Clean Energy or Polluting Energy? A Real Options Approach to Investment in the Power Sector

By
Artem Dzyuba

Thesis submitted to Central European University
Department of Economics

In partial fulfilment of the requirements for the degree of Master of Arts

Supervisor: Professor Andrzej Baniak

Budapest, Hungary
2007

Abstract

In modern Europe traditional energy producers must cover emission of carbon dioxide with emission allowances, which are traded on carbon markets. I examine a problem of investment in a power plant when the price of CO_2 emission allowances evolves stochastically. Three exclusive projects are available: coal-fired (severe polluter), gas-fired (moderate polluter) and wind (pollution free) power plants. I apply a real options approach to find out how a stochastic environment affects decision making under low and high gas prices. In the first scenario it is shown that under highly volatile CO_2 price a phenomenon of project domination may arise: the moderate polluter becomes completely unattractive. However, if a gas-fired power plant is flexible enough then it is always worth considering as an option. I also study more realistic case when gas prices are high and gas projects have no value compared to coal or wind ones.

Keywords: real options, energy economics, renewables, fossil-fuel power plants, project domination.

Acknowledgements

I wish to thank my parents who helped me to start and live this interesting life. My thanks also go to my supervisor Andrzej Baniak for his belief in my abilities and for his help. Also, I would like to thank Réka Futász who provided numerous useful comments on the text of my thesis. And of course, I am grateful to László Varró and Peter Simon Vargha for an extremely interesting research topic and their guidance.

Contents

List of Figures

1 Introduction

If a medieval feudal lord were given a chance to visit contemporary Europe, there would be at least one reason for him to smile in pleasure. He would see that he was absolutely right making his peasants pay taxes for the smoke from their chimneys. In the epoch of space flights and microbiology governments have come to the same idea as their historical colleagues centuries ago and started taking money for smoke.

Global warming concerns everybody living on the Earth. In the past decade Europe has undertaken important steps towards reduction of emission of greenhouse gases, which are responsible for global warming. The EU CO_2 Emission Trading Scheme, which commenced in January, 2005, defined emission caps for polluting industries. This scheme allocated among polluters free allowances to emit certain amount of carbon dioxide. When a pollution producer faces a shortage of free allowances, it must buy the necessary amount on the market of CO_2 emission allowances. The power generation sector takes 65% of total pollution output. With CO_2 emission being traded goods, investing in and running a fossil-fuel power station becomes a riskier and more unpredictable venture.

In the current thesis I investigate optimal investment rules in the energy sector. For that I consider three types of power generators that are different in their pollution activity. A coal-fired power plant (CPP) operates using cheap fuel, but it emits a lot of CO_2, which must be covered with allowances. An alternative might be a gas-fired power-plant (GPP), which pollutes less but requires expensive natural gas for operating. The study involves two extreme variants of GPPs. A base load GPP cannot be shut down when the income flow is negative since this action is too costly. A peak load GPP is absolutely flexible and might cease power generation at any time, instantly and at no cost. The list of available energy producers is concluded with a wind power plant, which provides very clean energy.

The model presented here makes several key assumptions. First, I assume uncertainty in the CO_2 price. To avoid very complicated mathematical issues, I do not consider any uncertainty beyond that. Second, the project investment is exclusive and irreversible. In other words, an investor may run only one power plant and cannot disinvest, should the expenses become unbearable. Third, the investor can postpone the investment until good times. As Dixit and Pindyck (1994) show in their seminal work, these conditions create value of waiting which can be expressed numerically. Following them, I apply a real options approach to find CO_2 price thresholds that trigger investment.

Investment in the energy sector has been widely studied in the literature, both with and without considering emission trading. Considerable efforts have been done towards studying investment in renewables and its interaction with conventional energy. For example, Fleten et al. (2005) consider investment in small-scale wind generators local needs. Energy surplus then can be sold to the grid. They study optimal timing and capacity under uncertainty of the electricity price.

In another work, Fletten and Näsäkkälä (2003) apply a real option approach to analyze investment in a gas-fired plant. This paper deals with stochastic spark spread, which is the cost of producing 1 MWh of energy out of gas. As in the present thesis, the authors investigate cases of both base and peak PP. They show that while an abandoning option is not valuable, the operation flexibility option cannot be neglected. They also incorporate constant penalty for the emission of greenhouse gases.

Furthermore, Neuhoff et al. (2006) consider investment in wind farms in the UK. They use specific econometrics methods to illustrate the effectiveness of wind power plants according to various historical data. Another interesting example is Murto and Nese (2002). In fact, my thesis is a further development of their ideas about decision making between generators with certain and uncertain costs. Murto and Nese consider investment in a peak GPP versus biofuel power plant which requires subsidies in order to be profitable. They find that there is a domain of the gas prices when investment in neither of projects is profitable enough and the investor decides to wait. However, the authors do not emphasize the role of CO_2 trading and do not involve a third project, as it is presented in the current thesis.

Studying investment in several projects, we cannot avoid issues of project domination. Project domination (more precisely, options domination) occurs when one set of options dominates another set thus making the latter not worth considering. The problem of project domination is a very recent issue. Dixit (1993) raises a simple question about multiple exclusive options and briefly outlines how to choose the right project. This result is opposed by Décamps et al.(2004), who point out quite tricky issues regarding critical thresholds. Dixit has not taken into account waiting areas which surround naive investment thresholds. However, the studied situations are relatively simple and domination rule is apparent there.

My study shows that under low enough CO_2 prices investing in a gas-fired PP may be appealing, especially when uncertainty is small. This sets two non-overlapping inaction intervals of price. Investment in either the coal or gas or wind project is the best step, should the price fall to the left, in between or to the right of these two intervals. When the price falls in any of them, it is better to wait. However, for a base load GPP, when volatility grows, the gas project becomes completely "out-of-money" compared to the coal and wind ones. In this case I say that the coal-wind project dominates the coal-gas-wind project. Peak GPP is flexible enough to always retain a non-empty investment region and coal domination does not happen under even high uncertainty. The thesis discusses interaction of the projects when a set of parameters changes: drift rate, volatility, price for gas and number of free allowances.

The rest of the paper is organized as follows. In Section 2 I first set up the model and define the relevant characteristics. Then options for the coal-wind and coal-gas-wind projects are studied. In the same section I introduce project domination. Section 3 illustrates the behavior of critical investment thresholds when model parameters change. Finally, Section 4 makes concluding remarks.

2 Model

2.1 Preliminaries

A conventional power station buys fuel and generates electricity which is sold to consumers. In my analysis, I consider three types of power plants: coal-fired (CPP), gas-fired (GPP) and wind (WPP) ones. A coal-fired PP is more expensive to build than a gas-fired one, but consumes much cheaper fuel. Another disadvantage is a higher level of pollution inflicted by a CPP. A wind farm has its fuel free of charge and pollution-free output, but it also comes at some cost. A unit capacity of a wind PP costs much and its average output efficiency is quite low.

In the current work I focus on the most simple and important characteristics of power stations. Most of them have flow nature, and only sunk cost is a stock parameter. Their full list is given below (signs in brackets show how transactions affect investor's welfare):

(+) Flow of income from generating electricity,

(—) Flow of the expenses of buying the fuel,

(—) Flow of the expenses of meeting carbon trade regulations,

(—) Other cost flow due to operating and maintenance cost,

(—) Instant (sunk) capital cost.

Current work studies investment in power generation under assumption of uncertainty in CO_2 emission cost. As for many other goods, the price for allowances to emit 1 ton of carbon dioxide evolves stochastically with time. Let us assume that the price for such an allowance follows the Geometric Brownian Motion. Leaving aside the precise language of stochastic differential equations, I adopt the widely used notation:

$$\frac{dp_{car}(t)}{p_{car}(t)} = \alpha dt + \sigma dz, \tag{1}$$

$$p_{car}(0) = \bar{p}_{car}.$$

where α is the drift rate of process, σ its volatility and dz the increment of a Wiener process. Equation (1) implies that p_{car} is distributed lognormally.

To simplify matters, I assume constant prices for electricity, coal and gas:

$$p_e = const, \quad p_c = const, \quad p_g = const.$$

We know that electricity trading is regulated by national governments thus I assume it constant. Also, bearing in mind that the carbon market is relatively new compared to "traditional" gas and coal markets with their developed long-term contracts, I set gas and coal prices constant and CO_2 price uncertain. Introducing at least one extra uncertainty results in very sophisticated mathematical issues which are out of paper's scope.

2.2 Values of Projects

Now let us turn to the investment project. We consider one unit project, i.e. that which has a capacity to produce 1 MWh of electricity. Note that the average output of a wind farm unit is given as $m \cdot 1$ MWh, where $m \approx 0.3$ due to volatile climate conditions. The basic time unit in our model is year and the power station life is assumed infinite. For the time being, conventional power plants in our model are base load, i.e. they operate even if the cost flow exceeds the revenue flow. Later I will drop the assumption about the inflexible regime of GPPs.

If $N = 8760$ is the number of hours in a year, then annual income flow has the form Np_e for a gas/coal PP and mNp_e for wind energy. Present value (PV) of income is

$$\int_0^\infty Np_e e^{-rt} dt = \frac{Np_e}{r} \qquad \left(\frac{mNp_e}{r} \text{ for wind} \right),$$

where r is the discount rate. In the risk-neutral world r is also a risk-free interest rate. We assume that $\alpha < r$ to avoid trivial cases.

Now let us turn to the expenses side. In exactly the same way we can write the PV of operating and fuel expenses:

$$\frac{N \cdot OC_i}{r} + \frac{Np_i}{\eta_i r},$$

where $i \in \{coal, gas\}$, OC_i operating cost and η_i thermal efficiency, share of fuel energy transformed into electricity.

CO_2 emission is another story. We should use the *expected* PV of its flow:

$$\mathbf{E}\int_0^\infty \left\{\frac{Nue_i p_{car}(t)}{\eta_i}\right\} e^{-rt}dt = \bar{p}_{car}\int_0^\infty \frac{Nue_i}{\eta_i}e^{-(r-\alpha)t}dt = \frac{Nue_i}{\eta_i\delta}\bar{p}_{car}.$$

Here:

i	Variable denoting source of energy (coal or gas)
u	Percentage of CO_2 which is **not** covered with free allowances
e_i	Emission factor, quantity (in tons) of CO_2
	per 1 MWh of burnt fuel
δ	So called convenience yield, $r-\alpha$ (greater than 0).

Once the investor decides to act, he pays the fixed cost $I_i, i \in \{gas, coal, wind\}$. Then we arrive to what is called then Net Present Value (NPV) of the project. For a coal/gas PP we have

$$NPV_i = \frac{Np_e}{r} - \frac{N\cdot OC_i}{r} - \frac{Np_i}{\eta_i r} - \frac{Nue_i}{\eta_i\delta}\bar{p}_{car} - I_i \tag{2}$$

and for the wind PP

$$NPV_w = \frac{mNp_e}{r} - \frac{N\cdot OC_w}{r} - I_w. \tag{3}$$

The reader might notice that in (2) and (3) we got linear functions with respect to p_{car}. For clear notation I drop the *car* index and rewrite (2):

$$NPV_i(p) = K_i - x_i p. \tag{4}$$

Now I construct the simplest approach to our problem. As the projects are exclusive, the investor should take the upper envelope of the three NPVs. Graphs shown in Figure 1 illustrate this rule. Note that the "gas" line might lie considerably below the "coal" line, so that the gas project will not matter. A naive NPV approach recommends to invest in that project for which NPV is the highest. However, this rule will mislead us, as it does not take into account the *future* evolution of the carbon dioxide price.

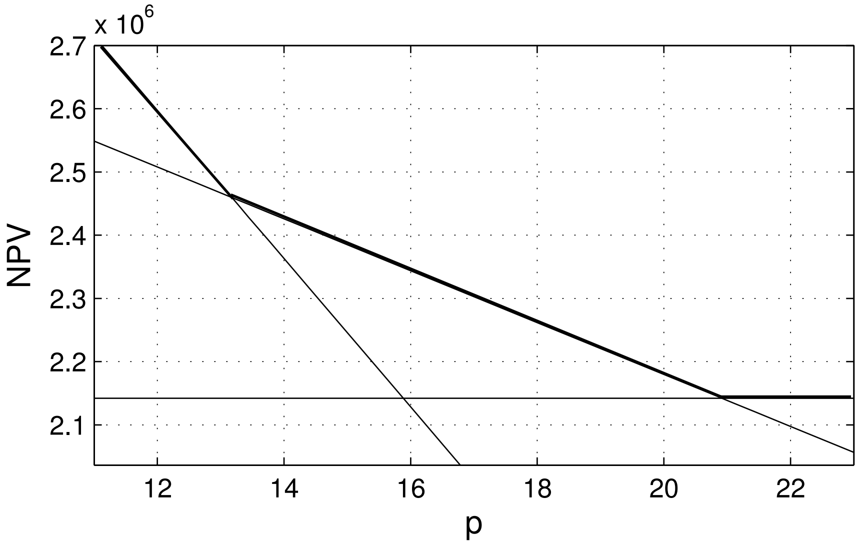

Figure 1: Net Present Values

2.3 Values of Options to Invest

2.3.1 Two projects

Knowing the NPV values enables us to derive the values of the options to invest in one of the projects. I start with a simple case, in which the investor faces only two projects at the same time. One of them uses conventional fuel and another is a unit of a wind farm.

Let $F_c(p)$ denote the value of the option to invest in a coal-fired PP or in a wind PP. Correspondingly, $F_g(p)$ stands for for the option to invest either in a gas-fired PP or in a wind PP. These functions satisfy a second order differential equation

$$\frac{1}{2}\sigma^2 p^2 F_i''(p) + \alpha p F_i'(p) - rF_i(p) = 0 \tag{5}$$

(see Dixit and Pindyck (1994) for derivations of the equation). The general solution to (5) is fairly simple and given by

$$A_i p^{\beta_1} + B_i p^{\beta_2}, \tag{6}$$

where degrees β_1 and β_2 can be found by putting (6) into (5) and solving a quadratic equation. We end up with

$$\beta_1 = \frac{1}{2} - \frac{r-\delta}{\sigma^2} + \sqrt{\left[(r-\delta)/\sigma^2 - \frac{1}{2}\right]^2 + 2r/\sigma^2} > 1, \tag{7}$$

$$\beta_2 = \frac{1}{2} - \frac{r-\delta}{\sigma^2} - \sqrt{\left[(r-\delta)/\sigma^2 - \frac{1}{2}\right]^2 + 2r/\sigma^2} < 0. \tag{8}$$

We have four unknown parameters out of which two were determined without almost any efforts. Let us turn to the coefficients. They can be determined because of the specific nature of real options. When the price of carbon dioxide is too small, the investor definitely tends to invest in conventional power. On the contrary, when emitting pollution is costly, investment in wind is more likely. In both cases the investor "kills" the option by exercising it. So in the "unsure" domain the option is "alive" and evolves according to (6). In all other situations the option is "dead" and its value coincides with the value of the chosen project.

Speaking more formally, there are two critical prices for each case, p_i^l and p_i^r ($p_i^l \leq p_i^r$), that trigger investment decision. They can be found from boundary conditions:

$$A_i(p_i^l)^{\beta_1} + B_i(p_i^l)^{\beta_2} = K_i - x_i p_i^l \tag{9}$$

$$A_i(p_i^r)^{\beta_1} + B_i(p_i^r)^{\beta_2} = NPV_w \tag{10}$$

These *value matching* conditions (Dixit and Pindyck, (1994)) are not enough, as now we have four unknown variables. But the real options theory also requires smoothness of the option value in the critical prices. In other words, the derivatives of the option value and the project value are equal:

$$\beta_1 A_i(p_i^l)^{\beta_1 - 1} + \beta_2 B_i(p_i^l)^{\beta_2 - 1} = -x_i \tag{11}$$

$$\beta_1 A_i(p_i^r)^{\beta_1 - 1} + \beta_2 B_i(p_i^r)^{\beta_2 - 1} = 0 \tag{12}$$

Conditions (11) and (12) are called *smooth pasting.* For more details regarding validity of conditions (9)-(12) the reader can refer to Dixit and Pindyck, (1994).

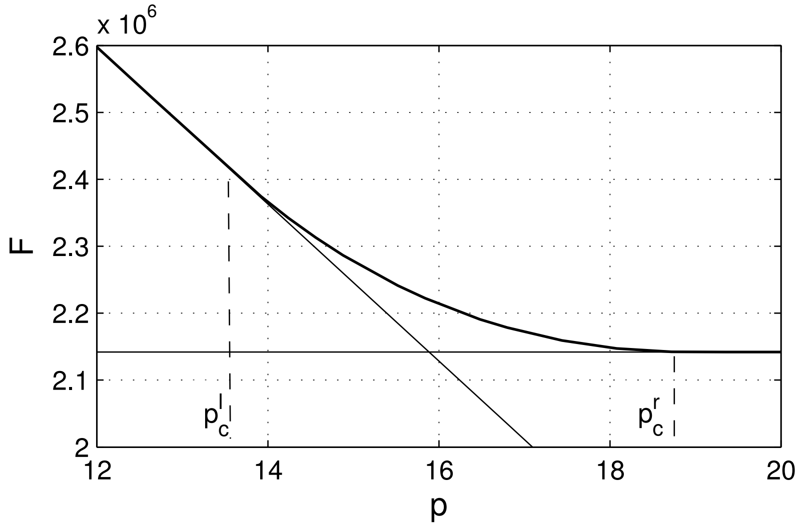

Figure 2: Value of a Coal-wind Option

The resulting system of four nonlinear equations is out of the question to be solved analytically. Moreover, even the usage of professional software cannot help here, as the problem seems too unstable. But we can express A_i and B_i from linear equations (11) and (12):

$$A_i = \frac{-\beta_2}{\beta_1 - \beta_2} p_i^{r-\beta_1} NPV_w$$

$$B_i = \frac{\beta_1}{\beta_1 - \beta_2} p_i^{r-\beta_2} NPV_w$$

Now the system can be easily solved numerically. To illustrate, how it works, I implement the known characteristics for a coal power plant. The reader will find more details about input data in the next section. From the equations we find that $p_c^l = 13.55$, $p_c^r = 18.92$. If the investor faces a carbon dioxide price lower than \$13.55, then he invests in the coal power plant. On the other hand, if the price is higher than \$18.92, the wind project is commenced. Between these values the investor prefers to wait.

In Figure 2 we can see an example of an option value to invest in the coal-wind project. In the inaction region (p_c^l, p_c^r) the value of the option exceeds that of the project. This means that information about CO_2 price distribution encourages the investor to wait for future price change. If the investor kills his option by investing, say, in the coal project, he might lose a lot, should the price go higher.

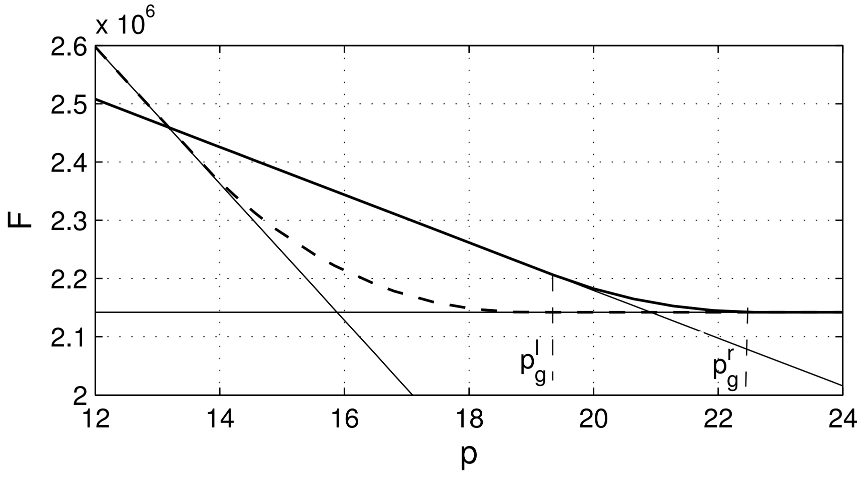

Figure 3: Values of a Coal-wind and Gas-wind Options

If we look at the gas project, we will see that compared to the coal one, investment thresholds are shifted to the right: $p_g^l = 19.35$, $p_g^r = 22.68$. Figure 3 illustrates both coal-wind and gas-wind projects. It is necessary to note that they are completely different projects. In one scenario the investor might choose a power plant out of coal-fired and wind ones. In another he can only choose between gas-fired and wind PPs. This restrictive assumption will be relaxed in the next subsection.

2.3.2 Three projects

Now I turn to the central issue of the thesis. Suppose the investor can freely choose between three exclusive irreversible projects: CPP, base GPP or WPP. He cannot run more than one project, and if the performance is poor, he cannot profitably sell his industry-specific capital. My task is to evaluate such an option to invest. Hereafter I set the gas price low enough for a gas project to be competitive. In fact, modern Europe currently sees very high gas prices.

Following Décamps et al. (2004), I state that under certain conditions we have four thresholds for making the investment choice. These thresholds produce dichotomy in the waiting area. One waiting domain now relates to the inability to decide between a coal and gas PP. Another represents doubts between gas and wind projects. Thus we have two disjoint waiting areas separated by an area of immediate investing in the gas industry.

It is of big interest for us to track the moment when the coal-wind project starts to dominate the coal-gas-wind one. We cannot simply check the magnitude of A_c/A_g or B_c/B_g as it was done in Dixit (1993) or Décamps et al (2004). In these works the alternative project in fact has zero value. This effectively eliminates either A_i or B_i, and we can easily view which option is higher. In our framework A_i and B_i are both positive and calculated numerically, which makes analytical comparison impossible. However, soon we will see how to distinguish coal-wind domination from other cases.

Again the option value $F_{cg}(p)$ satisfies equation (5) and has form given by (6) (in the inaction regions). But the coefficients of this function are different for these two waiting areas. We have to treat them separately for each of the inaction zones. The waiting area between gas and wind projects is the same as in the simple gas-wind case. So we do not stop at this case and move to the left waiting area for the coal-gas project. For this domain denote coefficients as A_{cg}, B_{cg} and its borders as p^l_{cg} and p^r_{cg}.

We arrive at a nonlinear system similar to (9)-(12). The only difference is in the second and fourth equations, where I use $NPV_g(p)$ instead of NPV_w:

$$A_{cg}(p^l_{cg})^{\beta_1} + B_{cg}(p^l_{cg})^{\beta_2} = K_c - x_c p^l_c, \tag{13}$$

$$A_{cg}(p^r_{cg})^{\beta_1} + B_i(p^r_{cg})^{\beta_2} = K_g - x_g p^l_g, \tag{14}$$

$$\beta_1 A_{cg}(p^l_{cg})^{\beta_1 - 1} + \beta_2 B_{cg}(p^l_{cg})^{\beta_2 - 1} = -x_c, \tag{15}$$

$$\beta_1 A_{cg}(p^r_{cg})^{\beta_1 - 1} + \beta_2 B_{cg}(p^r_{cg})^{\beta_2 - 1} = -x_g. \tag{16}$$

This system apparently cannot be solved analytically and has very bad quantitative features. However, linearity with respect to coefficients rescues us once again. After expressing them and turning to a 2-variable system we easily obtain the solution. In Figure 4 the reader can view the shape of the option. I do not stop here to discuss outcomes of system (13)-(16), as later the "Application" section will provide extensive numerical examples.

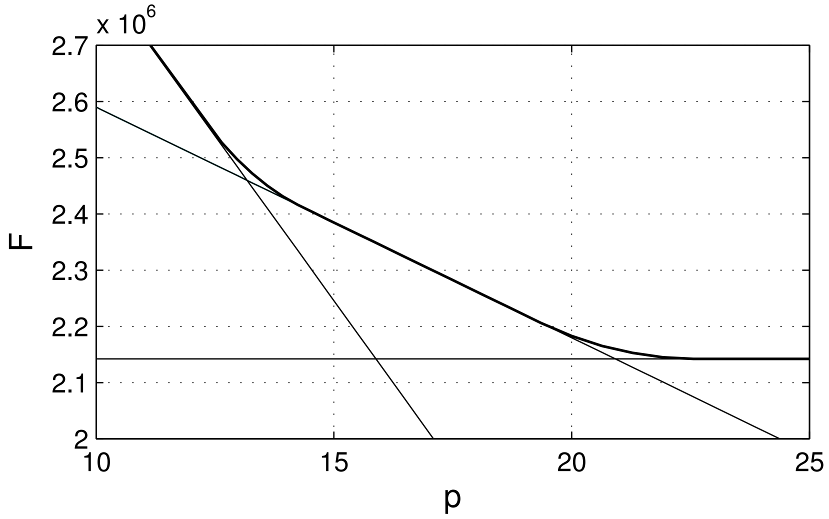

Figure 4: Value of a Coal-gas(base)-wind Option

2.4 Project domination

Now we are ready to discuss the domination matter. What happens if the uncertainty is too high, given market and power plants characteristics? It results in wider inaction intervals and their closeness. The waiting area in the coal-wind scenario also increases. When the closest edges of the coal-gas and gas-wind waiting regions converge in one point, the coal-gas-wind option converges to simply the coal-gas option. Before I proceed, I would like to note that although we say *project* domination, in fact this is *option* domination. Options to invest just in coal or wind "suppress" the option to choose from the full set: coal, gas or wind.

Let us put this in precise mathematical terms. As defined above, (p^l_{cg}, p^r_{cg}) and (p^l_g, p^r_g) represent coal-gas and gas-wind waiting interval in the coal-gas-wind scenario. In the coal-gas scenario the waiting region is (p^l_c, p^r_c). I will prove that if $p^r_{cg} = p^l_g$ then $A_{cg} = A_g = A_c$ and $B_{cg} = B_g = B_c$. Also it implies that $p^l_{gc} = p^l_c$ and $p^r_g = p^r_c$.

The arcs linking coal-gas and gas-wind curves, coincide in the point $p^r_{cg} = p^l_g$, let us name it p_0 for clarity. The right edge of the left arc is tangent to the value function of the gas project in p_0. On the other hand, the left edge of the right arc is also tangent to that function in p_0. This means that the functions smoothly meet in this point:

$$A_{cg}{p_0}^{\beta_1} + B_{cg}{p_0}^{\beta_2} = A_g{p_0}^{\beta_1} + B_g{p_0}^{\beta_2} \tag{17}$$

$$\beta_1 A_{cg}{p_0}^{\beta_1 - 1} + \beta_2 B_{cg}{p_0}^{\beta_2 - 1} = \beta_1 A_g{p_0}^{\beta_1 - 1} + \beta_2 B_c g{p_0}^{\beta_2 - 1} \tag{18}$$

Collecting the terms in the LHS leads to

$${p_0}^{\beta_1}(A_{cg} - A_g) + {p_0}^{\beta_2}(B_{cg} - B_g) = 0$$

$$\beta_1{p_0}^{\beta_1 - 1}(A_{cg} - A_g) + \beta_2{p_0}^{\beta_2 - 1}(B_{cg} - B_g) = 0$$

This system is linear with respect to $(A_{cg} - A_g)$ and $(B_{cg} - B_g)$. Its determinant is $(\beta_1 - \beta_2)p_0^{\beta_1+\beta_2-1}$ and it is positive as $\beta_1 > \beta_2$. Therefore, the system has only the trivial solution and

$$A_{cg} = A_g, \quad B_{cg} = B_g.$$

If we merge these two arcs, we will receive function $Ap^{\beta_1} + Bp^{\beta_2}$ over the merged inaction region. This function satisfies boundary conditions for both the CPP and WPP value curves. Because of this fact, A and B are defined in a unique way and are therefore equal to A_c and B_c of the coal-wind option.

This means that as long as there are two disjoint waiting areas, the coal-wind option is less or equal to the coal-gas-wind one. When $p_{cg}^r > p_g^l$, in other words, when inaction regions would overlap, the investor disregards the gas project. Opportunity to invest in a gas-fired PP merely adds no value to the option. Let now F be the solution to the whole investment problem. Then

$$F(p) = \begin{cases} F_{cg}(p) & \text{if} p_{gc}^r < p_g^l, \\ F_c(p) & \text{if} p_{gc}^r \geq p_g^l. \end{cases} \tag{19}$$

In section 3 I will show how the option to invest depends on various parameters. When altering these parameters, we will perhaps pass through the point when F changes its functional form according to (19). This will result in different threshold evolution: without opportunity to invest in gas, the coal project also takes risk that would otherwise fall on gas.

2.5 Peaking gas-fired PP

Up to this point I considered an absolutely inflexible GPP. Even when price for carbon dioxide becomes high, the power station cannot cease working, it operates at full capacity. Here I introduce a perfectly flexible GPP, which can be shut down instantly and at no cost should net revenue become negative. Coal-fired PPs are considered here as the base-load type because of a high reactivation cost. So only GPPs are assumed to be peaking here.

Denote flow of income as

$$\pi(p) = \max\{NT - Nk_0 p, 0\},$$

where T is the net revenue flow, not counting the CO_2 emission penalty, and $k_0 = \frac{ue_g}{\eta_g}$. Recall the components which make up flows of income and losses of a gas power plant. These components determine critical CO_2 price C when the plant halts operating:

$$\pi(p) = N\left(p_e - OP_g - \frac{p_g}{\eta_g} - k_0 C\right) = 0,$$

this yields

$$C = \frac{1}{k_0}\left(p_e - OP_g - \frac{p_g}{\eta_g}\right).$$

Consider value $V(p)$ of an installed project. It obeys almost the same rule as (5) but with an additional term $\pi(p)$:

$$\frac{1}{2}\sigma^2 p^2 V''(p) + \alpha p V'(p) - rV(p) + \pi(p) = 0. \tag{20}$$

This new term stands for money flow when we have an underlying asset (i.e. the project itself) alive. To make the parallel to (5) clearer, note that having an option alive means no installed PP which would generate profit. Hence the income flow is 0. If the investor had to pay for keeping the option alive, that loss flow would appear in (5).

Following Murto and Nese (2002), I briefly outline the properties of the project value and the option value. When $p > C$, the station is shut done and produces nothing ($\pi = 0$). Then the value is equal to $A_1(k_0p)^{\beta_1} + B_1(k_0p)^{\beta_2}$. When $p \to \infty$, the value tends to zero as the cost of waiting for good times increases. This rules out the first term: $A_1 = 0$.

In the operating area the solution to equation (20) is

$$V(p) = A_2(k_0p)^{\beta_1} + B_2(k_0p)^{\beta_2} + \frac{k_0C}{r} - \frac{k_0p}{\delta}$$

When CO_2 is free to emit, the value must be finite. But the second term goes to ∞ when $p \to \infty$. Thus, in the operating area $B_2 = 0$. The project value is

$$V(p) = \begin{cases} NA_2(k_0p)^{\beta_1} + \frac{Nk_0C}{r} - \frac{Nk_0p}{\delta} & \text{if } 0 < p \leq C, \\ NB_1(k_0p)^{\beta_2} & \text{if } p > C. \end{cases} \tag{21}$$

In the same way as before, I find options to invest in a two- and three-power plants project. The value of option $F_g^p(p)$ satisfies (5) and is subject to boundary conditions. The only difference is that for value matching and smooth pasting conditions I use (21) instead of a simple linear function. Of course one will invest in a peaking PP only when $p < C$ because only in that case will the plant operate. Although the notation for critical prices remains the same, the reader should remember that there is no connection with the base load case.

For a gas-wind project we have

$$A_g^p(p_g^l)^{\beta_1} + B_g^p(p_g^l)^{\beta_2} = NA_2(k_0p_g^l)^{\beta_1} + \frac{Nk_0C}{r} - \frac{Nk_0p_g^l}{\delta},$$

$$A_g^p(p_g^r)^{\beta_1} + B_g^p(p_g^r)^{\beta_2} = NPV_w,$$

$$\beta_1 A_g^p(p_g^l)^{(\beta_1-1)} + \beta_2 B_g^p(p_g^l)^{(\beta_2-1)} = \beta_1 Nk_0A_2(k_0p_g^l)^{(\beta_1-1)} - \frac{Nk_0}{\delta},$$

$$\beta_1 A_g^p(p_g^r)^{(\beta_1-1)} + \beta_2 B_g^p(p_g^r)^{(\beta_2-1)} = 0.$$

Applying numerical methods, we obtain the coefficients of the option and thresholds p_g^l, p_g^r that trigger investment in the gas-wind project.

Finally, I proceed to the coal-gas-wind scenario. As in the gas(peak)-wind case, I simply repeat the steps with the base-load PP, changing the RHS of the appropriate boundary conditions. Suppose we have two inaction regions. The right region, as in the base load case, is given by (p_g^l, p_g^r). The left one, (p_{cg}^l, p_{cg}^r), must be determined from the boundary conditions in the coal-gas(peak) case. The resulting system is

$$A_{cg}^p(p_{cg}^l)^{\beta_1} + B_{cg}^p(p_{cg}^l)^{\beta_2} = K_c - x_c p_{cg},$$

$$A_{cg}^p(p_{cg}^r)^{\beta_1} + B_{cg}^p(p_{cg}^r)^{\beta_2} = NA_2(k_0 p_{cg}^l)^{\beta_1} + \frac{Nk_0C}{r} - \frac{Nk_0 p_{cg}^l}{\delta},$$

$$\beta_1 A_{cg}^p(p_{cg}^l)^{(\beta_1-1)} + \beta_2 B_{cg}^p(p_{cg}^l)^{(\beta_2-1)} = -x_c,$$

$$\beta_1 A_{cg}^p(p_{cg}^r)^{(\beta_1-1)} + \beta_2 B_{cg}^p(p_{cg}^r)^{(\beta_2-1)} = \beta_1 Nk_0 A_2(k_0 p_{cg}^l)^{(\beta_1-1)} - \frac{Nk_0}{\delta}.$$

After solving this system again, the question about project domination arises. I apply the same approach as before. Namely, if $p_{cg}^r = p_g^l$, then the coal-gas-wind project degenerates to simply the coal-wind project. So, if F_{cg}^p is the option when $p_{cg}^r < p_g^l$, then the option in the coal-gas(peaking)-wind project is given by

$$F^p(p) = \begin{cases} F_{gc}^p(p) & \text{if} p_{cg}^r < p_g^l, \\ F_c(p) & \text{otherwice.} \end{cases}$$

Here I finish theoretical foundation of investing in energy generators. In the next section we move to various examples of optimal investing behavior. We should bear in mind that the two different GPPs discussed here are extreme cases. In practice, a GPP can often change its operating regime only with a delay and at some positive cost.

3 Applications

In this chapter I introduce several examples how options pricing methods work. For this purpose I study two cases: one is more descriptive and the other is more realistic. Going only into the latter will not provide enough insights to the three-projects problem because of obvious coal project domination. For ease of discussion, I introduce following short names:

- the coal-gas-wind project with a **peak** GPP is called the "full peak project" or just "peak project";
- the coal-gas-wind project with a **base** GPP is called the "full base project" or just "base project";
- "gas-free project" stands for the coal-wind project.

3.1 Input Data

I start with the characteristics of the power plants. This data was provided by MOL Group, Hungarian Oil and Gas Public Limited Company, which initiated and supervised this research project.

The capital expenditures (CAPEX, or sunk cost) of 1 MW of coal and wind energy is set at $1.2 mln. A gas-fired power station is cheaper in terms of average capacity cost which is $0.6 mln per 1 MW. Non-fuel operating expenditures (OPEX) are assumed $30000 per 1 MW per year and equal for all parties.

CPPs are heavy polluters, their emission factor is 342 $kgCO_2$ per 1 MWh of burnt fuel against just 188 $kgCO_2$ for gas-fired PPs. Moreover, coal power plants are less efficient than their gas analogs. A typical GPP produces nearly 55% of effective burnt energy, while a coal PP utilizes only 35%. Both gas- and coal-fired power stations operate 6000 hours a year. For wind energy, a 1 MW wind turbine produces only 0.3 MWh per hour. Additionally, a wind turbine can work all year round, i.e. 8760 hours a year.

In the EU Emission Trading Scheme power plants are given some amount of emission allowance free of charge. For the first, descriptive case I assume that 30% of emissions are free. In the second case study I involve several settings with no, few and many free allowances.

I assume the risk-neutral interest to be $r = 0.05$, as it was suggested in Murto and Nese (2002). As far as the carbon dioxide prise is concerned, I assume that by default it has zero trend rate α and volatility $\sigma = 0.2$. To highlight different properties of the model, I will show how it responds to different α and σ.

Finally, let me return to on price issues. The electricity price is set as $75 per MWh, which more or less corresponds to indicators of European Energy Exchange. The gas price is assumed to be different for the two scenarios and this is the key point. Current price for gas is about $26 per 1 MWh of burnt fuel. My analysis will show that such a high price makes the gas project very unattractive. I wish to demonstrate the capability of the model without limiting myself with modern trends. So at first I fix the gas price at $22 level. In such an environment the gas industry retains a part of the market.

3.2 Investment under a Low Gas Price

This subsection illustrates investors' behavior when both types of fossil-fuel PPs are worth studying. The analysis will include system's response to a variation of several key parameters. But first I consider option pricing in the primary settings: $\alpha = 0$, $\sigma = 0.2$, $u = 0.7$ and $p_g = \$22$. A base-load GPP is described first for its simplicity, with a peaking GPP following.

In Figure 5 the option value for a full base project is shown. Here the full project dominates the gas-free one. This means that for certain values of the CO_2 price the gas energy may be competitive. In the current example, the investor takes a cautious position and does not invest when $p \in (17.4, 20.45)$ and $p \in (27.64, 32.4)$. In the former case he cannot make up her mind between a coal and a gas PP. The latter case stands for choosing from the gas and the wind projects.

If the CO_2 price is higher than $32.4, then the investor makes the decision to invest

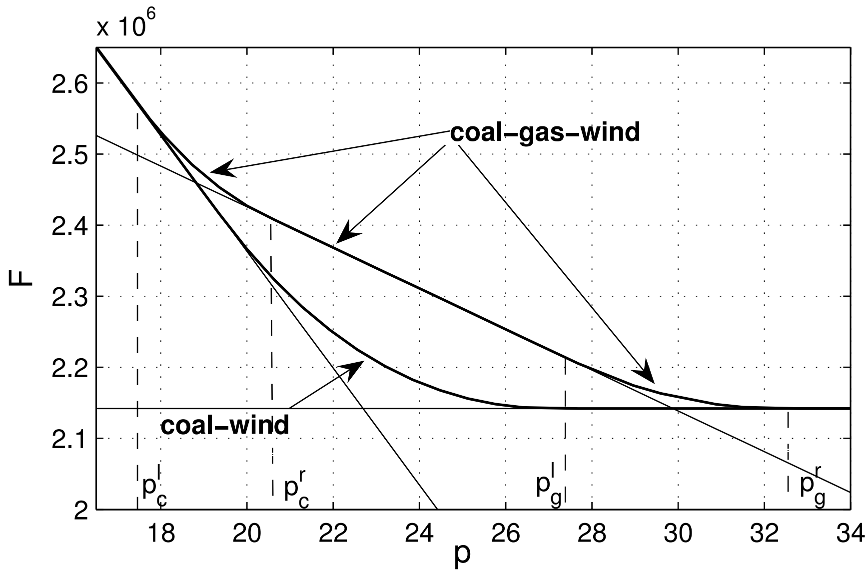

Figure 5: Value of a Coal-gas(base)-wind Option

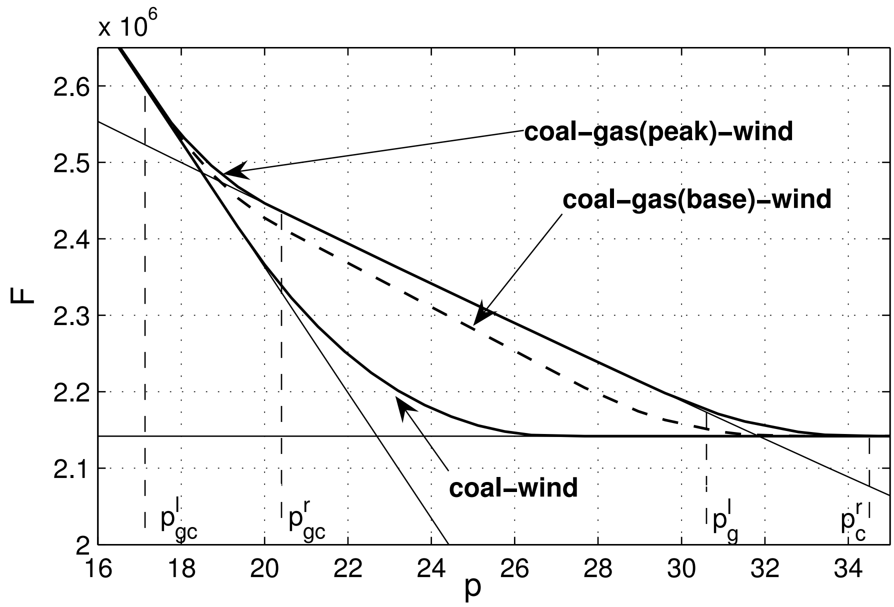

Figure 6: Values of Two Full Project Options with Base and Peak GPPs

in the wind project. Emission is so costly that even if it becomes cheaper shortly after, the expenses will be high anyway. But once the price falls in (20.45, 27.64), then the gas project is worth dealing with. Finally, when the price is below \$15.4, then the coal power plant looks the most appealing.

It is crucial that around the point where the CPP and GPP have the same NPV, the best strategy is to wait. The same is true with the GPP and WPP. This fact goes against the naive NPV rule of investing which suggest to invest immediately in the project with the highest NPV. The latter approach ignores benefits from waiting for another project to become more attractive.

Let us proceed with the option when the peak GPP project is available. This situation is illustrated in Figure 6. The solid line shows the option value of the peak project, the dash line stands for the base project.

As expected, the full peak project dominates both the gas-free and full base projects. Inaction regions for the peaking case are (17.08, 20.12) and (29.59, 34.33). One can see that the area for undertaking the gas project became larger than in the base case. The waiting intervals have shifted in opposite directions, keeping their length virtually unaltered.

Now I move to the characteristics of the optimal investment rule. I start with the most important parameter, the volatility of the carbon dioxide price. Again, first the base project is considered and the peak project comes next.

Looking at Figure 7, we see that the investment rule depends on volatility in a complex way. When σ is small, we have a rough rule of thumb: invest in coal if the CO_2 price is below \$20, invest in gas if the price is between \$20 and \$30, and spend money for the wind project otherwise. As σ gets larger, the zones of inaction grow and we cannot ignore them. The threshold for investing in coal goes down, the threshold for investing in wind goes up and the "gas" investment region shrinks. One can notice that the shapes of the threshold lines for coal and for wind look very similar.

Once $\sigma \approx 0.34$, the gas-free project starts to dominate the full project. Waiting regions merge in a single one. The gas project is no longer considered because under any price for CO_2 waiting or investment in wind or coal is better. Another valuable observation is the

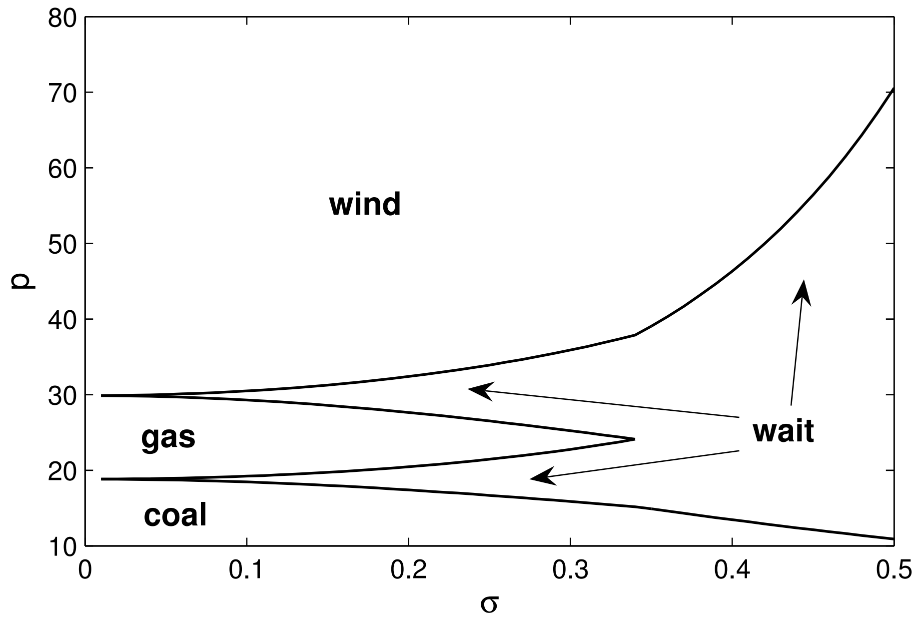

Figure 7: Critical Prices p as Functions of σ, Base GPP

break of smoothness in the upper and bottom critical prices. After $\sigma \approx 0.34$ the critical price for investing in coal starts to decline more quickly. The increase rate of the wind investment threshold also jumps significantly. With the further growing of the uncertainty the waiting zone grows very fast.

In Figure 8 the reader can see the optimal thresholds for the peak project (solid) and those for the base project (dash). The most interesting issue here is that the gas project is worthwhile at any level of uncertainty. Moreover, the gas project exhibits the nearly constant length ($11) of the investment region.

The bottom threshold is slightly lower than that of the base project. But upper threshold for wind investment grows at a very considerable rate. However, once base GPPs are out of consideration, the difference in the upper thresholds of the base and peak projects becomes close to constant.

The carbon dioxide price drift rate has a very important meaning. The higher this value, the more cautious one must be when thinking about investment in conventional energy. Moreover, a higher drift rate gives increasing value to a peaking GPP over a base load GPP. They both lose in terms of future profit but the peaking GPP loses less because

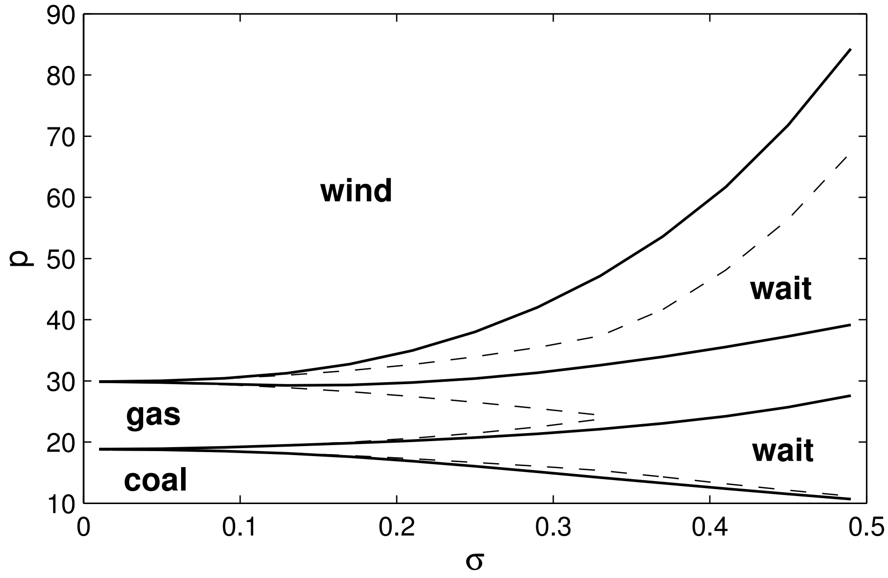

Figure 8: Critical Prices p as Functions of σ, Peak and Base GPPs

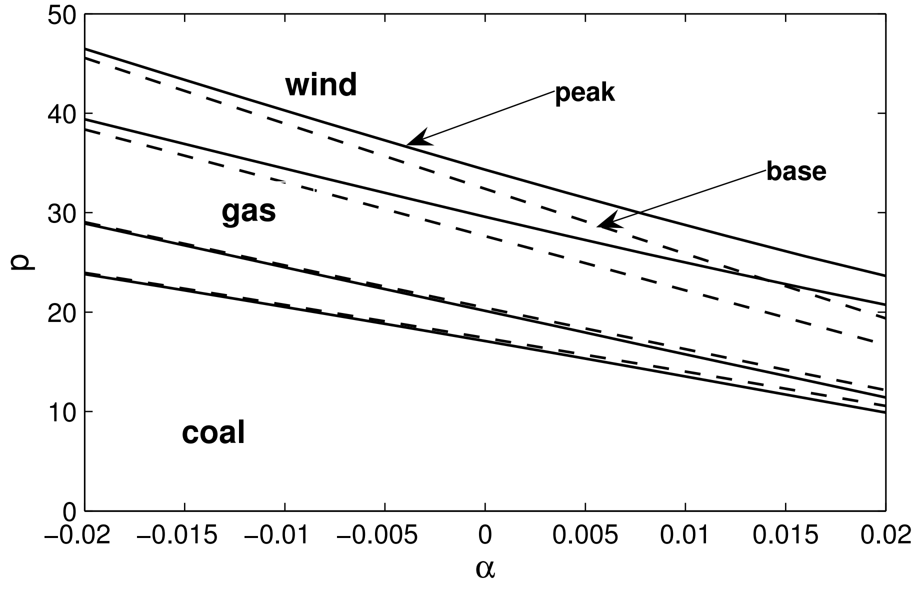

Figure 9: Critical Prices p as Functions of α, Peak and Base GPPs

of the flexible regime.

Figure 9 supports this idea. In this picture we see how the optimal thresholds respond when the drift rate is varied from -0.02 to 0.02. Again the solid lines depict critical prices for the peak case and the dashed lines are used for the base load case.

We see that for both cases the dependency of critical CO_2 prices on the drift rate is close to linear. When $\alpha = -0.02$, the peak and base power plants have almost the same critical thresholds. All the thresholds decline when α grows. Again, the investment zone for a peaking GPP decreases at slower rate than that for a base load GPP. The boundaries for the coal-gas waiting region are shifted to the left in the peak case. Correspondingly, for the gas-wind waiting region the peak case boundaries are shifted to the right. Later I will return to this situation and argue that all the lines meet in one focus.

So far we have assumed that the producer of the conventional energy must buy 70% of the emission allowances. In the next scenario I relax this condition. Remember that u stands for the percentage of emitted CO_2 for which allowances must be bought. Figure 10 shows the thresholds paths as u varies from 0.3 to 1. For a smaller value of u the model shows unstable results because of operating with big numbers. Overcoming these purely

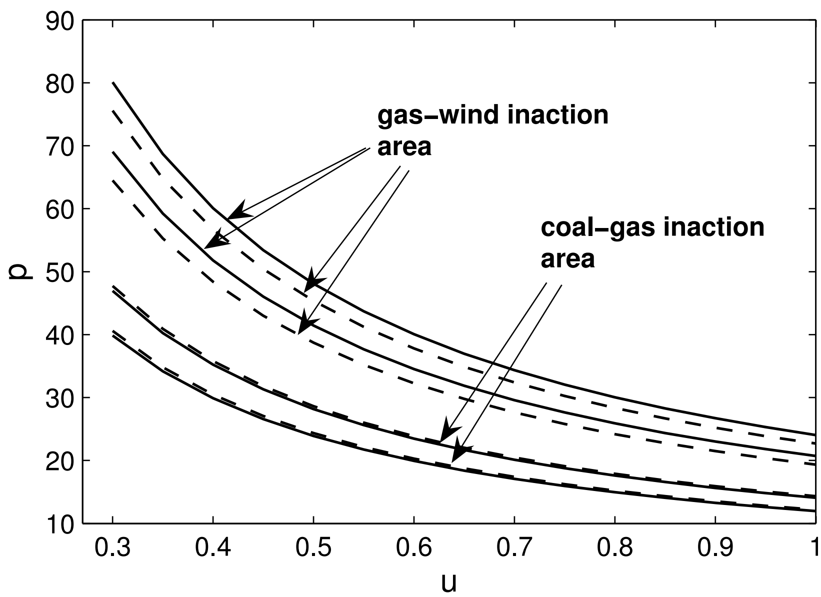

Figure 10: Critical Prices p as Functions of u, Peak and Base GPPs

mathematical issues requires the further complication of the methods, which are beyond this paper's scope.

All critical values move downwards at a decreasing rate as u increases. One can see that the coal-gas waiting region basically coincides for the base (dash line) and peak (solid line) projects. The difference is clearer for the gas-wind waiting area. Both kinds of projects have roughly the same length of waiting area, but for the peak case this window shifts to higher values of the CO_2 price. The share of free allowances affects the investment decision very much. In the peak project, for instance, $u = 0.3$ implies that waiting areas are (39.85, 48.95) and (69.04, 80.1). Under obligation to pay for every emitted ton of CO_2, the waiting intervals are (11.95, 14.08) and (20.72, 24.03).

I finish this descriptive case by studying the impact of the gas price on investing. Remember that our default value for gas was \$22 per 1 MWh of gas energy. However, it does not correspond to the current European prices for gas, which are at least \$26 per 1 MWh of gas energy. Figure 11 sheds some light on the project's evolution as the price for gas changes.

As usual, dash lines deal with the base project, solid lines are used for the peak project.

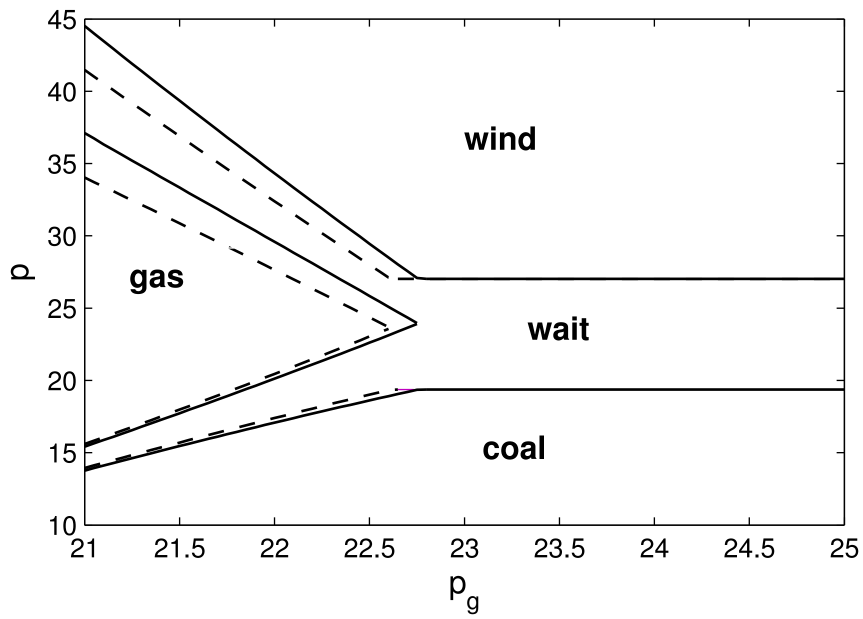

Figure 11: Critical Prices p as Functions of p_g, Peak and Base GPPs

When the gas price is fairly low, at \$21 level, the inaction regions are $(13.76, 15.41)$, $(37.1, 44.51)$ in the peak case and $(13.94, 15.6)$, $(34.03, 41.48)$ in the base one. When the price increases, the investing region for gas shrinks. The edges of the inaction regions move along straight lines. The coal-gas-wind project collapses at $p_g = 23.7$ for the base case and 23.96 for the peak one. From these moments the gas-free project starts dominating the full project. Evidently, the further evolution of the gas price gives no impact to the project. After these collapse points the range of the inaction region remains constant.

3.3 Investment under a Realistic Gas Price

The situation described above is too optimistic. The main purpose was to see what happens when three competitive projects are considered. In fact, current European prices are much higher than \$22, as assumed before. A reasonable price for gas may be at least \$26 (as of April 2006). But recently we saw that the opportunity to invest in a GPP does not affect the investment decision as long as the gas price exceeds the \$24 mark. Thus, we focus only on the coal-gas project.

Figure 12 depicts options values when $\alpha = 0, \sigma = 0.2$ and u equals either 1.0, 0.6 or 0.3. In the most severe conditions ($u = 1.0$) the firm invests in a CPP when CO_2 price is

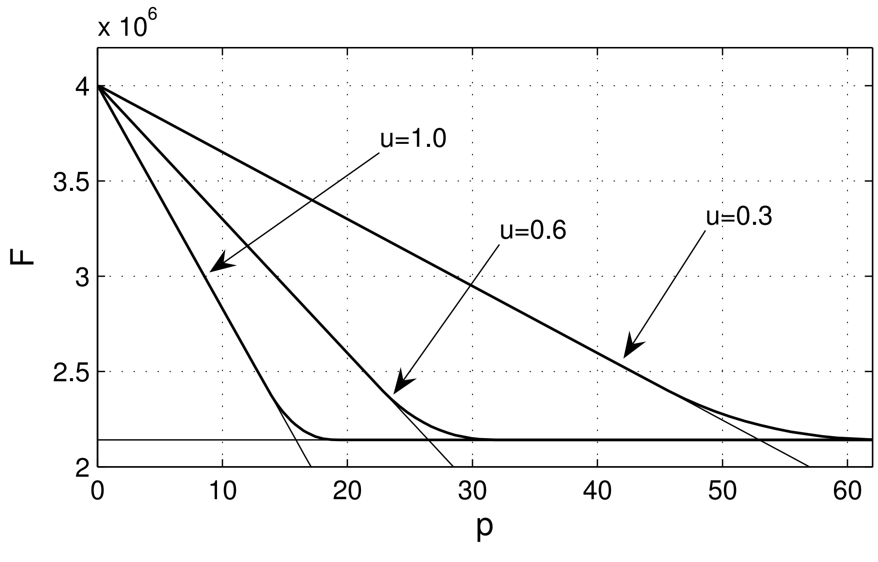

Figure 12: Values of Coal-wind Options, $u = 1.0$, 0.6 and 0.3

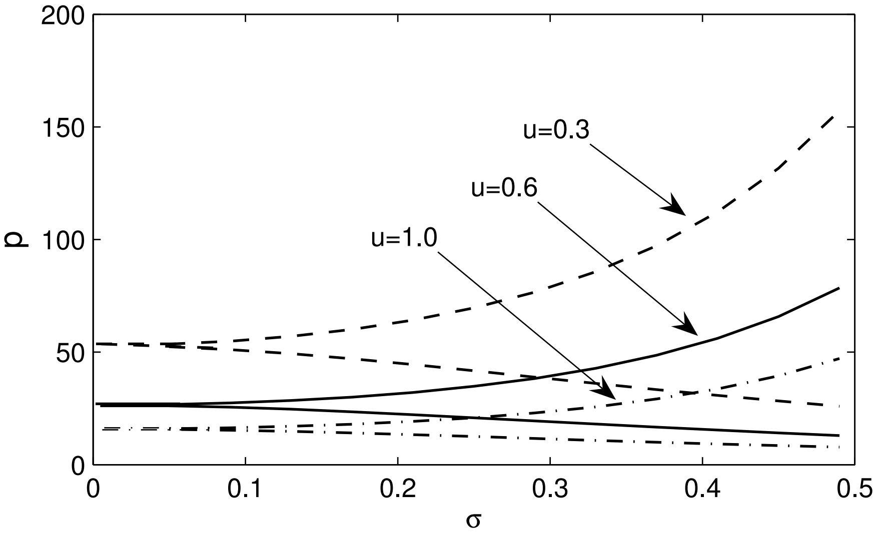

Figure 13: Critical Prices p as Functions of σ, $u = 1.0, 0.6$ and 0.3

below \$13.55 and invests in a wind farm when the price is higher 18.92. If the price falls between these values, the investor should wait.

When 40% of allowances are free, the inaction region is (22.59, 31.53). Under favourable conditions, when 70% of CO_2 emission is free of charge, the waiting interval is (45.18, 63.06). As u tends to $+\infty$, the investment thresholds also go to ∞ and the range of the waiting zone increases.

Now I turn to the model reaction when σ or α vary, and I start with volatility. As Figure 13 tells us, the fewer number of free allowances we have, the greater the impact of uncertainty is, as well as the rate of this impact. A lower u implies not only lower investment triggers but also a narrower waiting region.

When the level of uncertainty is low, say, 0.1, the waiting area is (15.21, 16.63) for $u = 1.0$, (25.33, 27.7) for $u = 0.6$ and (50.7, 55.49) when $u = 0.3$. Numbers related to moderate volatility $\sigma = 0.2$ were reported above. Finally, for the case of high price volatility equal to 0.4 the waiting regions are (9.42, 32.52), (15.7, 54.3) and (31.42, 108.5). As we can see, the waiting region might be very large, especially when uncertainty is high.

The first half of 2007 saw extremely low prices for carbon dioxide, as low as \$1-2. Under this circumstance, the model suggests to invest in coal energy. Even high uncertainty in

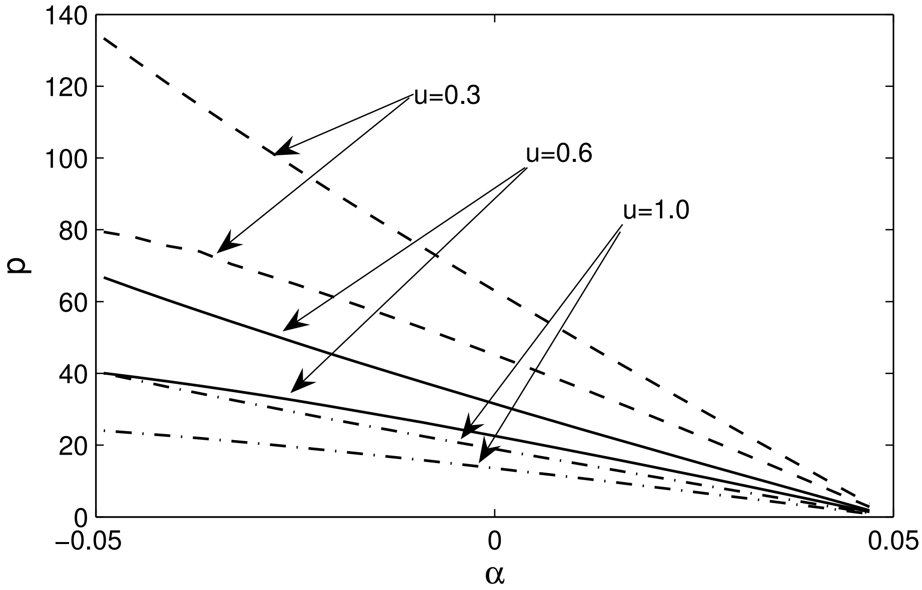

Figure 14: Critical Prices p as Functions of α, $u = 1.0, 0.6$ and 0.3

the price will not be a problem here. But in case of shortages at the allowances markets the price may go up, changing the investment plans.

Our next step is to investigate the effect of different drift rates on the investment rule. The threshold curves for $u = 1.0$, 0.6 and 0.3 can be viewed in Figure 14. Here dash lines stand for $u = 1.0$, solid for $u = 0.6$ and dash-dot for $u = 0.3$. The range for α is taken $(-r, r)$.

A larger number of free emission allowances augments critical thresholds for investment, but it also means their faster decline when the drift rate grows. The critical values converge to 0 as α approaches r. When α runs to r, the NPV of the loss from CO_2 emissions unboundedly grows. The region of optimal prices to invest coal or wait becomes smaller the closer to r becomes α. When $\alpha \geq r$, then at no price the coal project looks appealing. Thus the investor immediately invests in clean wind energy.

To make some use of this result, let us evaluate how the thresholds decline when α changes from -0.02 to 0.02. When $u = 1.0$, the coal threshold changes from 18.55 to 8.33, and the wind one falls from 27.05 to 11.17. When $u = 0.6$, the inaction zone shifts from (30.6, 45.07) to (13.89, 18.64). In the favorable regime ($u = 0.3$) thresholds fall from 61.16

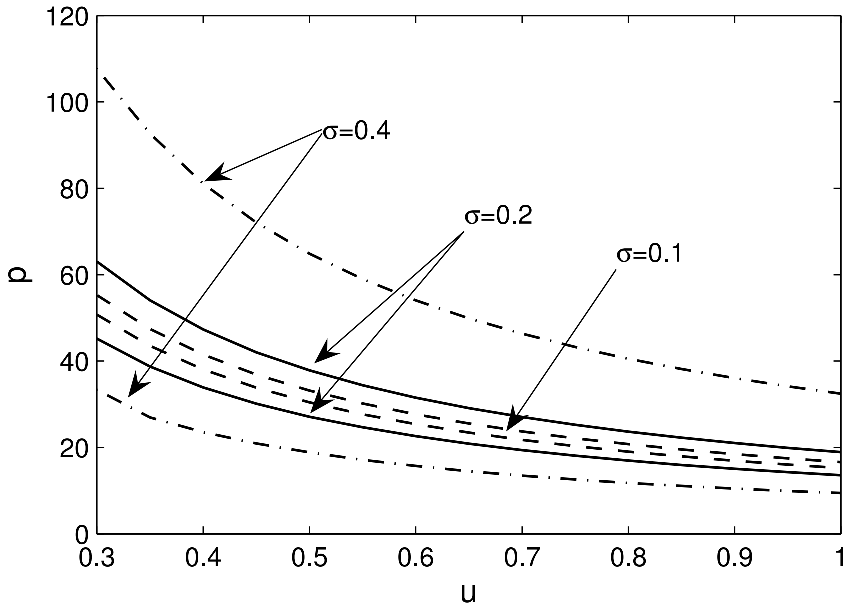

Figure 15: Critical Prices p as Functions of u, $\sigma = 0.1, 0.2$ and 0.4

and 90.16 to 27.77 and 37.23.

I conclude this paper by studying the impact of u, i.e. the percentage of emission allowances to buy. We can check this effect for different α and σ, but for brevity I take only the latter. Figure 15 demonstrates how thresholds change when u increases from 0.3 to 1. The greater σ, the wider the waiting interval is. This happens at an increasing rate with respect to σ.

One can notice that the graphs exhibit an almost constant percentage of the inaction area relatively to the coal investment region. When uncertainty is small, the waiting region is about 8.9% of the coal investment area. For moderate ($\sigma = 0.2$) and volatile ($\sigma = 0.4$) CO_2 markets this share is 39.7% for the former and 243.6% for the latter. Apparently, the range of the inaction interval increases at a strongly increasing rate.

4 Concluding Remarks

This work studied investment in the power sector under uncertainty in the CO_2 price for pollution emitters. The carbon dioxide factor was chosen in accordance with the EU Emission Trading Scheme, which is aimed to decrease the pollution rate in Europe. In my work I covered three kinds of power plants (PP): heavily polluting coal-fired PPs, gas-fired PPs with moderate pollution impact and environment-friendly wind PPs. The gas-fired power plant is assumed to be either perfectly flexible in operating regime (peak load) or perfectly inflexible (base load). All three projects are exclusive: an investor may commit only to one project (with the type of a GPP given exogenously).

I applied real options analysis to find the optimal investment rule. Uncertainty in future CO_2 prices, irreversibility of investment and the ability to wait imply that the traditional Net Present Rule does not work here. In fact, under any market situation there is at least one interval for the CO_2 price where the best strategy is waiting. The very important concept of project domination, introduced in the paper, might change the whole picture.

My findings showed that under favorable prices for gas the optimal investment rule looks complex. When the price volatility is small, a base GPP appears competitive. This circumstance creates a pair of waiting regions rather than one. When the CO_2 price falls to the left of the first interval, the coal project is commenced. If the price falls between them, the investor undertakes the gas project. In case of a high enough CO_2 price, the wind farm is the most profitable one. The investor prefers waiting should the price fall in any of inaction regions. Nonetheless, when volatility grows, the role of the base GPP project diminishes. At some point the coal-wind project starts dominating the full coal-gas-wind project. The investor forgets about the opportunity to invest in a base GPP and takes only coal as a source of polluting energy. Two waiting regions merge in one and the investment thresholds start changing more rapidly.

A peak GPP is much more competitive than a base one. It retains almost the same length of the investment area as volatility changes. In a reasonable range of CO_2 price volatility the coal-gas(peak)-wind project cannot be dominated by the coal-wind one.

I also presented the thresholds for gas prices when the gas investment opportunity becomes worthless. Under current EU gas prices gas projects are shown to be completely "out-of-money". The thesis treats the coal-wind project under different levels of free allowances to emit pollution. I showed how critical investment thresholds vary when the trend rate or volatility of the price changes.

There are two questions discussed in the current work, which can be developed further. The first one is more practical and concerns investment in the energy sector in general. I did not include some other types of electricity generators like nuclear- or hydro power plants. Also, different improving options like switching fuels, abandoning or purifying might be added. The second question arising from the first is the project domination. It is quite unclear in general how projects can dominate one another and how domination evolves. I believe that some moves towards the better understanding of this phenomenon must be done.

References

[1] Awerbuch, Sh. (2003): *Determining the Real Cost. Why renewable power is more cost-competitive than previously believed*, Renewable Energy World, March-April.

[2] Décamps, J.-P. et al. (2004): *Irreversible Investment in Alternative Projects*, Economics Theory, 28, p. 425-448.

[3] Dixit, A. K. (1993): *Choosing among Alternative Discrete Investment Projects under Uncertainty*, Economics Letter, 41, p. 265-268.

[4] Fleten, S.-E. and Näsäkkälä, E. (2003) *Gas Fired Power Plants: Investment Timing, Operating Flexibility and Abandonment*, Working Paper 04-03, Norwegian University of Science and Technology.

[5] Fleten, S.-E. et al. (2005) *Optimal Investment Strategies in Decentralized Renewable Power Generation under Uncertainty*, Paper, Munich Personal RePEc Archieve.

[6] Dixit, A. and Pindyck, R. (1994): *Investmtent under Uncertainty*, Princeton, New Jersey: Princeton University Press.

[7] Herbelot, O. (1992): *Option Valuation of Flexible Investments: The Case of Environmental Investments in the Electric Power Industry*, Unpublished Ph.D. dissertation, Massachusetts University of Technology, Cambridge, Massacusetts.

[8] Laurikka, H. and Koljonen, T. (2006): *Emission Trading and Investment Decisions in the Power Sector*, Energy Policy 34, p. 1063-1074.

[9] Neuhoff, K. et al. (2006): *Space and Time: Wind in an Investment Planning Model*, Cambridge Working Papers in Economics, Cambridge.

[10] Murto, P. and Nese, G. (2002): *Input Price Risk and Optimal Timing of Energy Investment: choice between fossil- and biofuel*, Working paper, Bergen Open Research Institute, Bergen.

[11] Paolella, M. and Taschini, Luca (2006): *An Econometric Analysis of Emission Trading Allowances*, Research Paper Series N06–26, Swiss Finance Institute.

[12] Pindyck, R. (2006): *Uncertainty in Environmental Economics*, Paper, MIT Center for Energy and Environmental Policy Research, Cambridge, Massacusetts.

[13] Reinauld, J. (2003): *Emission Trading and its Possible Impacts on Investment Decisions in the Power Sector*, Information Paper, International Energy Agency, Paris.

[14] The European Carbon Market Monthly Bulletin, 13 (2007): *What Is the Price of CO2: 1 euro or 17.5 euro?*, Caisse des Depot, Powernext Carbon.