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Carbon and energy prices under uncertainty: A theoretical analysis of fuel switching with non-equally efficient power plants

Vincent Bertrand[1]

European power producers have a major influence on the EU ETS, given that both their CO2 emissions and their EUA (European Union Allowance) allocations account for more than half of the total volumes of the scheme. Fuel switching is often considered as the main short-term abatement measure under the EU ETS. It consists in substituting combined cycle gas turbines (CCGTs) for hard-coal plants in power generation. Thereby coal plants run for shorter periods, and CO2 emissions are reduced. This paper provides a theoretical analysis of fuel switching, in a context where power plants involved are not equally efficient. We begin with some analyses which enable us to observe how differences in the efficiency of power plants impact the cost of fuel switching, and how this is related to the level of switching effort. Based on these preliminary analyses, we build the first partial equilibrium model taking into account the effect of differences in the efficiency of power plants involved in fuel switching. We also investigate the effect of the timing of fuel switching abatements, within the temporally defined environment of our dynamic partial equilibrium model. Results show that the gas price, uncontrolled CO_2 emissions and the timing of abatement (through the time of occurrence of random shocks on uncontrolled emissions) act together on the carbon price, and on its relationship with fuel prices.

Keywords: Tradable Emission Allowances, Fuel Switching, EU ETS, Efficiency of power plants, Partial Equilibrium Modeling

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A previous version of this paper was known as "The fuel switching process and tradable allowance prices: an equilibrium model for short-term carbon abatements in the European power sector". This work has been presented at the 21th Workshop on International Climate Policy (Zurich, October 2010), the 4th International Doctoral Meeting of Montpellier (Montpellier, May 2011), and at the 29th Journées de Microéonomie Appliquée (Brest, June 2012). The author would like to thank Michel Mougeot (CRESE, University of Franche-Comté), Florence Naegelen (CRESE, University of Franche-Comté), Jacques Percebois (CREDEN, University of Montpellier), Anna Creti (EconomiX, University Paris Ouest Nanterre la Défence) and three anonymous referees for helpful comments and suggestions on earlier versions of this paper. Any remaining errors are mine.

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Abstract

European power producers have a major influence on the EU ETS, given that both their CO_2 emissions and their EUA (European Union Allowance) allocations account for more than half of the total volumes of the scheme. Fuel switching is often considered as the main short-term abatement measure under the EU ETS. It consists in substituting combined cycle gas turbines (CCGTs) for hard-coal plants in power generation. Thereby coal plants run for shorter periods, and CO_2 emissions are reduced. This paper provides a theoretical analysis of fuel switching, in a context where power plants involved are not equally efficient. We begin with some analyses which enable us to observe how differences in the efficiency of power plants impact the cost of fuel switching, and how this is related to the level of switching effort. Based on these preliminary analyses, we build the first partial equilibrium model taking into account the effect of differences in the efficiency of power plants involved in fuel switching. We also investigate the effect of the timing of fuel switching abatements, within the temporally defined environment of our dynamic partial equilibrium model. Results show that the gas price, uncontrolled CO_2 emissions and the timing of abatement (through the time of occurrence of random shocks on uncontrolled emissions) act together on the carbon price, and on its relationship with fuel prices.

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1. Introduction

In order to reduce CO_2 emissions in a cost-effective way, the European Union (EU) has established the European Union Emission Trading Scheme (EU ETS), a cap-and-trade system for carbon emissions in the energy and industrial sectors. European power producers have a major influence on the European carbon market, given that both their CO_2 emissions and their EUA (European Union Allowance) allocations account for more than half of the total volumes of the EU ETS (Trotignon and Delbosc, 2008; Ellerman *et al.*, 2010). Thus carbon abatement decisions by European electricity producers are of major importance. Generating power with natural gas produces about half the CO_2 emissions of generating power with coal. Accordingly, substituting gas-fired plants (CCGTs – combined cycle gas turbines) for carbon-intensive coal-fired plants has become a way to achieve carbon abatements. This ability of power producers to reduce their CO_2 emissions by switching fuels from coal to gas is known as *fuel switching* and it is often considered as one of the main short-run abatement option under the EU ETS.

The question of fuel switching has been of growing interest since the creation of the EU ETS, and has given rise to an abundant empirical literature.[1] Many econometric studies have found that coal and gas prices are highly relevant in explaining the carbon price fluctuations (*e.g.* Mansanet-Bataller *et al.*, 2007; Alberola *et al.*, 2008; Bunn and Fezzi, 2009; Hintermann, 2010; Bertrand, 2011; Creti *et al.*, 2012), reflecting fuel switching. Among empirical papers, it is also worth mentioning simulations of Delarue and D'haeseleer (2008) and Delarue *et al.* (2010), which compute potential CO_2 abatements from fuel switching in several European countries. They report particularly high fuel switching potential in Germany, Spain, and in the UK. One can also mention works which simulate the cost of switching from coal to gas plants, considering several scenarios regarding carbon and fuel prices (*e.g.* Sijm *et al.*, 2005; Kanen, 2006; Delarue and D'haeseleer, 2007; Delarue *et al.*, 2007; Delarue *et al.*, 2010). By contrast, theoretical analyses of fuel switching are very scarce. Those works include Delarue and D'haeseleer (2007) and Delarue *et al.* (2007), which show how an efficient way of using a park of power plants leads to an indicator, the *switching point* or *fuel switching price*, which corresponds to the carbon price that makes fuel switching profitable. It is computed by equalizing the marginal cost of coal and gas power plants, including the cost of CO_2. In the same spirit, Hintermann (2010) uses the well known result which states that each firm equalizes its marginal abatement cost to the price of permits in equilibrium, to develop an expression for the carbon price with coal and gas prices as explanatory variables. However, among the few theoretical contributions, Carmona *et al.* (2009) is the only one which investigates fuel switching using partial equilibrium modeling. The authors consider a dynamic

[1] See Bertrand (2011) for an extensive review of this literature.

equilibrium model for a permit market, where each market participant produces electricity from coal plants and CCGTs, so that it can reduce part of its emissions by switching fuels from coal to gas. As a simplification, Carmona *et al.* (2009) assume a single type of CCGTs and a single type of coal plants for each firm, so that differences in the efficiency of power plants are not taken into account. As a consequence, their abatement cost function, which represents the expense generated by switching from coal plants to CCGTs, does not depend on the level of switching effort. Therefore, when coal and gas prices are fixed, the marginal abatement cost is constant, equal to a single switching price, whatever the value of the switching effort. As expected, their results demonstrate that the carbon price is an increasing function of the gas price, and a decreasing function of the coal price. They also find that the carbon price depends on the difference between the required level of CO_2 abatements (which is defined as the difference between CO_2 emissions in the “business-as-usual” scenario and initial endowments of allowances) and the optimal level of fuel switching effort.

To date, very few papers have studied the effect of differences in the efficiency of power plants involved in fuel switching. All rely on empirical analyses, in which the fuel switching cost is simulated, assuming different efficiency rates for coal plants and CCGTs (Sijm *et al.*, 2005; Delarue *et al.*, 2010, Bertrand, 2012).[2] However, to the best of our knowledge, no previous theoretical work has investigated this question using partial equilibrium modeling. This paper fills this gap in literature, by providing the first partial equilibrium model for fuel switching, taking into account the effect of differences in the efficiency of power plants. This extends the analysis of Carmona *et al.* (2009), which considered a partial equilibrium model for fuel switching, assuming one representative type of coal and gas plants for each power producer. By contrast, we consider a situation in which each power producer own different types of CCGTs, and, accordingly, it may find it profitable to switch some of these power plants and not the others. Our aim is to identify how the fuel switching behavior is modified in this context, and what are the implications. We also investigate the effect of the timing of abatements, within the temporally defined stochastic environment of our dynamic partial equilibrium model. The ability to adapt to a rise in uncontrolled emissions depends on how much time firms have before the end of the Phase. This would affect the fuel switching behavior, and the relationships between uncontrolled emissions, the carbon price and fuel prices.[3]

[2] Delarue *et al.* (2010) simulate the switching price with several more or less efficient types of power plants. They consider efficiency rates ranging from 36 to 38% for coal plants, and from 36 to 50% for CCGTs. Thus, for a given carbon price, the authors illustrate that fuel switching may be a profitable option with some power plants, and not with others. Sijm *et al.* (2005) estimate that the switching price declines by 22% when the efficiency rate of CCGTs involved is increased from 53% to 62%.

[3] Uncontrolled emissions (or “business-as-usual” emissions) are CO_2 emissions before any abatement measures. They are exogenous for power producers, determined by their level of production which is set by random electricity demand.

We focus our analysis on differences in the efficiency of gas plants, whereas, as a simplification, we neglect those of coal plants (throughout the paper, when we refer to gas and coal plants, we mean CCGTs and hard-coal plants). First, the dispersion in efficiency rates of CCGTs is much higher than that of coal plants involved in fuel switching. Furthermore, based on a preliminary analysis (section 2), we identified that the impact of differences in the efficiency of coal plants is ambiguous and weak, whereas it is unambiguous and much more significant for CCGTs. Accordingly, the analysis presented in section 4 only takes into account the effect of differences in the efficiency of CCGTs. We use a dynamic partial equilibrium model along the lines of the equilibrium models for tradable permits developed since the pioneering work of Montgomery (1972).[4] Using a cost function that represents the expense engendered by fuel switching, we follow the same strategy as in Carmona *et al.* (2009). Unlike them however, the level of switching effort influences the sensitivity of the marginal cost of fuel switching with respect to fuel prices. This reflects the fact that, in our case, power plants used in the fuel switching process do not all have the same energy efficiency. Thus, the level of switching effort determines the efficiency of power plants involved in the switching process, which, in turn, affects the marginal cost of fuel switching and its dependence on fuel prices. Since the level of switching effort depends on uncontrolled CO_2 emissions, an important implication is that the dependence of the marginal abatement cost on fuel prices would be affected by uncontrolled CO_2 emissions, which are uncertain.

Among our main results, we demonstrate that abatement depends on fuel prices. In turn, the carbon price depends on fuel prices so that it increases with the gas price and decreases with the coal price. We also find that uncontrolled CO_2 emissions influence the carbon price and that the time of their occurrence in the Phase matters. Furthermore, we show that the influence of the gas price on the carbon price depends on the level of uncontrolled CO_2 emissions, due to differences in the efficiency of gas plants that are used in the fuel switching process. Thus, the relationship between the carbon price and the gas price depends on the intersection between the volume of uncontrolled emissions and their time of occurrence in the Phase. All of that determine the sensitivity of the carbon price with respect to the gas price. On the one hand, the fuel switching process that we describe implies that ever less efficient gas plants are substituted for coal plants when the switching effort increases. As a consequence, when uncontrolled emissions increase, the switching effort intensifies and more gas must be consumed to abate one tonne of CO_2, which leads to having the gas price a greater influence on the marginal cost of fuel switching and on the carbon price. On the other hand, a positive shock on uncontrolled emissions will lead to an even greater dependence of the carbon price on the gas price if this shock occurs in a period which is close to the end of the Phase. The logic arises from the ability to adapt to a rise in uncontrolled emissions.

[4] See Bertrand (2013) for a literature review.

Indeed, if a rise in uncontrolled emissions suddenly occurs in a period which is close to the end of the Phase, it is difficult for firms to postpone abatement efforts later in the Phase. Therefore, in such a situation, a great switching effort would have to be performed in a small time interval, which would make the marginal cost of abatement even more sensitive to the gas price.

Until now, several papers have shown that the carbon price depends on energy prices. Most of them rely on econometric estimations (*e.g.* Mansanet-Bataller *et al.*, 2007; Alberola *et al.*, 2008; Bunn and Fezzi, 2009; Hintermann, 2010; Bertrand, 2011; Creti *et al.*, 2012), and some on simulation or theoretical analyses (Sijm *et al.*, 2005; Kanen, 2006; Delarue and D'haeseleer, 2007; Delarue *et al.*, 2007; Carmona *et al.*, 2009; Delarue *et al.*, 2010; Bertrand, 2012). Other papers, have investigated the effect of uncontrolled CO_2 emissions and their time of occurrence (*e.g.* Seifert *et al.*, 2008; Hintermann, 2010). This paper extends these previous works by showing that the gas price, uncontrolled CO_2 emissions and the timing of abatement (through the time of occurrence of random shocks) act together on the carbon price, and on its relationship with fuel prices. Such contribution would serve as a bridge between two strands of literature: the one focusing on the price fundamentals, neglecting the timing aspect, and the one which focuses on the timing issues, neglecting the effect of price fundamentals such as energy prices.

The remainder of the paper is organized as follows. Section 2 introduces fuel switching, and the way differences in the efficiency of power plants affect the switching behavior and the cost of fuel switching. In section 3, we describe the characteristics of the cost function we will use in the model. Next, in section 4, the model and results are presented. To conclude, section 5 summarizes the main findings and their value for practical applications.

2. Fuel switching and efficiency of power plants

Fuel switching takes place in the short run, because it happens in a context where the number of power plants and their energy efficiencies are fixed. Fuel and carbon prices determine the demand for carbon allowances by setting the composition of power generation, and which technology (coal plants or CCGTs) is brought online first. In this way, as power producers are the main actors in the EU ETS, fuel prices strongly influence the carbon price.

2.1 Merit order and fuel switching

The basic idea of fuel switching is that with a high enough CO_2 price (and a low enough gas/coal price ratio), coal plants switch places with gas plants in the merit order.[5] When power producers do

[5] The merit order is the ranking of all power plants of a given park by marginal cost of electricity production. Technologies are stacked in order of increasing marginal cost, so that power producers add more and more expensive

not integrate the carbon cost into their decisions ("business-as-usual" scenario), coal plants are usually brought on line first, because of their lower fuel cost. Gas plants are used next, during shorter periods, when demand for power is higher. However, with a high enough carbon price, gas plants may be preferable to coal plants, due to their lower carbon intensity. That is, if the cost of increased carbon emissions with coal plants is higher than the additional fuel cost associated with the decision to produce with gas rather than with coal, it is cheaper to use gas plants first instead of coal plants. If such switching occurs, CO_2 emissions are reduced because coal plants are brought on line for shorter periods (*i.e.* they move higher in the merit order), but the fuel cost to generate electricity is increased. Therefore, all other things being equal, a relatively high gas price (and/or a relatively low coal price) encourages power producers to use more coal, which drives up demand for allowances and the carbon price (and *vice versa*).

Fuel switching we describe in this paper refers to the ability of power producers to reduce their CO_2 emissions by generating electricity with CCGTs where they previously used hard-coal plants.[6] This happens in intermediate levels of production that occur between 20 and 80% of the time (*i.e. intermediate load*).[7] To illustrate this, let us assume a simplified park of power plants which may be representative of countries where fuel switching can occur (*i.e.* countries with a high proportion of coal plants and CCGTs in intermediate load). This is given in Table 1.

[insert Table 1]

Applying the merit order principle to this power system, we obtain the merit order curve given in Figure 1 (values of marginal costs are arbitrary but consistent with what we observe in practice, see Kanen (2006) and Delarue *et al.* (2010)).

[insert Figure 1]

If we introduce a carbon price, CCGTs may become preferable to coal plants, due to their lower carbon output. Hence, with a high enough carbon price, coal plants switch places with gas plants in the merit order. This is illustrated in Figure 2.

[insert Figure 2]

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plants to production as demand increases.

[6] Fuel switching can also occur with other plants for other levels of load (e.g., between oil plants and open cycle gas turbines, or between hard-coal and lignite). However, as the quantities of carbon involved in switching between hard-coal plants and CCGTs are much higher, we focus on this type of switching (as usual in the literature about the EU ETS).

[7] Following Unger (2002), we distinguish between base (more than 80% of the time), peak (less than 20%) and intermediate load (between 20 and 80%). Thus we point out that fuel switching we describe here does not happen in base or peak load, but only in intermediate load.

In Figure 2, the *switching zone* is the lower part of intermediate load, which corresponds to longer time periods than the remaining part of intermediate load. Hence, if fuel switching happens, power producers decide to use CCGTs in the switching zone, which allows them to reduce their CO_2 emissions compared with the BAU scenario.

Note that inclusion of Renewable Energy Sources (RES) would affect the merit order and abatements from fuel switching. Indeed, injecting RES such as wind or solar at the bottom of the merit order would translate into a displacement of the generation interval in which fuel switching occurs (*i.e.* T3s and T4s, as defined in this paper, would move higher in the merit order). According to Weigt *et al.* (2012), this displacement, when caused by a RES policy in combination with an ETS policy, may result in higher abatements than the sum of the abatements resulting from using either instrument alone.[8] Another abatement measure coming from RES is the biomass co-firing in existing coal plants. This allows power producers to reduce their CO_2 emissions, because it substitutes biomass, with zero emissions under the EU ETS, for coal, which produces the highest CO_2 emissions. As with fuel switching, co-firing provides opportunities to reducing CO_2 emissions using existing installations, and is not subject to problems of intermittency when used to generate electricity (as with wind or solar). As opposed to fuel switching, some investments are needed to retrofit coal plants. However, co-firing does not necessarily entail changes in the dispatch of power plants, if the induced variation in the marginal cost of coal plants is not so great as to displace them in the merit order.[9]

2.2 Switching effort and efficiency of power plants

The level of switching effort has to be taken into consideration, because it determines the efficiency of power plants involved in fuel switching. Indeed, a power producer owning several more or less efficient types of coal plants and CCGTs will substitute ever less efficient CCGTs for ever more efficient coal plants, as the fuel switching effort increases. On the one hand, as the fuel switching effort increases, power producers tend to use ever less efficient CCGTs in the fuel switching process, because they want to produce first with units that are less costly to run (*i.e.* the most efficient). On the other hand, as the fuel switching effort increases, power producers tend to drop ever more efficient coal plants, because they want to shut down first coal plants that are more costly to run.

[8] As long as the RES injection is not so great as to replace all fossil-fired generation, this does not affect the analysis developed in this paper. However, as the RES injection displaces fossil-fired generation, fuel switching would occur higher in the merit order, generating fewer abatements. These considerations are beyond the scope of this paper. The interested reader should refer to Weigt *et al.* (2012).

[9] Here again, these considerations are beyond the scope of this paper. The interested reader should refer to Le Cadre *et al.* (2011) and Bertrand (2013), for analyses of the cost of biomass co-firing, the impact on the merit order, and the biomass and CO_2 breakeven points for co-firing.

To illustrate this, we take the example of the power system in Table 1 again. However, we assume three different types of CCGTs with efficiency rates of 45, 50 and 55%, respectively. We also assume three different types of coal plants with efficiency rates of 36, 38 and 40%, respectively. [10] Let us define T_4^{55}, the CCGT of 55% efficiency, T_4^{50}, the CCGT of 50% efficiency, and T_4^{45}, the CCGT of 45% efficiency. T_3^{40} is the coal plant of 40% efficiency, T_3^{38}, the coal plant of 38% efficiency, and T_3^{36}, the coal plant of 36% efficiency. In addition, we assume three levels of switching effort: low (= one T4 in the switching zone), medium (= two T4s in the switching zone) and high (= three T4s in the switching zone). As we explained just before, power producers substitute ever less efficient CCGTs for ever more efficient coal plants, as the fuel switching effort rises. Therefore, in our example, a power producer will switch only T_4^{55} for the low level of effort, T_4^{55} and T_4^{50} for the medium level, T_4^{55}, T_4^{50}, and T_4^{45} for the high level. Taking into account differences in the efficiency of coal plants, T_4^{55} is substituted for T_3^{36} in the low level of effort. T_4^{55} is substituted for T_3^{36} and T_4^{50} for T_3^{38} in the medium level of effort. Finally, in the high level of effort, T_4^{55} is substituted for T_3^{36}, T_4^{50} for T_3^{38}, and T_4^{45} for T_3^{40}. This is summarized in Table 2.

[insert Table 2]

Assuming that only a medium level of switching effort is a profitable option (*i.e.* it would be worth switching to 55 and 50% efficiency CCGTs, but not to 45% ones), the merit order would be modified as in Figure 3.

[insert Figure 3]

As we can deduce from Figure 3, for any level of electricity production where switching is possible (*i.e.* in intermediate load, when some CCGTs are available), the proportion of CCGTs in the switching zone may vary (depending on carbon, coal and gas prices). If the proportion of CCGTs in the switching zone rises, carbon emissions decrease and, consequently, fewer allowances are used. Hence, the proportion of CCGTs in the switching zone and allowances can be considered as substitutable inputs for electricity production, and there is an arbitrage for power producers, which depends on the difference between the fuel switching cost and the cost of buying permits.

[10] According to the literature, in most cases, the efficiency rate of coal plants involved in fuel switching (*i.e.* which are hard-coal plants, dedicated to intermediate load) is around 38% while it ranges from 45% to 55% (and, sometimes, and it can reach 60% or more) for CCGTs (Sijm *et al.*, 2005; Kanen, 2006; Delarue and D'haeseleer, 2007; Delarue *et al.*, 2010). Of course, there are other coal plants which are very different of those used in fuel switching with CCGTs. They may be significantly more efficient (*e.g.* circulating fluidized bed combustion technologies) or less efficient (*e.g.* lignite), but they are not used in intermediate load, and thus they are not involved in the fuel switching we describe here.

2.3 Cost of fuel switching and efficiency of power plants

Let us first introduce the fuel switching price, which is the usual indicator for the cost of fuel switching. This will help us to illustrate the effect of differences in the efficiency of power plants on the fuel switching cost. Next, we present the cost function we will use in the model of section 4.

Fuel switching price

The fuel switching price corresponds to the carbon price that makes coal plants and CCGTs equally attractive under the EU ETS. It is computed by equalizing the marginal cost of coal and gas power plants, including the cost of CO_2. This reflects the breakeven points, which express how advantageous fuel switching is at a certain point in time, given the fuel and CO_2 prices.

We define the marginal costs of one MWh of electricity (in Euros) with coal and gas plants, respectively, as: $MC_c^{BAU} = h_c\, C$ and $MC_g^{BAU} = h_g\, G$, in the BAU scenario, $MC_c^{EUETS} = h_c\, C + e_c\, p$ and $MC_g^{EUETS} = h_g\, G + e_g\, p$, under the EU ETS. Here, e_c and e_g are emission factors (tCO_2/MWhe) of coal and gas plants, respectively. h_c (tcoal/MWhe) and h_g (MWhp/MWhe) are heating rates measuring how much fuel is consumed to generate one MWh of electricity with the same plants. C, G and p are the prices of coal (Euros/tonne), gas (Euros/MWhp) and CO_2 (Euros/tCO_2). Using these notations, the switching price, as defined in literature (*e.g.* Delarue and D'haeseleer, 2007; Carmona *et al.*, 2009), can be derived by equalizing MC_c^{EUETS} and MC_g^{EUETS}:

$$SW = \frac{h_g\, G - h_c\, C}{e_c - e_g}. \qquad \textbf{(1)}$$

SW represents the additional fuel cost (Euros/tCO_2) associated with switching from coal plants to CCGTs to abate one tonne of CO_2. It can also be defined as the carbon price that makes CCGTs and coal plants equally attractive. Thus, fuel switching occurs (not occurs, respectively) if and only if $p > SW$ ($p < SW$, respectively).

So far, we implicitly assumed that all plants involved in fuel switching were equally efficient. However, differences in the efficiency of power plants influence the values emissions and heating rates, which, in turn, determine value of the switching price, for any coal and gas prices. Let us define h_g^i and e_g^i (h_c^j and e_c^j, respectively), the heating and emissions rates associated with CCGTs of *i*% efficiency (coal plants of *j*% efficiency, respectively). Furthermore, we call η_i the efficiency rate of *i*% efficiency CCGTs, and η_j the efficiency rate of *j*% efficiency coal plants (MWhe/MWhp). Thus, one can compute h_c^j using equations: $h_c^j = 0.144/\eta_j$, where 0.144 represents the quantity of coal in tonnes per MWhp (Carmona *et al.*, 2009). Likewise, $h_g^i = 1/\eta_i$. Finally, e_g^i and e_c^j can be computed using equations: $e_g^i = 0.202/\eta_i$ and $e_c^i = 0.341/\eta_j$, where 0.202

and 0.341 are the primary energy emission factors (tCO_2/MWhp) of natural gas and hard-coal, respectively (IPCC, 2006). As an illustration, we take again our example with the three types of gas (45, 50 and 55%) and coal (36, 38 and 40%) plants. The values of heating and emission rates can be calculated for each type of power plant, as in Table 3.

[insert Table 3]

Combining **(1)** with the values given in Table 3, we observe that, actually, there is one switching price, $SW_{i,j}$, for any given pair of *i*% CCGT and *j*% coal plants. Thus, for any given fuel prices, there are several switching prices associated with different pairings of coal and gas plants. This creates a *switching band*, and, accordingly, it may be profitable to switch certain plants (for which $p > SW_{i,j}$) and not others. This is illustrated in Figure 4.

[insert Figure 4]

According to Figure 4, we always have $SW_{45,40} > SW_{50,38} > SW_{55,36}$, which means that the switching price (*i.e.* the marginal cost of fuel switching) increases when the level of switching effort rises (see Table 2).[11] Indeed, because power producers substitute ever less efficient gas plants for coal plants, the marginal fuel switching cost increases, due to a rising cost for gas consumption. With coal plants, the reasoning should be reversed. That is, when the fuel switching effort increases, power producers tend to drop ever more efficient coal plants. However, as opposed to what happens with gas, modifying the efficiency rate of coal plants induces two opposite effects for the avoided coal consumption associated with fuel switching (this is described in the remainder of this section). Therefore, it is difficult to conclude on the total effect, and, with the low dispersion in the efficiency rates of coal plants involved in fuel switching, this would make the total effect be weak.[12]

Marginal cost of switching, fuel prices and level of switching effort

We saw that the efficiency of power plants involved in fuel switching depends on the level of switching effort. Hence, the marginal cost of switching increases with the level of effort, due to a rising cost for gas consumption. Moreover, the level of switching effort also influences the sensitivity of the marginal cost of switching to fuel prices. More precisely, in case of gas, the marginal cost of fuel switching becomes more sensitive to the gas price when the switching effort increases. This is because, as the switching effort increases, power producers switch gas plants that consume more

[11] Note that assuming $SW_{45,40} > p > SW_{50,38} > SW_{55,36}$ leads to the medium level of switching effort, as illustrated in Figure 3.

[12] Similar values for efficiency rates of coal plants involved in fuel switching can be found in Sijm *et al.* (2005), Kanen (2006), Delarue and D'haeseleer (2007), Delarue *et al.* (2010), etc.

and more gas to generate one *switched MWh* of electricity.[13] Therefore, the volume of CO_2 emissions per switched MWh increases, meaning that more switched MWhs have to be generated to abate one tonne of CO_2. As a consequence, the gas consumption needed to abate one tonne of CO_2 increases. To summarize, the total effect of increasing the level of switching effort (and thus decreasing the efficiency of CCGTs) can be decomposed into two effects: the gas consumption per switched MWh increases (*effect 1*); the number of switched MWhs needed to abate one tonne of CO_2 increases (*effect 2*). Taking into account effects 1 and 2, we see that the gas consumption per tonne of CO_2 abatement increases when switching effort intensifies, and, as a consequence, the marginal cost of fuel switching becomes increasingly dependent on the gas price.

Let us take again the example with the three types of gas (45, 50 and 55%) and coal (36, 38 and 40%) plants. In this case, using the values of heating and emission rates we computed in Table 3, one can illustrate effects 1 and 2 as in Table 4.

[insert Table 4]

Table 4 indicates that, as the level of switching effort increases, each switched MWh comes with a higher gas consumption (effect 1, column 2) and less CO_2 abatement (column 3). Therefore, more switched MWhs have to be generated to abate one tonne of CO_2 (effect 2, column 4). Overall (effect 1 and effect 2), the gas consumption needed to abate one tonne of CO_2 increases (column 5), and the marginal cost of fuel switching becomes increasingly dependent on the gas price. This can also be shown by looking at the absolute value of the first derivative of equation **(1)** with respect to the gas price:

$$\left|\frac{\partial SW}{\partial G}\right| = \left|\frac{h_g}{e_c - e_g}\right| = \frac{h_g}{e_c - e_g}, \quad \textbf{(2)}$$

When decreasing the efficiency of CCGTs, the values of h_g and e_g increase. The increase in h_g tends to increase the value of **(2)**, which correspond to effect 1. On the other hand, the increase in e_g contributes to increase the value of **(2)**, which correspond to effect 2. Here again, we conclude unambiguously that when efficiency of CCGTs decrease the marginal cost of switching becomes more dependent on the gas price.

As with the gas price, one can use the absolute value of the first derivative of equation **(1)** with respect to the coal price, to investigate the effect of modifying the efficiency rate of coal plants:

[13] For convenience, we call *switched MWh* each MWh of electricity generated by switching coal and gas plants (*i.e.* by using T4s in place of T3s in the switching zone).

$$\left|\frac{\partial SW}{\partial C}\right| = \left|\frac{-h_c}{e_c - e_g}\right| = \frac{h_c}{e_c - e_g}, \quad \textbf{(3)}$$

When the efficiency of coal plants increases, the values of h_c and e_c decrease. This creates two opposite effects on **(3)** that make the total effect unpredictable. Hence, we cannot conclude on how modifying the efficiency of coal plants impacts the sensitivity of the marginal cost of switching to the coal price.

As in the case of gas, the total effect of increasing the level of switching effort (and thus increasing the efficiency of coal plants) can be decomposed into two effects: the avoided coal consumption per switched MWh decreases (*effect 1*); the number of switched MWhs needed to abate one tonne of CO_2 increases (*effect 2*). Unlike what happens with gas, those two effects work in opposite directions, and, therefore, it is difficult to conclude on the total effect of a rise in efficiency of coal plants. This is illustrated in Table 5.

[insert Table 5]

On the one hand, when the switching effort increases, the avoided coal consumption per switched MWh decreases because more efficient coal plants are shut down (effect 1, column 2). Therefore, each switched MWh depends less on the coal price as the switching effort rises. This contributes to reducing the (negative) influence of the coal price on the marginal cost of switching. On the other hand, the number of switched MWhs needed to abate one tonne of CO_2 increases (effect 2, column 4). In other words, more MWhs generated with coal have to be replaced by MWhs generated with gas to abate one tonne of CO_2. This contributes to increasing the (negative) influence of the coal price on the marginal cost of switching. Taking into account effects 1 and 2, one can conclude that the net effect is that the avoided cost for coal consumption per tonne of CO_2 abatement increases (column 5) when the switching effort intensifies (*i.e.* effect 2 dominates effect 1). Accordingly, one would expect the marginal cost of fuel switching to become more (negatively) dependent on the coal price. However the net effect is very small compared with gas, where effects 1 and 2 work in the same direction (Table 4). In addition to these two opposite effects, the dispersion in the distribution of the efficiency rates of coal plants is small. This makes the net effect being still smaller. Actually, when looking at Table 5 we observe that the net effect is almost not impacted when taking into account differences in the efficiency of coal plants, while neglecting differences in the efficiency of CCGTs.

In view of all the elements we described above, we choose to focus our analysis on differences in the efficiency of gas plants, whereas, as a simplification, we neglect those of coal plants. Indeed, as illustrated in this section, the impact of differences in the efficiency of CGGTs is unambiguous, and much more significant since, compared with coal plants, the dispersion in efficiency rates is much higher for CCGTs. The work presented in the next section provides the first partial equilibrium model for fuel switching, taking into account the effect of differences in the efficiency of CCGTs.

3. Differences in the efficiency of gas plants and fuel switching process: cost function and trading opportunities

In this section we discuss how characteristics we described before can be included in a cost function for fuel switching. We also show that mutually beneficial trading opportunities may exist among firms which own different types of CCGTs. Once a proper cost function is derived, it is used in the model of section 4.

Stepwise constant marginal cost function for fuel switching

Using the switching price as defined in equation **(1)**, one can derive a first cost function for switching with the appropriate properties as mentioned above. In this case, the Marginal Abatement Cost (MAC) curve is stepwise constant. Each step corresponds to a constant marginal cost equal to a certain switching price. As an illustration, let us assume two power producers, A and B, which own a park of power plants with CCGTs and coal plants, all dedicated to intermediate load production (as before, we do not consider other technologies dedicated to peak and base load). Each one has three different types of CCGTs, and only one type of coal plants. Furthermore, CCGTs of A are globally more efficient than CCGTs of B. We say that A has a *profile* of CCGTs which is more efficient than that of B. By contrast, there is a unique profile of coal plants for A and B, in which units are all 38% efficiency. Table 6 presents profiles of CCGTs for A and B.

[insert Table 6]

Using Table 6, we can represent the stepwise constant MAC curves of A and B, as in Figure 5.

[insert Figure 5]

Figure 5 shows that, as the switching effort increases, we move to higher switching prices, associated with dirtier CCGTs, which reflect higher (constant) marginal costs of switching. Moreover, since the heating and emission rates increase, the switching prices become more dependent on the gas price. Figure 5 also indicates that A is more efficient than B. Hence, mutually beneficial trading opportunities exist between A and B, due to differences in their profiles of CCGTs. To illustrate, let us define $\Xi = \xi_A^k + \xi_B^k$, the overall abatement effort of A and B to comply with an emission standard. ξ_A^k and ξ_B^k are the switching efforts of A and B, with k = {$Trade$, $NoTrade$}, so that $\xi_A^{NoTrade} = \xi_B^{NoTrade} = \Xi/2$ if emission trading is not allowed. However, when emission trading is allowed, if $SW_{51} < p < SW_{47}$, A can make profits by increasing its switching effort ($\xi_A^{Trade} > \xi_A^{NoTrade}$), while it is profitable for B to reduce its switching effort ($\xi_B^{Trade} < \xi_B^{NoTrade}$). On the one hand, when $SW_{51} < p$, it is worth switching all the T_4^{51} units that are available. Thus, A increases its switching effort from $\xi_A^{NoTrade}$ to ξ_A^{Trade}, and unused allowances are sold to B with a profit per unit equal to $p - SW_{51}$. On the other hand, when $SW_{47} > p$, switching the T_4^{47} plants is not a profitable option. Thus, B reduces its switching effort from $\xi_B^{NoTrade}$ to ξ_B^{Trade}, and lacking allowances are bought from A with a discount per tonne of CO_2 equals to $p - SW_{47}$.

Fuel switching cost function for the model

A cost function with a continuous marginal cost curve is more convenient for optimization. Thus, we assume that the following cost function can be retained for the model:

$$C(\xi_i) = \frac{1}{2}\xi_i^2 c(G) - \xi_i c(C), \qquad \textbf{(4)}$$

where C and G are coal and gas prices and ξ_i is switching effort of firm *i*. $c(C)$ and $c(G)$ stand for the influences of fuel prices on the fuel switching cost. Fuel prices are assumed exogenous. As a consequence, demand for fuels triggered by fuel switching efforts is supposed to have no influence on fuel prices. Of course this hypothesis does not fully fit reality, but it can be supported in some respects. First of all, the volume of CO_2 abatements that can be obtained by fuel switching is limited since, in each period, available gas capacities are limited (Bertrand, 2012). This implies that fuel markets should not be very strongly affected by changes in demands for fuels created by the EU ETS. Secondly, European fuel markets are highly integrated into world markets since more than the half of fuels consumed in European countries are imported from outside of Europe (Hintermann, 2010). At the same time, demand for fuels of European power producers is relatively small compared to overall quantities consumed throughout the world. Therefore, variations in fuel demands for switching purposes should not be very important for world and European fuel prices.

In equation **(4)**, convexity allows representing the rising dependence of the marginal cost of fuel switching on the gas price, as the switching effort increases. For simplicity, we assume that $c(C)$ and $c(G)$ are linear in fuel prices. Equation **(4)** is modified as follows:

$$C_i(\xi_i) = \frac{1}{2}\xi_i^2 a_i G - \xi_i bC, \qquad \textbf{(5)}$$

where $a_i > 0$ and $b > 0$ are parameters that show how fuel prices are taken into account in $c(C)$ and $c(G)$, and then how fuel prices influence the fuel switching cost.

Cost function **(5)** satisfies the properties we discussed in section 2.3. Indeed, when the switching effort (ξ_i) rises, for any given fuel prices, the marginal cost of switching ($\partial C_i(\xi_i)/\partial \xi_i$) increases and becomes more dependent on the gas price. Hence, convexity allows us to represent the rising dependence of the marginal cost of switching on the gas price, as the switching effort increases. Thus, the higher ξ_i is, the higher the impact of the gas price on the marginal cost of switching is. On the contrary, we have a constant influence of the coal price on the marginal cost of switching, whatever the value of ξ_i. This reflects our assumption that each firm owns only one type of coal plants.

Another important aspect of equation **(5)** is the way we introduce heterogeneity. This is accounted for by a_i, which is a firm-specific parameter measuring the efficiency of a given firm *i* to abate CO_2 by fuel switching. The value of a_i depends on how efficient are the CCGTs of a given firm i. That is a firm with a profile of CCGTs which is globally weakly efficient (*e.g.* a profile where most of the CCGTs are around 45% efficiency) has a high value for a_i, so that this firm is weakly efficient to abate CO_2 by fuel switching. On the contrary, a firm with a profile of CCGTs which is globally strongly efficient (*e.g.* a profile where most of the CCGTs are around 55% efficiency) has a low value for a_i, so that this firm is strongly efficient to abate CO_2 by fuel switching. Accordingly, we assume that a_i can take any value between $\underline{a}$ (firm with the highest efficiency) and $\overline{a}$ (firm with the lowest efficiency) with $\underline{a} < \overline{a}$. By contrast, parameter b has the same value for each firm. This means that the profile of coal plants is the same for each firm. In other words, not only does each firm have a profile of coal plants in which all the units have the same efficiency rate (and thus C has a constant influence on $\partial C_i(\xi_i)/\partial \xi_i$ whatever the value of ξ_i), but, in addition, there is a unique profile of coal plants for all the firms. For instance, taking again our illustration with power producers A and B, there is unique profile of coal plants for A and B in which all the units of A and B have the same efficiency rate of 38%. However, A has a profile of CCGTs which is more efficient than that of B (Table 6). Therefore, $a_A < a_B$, which means that A is more efficient than B to abate CO_2 by fuel switching. The slope of the MAC curve of B is steeper than that of A, and, therefore, A can abate more CO_2 for any given carbon price. This can be illustrated in the same way as we did in Figure 6, when considering a stepwise constant MAC, equal to the switching price.

4. The model

We consider a continuum of power producers whose carbon emissions are constrained by an emission trading scheme such as the EU ETS. Each firm, indexed by $i \in [0,1]$, is assumed to be a price taker on the carbon market. In addition, we assume that each firm owns a fixed park of electricity generation plants (*i.e.* the number of units and the energy efficiency of each one cannot vary in the considered time interval) in which there are coal-fired plants, all of the same type, and different types of gas-fired plants with different efficiency rates.

In the EU ETS, there are several years in a Phase. Theoretically, firms build a compliance strategy for each year, because at the end of each year they have to surrender a number of allowances equal to their CO_2 emissions recorded during this year. However, in practice, the EU ETS rule allows firms to borrow permits from the following year for compliance in the current year.[14] This enables firms in each year, to postpone the current emission constraint to the following year. As a consequence, within a Phase, firms have the ability, year by year, to postpone the emission constraint of each year to the end of the Phase. So, carbon trading in a Phase works as if there were only one constraint per Phase. Accordingly, we set the time horizon so that it corresponds to a Phase in the EU ETS where there are T periods, and only one compliance constraint. Thus, firms make their decisions in each period, indexed by $t \in [1, \ldots, T]$, and, at the end of period T, the authorities check that the number of allowances held by each firm is equivalent to its carbon emissions recorded throughout the Phase. Therefore, at the end of period T, each firm has to satisfy the following compliance constraint:

$$\sum_{j=1}^{T} u_{j,i} - \sum_{j=1}^{T} \xi_{j,i} = \delta_i + \sum_{j=1}^{T} \theta_{j,i}, \qquad \textbf{(6)}$$

where, for a firm i in a period t, $u_{t,i}$ stands for uncontrolled CO_2 emissions, $\xi_{t,i}$ is the switching effort (*i.e.* the number of tonnes of CO_2 not emitted thanks to fuel switching) and $\theta_{t,i}$ represents the number of permits traded on the market (where $\theta_{t,i} > 0$ if permits are bought, and $\theta_{t,i} < 0$ if permits are sold). Finally, δ_i is the number of allowances allocated to a firm i for the whole Phase (known since the beginning of the first period). We assume that there is a single constraint on the total amount of emissions over the T time periods, and that all permits are issued at the beginning of

[14] Each participating installation receives its allocation of EUAs at the beginning of each year, on February 28. In addition, installations must surrender the allowances corresponding to their previous year's verified emissions before April 30. For example, for the 2010 emissions, April 30 of 2011 was the deadline to surrender allowances corresponding to verified emissions. This implies that firms can use allocations of year t+1 to cover emissions of year t. This means that firms can borrow permits from the following year for compliance in the current year.

first period. Therefore, firms can freely transfer permits across time periods, and thus, implicitly, banking and borrowing are allowed.[15]

In each period *t*, in order to comply with the policy at the end of the Phase, firms can trade allowances on a competitive secondary market, at a price p_t, or, alternatively, reduce their CO_2 emissions by fuel switching. Accordingly, the total cost of compliance of a firm i in each period t is given by:

$$CT_i(\theta_{t,i}, \xi_{t,i}) = p_t \theta_{t,i} + C_i(\xi_{t,i}), \qquad \textbf{(7)}$$

where $C_i(\xi_{t,i}) = \frac{1}{2}\xi_{t,i}^2 a_i G_t - \xi_{t,i} b C_t$ is the fuel switching cost, as given by equation **(5)**, and $a_i \in [\underline{a}, \overline{a}]$ with $\underline{a} < \overline{a}$ (*i.e.* $\underline{a} \equiv a_0$ and $\overline{a} \equiv a_1$, since $i \in [0,1]$). In each period *t*, the problem of a firm is to choose $\xi_{t,i}$ and $\theta_{t,i}$ to minimize the cost of compliance in such a way that the firm will comply with the compliance constraint at the end of period *T*. At the beginning of each period *t*, a firm observes p_t, C_t, G_t, $u_{t,i}$, δ_i and *D*, the overall number of allowances allocated to all firms for the Phase. In addition, p_j, C_j, G_j, $\xi_{j,i}$, $\theta_{j,i}$ and $u_{j,i}$ are known $\forall j \in \{1, \ldots, t-1\}$. However, $p_{j'}$, $C_{j'}$, $G_{j'}$, $\xi_{j',i}$, $\theta_{j',i}$ and $u_{j',i}$ are unknown $\forall j' \in \{t+1, \ldots, T\}$. In that case, these are stochastic variables whose exact values are known only at the beginning of the period j' at hand. We note them $\tilde{p_{j'}}$, $\tilde{C_{j'}}$, $\tilde{G_{j'}}$, $\tilde{\xi_{j',\iota}}$, $\tilde{\theta_{j',\iota}}$ and $\tilde{u_{j',\iota}}$.[16]

Firms solve an optimization problem in each period *t*, where their decisions depend on the realizations of stochastic state variables that are uncontrolled CO_2 emissions and fuel prices. Moreover, they have to take into account the optimal decisions from the future and from the past. Therefore, we have a dynamic optimization problem, which is solved by backward induction.

4.1 Equilibrium strategies of firms

Because the problem is solved by backward induction, we have to begin the resolution with the last period of the Phase. In period *T*, each firm achieves its optimal strategy by solving the problem:

$$\min_{\theta_{T,i}\ ,\ \xi_{T,i}} \quad CT_i(\theta_{T,i}, \xi_{T,i}) = p_T \theta_{T,i} + C_i(\xi_{T,i})$$
$$s.t \quad \sum_{j=1}^{T} u_{j,i} - \sum_{j=1}^{T} \xi_{j,i} = \delta_i + \sum_{j=1}^{T} \theta_{j,i} \qquad \textbf{(8)}$$

[15] A similar treatment can be found in Tietenberg (1985), and in numerous recent papers investigating the carbon price behavior in the EU ETS (*e.g.* Seifert *et al.*, 2008; Carmona *et al.*, 2009; Hintermann, 2010; Hitzemann and UhrigHombourg, 2010; Barrieu and Fehr, 2011).

[16] From a period *t-s* ($\forall s > 0$) we note $\tilde{v_t}$ any random variable v_t whose realization is known at the beginning of *t*. Moreover, we note $E_{t-s}[\tilde{v_t}] = \bar{v_t}$ the expected value of $\tilde{v_t}$ in *t-s*.

Solving problem **(8)**, we get the *least cost solution* which yields the optimal effort condition,

$$\xi_{T,i} = \frac{p_T + bC_T}{a_i G_T}. \quad \textbf{(9)}$$

According to **(9)** the optimal effort is an increasing function of coal and permit prices, while it is a decreasing function of the gas price. These relationships can be readily understood by considering that the switching effort is a substitute for coal consumption and the purchasing of permits, whereas it entails an increase in gas consumption. Moreover, we see that the optimal switching effort is a decreasing function of a_i. It means that firms with a higher efficiency to abate CO_2 make a higher switching effort for any given prices p_T, C_T and G_T.

Combining **(9)** and the compliance constraint **(6)**, we derive the optimal demand of allowances in the last period,

$$\theta_{T,i} = \sum_{j=1}^{T} u_{j,i} - \sum_{j=1}^{T-1} \xi_{j,i} - \sum_{j=1}^{T-1} \theta_{j,i} - \delta_i - \frac{p_T + bC_T}{a_i G_T}. \quad \textbf{(10)}$$

Unsurprisingly, permit demand increases with the gas price and decreases with the coal price. The reason is that firms reduce their demand for coal when the coal price goes up relatively to the price of gas. Therefore, as gas consumption increases, CO_2 emissions decline and demand for allowances falls off.

Let us now introduce the market clearing condition that the carbon market has to satisfy in each period, in order to be in equilibrium. It states that, in each period, a permit purchased by one firm has to be sold by another, so that the sum of all permits bought and sold must be equal to zero:

$$\int_0^1 \theta_{t,i} di = 0, \forall t \in [1, \ldots, T].[17] \quad \textbf{(11)}$$

Integrating **(10)** on [0,1] and applying **(11)** to each period, we get:

$$p_T = aG_T \left[\sum_{j=1}^{T} u_j - \sum_{j=1}^{T-1} \Xi_j - D \right] - bC_T, \quad \textbf{(12)}$$

where $D = \int_0^1 \delta_i di$, $u_t = \int_0^1 u_{t,i} di$, $\Xi_t = \int_0^1 \xi_{t,i} di$ and $a = \int_0^1 a_i di$.

[17] For proof of the existence of this intertemporal equilibrium, see Rubin (1996). In addition, Rubin (1996) shows that this intertemporal equilibrium is efficient (*i.e.* it corresponds to the least cost solution).

In **(12)**, u_j stands for aggregate uncontrolled CO_2 emissions recorded during a period *j*, *D* is the sum of the allocations of allowances for all firms for all the *T* periods (*i.e.* the aggregate cap on CO_2 emissions) and Ξ_j represents the aggregate fuel switching effort by firms for a period j.

We can now turn to period *T*-1. In this period, firms have to solve the following problem:

$$\min_{\theta_{T-1,i}\ ,\ \xi_{T-1,i}} \quad CT_i(\theta_{T-1,i},\xi_{T-1,i}) = p_{T-1}\theta_{T-1,i} + C_i(\xi_{T-1,i}) + \beta E_{T-1}[\tilde{p_T}\tilde{\theta_{T,i}} + C_i(\tilde{\xi_{T,i}})]$$

$$s.t \quad \sum_{j=1}^{T-1} u_{j,i} + \tilde{u_{T,i}} - \sum_{j=1}^{T-1}\xi_{j,i} - \tilde{\xi_{T,i}} = \delta_i + \sum_{j=1}^{T-1}\theta_{j,i} + \tilde{\theta_{T,i}} \tag{13}$$

where $C_i(\xi_{t,i}) = \frac{1}{2}\xi_{t,i}^2 a_i G_t - \xi_{t,i} bC_t$ with $t \in [T-1\ ,T]$, and $\beta = \frac{1}{1+r}$ is a discount factor associated with a constant risk-free interest rate, *r*.

We consider arbitrary price changes for allowances which are exogenous for firms. Then we assume that the percentage change in allowance prices per unit of time equals the interest rate: $(p_{t+1} - p_t)/p_t = r$ so that $p_t = \beta p_{t+1}$ (and so $p_t = \beta \bar{p_{t+1}}$ with $E_t[\tilde{p_{t+1}}] = \bar{p_{t+1}}$), $\forall t$, where $\beta = 1/(1+r)$ is a discount factor and *r* is a constant risk-free interest rate. As pointed out in Rubin (1996), assuming this kind of changes for allowance prices is equivalent to assuming that the firm buys or sells an intermediate number of allowances in each period (*i.e.* this is equivalent to assuming a non-bounded solution over the entire time horizon).[18] Without this assumption, it would be optimal to buy as many permits as possible if $p_t < \beta \bar{p_{t+1}}$, or buy zero permits (and sell as many permits as possible) if $p_t > \beta \bar{p_{t+1}}$. Thus, this assumption is a necessary technical requirement to avoid corner solutions.[19]

Solving problem **(13)**, we get the *least cost solution* $p_{T-1} = C_i'(\xi_{T-1,i})$, which yields the optimal effort condition in *T*-1:

$$\xi_{T-1,i} = \frac{p_{T-1} + bC_{T-1}}{a_i G_{T-1}}. \tag{14}$$

Combining **(14)** and **(9)** with the compliance constraint of problem **(13)**, we get the optimal demand for allowances in *T*-1:

[18] Without this assumption, it would be necessary to set bounds on the maximum number of permits that can be bought and sold in each period, to avoid corner solutions. See Rubin (1996).
[19] In a discrete-time setting, Tietenberg (1985) showed that the rate of increase in the permit price must be equal to the interest rate in order to achieve a competitive equilibrium which corresponds to the least-cost solution. Rubin (1996) and Schennach (2000) derived the same result in continuous-time setting.

$$\theta_{T-1,i} = \sum_{j=1}^{T-1} u_{j,i} + \tilde{u_{T,i}} - \sum_{j=1}^{T-2} \theta_{j,i} - \tilde{\theta_{T,i}} - \delta_i - \sum_{j=1}^{T-2} \xi_{j,i} - \frac{p_{T-1}+bC_{T-1}}{a_i G_{T-1}} - \frac{\tilde{p_T}+b\tilde{C_T}}{a_i \tilde{G_T}}. \quad \textbf{(15)}$$

Integrating on $[0,1]$ and applying the market clearing condition **(11)** to each period, we obtain:

$$\frac{p_{T-1}+bC_{T-1}}{aG_{T-1}} = \sum_{j=1}^{T-1} u_j + \tilde{u_T} - D - \sum_{j=1}^{T-2} \Xi_j - \frac{\tilde{p_T}+b\tilde{C_T}}{a\tilde{G_T}}\,. \quad \textbf{(16)}$$

Assuming that carbon, coal and gas markets are informationally efficient, the current prices fully incorporate all information about their future values. Therefore, we have the following conditions: $p_{T-1} = \beta E_{T-1}[\tilde{p_T}] = \beta \bar{p_T}$, $G_{T-1} = \beta E_{T-1}[\tilde{G_T}] = \beta \bar{G_T}$ and $C_{T-1} = \beta E_{T-1}[\tilde{C_T}] = \beta \bar{C_T}$.[20] Finally, taking the expectation of **(16)** and using the last three conditions, we get[21]:

$$p_{T-1} = \frac{1}{2} \cdot aG_{T-1} \left[\sum_{j=1}^{T-1} u_j + \bar{u_T} - \sum_{j=1}^{T-2} \Xi_j - D \right] - bC_{T-1}\,. \quad \textbf{(17)}$$

As explained by fuel switching, the carbon price increases with the gas price and decreases with the coal price. More interestingly, we see that the difference between uncontrolled emissions (past, present and future) and the cap (D) influences the relationship between the gas price and the price of allowances. Indeed in **(17)**, the bracketed term (which determines the dependence of p_{T-1} on G_{T-1}) increases when uncontrolled emissions increase with respect to D. This evolution in the relationship between the gas price and the carbon price is the consequence of the firms' behavior, which substitute ever less efficient gas plants for previously used coal plants, as the fuel switching effort rises. This mechanism will be further discussed in Proposition 2. Still in the bracketed term, the presence of $\sum_{j=1}^{T-2} \Xi_j$ shows that the higher past switching efforts are, the smaller the impact of G_{T-1} on p_{T-1} is. The reason is that, all other things being equal, in order to attain the expected needed level of abatement for the Phase (*i.e.* the level needed to comply with the cap-and-trade during the current Phase), efforts during present and future periods will be as low as efforts made in the past have been high. A high level of past efforts leads to diminishing the influence of the gas price on the carbon price since, in this case, subsequent efforts are expected to be small, and thus the gas plants that would be used in fuel switching would be more efficient.

As for **(17)** in period T-1, we can find the backward induction solution of any period

[20] For more details on the informational efficiency of markets, see Fama (1965) and Malkiel (2003).

[21] For sake of expositional simplicity, we neglect the covariance terms in expectation (which is equivalent to assuming that random variables are independent). Having computed the corresponding empirical covariances (toward which the neglected covariances converge) for the time period 2008-2013, we observed they have very low values compared with other variables in the bracketed term of **(17)**. Thus, neglecting the covariance terms is not a very strong assumption. The full derivation of the solution taking into account the covariance terms as well as our data set are available upon request.

$t \in [1,\dots,T]$, given that we know the solutions of subsequent periods. Therefore, we can skip the chain of solution, and we directly consider the case of a period *t* that may be anywhere between the first and the last period. In such a period, firms have to solve the problem:

$$\min_{\theta_{t,i},\ \xi_{t,i}} \quad CT_i(\theta_{t,i},\xi_{t,i}) = p_t\theta_{t,i} + C_i(\xi_{t,i}) + \sum_{j=t+1}^{T}\beta^{j-t}E_t\left[\tilde{p}_j\tilde{\theta}_{j,i} + C_i(\tilde{\xi}_{j,i})\right]$$

$$s.t \quad \sum_{j=1}^{t}u_{j,i} + \sum_{j=t+1}^{T}\tilde{u}_{j,i} - \sum_{j=1}^{t}\xi_{j,i} - \sum_{j=t+1}^{T}\tilde{\xi}_{j,i} = \delta_i + \sum_{j=1}^{t}\theta_{j,i} + \sum_{j=t+1}^{T}\tilde{\theta}_{j,i} \qquad \textbf{(18)}$$

where $C_i(\xi_{t,i}) = \frac{1}{2}\xi_{t,i}^2 a_i G_t - \xi_{t,i} b C_t$ and $E_t[C_i(\tilde{\xi}_{j,i})] = \frac{1}{2}\tilde{\xi}_{j,i}^{\ 2} a_i \tilde{G}_j - \tilde{\xi}_{j,i} b \tilde{C}_j$ with $j = t+1,\dots,T$.

Following the same strategy as for the resolution in *T*-1, we get

$$\frac{p_t + bC_t}{aG_t} = \sum_{j=1}^{t}u_j + \sum_{j=t+1}^{T}\tilde{u}_j - \sum_{j=1}^{t-1}\Xi_j - D - \frac{\sum_{j=t+1}^{T}\tilde{p}_j + b\sum_{j=t+1}^{T}\tilde{C}_j}{a\sum_{j=t+1}^{T}\tilde{G}_j}, \qquad \textbf{(19)}$$

which is analogous to **(16)**.

Again, we use the market efficiency argument by extending it with more than two periods. Then, if coal, gas and carbon markets are informationally efficient, we have the following conditions: $p_t = \beta^{j-t}E_t[\tilde{p}_j] = \beta^{j-t}\bar{p}_j$, $G_t = \beta^{j-t}E_t[\tilde{G}_j] = \beta^{j-t}\bar{G}_j$ and $C_t = \beta^{j-t}E_t[\tilde{C}_j] = \beta^{j-t}\bar{C}_j$, $\forall\, j \in [t+1,\dots,T]$. Hence, taking the expectation of **(19)** and using the last three conditions, we obtain[22]:

$$p_t = \frac{1}{T-t+1}aG_t\left[\sum_{j=1}^{t}u_j + \sum_{j=t+1}^{T}\bar{u}_j - D - \sum_{j=1}^{t-1}\Xi_j\right] - bC_t, \qquad \textbf{(20)}$$

which is a generalization of **(17)** for any period $t \in [1,\dots,T]$. As before, the impact of the gas price on the carbon price depends on the difference between uncontrolled emissions and D, and on the past switching efforts.

Before going further in the resolution, let us present a first result which is reached by comparing **(20)** and **(12)**. It is summarized in the following proposition:

PROPOSITION 1

Shocks that may affect the gas price and uncontrolled carbon emissions have a stronger impact on the price of allowances if they occur in a period t which is closer to the last period (T).

[22] As in period *T*-1 we neglect the covariance terms when taking expectation. Here again, the full derivation of the solution taking into account the covariance terms is available upon request.

Proof: the value of $\frac{1}{T-t+1}$ in **(20)** is an increasing function of *t*. □

Previous studies have shown that the carbon price becomes more sensitive to shocks on uncontrolled emissions when we move toward the last period of the Phase (Seifert *et al.*, 2008; Hintermann, 2010). The result of Proposition 1 shows that the same pattern holds for the gas price influence. As briefly explained for **(17)**, the carbon price becomes more dependent on the gas price when uncontrolled emissions increase (since the switching effort rises, and so dirtier gas plants are used). Proposition 1 also states that a positive shock on uncontrolled emissions leads to an even greater dependence of the carbon price on the gas price if this shock occurs in a period which is close to *T*. The logic arises from the fact that the ability to adapt to a rise in uncontrolled emissions is smaller in periods that are close to the end of the Phase. Indeed, efforts that might be necessary between *t* and *T* are more difficult to postpone until later in the Phase when *t* is close to *T*. Therefore, the perspective of having to perform a major switching effort in this small time interval will make the abatement cost more sensitive to the gas price. Likewise, we can also argue that if a shock appears in a period which is close to *T*, the probability that it will be neutralized by an opposite shock in a later period is smaller (because of a small time interval between *t* and *T*), and so it has a stronger impact. Consequently, in order to deal with such a positive shock, many firms will be willing to buy allowances at a higher price (higher than if they were in a period located earlier in the Phase). As a result, the market value of the switching effort will increase, leading to a gas rush for firms that can perform abatements by switching fuels. That is why the allowance price will be more dependent on the gas price in this situation.[23]

Another result comes from the value of *T* in $\frac{1}{T-t+1}$ of **(20)**. Actually, the gas price and the bracketed term have a weaker impact on the carbon price when *T* increases. It is interesting because it shows consequences when moving from non-fungibility between Phases (as between Phase 1 and Phase 2 of the EU ETS) to a regime with perfect fungibility. Assuming a perfect fungibility between Phases, firms would have an unrestricted ability to bank and borrow permits between Phases. This translates into a situation where Phases would merge as a single Phase with a higher *T*, reflecting all the years of all the Phases. In case of the EU ETS, whereas Phase 1 and Phase 2 were clearly distinct, there are now some connections between Phase 2 and Phase 3. It is now possible to bank permits in Phase 2 to use them in Phase 3. However, inter-phase borrowing is still forbidden. Nevertheless, we moved from a perfect non-fungibility to a partial fungibility. Thus, allowing inter-

[23] Imagine that uncontrolled emissions increase suddenly and unexpectedly in the last period of the Phase. In such a situation, a lot of firms will want to buy permits before the end of the period. Therefore, the market value of the switching effort will rise, given that permits can be sold at a higher price. This will increase the attractiveness of gas, the level of switching effort, and finally, the dependence of the allowance price with respect to the gas price.

phase borrowing would merge Phases in a single T, with a higher value. This would make the gas price and uncontrolled emissions having a weaker influence on the carbon price, because abatements would be smoothed on a larger time interval.[24]

4.2 Equilibrium solution

In **(20)** some values are endogenous to the model. Therefore, in order to get an expression that depends on exogenous variables alone, we run an iterative algorithm that uses **(20)** by starting from the first period. Applying **(20)** to the first two periods, we obtain two equations for p_1 and p_2. Afterwards, as $\Xi_t = \frac{p_t + bC_t}{aG_t}$, $\forall t \in [1, \ldots, T]$, we can substitute p_1 in p_2. We then get the full expression for p_2:

$$p_2 = aG_2 \left[\frac{1}{T} u_1 + \frac{1}{T-1} u_2 - \frac{1}{T(T-1)} \bar{u_2} + \frac{1}{T} \sum_{j=3}^{T} \bar{u}_j - \frac{1}{T} D \right] - bC_2. \tag{21}$$

Continuing the same process for the following periods, we get a chain of equations $\{p_1, p_2, \ldots, p_T\}$ that enables us to deduce the full solution for any period *t* in the interval.[25] That is:

$$p_t = aG_t \left[\sum_{j=1}^{t} \left(\frac{1}{T-j+1} u_j - \frac{j-1}{T(T-j+1)} \bar{u}_j \right) + \frac{1}{T} \sum_{j=t+1}^{T} \bar{u}_j - \frac{1}{T} D \right] - bC_t \tag{22}$$

The remainder of this section will discuss the results that follow from **(22)**. They are summarized in the next propositions.

PROPOSITION 2

In each period t, the influence of the gas price on the price of allowances increases when the level of past, present and future uncontrolled emissions increases with respect to the cap on carbon emissions.

Proof: the bracketed term in **(22)** is increasing with respect to u_j, $\forall j \in [1, \ldots, t]$, and $\bar{u}_j$, $\forall j \in [t+1, \ldots, T]$, whereas it is a decreasing function of *D*. □

Proposition 2 indicates that fuel prices and uncontrolled emissions exert a combined influence on the carbon price. Previous papers have shown that the carbon price depends on coal and gas price

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[24] Note that an implicit inter-phase borrowing may happen between the last year of a Phase and the first year of the following Phase. Since firms receive allocations of a year *t*+1 before they have to surrender EUAs corresponding to verified emissions of *t*, EUAs from *t*+1 may be used to cover emissions of *t*. Therefore, if *t* and *t*+1 are located in two different Phases, an implicit inter-phase borrowing happens.

[25] One can show that **(22)** stands for any period $t \in [1, \ldots, T]$ using a recurrence proof.

through theoretical (*e.g.* Delarue *et al.*, 2007; Carmona *et al.*, 2009; Hintermann, 2010) and econometric (*e.g.* Mansanet-Bataller *et al.*, 2007; Alberola *et al.*, 2008; Bunn and Fezzi, 2009; Creti *et al.*, 2012) works. Others have found that the carbon price depends on the level of uncontrolled emissions (*e.g.* Maeda, 2004; Seifert *et al.*, 2008; Hintermann, 2010). However, to the best of our knowledge, no previous work has found that the gas price and uncontrolled emissions act together on the carbon, as in Proposition 2. This contributes to the literature about carbon markets.

This result is explained by the fuel switching behavior, in a context where gas plants do not all have the same efficiency. Indeed, the fuel switching process that we describe implies that ever less efficient gas plants are substituted for coal plants when the switching effort increases. Therefore, when uncontrolled emissions rise, the required switching effort increases, which entails an increased gas consumption to abate each tonne of CO_2. Accordingly, the cost of the gas consumption needed to abate one tonne of CO_2 increases with uncontrolled emissions (*i.e.* with the switching efforts made in response to rising uncontrolled emissions), leading to a greater sensitivity of the marginal cost of switching with respect to the gas price. As a consequence, the carbon price depends more heavily on the gas price. Actually, Proposition 2 indicates that the carbon price increases with the level of uncontrolled emissions for two reasons: a reduced supply of permits (because the cap becomes more stringent) and a rising gas cost for fuel switching. Moreover, together with Proposition 1, Proposition 2 shows that, in each period *t*, the sensitivity of the carbon price with respect to the gas price is determined by the intersection between the volume of uncontrolled emissions and the temporal location of the current period (*t*) in the Phase.

To illustrate Proposition 2, Figure 6 plots the carbon price, p_t, as a function of the gas price, G_t, and the total uncontrolled emissions over the Phase, u.

[insert Figure 6]

In Figure 6, we applied a simplified version of **(22)** in order to graphically illustrate Proposition 2:

$$p = aG\left[\frac{1}{T}(u - D)\right] - bC, \qquad \textbf{(23)}$$

The values of u and D were chosen so as to remind the position of the power sector in Phase 2 (Table 7).

[insert Table 7]

The value of T has been fixed at 5, which corresponds to the five years in Phase 2. Using price data for coal (Euros per tonne, CIF-ARA AP2I daily price index from McCloskey), gas (Euros per

MWhp, NBP from ICE) and EUAs (Euros per tCO_2, Bluenext), from February 2008 to December 2012, with $\Delta = u - D = 161$ (see Table 7) and $T = 5$, we estimated parameters a and b (OLS and maximum likelihood).[26] We obtained: $a = 0.0022$ and $b = 0.013$. Finally, we took 75.3 as value for the coal price (*i.e.* the average coal price between February 2008 and December 2012) to plot the solution.

In Figure 6, the dependence of the carbon price on the gas price appears in the slope of the *G*-directional characteristic curves (straight lines, in this case). Moving along the *Δ*-axis, when uncontrolled emissions increase, we observe an increasing *G*-directional steepness. In other words, the slope of the *G*-directional characteristic curves increases when uncontrolled emissions increase. This reflects the fact that the influence of the gas price on the carbon price increases when the level of past, present and future uncontrolled emissions increases with respect to the cap on emissions (*i.e.* when $\Delta = u - D$ increases).

In the following propositions, we go further in the description of the influence of carbon emissions and their time dependency.

PROPOSITION 3

In each period t, it is ex post forecasting errors concerning past and current uncontrolled carbon emissions that affect the allowance price, rather than their levels alone.

<u>*Proof*</u>: in **(22)**, $\forall j \in [1, \ldots, t]$, these are differences between u_j and $\bar{u}_j$ which determine the influence of past and current uncontrolled emissions on the value of the bracketed term, and not only the values of u_j.[27] □

Proposition 3 completes Proposition 2 by showing that for past and current periods, it is *ex post* forecasting errors on uncontrolled emissions that determine the sensitivity of the allowance price with respect to the gas price. Some authors have already shown that errors of forecasting concerning CO_2 emissions influence, *ex post*, the carbon price. This has been done through theoretical (Maeda, 2004; Hintermann, 2010) and econometric (Alberola *et al.*, 2008) works. We find, in addition, that these errors have an impact on the relationship between the gas price and the carbon price.

The timing of the current period within the Phase may be important. However, for past uncontrolled emissions, the timing of the periods in which they occurred may also matter. This is described in the

[26] Estimations have been made using the *Climate Economics Chair* database.

[27] Let A and B be the terms in factor of, respectively, u_j and $\bar{u}_j$, $\forall j \in [1, \ldots, t]$. We see that $A > B, \forall j \in [1, \ldots, t]$, so that if we have $u_j \geq \bar{u}_j$, then necessarily $Au_j - B\bar{u}_j > 0$.

following proposition.

PROPOSITION 4

In each period t, the more recent a given past period is, the stronger the impact of the forecasting error on uncontrolled emissions that occurred in this period is.

Proof: in **(22)**, values of the terms in factor of u_j and $\bar{u}_j$, $\forall j \in [1, \ldots, t]$, increase when we consider a period j which is closer to period t.[28] □

Proposition 4 indicates that past uncontrolled emissions have a weaker influence on the carbon price of period t (and on the relationship between carbon and gas prices in this period) when they come from a distant past. The reason is that when we consider a distant past period with respect to period t, the time interval between t and this past period is large enough to enable firms to smooth their abatement efforts across periods. As a result, the proportion of the whole switching effort (to be made in response to uncontrolled emissions that occurred in this distant past period) will be smaller in period t, given that this effort has been spread out over a large number of periods. As a consequence, those past uncontrolled emissions will have a weaker impact on the present than emissions that occurred more recently. On can also argue that the probability that a shock on a past u_j would be neutralized by an opposite shock on a subsequent $u_{j'}$ (where $j < j' \leq t$) is smaller when we consider a period j which is close to t (because of the small time interval between j and t). Accordingly, uncontrolled emissions of a recent past period will have a stronger impact on the present than emissions that occurred earlier in the past.

5. Conclusion

This paper provides a theoretical analysis of coal-to-gas fuel switching, in a context where power plants involved are not equally efficient. We begin with some analyses which enable us to observe how differences in the efficiency of power plants impact the cost of fuel switching, and how this is related to the level of switching effort. Based on these preliminary analyses, we build a partial equilibrium model, taking into account the effect of differences in the efficiency of power plants involved in fuel switching. To the best of our knowledge, no previous work has investigated this question using partial equilibrium modeling. This paper fills this gap in literature.

Our paper extends previous literature in essentially three directions. First, we demonstrate that the level of switching effort influence the marginal cost of fuel switching and its dependence on

[28] As before we call A and B the terms in factor of, respectively, u_j and $\bar{u}_j$, $\forall j \in [1, \ldots, t]$. So, $\partial A / \partial j > 0$, $\forall j$, and $\partial B / \partial j > 0$, $\forall j$ when $T \geq 1$.

fuel prices. In particular, the marginal cost of fuel switching is shown to be increasingly dependent on the gas price as the switching effort rises. However, the net effect is undetermined for the coal price and it is expected to be small.

Second, we provide the first partial equilibrium model for fuel switching, taking into account the effect of differences in the efficiency of power plants. We show that the influence of the gas price on the carbon price depends on the level of uncontrolled CO_2 emissions. This is explained by the fuel switching process we describe, in which ever less efficient gas plants are substituted for coal plants as the switching effort increases. Hence, when uncontrolled emissions increase, the switching effort intensifies, and more gas must be consumed to abate one tonne of CO_2. This leads to having the gas price a greater influence on the marginal cost of fuel switching, and thus on the carbon price. This results in a stronger correlation between carbon and gas prices, which may have important implications for power producers and other market participants involved in emission trading.

Finally, we also investigate the effect of the timing of fuel switching abatements, within the temporally defined stochastic environment of our model. We find that the ability to adapt to a rise in uncontrolled emission depends on how much time firms have before the end of the Phase, which affects the relationship between uncontrolled emissions, the carbon price, and fuel prices. A positive shock on uncontrolled emissions will lead to an even greater dependence of the carbon price on the gas price if this shock occurs at the end of the Phase. Indeed, in such a situation, a great switching effort would have to be performed in a small time interval, which would make the marginal cost of abatement even more sensitive to the gas price.

In summary, this paper shows that the gas price, uncontrolled CO_2 emissions and the timing of abatement (through the time of occurrence of random shocks on uncontrolled emissions) act together on the carbon price, and on its relationship with fuel prices. Such contribution would serve as a bridge between two strands of literature: the one focusing on the price fundamentals, neglecting the timing aspect, and the one which focuses on the timing issues, neglecting the effect of price fundamentals such as energy prices.

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Tables

Table 1: Composition of illustrative power system.

Fuel	Technology	Number of plants	Unit power (GW)	Total installed capacities (GW)
T1	Hydro	1	1	1
T2	Nuclear	3	1	3
T3	Hard-coal	3	1	3
T4	CCGT	3	1	3
T5	Open cycle gas turbine	2	1	2
T6	Oil	1	1	1
T7	Diesel	1	1	1

Table 2: Efficiency of power plants and level of switching effort.

Switching effort	Type of switching	Marginal switching – one type of coal plants	Marginal switching – different type of coal plants
Low	T_4^{55} for one T3	T_4^{55} and T3	T_4^{55} and T_3^{36}
Medium	T_4^{55} and T_4^{50} for two T3s	T_4^{50} and T3	T_4^{50} and T_3^{38}
High	T_4^{55}, T_4^{50} and T_4^{45} for three T3s	T_4^{45} and T3	T_4^{45} and T_3^{40}

Table 3: Emission and heating rates for different types of power plants.

Efficiency rate of CCGTs (η_i)	h_g^i	e_g^i
45%	2.222	0.449
50%	2.000	0.404
55%	1.820	0.367
Efficiency rate of coal plants (η_j)	h_c^j	e_c^j
36%	0.400	0.947
38%	0.379	0.897
40%	0.360	0.852

Table 4: Gas consumption per tonne of CO_2 abatement and switching effort.

Level of switching effort (see Table 2)	One type of coal plants (38%)			
	Gas consumption per switched MWh – h_g^i of Table 3 – (*effect 1*)	Abatement per switched MWh (tCO_2) – e_g^i and e_c^j of Table 3	Number of switched MWhs needed to abate one tonne of CO_2[a] (*effect 2*)	Gas consumption per tonne of CO_2 abatement[b] (*total effect*)
Low	1.820	$e_c^{38} - e_g^{55}$ = 0.53	1.890	3.440
Medium	2.000	$e_c^{38} - e_g^{50}$ = 0.50	2.000	4.000
High	2.222	$e_c^{38} - e_g^{45}$ = 0.45	2.222	4.937
Level of switching effort (see Table 2)	Different types of coal plants			
	Gas consumption per switched MWh – h_g^i of Table 3 – (*effect 1*)	Abatement per switched MWh (tCO_2) – e_g^i and e_c^j of Table 3	Number of switched MWhs needed to abate one tonne of CO_2[a] (*effect 2*)	Gas consumption per tonne of CO_2 abatement[b] (*total effect*)
Low	1.820	$e_c^{36} - e_g^{55}$ = 0.58	1.720	3.130
Medium	2.000	$e_c^{38} - e_g^{50}$ = 0.50	2.000	4.000
High	2.222	$e_c^{40} - e_g^{45}$ = 0.40	2.500	5.555

[a]: 1 tonne CO_2 = $(e_c^j - e_g^i)$×Number of switched MWhs needed to abate one tonne of CO_2.
[b]: total effect = effect 1 × effect 2.

Table 5: Avoided coal consumption per tonne of CO_2 abatement and switching effort.

Level of switching effort (see Table 2)	One type of CCGTs (50%)			
	Avoided coal consumption per switched MWh – h_c^j of Table 3 – (*effect 1*)	Abatement per switched MWh (tCO_2) – e_g^i and e_c^j of Table 3	Number of switched MWhs needed to abate one tonne of CO_2[a] (*effect 2*)	Avoided coal consumption per tonne of CO_2 abatement[b] (*total effect*)
Low	0.400	$e_c^{36} - e_g^{50}$ = 0.55	1.820	0.728
Medium	0.379	$e_c^{38} - e_g^{50}$ = 0.50	2.000	0.758
High	0.360	$e_c^{40} - e_g^{50}$ = 0.45	2.222	0.799
Level of switching effort (see Table 2)	Different types of CCGTs			
	Avoided coal consumption per switched MWh – h_c^j of Table 3 – (*effect 1*)	Abatement per switched MWh (tCO_2) – e_g^i and e_c^j of Table 3	Number of switched MWhs needed to abate one tonne of CO_2[a] (*effect 2*)	Avoided coal consumption per tonne of CO_2 abatement[b] (*total effect*)
Low	0.400	$e_c^{36} - e_g^{55}$ = 0.58	1.720	0.688
Medium	0.379	$e_c^{38} - e_g^{50}$ = 0.50	2.000	0.758
High	0.360	$e_c^{40} - e_g^{45}$ = 0.40	2.500	0.900

[a]: 1 tonne CO_2 = $(e_c^j - e_g^i)$×Number of switched MWhs needed to abate one tonne of CO_2.
[b]: total effect = effect 1 × effect 2.

Table 6: Profiles of CCGTs for firms A and B. T_4^i denotes CCGTs of *i*% efficiency.

Profiles of firm A (the most efficient)	**Profiles of firm B** (the less efficient)
T_4^{55}	T_4^{53}
T_4^{51}	T_4^{47}
T_4^{49}	T_4^{45}

Table 7: Allocated allowances and estimated baseline emissions of the power sector in Phase 2 of the EU ETS (million tonne CO_2). The allocation data and the baseline emission estimates come from Trotignon (2012).

Year	Allocated allowances	Estimated baseline emissions
2008	994	1084
2009	994	1014
2010	994	1032
2011	994	1001
2012	994	999
Total	D = 4968	u = 5129

Figures

Figure 1: Merit order without carbon cost.

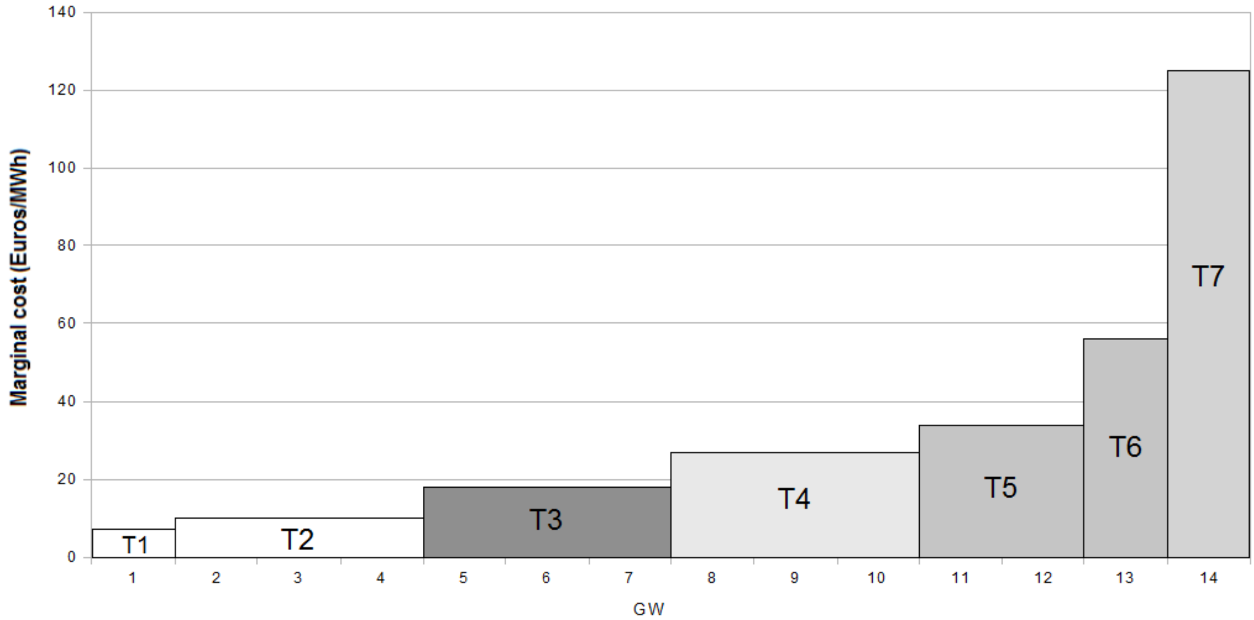
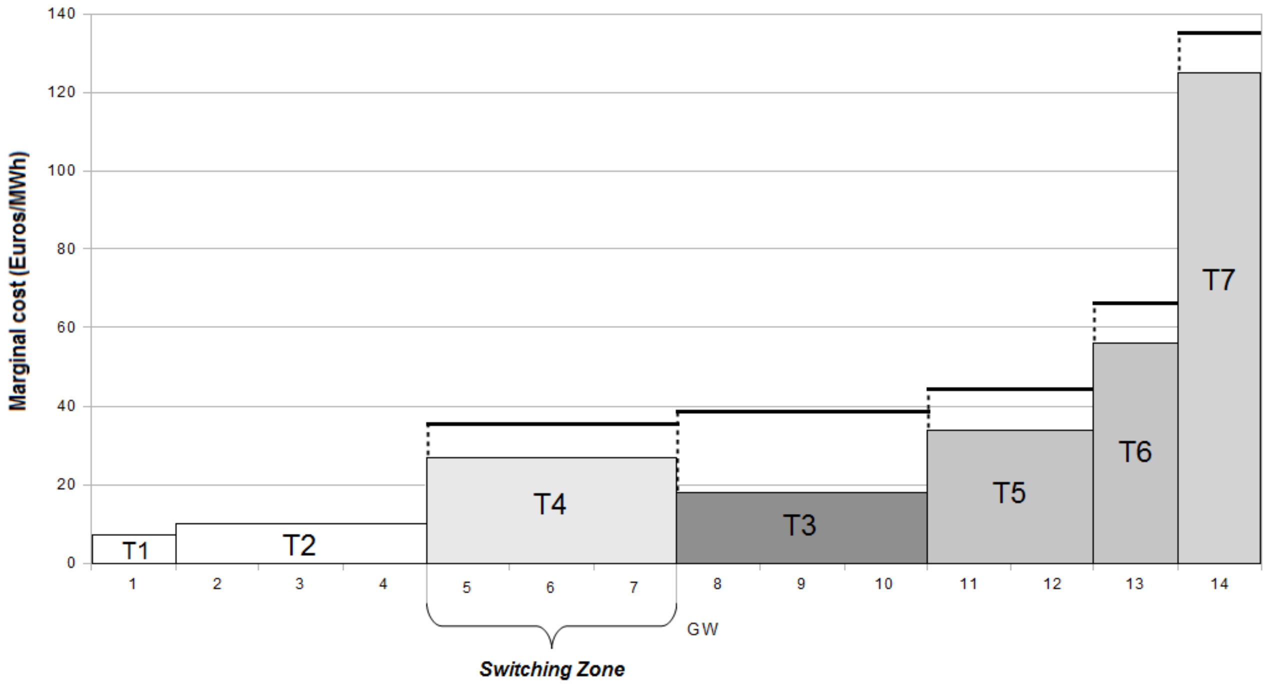


Figure 2: Change in the merit order after fuel switching.



Note: The parts above the areas reflecting fuel cost (the same as in Figure 3) correspond to the cost of CO_2 emissions.

Figure 3: Change in the merit order after a medium level of switching effort.

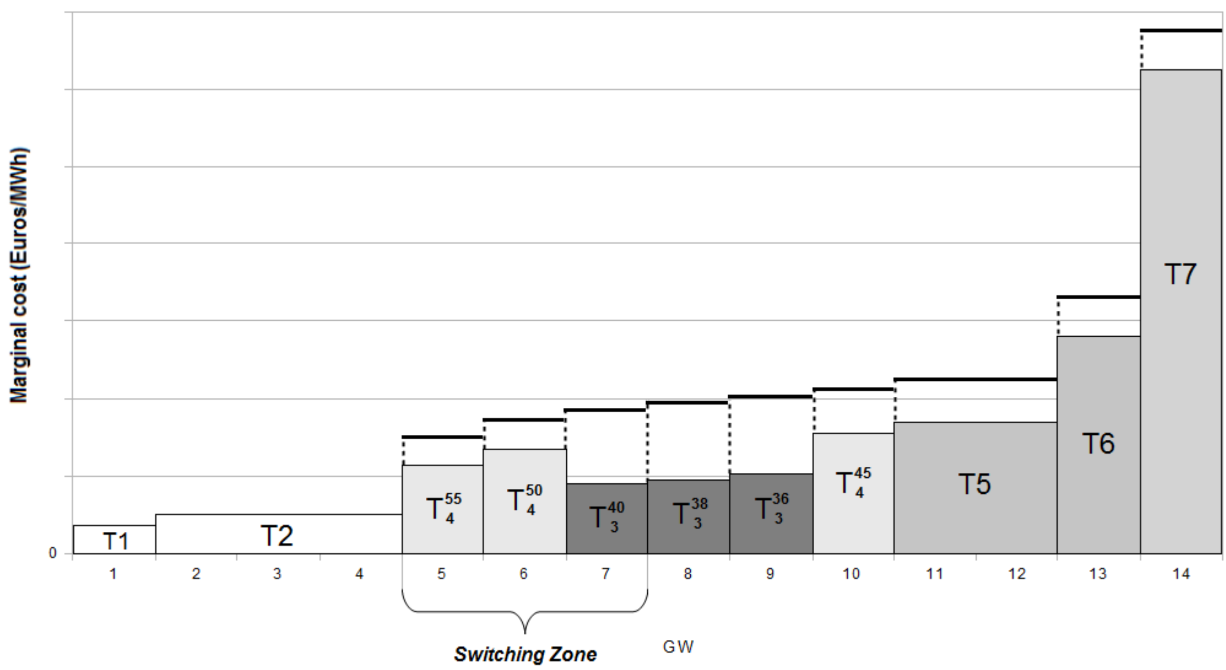


Figure 4: Switching band. Switching price are computed from equation **(1)**, using the NBP daily gas price and the CIF-ARA AP2I daily coal price index.

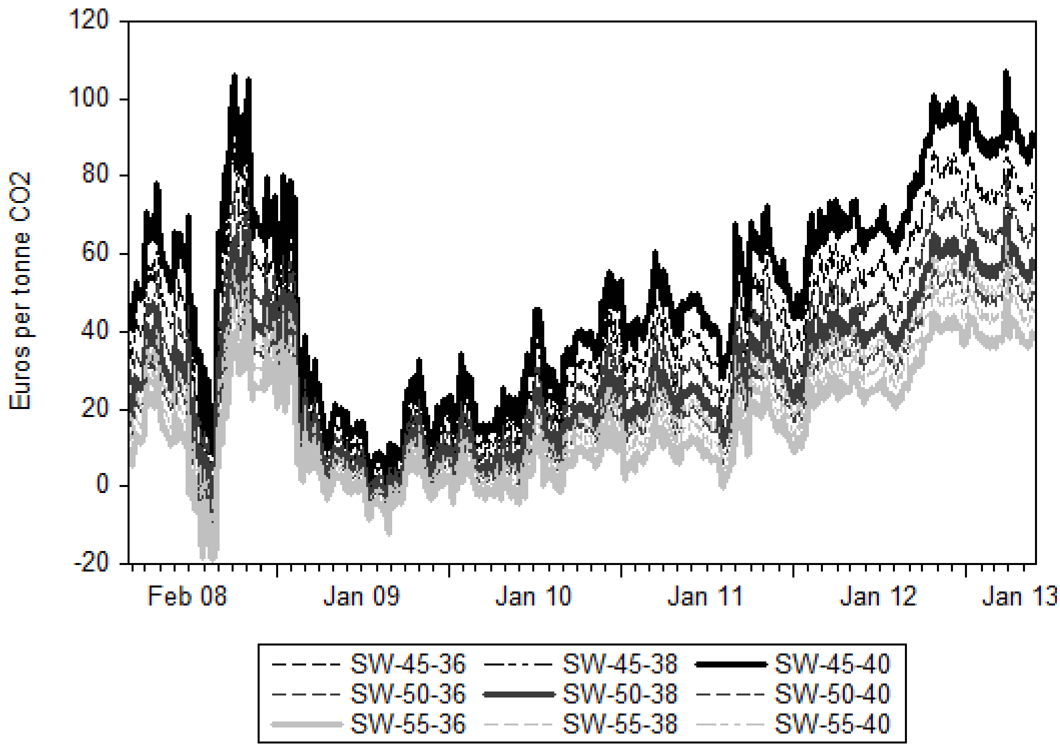


Figure 5: Stepwise constant MAC for switching of firms A and B. Switching prices reflect values given by equation **(1)**. SW_i denotes the switching price associated with CCGTs of i% efficiency.

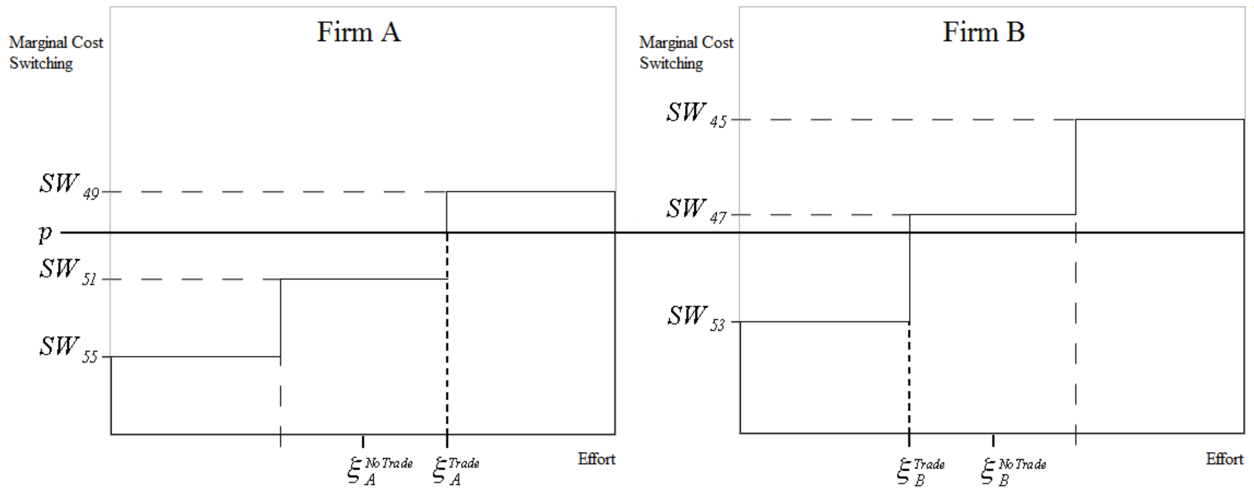
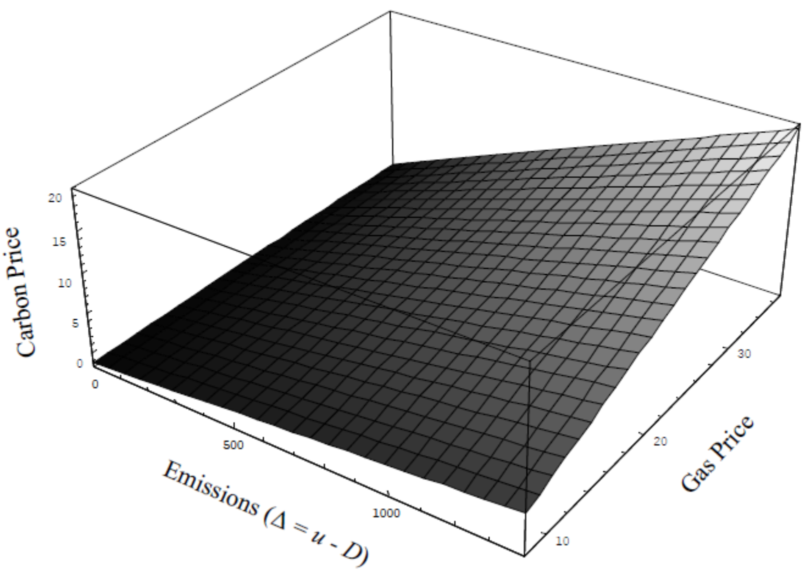


Figure 6: Surface representing the influence of the gas price on the carbon price depending on the level of uncontrolled emissions. The graph is based on equation **(23)**, a simplified version of equation **(22)**.



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