample prices come from markets that are geographically very close to each other. We have a complete data set over 180 weeks when all four price series are available, namely May-2006 to September-2009.

Figure 2 shows the trends in CDS and CSS for this period. CSS is calculated for a gas plant with 55% efficiency. In the case of CDS we calculate the value for two different energy efficiency parameters: 30% and 40%. Most of the stock of coal-fired plants can be found between these two values, while the older, less efficient plants are around 30%. Most of the time all three series are positive. Although there are large deviations at different points they quickly return to the average. This trend is therefore consistent with a mean reverting process. There is only one period (May 2008 to September 2008) for CDS (30%) in which the spread is significantly negative.

Figure 3 also shows the trend of the climate spread. In the case of CDS (40%) the climate spread is positive (CDS $>$ CSS level) most of the time, although there is a tendency for the climate spread value to decrease. For the case of CDS (30%), the climate spread is negative for most of the sample. These results illustrate the significance of carbon prices but also the effect of efficiency levels.

Finally, a cursory statistical analysis for CSS, CDS and CS series provide more exact estimates; see Table 1. The average value for CSS (12,97€/MWh) falls between the averages for both CDSs (9.15€/MWh and 19.22€/MWh, respectively). The average CS for a plant with 30% efficiency is negative (-3.83 €/MWh) but with 40% this spread changes to positive (6.25 €/MWh).

[1] However, it has to be considered that certain margin is always necessary to cover fixed cost.

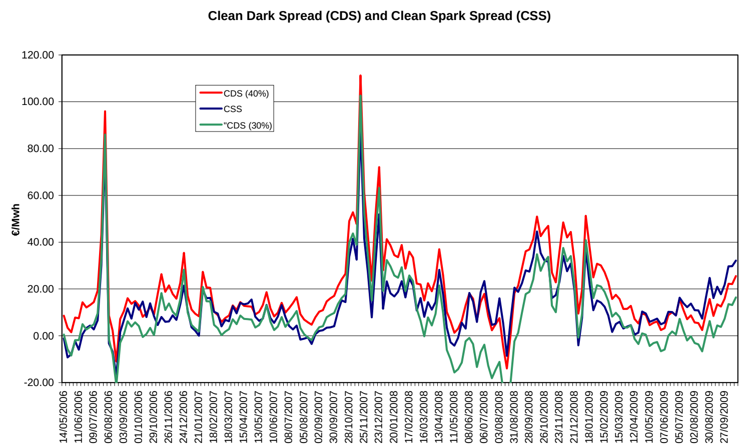

Figure 2: Clean Dark Spread (CDS) and Clean Spark Spread (CSS).

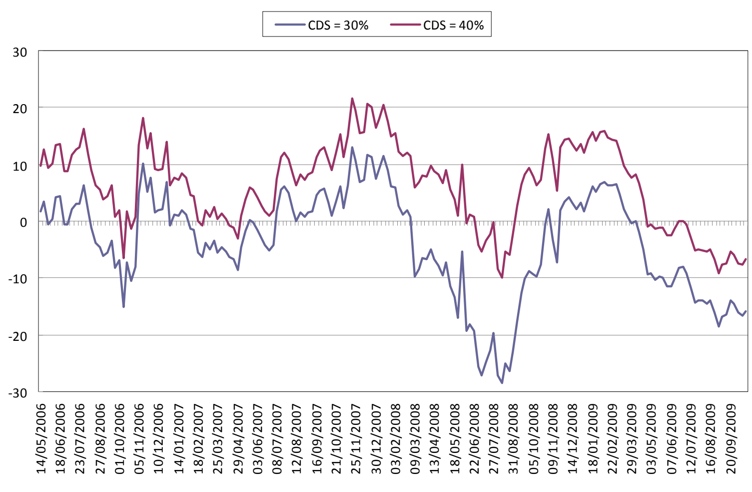

Figure 3: Climate Spread (CS).

Table 1: Basic statistics of CSS, CDS, and CS weekly series (05/14/2006–10/18/2009).

	CSS	CDS (0.30)	CDS (0.40)	CS (0.30)	CS (0.40)
Average (€/MWh)	12.97	9.15	19.22	-3.83	6.25
Media (€/MWh)	10.55	5.88	14.36	-1.80	7.55
Min (€/MWh)	-17.20	-33.62	-13.98	-28.46	-9.90
Max (€/MWh)	89.65	102.65	111.27	13.00	21.62
Standard deviation	13.50	16.97	16.55	9.07	7.35
Coefficient of variation	1.04	1.86	0.86	-2.37	1.18
Skewness	2.00	1.78	2.06	-0.63	-0.23
Excess kurtosis	8.14	6.90	7.14	-0.13	-0.81

3 STOCHASTIC MODELS AND ESTIMATION

In this section we present and estimate the stochastic models used in this study. We consider a constant margin in the long run for gas-fired power plant M_e and three stochastic variables: the gas price G_t, coal price C_t and the emission allowance price A_t.

3.1 The margin of a gas-fired power plant

We assume that the margin M_t (in €$/MWh$) for a gas-fired power plant follows the Ornstein-Uhlenbeck mean-reverting stochastic process. This model allows margin to take on negative and positive values depending on the prevailing conditions:

$$dM_t = k_M(M_e - M_t)dt + \sigma_M dW_t^M,$$

where M_t is the value of the margin at time t, M_e is the value that the margin tends to in the long-term and k_M is the speed of reversion to this value. Besides, σ_M is the instantaneous volatility of the margin and dW_t^M stands for the increment to a standard Wiener process. From this model it is easily deducted that the time-t expected value is given by:

$$E(M_t) = M_0 e^{-k_M t} + M_e(1 - e^{-k_M t}).$$

For high values of k_M the model provides values that are close to the long-term value. This also happens for values more distant in time, since $k_M t$ has a positive value. Hence, for these cases we get:

$$E(M_t) \simeq M_e.$$

The margin is computed as follows[2]:

$$M_t = S_t - \frac{G_t + 0.20196 A_t}{E_G},$$

[2] According to IPCC (2004) guidelines a representative gas-fired power plant has an emission factor of 56,1 kgCO2/GJ for a plant with 100% efficiency. In our case, and for an efficiency of 55%, the emission factor is equivalent to 0.20196 tonne of CO2/Mwh.

where S denotes electricity price (€/MWh), G is the price of natural gas (€/MWh), E_G is the net thermal efficiency of a gas plant, and A is the price of a EU emission allowance (€/tCO_2).

Estimation. In order to estimate the margin of gas-fired power plants, we use the sample data presented in Section 2.3. It contains observations for 180 weeks ranging between 05/14/2006 and 10/18/2009. We use the following OLS regression model to estimate the parameter M_e:

$$M_{t+\Delta t} = a_M + b_M M_t + \varepsilon_{t+\Delta t}.$$

Hence we obtained:

Table 2. OLS estimates of the margin process.

	Estimate	Std. Error	t-statistic	$p-$value
$\widehat{a}_M$	5.6261	1.1458	4.9102	<0.00001
$\widehat{b}_M$	0.5772	0.0616	9.3668	<0.00001

With $\sigma_\epsilon = 11.0666$ the estimate for M_e is:

$$\widehat{M}_e = \frac{\widehat{a}_M}{1-\widehat{b}_M} = 13.30691$$

This value ($M_e = 13,31$) will be used as constant along the study. Additionally, we have obtained the value for the following parameters:

$$\widehat{k}_M = -\frac{\ln \widehat{b}_M}{\Delta t} = 28.6556,$$

$$\widehat{\sigma}_M = \sqrt{\frac{2(\sigma_\epsilon)^2 \ln \widehat{b}_M}{\Delta t[\widehat{b}_M^2 - 1]}} = 102.5952.$$

Fig. 4 shows the partial autocorrelation function of the $M_e$weekly series. Only the first lag is significantly different from zero,which is compatible with an AR(1) process and suggests that the M_e series is stationary.

Finally, to justify the use of a constant margin in the long term for the gas-fired plant we use now the parameters in a Monte Carlo simulation with the following equation:

$$M_{t+\Delta t} = M_e(1 - e^{-k_M \Delta t}) + M_t e^{-k_M \Delta t} + \sigma_M \sqrt{\frac{1-e^{-2k_M \Delta t}}{2k_M}} \epsilon_t,$$

where ϵ_t is an standardized white noise. $M_0 = \widehat{M}_e = 13.30691$; $\widehat{k}_M = 28.6556$ and $\widehat{\sigma}_M = 102.5952$. We generate 40.000 simulations for a period of 10 years. We consider 10 steps per month which accounts for 1,200 steps per simulation. Results can be represented graphically and obtain the mean and standard deviation. As Figure 5 shows the average for M_e is 13.30691 with a standard deviation of 0.0977.

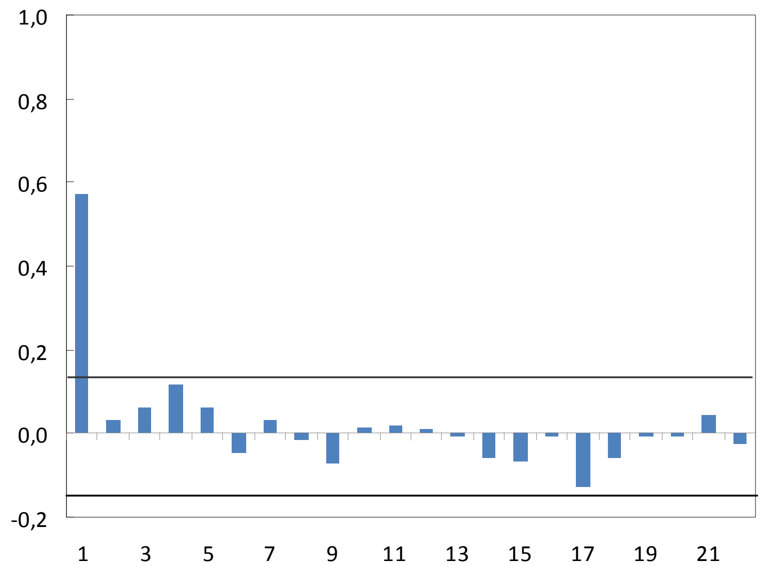

Figure 4: Partial autocorrelation function of M_e.

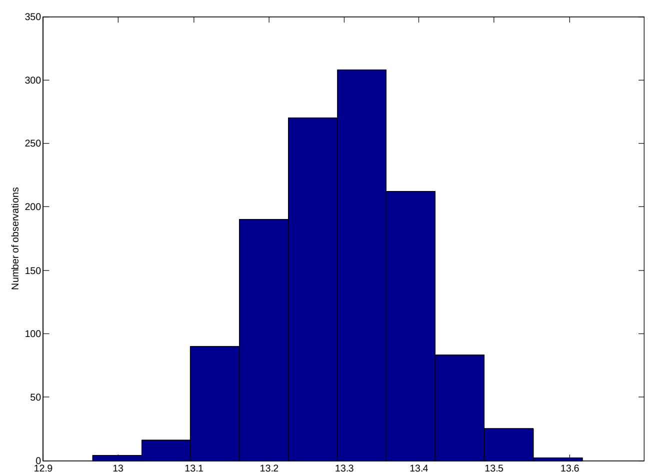

Figure 5: Histogram for M from Monte Carlo simulation.

3.2 Stochastic Models for natural gas, coal, and carbon

We specify the long-term prices as mean-reverting stochastic processes described by the following system of differential equations in a risk-neutral world:

$$\begin{aligned} dG_t &= df(t) + [k_G(G_m - (G_t - f(t))) - \lambda_G(G_t - f(t))]dt + \sigma_G(G_t - f(t))dW_t^G = \\ &= df(t) + [k_G G_m - (k_G + \lambda_G)(G_t - f(t))]dt + \sigma_G(G_t - f(t))dW_t^G, \end{aligned}$$

$$dC_t = [k_C(C_m - C_t) - \lambda_C C_t]dt + \sigma_C C_t dW_t^C,$$

$$dA_t = (\alpha - \lambda_A)A_t dt + \sigma_A A_t dW_t^A,$$

with:

$$dW_t^G dW_t^C = \rho_{GC}dt \ ; \ dW_t^G dW_t^A = \rho_{GA}dt \ ; \ dW_t^C dW_t^A = \rho_{CA}dt.$$

Regarding notation, G_t , C_t and A_t are the price at time t of natural gas, coal and carbon. G_m and C_m are the levels to which deseasonalized natural gas and coal prices tend in the long run. $f(t)$ is a deterministic function that captures the effect of seasonality in natural gas prices. This function is defined as follows $f(t) = \gamma \cos(2\pi(t + \varphi))$, where the time t is measured in years and the angle in radians; when $f(t = -\varphi)$=γ the seasonal maximum value is reached. k_G and k_C are the speed of reversion towards the "normal" level of gas and coal. They can be computed as $k_G = \ln 2/t_{1/2}^G$, where $t_{1/2}^G$ is the expected half-life for natural gas deseasonalized, i.e. the time required for the gap between $G_0 - f(0)$ and G_m to halve; similarly $k_C = \ln 2/t_{1/2}^C$. α is the drift rate of carbon price. σ_G , σ_C and σ_A are the instantaneous volatility of natural gas, coal and carbon, which determines the variances at t of G_t, C_t and A_t. λ_G, λ_C and λ_A are the risk premium for gas, coal and carbon. dW_t^G, dW_t^C and dW_t^A are the increments to a standard Wiener process. They are normally distributed with mean zero and variance dt.

The time-0 expected value of gas price at time t, or equivalently the futures price of natural gas for delivery at t, is:

$$F(G_0, t) = E(G_t) = f(t) + \frac{k_G G_m}{k_G + \lambda_G}[1 - e^{-(k_G+\lambda_G)t}] + (G_0 - f(0))e^{-(k_G+\lambda_G)t}.$$

In this case, $F(G_0, \infty) - f(\infty) = k_G G_m/(k_G + \lambda_G)$.

In the case of a commodity that is traded for a period, e.g., when an amount of natural gas equivalent to 1 MWh is delivered every hour over a month, we can compute

$$
\begin{aligned}
F(G_0,\tau_2,\tau_1) &= \frac{1}{\tau_2-\tau_1}\int_{\tau_1}^{\tau_2} f(t)dt + \frac{1}{\tau_2-\tau_1}\int_{\tau_1}^{\tau_2}[E(G_t)-f(t)]dt = \\
&= \frac{1}{2\pi}\frac{1}{\tau_2-\tau_1}\gamma[\sin(2\pi(\tau_2+\varphi)) - \sin(2\pi(\tau_1+\varphi))] + \\
&\quad + \frac{k_G G_m}{k_G+\lambda_G} + \frac{1}{\tau_2-\tau_1}\frac{(G_0-f(0)) - \frac{k_G G_m}{k_G+\lambda_G}}{k_G+\lambda_G}\left[e^{-(k_G+\lambda_G)\tau_1} - e^{-(k_G+\lambda_G)\tau_2}\right].
\end{aligned}
$$

The same equation applies for the case of coal, but without seasonality:

$$
\begin{aligned}
F(C_0,\tau_2,\tau_1) &= \frac{1}{\tau_2-\tau_1}\int_{\tau_1}^{\tau_2} E(C_t)dt = \\
&= \frac{k_C C_m}{k_C+\lambda_C} + \frac{1}{\tau_2-\tau_1}\frac{C_0 - \frac{k_C C_m}{k_C+\lambda_C}}{k_C+\lambda_C}\left[e^{-(k_C+\lambda_C)\tau_1} - e^{-(k_G+\lambda_G)\tau_2}\right].
\end{aligned}
$$

Concerning the price of the emission allowance we adopt a GMB process. The expression for the futures price is a particular case of that used for the fuel commodity, specifically:

$$F(A_0,t) = E(A_t) = A_0 e^{(\alpha-\lambda_A)t}.$$

3.3 Estimation

We estimate the parameters in the three stochastic models using daily prices and non-linear least-squares. The sample period stretches from 01/02/2009 to 11/27/2009, i.e., 231 days. The data available on each day include futures prices of contracts with monthly, quarterly, seasonal[3] and yearly maturities.

In Table 3 we show the results from this estimation. The second column present the estimated value and the third a confidence interval of 95%.

Table 3:

Parameter	Value	Interval 95%	
$C_m^* = \frac{k_C C_m}{k_C+\lambda_C}$	105.27	101.57	108.96
$k_C+\lambda_C$	0.69	0.58	0.79
$G_m^* = \frac{k_G G_m}{k_G+\lambda_G}$	25.04	24.04	26.04
$k_G+\lambda_G$	0.85	0.65	1.05
φ (days)	-21.7	-33.20	-10.24
γ	3.29	2.64	3.93
$\alpha^* \equiv \alpha - \lambda_A$	0.054	0.048	0.061
σ_A	0.4879		

[3] The seasonal natural gas futures prices include two semester seasons: April-September and October-March.

To estimate the correlations we use the spot prices of coal, natural gas and emission allowance; in the case of natural gas spot prices are seasonally adjusted. Using the formulas for the behavior in the real (not risk-adjusted) world:

$$\frac{d(G_t - f(t))}{G_t - f(t)} = \frac{k_G G_m}{G_t - f(t)} dt - k_G dt + \sigma_G dW_t^G,$$

$$\frac{dC_t}{C_t} = \frac{k_C C_m}{C_t} dt - k_C dt + \sigma_C dW_t^C,$$

$$\frac{dA_t}{A_t} = \alpha dt + \sigma_A dW_t^C.$$

After discretization these formulas the residuals from regressions allow us to calculate the corresponding correlations:

$$\rho_{GC} = 0.2652 \; ; \; \rho_{GA} = 0.2572 \; ; \; \rho_{CA} = 0.2797.$$

On the other hand, the risk-free interest rate is taken to be $r = 3.22\%$.[4] As the ARA coal is traded in US dollars per tonne, it is also necessary to transform the price with the exchange rate. The exchange rate used is $c = 1.4934.\$/\text{Euro}$ (the rate on 11/27/2009, where the interest rates of the euro and U.S. dollar to 15 years were at similar levels).

3.4 The margin of a coal-fired power plant

The profit margin of a coal station depends on the price of electricity, which we consider to be tied in the long term to the price of gas and emission allowance. Electricity price is determined by the following equation:

$$S_t = M_e + \frac{G_t + 0.20196 A_t}{E_G}.$$

Therefore, the margin MC for a coal plant (€$/MWh$) is:[5]

$$MC_t = M_e + \frac{G_t + 0.20196 A_t}{E_G} - \frac{C_t + 0.34056 A_t}{E_C},$$

which is equivalent to

$$MC_t = M_e + (\frac{G_t}{E_G} - \frac{C_t}{E_C}) + (\frac{0.20196 A_t}{E_G} - \frac{0.34056 A_t}{E_C}).$$

[4] This corresponds to the rate of the German public debt in November 2009.

[5] In the case of coal-fired plant that use bituminous coal the emission factor considered if 94.6 $Kg\ CO_2/GJ$ or 0.3456 $tonnes\ CO_2/Mwh$.

As a result, the margin at time t is a function of the three stochastic variables: the gas price, G_t, the coal price, C_t,[6] and the emission allowance price, A_t, alongside the efficiency parameters for coal E_C and gas-fired power plants E_G.

At one level, the second term of the equation is positive (as the price gap between gas and coal is normally positive), although is effect main be reduced by the efficiency parameter:

$$\frac{G_t}{E_G} - \frac{C_t}{E_C}.$$

On the other hand, the third term of the equation is negative. The emission factor of a coal plant is greater which implies that more emissions allowance should be paid. Similarly, the lower the efficiency the greater the cost in terms of emissions:

$$\frac{0.20196 A_t}{E_G} - \frac{0.34056 A_t}{E_C}.$$

Finally, when both price processes are expected to reach their long-term equilibrium levels we have:

$$\frac{G_m}{E_G} - \frac{C_m}{E_C}.$$

The evolution of the margins of the coal plants will be influenced by the evolution of the price of emission allowances. If they increase over time the margins will decline.

We choose a efficiency value for gas-fired plants $E_G = 0.55$ and $E_C = 0.30$ [7] for coal plants. An efficiency of 30% is a representative value for old coal plants, although the average value of the coal plant stock is around 40% (IPCC [16]). For a coal plant with $E_C = 0.30$ emissions are 1.135 tCO_2/MWh; for $E_C = 0.40$ the emissions are 0.851 tCO_2/MWh.

4 VALUING THE OPTION TO ABANDON

We assess the option to abandon an operating coal-fired power (in exchange for a salvage value) using a multidimensional lattice method[8]. The value of a coal plant as considered in our model depends, primarily, on three price processes. Two of them follow a mean-reverting process (gas and coal) whereas the other

[6] Firstly, we transform coal Ara from USD/tonne to EUR/tonne using 1.4934 USD/EUR as exchange rate. Secondly, we transform from EUR/tonne to EUR/Mwh using the the following factors: 29.31 GJ/tonne and 1 GJ=0.27777 Mwh. Therefore: $C_t(€/tonne)/29.31/0.2777 = C_t(€/Mwh)$

[7] Data from new stations suggest efficiency levels that are close to 40%.

[8] Solutions for multi-dimensional options must resort to numerical methods which fall within three main categories, namely: lattice methods, finite difference methods, and Monte Carlo simulation. Lattice methods are generally considered to be simpler, more flexible and, if dimensionality is not too large, more efficient than other methods.

one is governed by a standard GBM (emission allowances). The numerical estimates are used in a three-dimensional binomial lattice to assess the value of the option to abandon. The methodology is similar to that in Boyle et al. [6] and Gamba and Trigeorgis [9], but our procedure allows for mean-reverting stochastic processes (as opposed to standard GBMs) and can be used to value American-type options (as opposed to European-type options). More information of this approach can be found in Abadie et al.[3].

At time t, the option to abandon a coal-fired power plant will depend on gas G_t , coal C_t and emission allowance A_t price process. In the base case we assume a remaining life of 10 years. Assuming 12 steps per year ($\Delta t = 1/12$), the number of steps in the lattice are 120. Proceeding backwards through the lattice we get an amount which shows the value of the plant with its options[9]. At final time T we assume a remaining value for the plant (RV). At earlier times we choose the best of the following three options:

a) produce and continue:

$$P_M(MC_t - VC) - \frac{FC}{12} + e^{-r\Delta t}(p^*_{uuu}W^{+++} + p^*_{uud}W^{++-} + p^*_{udu}W^{+-+} + \\ + p^*_{udd}W^{+--} + p^*_{duu}W^{-++} + p^*_{dud}W^{-+-} + p^*_{ddu}W^{--+} + p^*_{ddd}W^{---}),$$

where VC (per MWh) is monthly variable cost (that included the fuel cost and the CO_2 emission allowance cost). FC is the fixed cost, computed monthly, that are also paid even if the plant is not producing.[10]

b) temporarily close down and wait:[11]

$$-\frac{FC}{12} + e^{-r\Delta t}(p^*_{uuu}W^{+++} + p^*_{uud}W^{++-} + p^*_{udu}W^{+-+} + p^*_{udd}W^{+--} + \\ + p^*_{duu}W^{-++} + p^*_{dud}W^{-+-} + p^*_{ddu}W^{--+} + p^*_{ddd}W^{---}).$$

c) abandon and obtain the remaining (salvage) value RV.[12]

Thus we obtain the value at the initial time (W_0). By fixing some parameters while changing another ones we can derive the optimal carbon prices for switching among states. The early exercise boundary is obtained when the value of the plant is equal to the residual value ($W_0 = RV$).

The parameter values adopted, based on IEA [10], Tester et al. [25], and U.S. DoE[13] are the following:

---

[9] We assume a 500 MW coal plant with a capacity factor of 80%. This accounts for a monthly production of $P_M = 292{,}000$ MWh when operating and zero otherwise.

[10] Both fixed and variable costs (FC, VC) are considered net of any potential subsidy. Public subsidies would alter the decision making process.

[11] We are assuming there are no cost associated to plant state changes, or that these costs are negligible.

[12] This residual value RV is considered net of abandonment costs (those of decommissioning and others).

[13] www.eia.doe.gov/oiaf/aeo/excel/aeo2010%20tab8%202.xls

- We assume a 500 MW coal plant with a capacity factor of 80%. This accounts for a monthly production of $P_M = 292,000$ MWh when operating (and zero otherwise).

- We assume a remaining value RV that is 25% of the investment in a new gas-fired plant[14]. The remaining value depends of numerous specific factors such as the value of land or some infrastructures associated. For an average cost of 1,111.5 M$ for a 500 MW gas station (IEA [14]) and exchange rate 1.4943 $/€. The RV is 186.1 M€; its relevance is limited as this value is obtained in any case at the end of the life of the facility.

- O&M fixed cost are 28.15 $/kW. This is equivalent to 785,400 € per month.

- O&M variable cost are 4.69 $/MWh. This is equivalent to 3,14 €/MWh.

5 RESULTS

This section presents the results from the data and price models. To explore the future of coal-fired power plants in more detail we study different possibilities for the main parameters considered in the base case. We focus on the impact of different relevant variables, such as allowance prices, allowance volatility, the coal and gas prices, the efficiency of coal-fired plants and their remaining value and remaining life. Finally, we also study the impact of a situation where the possibility of a coal-fired plant operating as a peak time plant is not available.

5.1 Results in the base case

Table 4 shows the total value of the coal-fired plant considered for different CO_2 prices. The second column shows the total present value (in M€) for a plant with a remaining lifetime of 10 years. The third column shows the total present value of a plant with 5 years remaining. The last column represents the residual value. In the base case we assume a remaining value of 25% of the initial investment in a gas plant. This value is therefore constant for all the price scenarios.

A coal-fired plant with 5 years of useful lifetime remaining, as shown in the third column, would need to face CO_2 prices of €80-90/tCO_2 in order to decide to switch from operating to closing. The precise breakpoint price is €83.2/tCO_2. Above this price the value of the plant if it continues in operation is exceeded by its salvage value if it is abandoned. Since optimal management is required for maximizing the plant value, above the trigger carbon price the option to abandon will be exercised, in which case the plant will be worth 186.1 M€; thus

[14] We assume that part of the initial investment can be used again, for instance the plot of land.

keeping the plant alive is no longer optimal. In the case of an operating coal-fired plant with 10 years ahead (base case) the chances for closing are tighter; CO_2 prices would have to reach €162.40/tCO_2 to make the switch worthwhile.

Figure 6 shows this result. The blue and red lines, respectively, show the value of operating plants with remaining lifetimes of 5 and 10 years for different CO_2 prices. The green line shows the residual value. Since operating a plant is a right, not an obligation, its value cannot be lower than the abandonment value. As can be seen, for low CO_2 prices, the best decision is to operate, and for higher prices the values start to converge to the residual value. When the blue and red lines merge with the green line keeping the plant operative is no longer a rational decision.

These base case results show that a very restrictive situation is necessary before coal-fired power plants are abandoned for other alternatives. For 10 years of remaining lifetime the CO_2 price needed for this to occur is almost ten times the average value of CO_2 on the ETS market. However, an interesting point shown in Figure 6 is that when a coal-fired plant gets older the value of operating decreases, i.e. the blue and red lines move down leftward. Therefore, although CO_2 prices alone are very unlikely to make a plant close they can certainly bring forward this decision.

Table 4. Value of the option to operate or abandon (M€).

A_t (€/tCO_2)	Operate (RL =10y)	Operate (RL =5y)	Residual Value
10	574.2	356.0	186.1
20	451.9	287.4	186.1
30	375.2	246.5	186.1
40	323.8	221.1	186.1
50	287.5	205.1	186.1
60	261.3	195.2	186.1
70	241.8	189.4	186.1
80	227.1	186.6	186.1
90	215.9	186.1	186.1
100	207.4	186.1	186.1
110	200.8	186.1	186.1
120	195.9	186.1	186.1
130	192.2	186.1	186.1
140	189.5	186.1	186.1
150	187.8	186.1	186.1
160	186.6	186.1	186.1
170	186.1	186.1	186.1
180	186.1	186.1	186.1
190	186.1	186.1	186.1

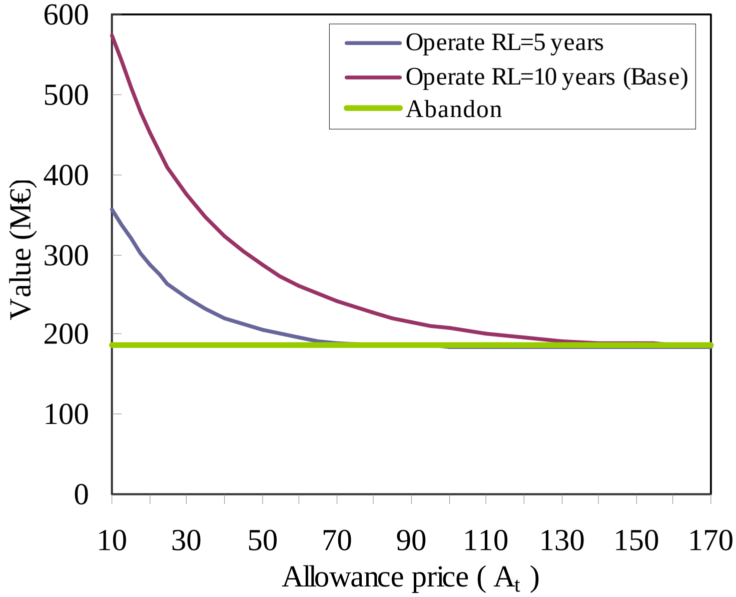

Figure 6: Value of the option to operate or abandon as a function of the allowance price (A_t).

5.2 Sensitivity analysis

5.2.1 Sensitivity to changes in allowance price

CO_2 prices have been very volatile over the first five years of functioning of the Emissions Trading Scheme (EU ETS) in Europe. In Phase I (2005-2007) the CO_2 futures prices for 2007 delivery ranged between almost €0 and €30 per ton of CO_2 just in the twelve months from May 2006 to May 2007. So far, in Phase II (2008-2012) allowance future prices have been relatively more stable, but they still ranged between €15 and €25 per ton. Upon the economic recession prices have dropped between €10 and €18 per ton from January 2009 to October 2009.

In this section we analyze the effect of CO_2 price volatility together with the remaining life (RL) of the plant. Given the past trend, the figure for volatility of CO_2 prices used in this study in the base case scenario can be considered as an upper value. As this could change in the future, so a sensitivity analysis of this parameter is vital.

Table 5 shows the effect of volatility. Each row represents the threshold CO_2 price at which it is worth exercising the option to abandon the plant. The columns represent three alternatives considered for the remaining lifetime of the plant: 5, 10 (the base case) and 15 years.

The result for a plant with a residual lifetime of 10 years shows that the higher the volatility is the higher the CO_2 price required to trigger the option to abandon the plant is. High volatility means that very high CO_2 prices are possible, but also very low ones. As coal-fired plants always have the possibility of producing or waiting for better conditions, high volatility negatively affects the abandonment option. coal-fire plants enjoy the benefits of producing when CO_2 prices are low, but when prices are high they can always decide to wait and assume only the fixed cost. For a volatility of 0.05 the price for plant with $RL = 5$ years abandonment would be €39.1/tCO_2. If volatility increases to 0.2 or to 0.5 the price also with $RL = 5$ increases to €44.4and €86.3/tCO_2, respectively.

This result is also sensitive to the remaining life (RL) parameter. The higher RL considered is, the higher the CO_2 required to trigger the option to abandon the plant is . A longer residual lifetime means more possibilities of obtaining profits through production. Again, under those circumstances when the conditions are not favorable the plant can simply wait. Since residual value is considered as fixed and proportional to the initial investment in the plant, it is obvious that a longer RL means more value in the option to continue.

Figure 7 shows this trend. The top left part of each line represents the abandonment option and the bottom right part the operation region. The line represents exactly the threshold between the two options for the three alternative RLs. The effect of RL is not to be very great for low volatility levels but when volatility increases the difference is not negligible. For a volatility of 0.3 the optimal price of CO_2 is €52.7/tCO_2 for 5 years, €73.8/tCO_2 for 10 years and €88.5/tCO_2 for 15 years.

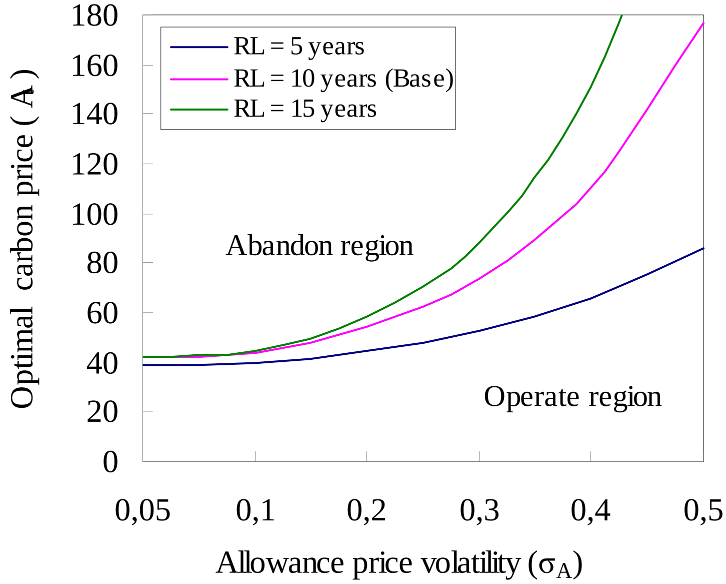

Figure 7: Threshold allowance price (A_t) for different residual life (RL) as a function of allowance price volatility (σ_A).

Table 5. Sensitivity to changes in allowance volatility ($\alpha^* = 0.054$).			
σ_A	RL =5y	RL =10y	RL =15y
0.05	39.1	41.8	42.0
0.1	40.0	43.9	44.6
0.2	44.4	54.1	58.6
0.3	52.7	73.8	88.5
0.4	66.0	109.9	151.2
0.5	86.3	176.5	270.5

We can also analyze the effect of a change in the parameter referring to an increase in the slope $\alpha^* \equiv \alpha - \lambda_A$ of price in the futures markets, in the context of the allowance price, and separately from volatility. Table 6 shows the results for the base case parameter and expected growth rates of 10 and 20 percent for the case of a coal-fired plant with an RL of 5 years. The results show that the expectation of higher allowance prices in the future means a lower price of CO_2 for triggering abandonment. Therefore, as Figure 8 suggests, for a 20% growth in expected price and volatility below 0.3, prices of around 30 €/t$CO_2$are enough to trigger abandonment of plants.

Finally, as we have seen, high volatility in CO_2 prices significantly delays the abandonment of coal and, therefore, the possibilities of encouraging other investments in low-carbon technologies. Hopefully, a regime with more predictable

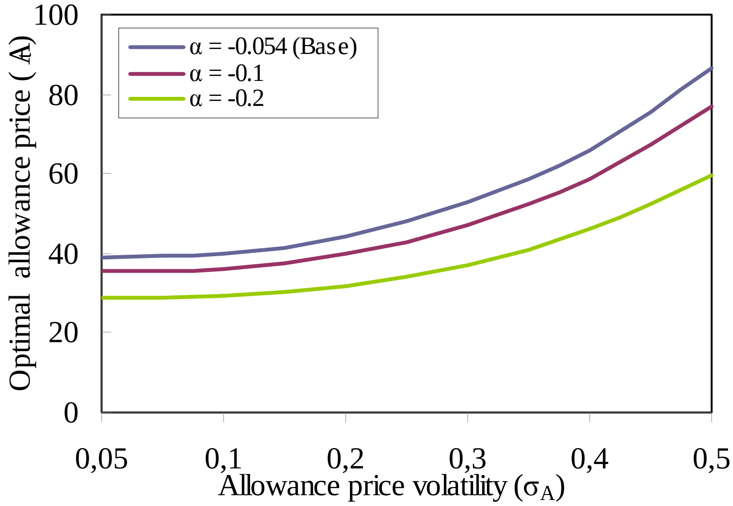

Figure 8: Threshold of allowance price (A_t) for different drif rates (α^*) as a function of allowance price volatility (σ_A).

carbon prices is possible (for example including a safety-valve mechanism in the ETS that includes both a floor and a ceiling on CO_2 prices), so that volatility can be reduced considerably. This is not the case for volatility in energy inputs, as coal and gas depend on more globally integrated energy markets. This is the next sensitivity analysis to be carried out.

Table 6. Sensitivity to changes in volatility and drift rates ($RL = 5$ year).

σ_C	$\alpha - \lambda_A$ =0.054	$\alpha - \lambda_A = 0.1$	$\alpha - \lambda_A = 0.2$
0.05	39,1	35.5	28.8
0.1	40.0	35.9	29.3
0.2	44.4	39.8	31.7
0.3	52.7	47.2	37.2
0.4	66.0	58.7	46.0
0.5	86.3	76.8	59.8

5.2.2 Sensitivity to changes in long-term prices of coal and gas

This section analyses the effect on the decision to operate coal-fired plants of different coal prices and different gas prices. The results of this sensitivity analysis appear in Table 7 and Figure 9.

Each row in Table 7 represents the threshold CO_2 price for exercising the option to abandon for long-term futures coal prices $C_m^* = k_C C_m/(k_C + \lambda_C)$

$/tcoal increasing from 100 (units) to 150. The columns represent the two alternatives considered for long-term deseasonalized futures gas prices $G_m^* = k_G G_m/(k_G + \lambda_G)$ €/MWh: 25.04 (base case) and 20. These two alternatives are represented in Figure 9 by red and blue lines respectively. The result for the base case shows that as the price of coal increases the CO_2 price needed to trigger the option to abandon drops. For a coal price of 100 $/tonne the CO_2 price for making the switch effective is €176.8/tCO_2. When it increases to 120 $/tonne the threshold price decreases to €138/tCO_2 and when it reaches 150 the latter price drops to €91/tCO_2. This trend is shown in Figure 9, where this time the right-hand parts of the lines represent the abandonment region and the left-hand part represent the operation region.

From the table and the figure the great impact of variation in gas prices is also very clear. If the price of gas decreases it is more likely that coal-fired plants will be abandoned, as the threshold price of CO_2 moves down. This impact can be shown by the gap between the red and blue lines.

Conversely, only very high CO_2 prices could offset an increase in gas prices. In fact, for a coal price of 100 $/tonne an increase in gas prices from 20 €/MWh (base case) to 25.04 causes the optimal price of CO_2 to rocket from €95.6/tCO_2 to €176.8/tCO_2. This means that a 25% increase in the price of gas needs an increase of 85% in the price of CO_2.

Table 7. Sensitivity to changes in long-term coal and gas prices.

C_m^*	G_m^*=20	G_m^*=25.05
100	95.6	176.8
110	81.0	156.3
120	67.9	138.0
130	56.6	120.9
140	46.4	105.3
150	37.9	91.6

5.3 Sensitivity to changes in useful life and residual value of the coal plant

The decision whether to abandon a coal-fired plant in operation is also affected by the remaining life of the plant. In this section we analyze the effect of this variable together with the residual value.

The results appear in Table 8. Each row represents the threshold CO_2 price for triggering the option to abandon the plant for different remaining useful lifetimes ranging from 1 to 10 years. The columns represent three alternatives considered for the residual value of the plant: 0%, 25% (the base case) and 50% of the investment cost. In the first alternative we are assuming that there is no inherent value in the plant to be recovered and, therefore, the value of the option to abandon is zero. In this case the abandonment option would be chosen only if the present value of continuing in operation is negative.

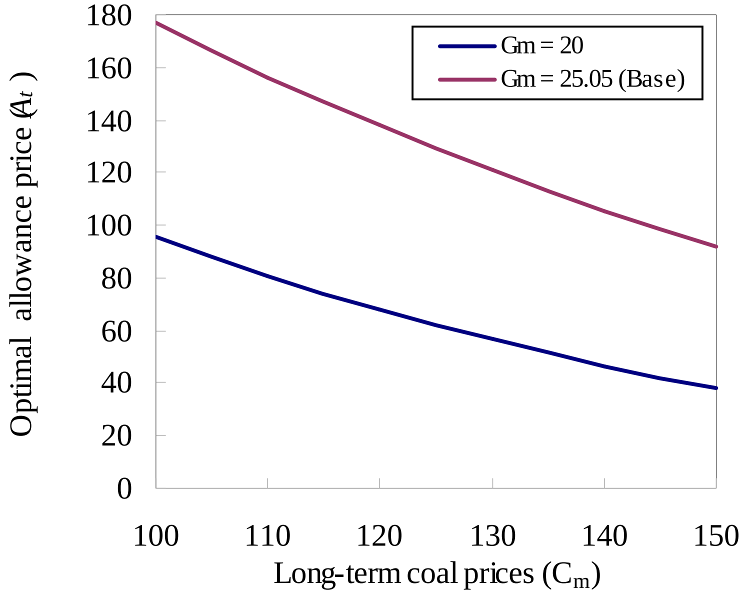

Figure 9: Threshold allowance price (A_t) for different long-term gas prices (G_m^*) as a function of long-term coal prices (C_m^*).

The result for an RV of 25% shows clearly that the closer a coal plant gets to the end of its useful lifetime, the lower the price of CO_2 needs to be to trigger the option to abandon. For a coal-fired plant with a ten year useful lifetime the price needs to be €162.4/tCO_2. However, as the number of years decreases the optimal price also starts decreasing. In fact, for plants with less than 3 years of remaining lifetime a price of less than €50/tCO_2 suffices to trigger abandonment.

This result is also sensitive to the RV parameter. The higher the residual value is considered to be, the lower the CO_2 price required to trigger abandonment of a plant. In the case of a power plant with an RV of 50% a price of €50/tCO_2 suffices to trigger the closure of those power plants with less than 4 years of life remaining. However, if the RV is 0%, at this price only plants with less than 2 years remaining will be closed.

Figure 10 clearly shows this trend. The left-hand part of each line is the abandonment region and the right-hand part the operation region. The line represents exactly the threshold between the two options for all three alternative RVs.

This result can also be connected with Figure 6. An increase in residual value means moving the green constant line up from the zero level when the residual value is 0%. The higher this line goes, the lower the price of CO_2 needs to be for abandonment to be considered.

Table 8. Sensitivity to changes in useful life and residual value.

RL (y)	$RV = 0$ %	$RV = 25\%$	$RV = 50\%$
1	19.2	13.9	10.3
2	47.2	32.6	23.8
3	72.9	50.7	37.6
4	98.1	67.4	49.9
5	122.7	83.2	61.3
6	149.7	100.9	72.1
7	177.1	115.2	82.7
8	205.7	131.6	93.6
9	232.3	147.3	104.3
10	260.2	162.4	115.6

5.3.1 Sensitivity to changes in the plant's thermal efficiency

All the results obtained in the sensitivity analysis point in the same direction: it is very unlikely for a base case coal-fired plant to be abandoned due to CO_2 prices. Only those plants that have less than five years of RL and operate in a context of low volatility are candidates for this choice. In this section we add another important factor: the effect of the plant's thermal efficiency.

Table 9 shows the effect of thermal efficiency in the oldest coal-fired power plants, those with 5 year RLs. Each row represents the threshold CO_2 price for triggering the option to abandon for efficiency levels ranging from 25 to

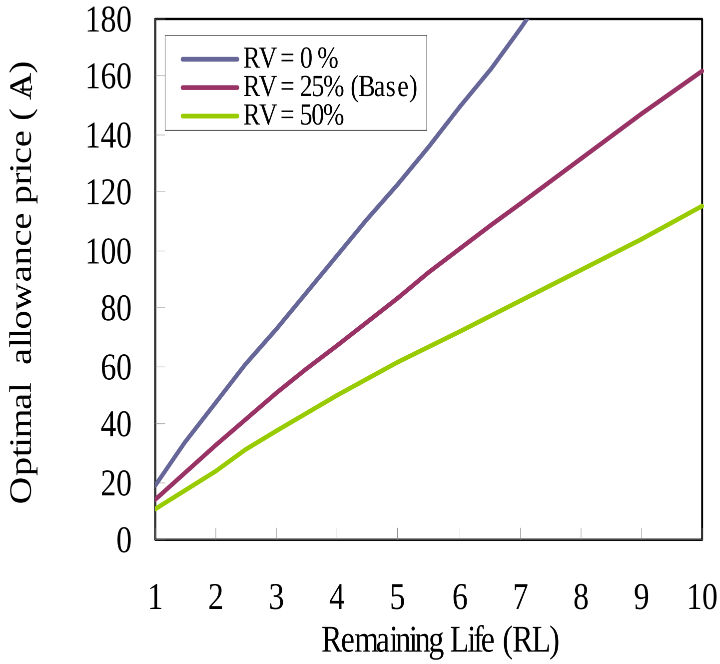

Figure 10: Threshold allowance price (A_t) for different residual value (RV) as a function of remaining life (RL).

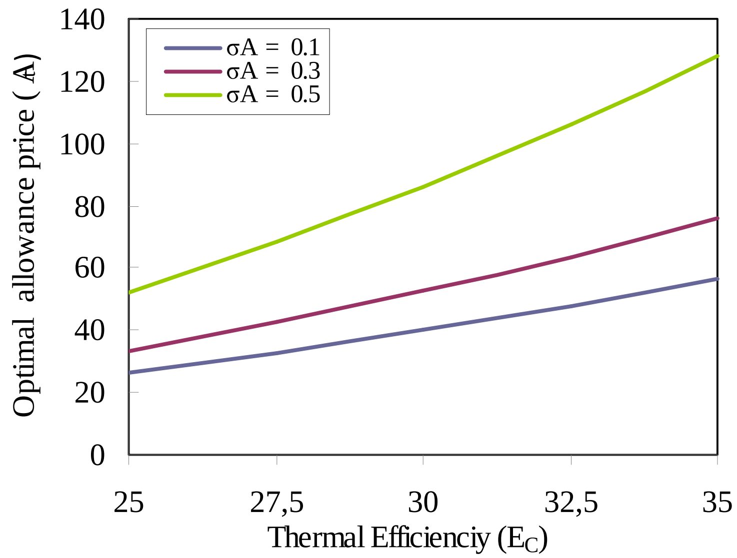

Figure 11: Threshold allowance price (A_t) for different allowance price volatility (σ_A) as a function of thermal efficiency (E_C).

35%. The columns represent three alternatives considered for the volatility of the plant: 0.1, 0.3 and 0.5.

The results show clearly that the more efficient the plant the higher the price of CO_2 needs to be to trigger the option to abandon. For a volatility σ_A =0.3 and efficiency $E_C = 30\%$ the price needs to be 52.7 €/tCO_2. However, as efficiency decreases to 25% this price falls to 33.4 €/tCO_2. With volatility of less than 0.1 the optimal price decreases from 56.2 €/tCO_2 for an efficiency of 35% to 26.2 €/tCO_2 for an efficiency of 25%. This trend can be seen in Figure 11.

Table 9. Sensitivity to changes in thermal efficiency and allowance price volatility (RL = 5y).

E_C (%)	$\sigma_A = 0.1$	$\sigma_A = 0.3$	σ_A= 0.5
25	26.2	33.4	52.3
27,5	32.8	42.6	68.5
30	39.9	52.7	86.3
32,5	47.5	63.6	106.1
35	56.2	75.8	128.1

5.4 Results for the case of no flexibility

The above sections analyze the circumstances under which coal-fired plants would opt-out. Results and sensitivity analyses show that this option is very hard to trigger and in fact would only be exercised in the case of high CO_2 prices and low volatility. One of the reasons behind this result is that coal-fired plants can always decide to work as peaking plants. These are power plants that generally run only when there is a high demand for electricity. Although peaking plants are generally gas turbines, an increase in the price of CO_2 could displace some coal-fired plants to operate when the conditions are favorable and remain inactive when they are not. The option to operate as a peaking plant may be worth more than the option to abandon a plant. In our case, decisions are taken on a monthly basis (not daily), so the term "peaking" must not be interpreted *strictu sensu*. Instead, what we mean is that these plants can operate occasionally under the right circumstances.

In this section we measure how the optimal decisions change when the flexibility of operating as a peaking unit is not available and plants must decide between producing all the time (base load plants) and abandonment.

Table 10 shows the results for a plant with a 10 year RL. The first column shows the total present value (in M€) for a plant with no flexibility. The second column shows the total present value of a plant with the possibility of waiting. The third column shows the total present value of the plant if it is abandoned.

As shown in the second column and explained in Section 5.1., CO_2 prices would have to reach 162.40 €/tCO_2 to trigger the switch from operating to closing. Below this price the value of continuing to operate is lower than the value of the plant if abandoned. However, when flexibility is not available the breakpoint is much lower and CO_2 prices of between 40 and 50 €/tCO_2 suffice to trigger the switch (the exact break point is 45.6 €/tCO_2). Figure 12 shows this result. The blue and red lines, respectively, show the values of operating a plant with and without flexibility for different CO_2 prices, and the green line shows the value of the option to abandon the plant. comparing the first and second columns provides an indication of the value of flexibility. As long as this flexibility exists in the market, the abandonment of coal-fired plants is very unlikely even in a strong carbon-constrained situation.

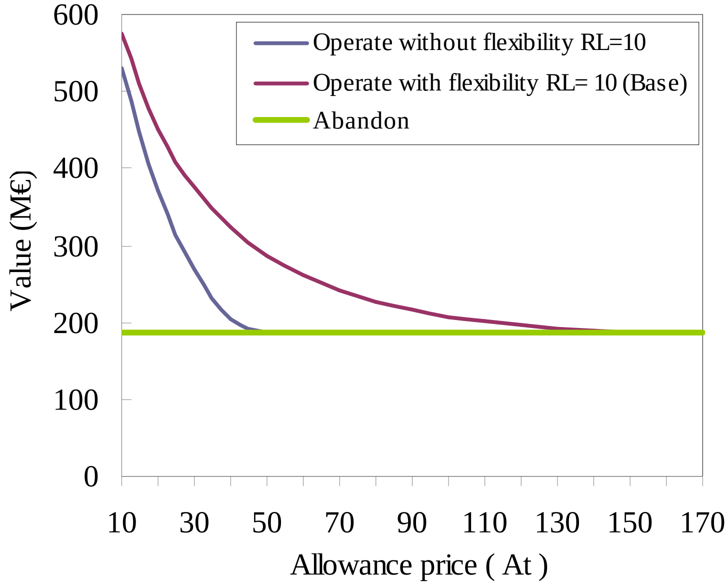

Figure 12: Value of the option to operate with and without flexibility and to abandon as a function of the allowance price (A_t).

Table 10. Value of the option to operate (RL =10) or abandon (Million €).

A_t	Rigid Operation	Flexible Operation	Residual Value
10	530.7	574.2	186.1
20	369.9	451.9	186.1
30	263.7	375.2	186.1
40	203.1	323.8	186.1
50	186.1	287.5	186.1
60	186.1	261.3	186.1
70	186.1	241.8	186.1
80	186.1	227.1	186.1
90	186.1	215.9	186.1
100	186.1	207.4	186.1
110	186.1	200.8	186.1
120	186.1	195.9	186.1
130	186.1	192.2	186.1
140	186.1	189.5	186.1
150	186.1	187.8	186.1
160	186.1	186.6	186.1
170	186.1	186.1	186.1

6 CONCLUDING REMARKS

Climate policy is altering the role of coal-fired power plants in the developed world. Rising prices for carbon emissions will increase the risk associated to this technology if compared to other options such as gas, nuclear or renewable. In fact, although many utilities are not facing climate policy, the prospect of higher CO_2 prices and environmental regulations is already altering utilities' decisions. Many projects for building new coal-fired power plants in the US and the EU have been cancelled or delayed, even though electricity consumption has steadily been growing. CCS technology could be a solution for this dilemma, by setting a maximum price on coal-based electricity, but still needs to be developed. In an optimist case CCS could be ready at commercial scale by 2020-2030 with a cost per kW 32-62% higher if compared with the traditional pulverized coal power plant. Therefore, there could be a period where the coal-fired plants would have to face (presumably) high CO_2 prices which will erode its profitability. This situation could be harder for those coal-fired plants that are older and less efficient. In the US around 75% of the total installed coal-fired capacity consists of plants older than 35 years and in Europe 25% of the total stock have more than 25 years.

To date, several papers have analyzed the prospects for coal in a carbon-constrained situation, using different approaches and techniques. This paper analyzes the conditions under which a coal-fired station that is currently operating could decide to abandon the plant and obtain its rescue value. We assess this question from the viewpoint of a firm following a real options approach. We consider a coal-fired power plant that operates under restrictions on carbon dioxide emissions in an electricity market where gas-fired plants are the marginal units that set the price of electricity. We consider three sources of uncertainty or stochastic variables: the coal price, the gas price and the emission allowance price. The underlying parameters are derived from futures markets and are used in a three-dimensional binomial lattice to assess the value of the option to abandon.

Our results show that the conditions that have to be satisfied to abandon an operational coal-fired plant are very hard to be met. Given the actual trends in prices a coal-fired plant with 5-10 years of useful lifetime remaining would need to face CO_2 prices between 83.2-162.40 €/tCO_2 in order to decide to switch from operating to closing. CO_2 prices alone are very improbable to make a plant close as coal-fired plants. However, as the value of operating decreases when the plant gets older, it can bring forward this decision.

The sensitivity analysis conducted shows also the impact of different key variables, such as coal, gas and CO_2 allowance prices, the efficiency of coal-fired plants or their residual (salvage) value and remaining life. One of the relevant factors is the volatility of CO_2 allowances prices. Allowance volatility has been very high in the past and reducing this uncertainty would be determinant. After all, this is a variable that reasonably can be reasonably kept under control with the correct policy measures, such as introducing a floor/ceiling in the CO_2 market or using a tax instrument.

Finally, these quantitative results show that although it seems very unlikely that new coal-fired power plants will be built in the future in developed countries, the existing ones will opt (if they can) to work as peaking plants and run only when the conditions are favorable. This situation could displace the merit order in some liberalized electricity markets.

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