Robust MACCs? The Topography of Abatement by Fuel Switching in the European Power Sector

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ABSTRACT

This paper employs a simulation model of the European power sector to analyze the abatement response to a CO_2 price through fuel switching, one of principal means of reducing greenhouse gas emissions in any economy. Abatement is shown to depend not only on the price of allowances, but also and more importantly on the load level of the system and the ratio between natural gas and coal prices. The interplay of these different determinants vitiates any simple relation between a CO_2 price and abatement and requires the development of a more than two dimensional graphics to illustrate these complex relationships. In the terms of the literature on the use of marginal abatement cost curves (MACCs), we find that these MACCs are not robust as usually defined and we suggest that the more complex topography developed in this paper may be more helpful in visualizing this abatement response to a CO_2 price.

KEYWORDS: Fuel switching; Marginal Abatement Cost Curve (MACC); CO_2 abatement; Electricity generation simulation; European Union Emission Trading Scheme;

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1 INTRODUCTION

The cost of reducing greenhouse gas emissions is an important issue in climate change policy, especially where a global trading regime is envisaged as in the Kyoto Protocol. An often used means of depicting the relationship between reductions and costs has been Marginal Abatement Cost Curves (MACCs) [1]. They offer a simple and attractive tool for policy makers and researchers because they are straightforward to use and directly present a cost related to certain emission reduction target [2]. However, they are usually partial equilibrium depictions of abatement costs and, even when derived from Computable General Equilibrium (CGE) models, a number of factors that can cause welfare costs to diverge from the total cost as depicted by the integration beneath any given MACC are ignored [3].

One of the issues surrounding the use of MACCs has concerned “robustness”, whether the curves are relatively stable in p-q space with respect to the actions taken by other nations or to changes in the assumptions of the underlying models. This issue was first raised in [2] and extensively discussed in [4]. This paper contributes to that literature not only in analyzing the “robustness” of one particular but significant component of the usually economy-wide abatement depicted by MACCs, but also by cautioning about the use of MACCs for evaluating the relationship between carbon prices and abatement for periods shorter than the year-long or multi-year periods. In doing so, we develop a more complex topography of abatement by fuel switching in the European power sector to provide a better understanding of the influence of factors other than the carbon price, namely, fuel prices and load.

Basically, two ways exist to construct a MACC: a so-called ‘top-down’ approach and a ‘bottom-up’ approach [1][5]. The top-down approach is based on macro-economic models, typically CGE models. To set up a MACC, an emission constraint is included in the model optimization, and the shadow price for this emission constraint presents the marginal cost of this level of abatement. A MACC is then derived by running the model for several emission restrictions and tracing out the marginal costs. The bottom-up approach is an engineering approach, estimating the cost and emission reduction potential of certain technology improvements and changes, or calculating the emission reduction potentials for different levels of CO_2 costs.

The main advantage of the top-down approach lies in the fact that it models a whole market, with all its interactions: inputs as capital, labor, natural resources, as well as all

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side effects and feedbacks resulting from policy measures. The main disadvantage is the sacrifice in technical detail. Conversely, the main advantage of the bottom-up approach is the high level of technical detail, while its disadvantage is the fact that prices are exogenous and that it neglects market interactions and other feedbacks that might occur as consequence of policy action [5][6].

Ellerman and Decaux [2] presented a first MACC analysis, by introducing MACCs resulting from the CGE model EPPA. They focused on opportunities for emission trading amongst regions. In their analysis, they also tested the robustness of the derived MACCs, i.e., how a MACC of certain region is affected if other regions change the level of abatement. The MACCs turned out to be quite robust, mainly because the reference emission levels were adjusted to account for the actions taken by other regions, which were assumed to be independent of the policy of the region for which the MACC was being derived [3][4].

Klepper and Peterson [4] discuss the influence of fossil fuel prices on MACCs. They employ the CGE model DART. In such a CGE model, fossil fuel prices are determined endogenously and depend on abatement levels all over the world. MACCs are highly dependent on these fossil fuel prices, but tend to be robust in terms of absolute or relative emission reduction levels (compared to a particular baseline situation, not explicitly shown). Morris et al. [3] stress that how to construct a MACC (i.e., how to define this baseline) should really depend on the use. They also illustrate the path dependence of MACCs through time and demonstrate the effect of including non- CO_2 greenhouse gas emissions in the analysis.

The work presented in this paper differs from the existing literature in two important aspects. First, it addresses only one sector of the economy, albeit an important one for the abatement of greenhouse gas emissions, the electric power sector. Second, it focuses solely on short-term abatement through fuel switching without considering changes in the capital stock of generating plants that result from investment in response to the carbon price that are typically included in most modeling analyses. Therefore, the MACCs presented in this work cover only part of a ‘full’ MACC, that reflects the entire economy and all technological options. This paper adds to the literature on the use of MACCs and their robustness by providing a formal discussion of the full interplay of the three above-mentioned determinants of abatement (carbon price, fuel price and load).

The results presented here are based on a simulation model with plant-specific detail concerning electricity generation and with given fuel prices that are assumed to be

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independent of abatement (bottom-up approach). The purpose of this paper is not to estimate actual abatement by the European power system in response to the CO_2 price created by the European Union's Emissions Trading Scheme (EU ETS). Such estimates are presented in [7][8]. Instead, the goal of this paper is to explain how the interplay of the CO_2 price, the relative prices of natural gas and coal, load, and system configuration affect abatement and MACCs. As will become readily clear, a simple relationship between price and abatement does not exist. In broadest terms, that relationship depends on the utilization of the existing stock of generating plants (which can change over time) and the relative prices of coal and natural gas.

This paper proceeds as follows. The next section briefly discusses the simulation model used in this work. The third section of the paper discusses the effect of the level of load on abatement and MACCs, at fixed fuel prices. The fourth section discusses the effect of fuel prices while the fifth section develops a full topography of short-term CO_2 abatement in the European power sector. The sixth section concludes the paper.

2 SIMULATION MODEL

2.1 *Description of the simulation model*

The analysis in this paper is based on the simulation model E-Simulate, which was developed at the University of Leuven [9]. The model simulates annual electricity generation and related CO_2 emissions, on an hourly level (8760 hours), in a set of ten interconnected zones representing 21 countries. Given the composition of the different power systems and the hourly demand levels for electricity by zone, the model commits power plants and decides on electricity generation (dispatching), according to lowest cost. The model allows trade of electricity among the ten zones, limited by the interconnection capacity connecting these zones. Perfect competition is assumed, both within zones as for trade between zones. The optimization is carried out by means of an advanced heuristic method [10]. After applying a basic solution (respecting the minimum operating points of power plants), corrections are made concerning minimum up and down times. The output of the model consists of electricity generation and related CO_2 emission, on a power plant and hourly level.

Typical elements of electricity generation are incorporated in the model. Pumping units, used for peak shaving, are dealt with in a specific optimization, prior to the general unit

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commitment. Furthermore, electricity generation from non-dispatchable sources (like wind, photovoltaics and cogeneration) is treated as a correction on the electricity demand (negative load). Power plants also have a certain limited availability, accounting for unexpected outages, which is taken into account in a ‘derated power’ approach. This means that every power plant has a certain fraction of its full power constantly available. Next to this derated power approach, power plants are also scheduled for maintenance during a given number of days during the year (typically at moments of low load). Reliability is incorporated in the model, by enforcing a certain amount of reserves, corresponding to the size of the largest unit (i.e., the system is N-1 secure). For further details on the model, its functioning and illustrative simulations regarding, e.g., the effects of certain input parameters (power system, fuel prices, etc.), we refer to [9][11][12].

2.2 *Model set-up and validation*

The ten-zonal implementation is presented in Table 1. Not all member states of the European Union are incorporated. Some countries were left out because of their lack of interconnection with the rest of Europe. The non-EU countries Switzerland and Norway are incorporated, because of their high level of integration with the European system. In the remainder of this paper, only results aggregated over all zones will be discussed, i.e., no zone- or country-specific results are subject of discussion.

Table 1: Composition of the different zones considered in the model.

Zone	Countries
1	United Kingdom (UK), Ireland (IRL)
2	Spain (ES), Portugal (PT)
3	Belgium (BE), the Netherlands (NL), Luxembourg (LU)
4	France (FR)
5	Italy (IT)
6	Denmark (DK), Finland (FI), Sweden (SE), Norway (NO)
7	Poland (PL)
8	the Czech Republic (CZ), the Slovak Republic (SK), Hungary (HU), Slovenia (SL)
9	Austria (AT), Switzerland (CH)
10	Germany (DE)

The electricity generation systems of all the countries modeled are based upon the

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EURPROG 2006 report of Eurelectric [13][1]. The load profiles (hourly) and absolute values are taken from ENTSO-E [14], Energinet.dk [15], Fingrid Oyj [16], Statnett [17], National Grid [18], Soni [19], and Eirgrid [20]. The capacities of the connections linking the zones are based on the Net Transfer Capacities (NTC), taken from ENTSO-E [14]. The configuration of the model used for the simulations in the following sections, is based on data corresponding to the year 2005.

When comparing results obtained with the model with actual historic generation for 2005, a reasonably good match is obtained. Table 2 presents numbers for both simulated and historic electricity generation (aggregated over all zones), per fuel. The good match between simulated results and actual numbers demonstrates that the abatement relationships are those that exist in the actual operational system instead of as they might be supposed to exist based on a purely theoretical simulation of the same system.

Table 2. Electricity generation comparison between historic values and simulation results for the year 2005.

2005	Generation (all zones)				[TWh]				
	nuclear	coal	lignite	gas	oil	hydro	oth. ren.	other	total[a]
Historic real	936,6	570,8	268,1	616,0	104,7	427,1	124,1	58,4	3108,7
Simulation	925,4	624,5	317,0	560,8	72,3	428,1	115,3	63,4	3106,7
	Share in total generation (all zones)				[%]				
	nuclear	coal	lignite	gas	oil	hydro	oth. ren.	other	
Historic real	30%	18%	9%	20%	3%	14%	4%	2%	
Simulation	30%	20%	10%	18%	2%	14%	4%	2%	

[a] Note that a possible minor difference exists on the total actual and simulated electricity generation. This is due to possible slight deviations in total demand modeled, or from a different use of pumping units, which can affect total generation.

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[1] Given the electricity generating capacity for each country and year, both in terms of fuel (e.g., gas, coal, nuclear, etc.) and technology type (e.g., classic thermal, combined cycle, gas turbine, etc.), together with the amount of CHP installed per fuel, an accurate representation of each power system can be created on power plant level that matches the installed capacity in terms of fuel as well as in terms of technology (with a range in capacities per fuel and per technology).

3 THE EFFECT OF LOAD

3.1 *Generation and emissions with invariant fuel prices*

A prerequisite for fuel switching is the availability of generation capacity with lower emissions[2]. For instance, if every power plant in the system is running at its full capacity, no fuel switching potential remains. If, however, load is relatively low and most of it is met with coal-fired generation, any unutilized gas-fired power plants would be available to replace the generation from the coal plants given the correct economic incentives. Accordingly, potential abatement from fuel switching depends upon the availability of lower emitting capacity, generally natural gas, as that availability is affected by diurnal, weekly, and seasonal variations in load. Since this potential abatement is also dependent on fuel prices and in order to isolate the effect of load on abatement, constant fuel prices are assumed throughout the year at the average prices in 2005 (5.7 €/GJ for natural gas and 1.9 €/GJ for coal).

When run over an annual period, E-Simulate produces 8760 values for electricity generation for each hour of the year with corresponding CO_2 emissions. **Figure 1** (a) presents these values, sorted according to load. The EU-wide electricity generation in 2005 varies from about 230 GW with less than 100,000 tons of CO_2 emissions per hour during summer off peak hours to about 430 GW and more than 200,000 tons of CO_2 emissions per hour during winter peak hours. When these hourly plots are fitted with a linear curve, a relatively constant slope of 600 ton/GWh is obtained. This reflects the average carbon content of the mix of fossil fuels used in the available generating plants as they are activated to meet increasing EU-wide load[3].

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[2] In this paper we only consider switching electricity generation from one power plant to another, not adjusting a certain plant to make it run on a different fuel, e.g., adjusting a certain coal plant to make it run on natural gas.

[3] Coal burned at 36% efficiency: 951 ton/GWh; Gas burned at 50% efficiency: 413 ton/GWh; Gas burned at 36% efficiency: 574 ton/GWh; Oil burned at 35% efficiency: 771 ton/GWh.

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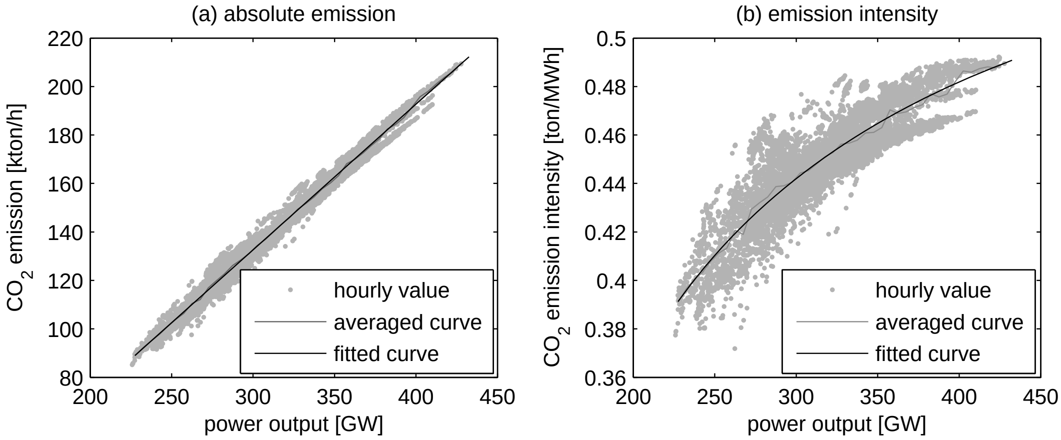

Figure 1. Hourly CO$_2$ emissions, with both an averaged and linear fitted curve; (a) absolute emissions [kton/hour]; (b) emission intensity [ton/MWh].

In the same manner, **Figure 1** (b) depicts the system-wide CO$_2$ emissions intensity[4] as load increases. With a relative low carbon mix of generating plants at low loads (nuclear, hydro), the average intensity starts out at about 400 kg per MWh but it rises as load increases and tends to flatten out as the increasing load includes decreasing amounts of the less expensive generation from coal plants.

3.2 ***CO$_2$ price effects***

Figure 2 shows average hourly CO$_2$ emissions at the different CO$_2$ prices and the resulting abatement as a function of load[5]. As load increases, emissions increase regardless of the CO$_2$ price, as shown by panel (a); however, the extent to which emissions are reduced in response to any given carbon price depends on load, as shown in panel (b).

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[4] This emission intensity is defined as the absolute emission during a specific hour divided by the electricity produced during that hour.

[5] These curves are constructed by grouping (averaging) the 8760 data points in steps of 50 GW.

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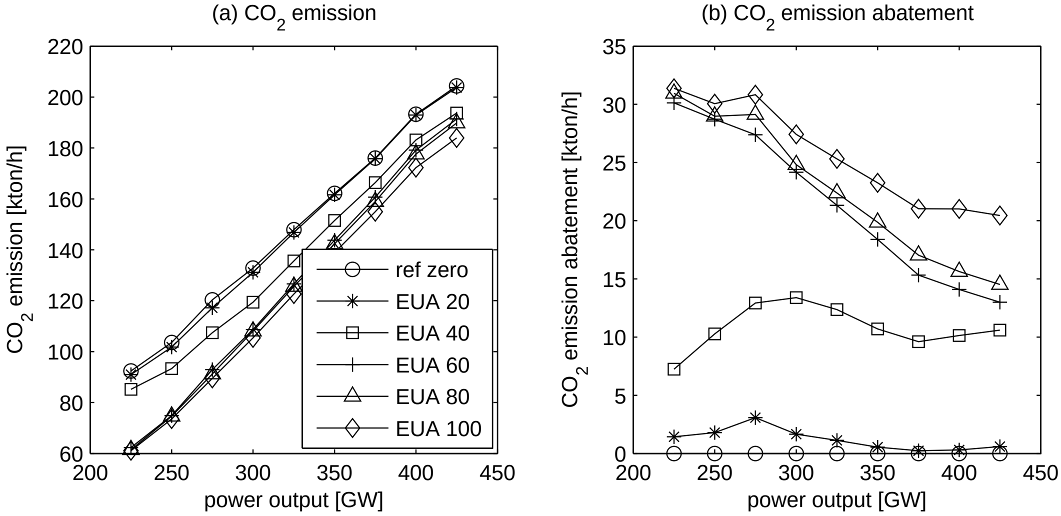

Figure 2. (a) CO_2 emission at different EUA prices; (b) corresponding CO_2 abatement (compared to zero EUA reference case). The legend in (a) applies also in (b).

With a fuel price for natural gas that is three times the coal price, as assumed here, a 20 €/ton CO_2 value yields very little abatement. Some abatement from fuel switching occurs at low load levels, but a CO_2 price of 20 €/ton is not high enough to encourage much fuel switching at these fuel prices. However, the picture for a EUA price of 40 €/ton is quite different. In this case, a relatively constant abatement of about 10 kton/hour can be noticed throughout the entire load spectrum. Still higher CO_2 prices cause more lower emitting plants to substitute for coal, especially at the lower load levels, and thereby to create significant abatement. Nevertheless, abatement diminishes as load increases since the higher load pulls more gas-fired generation into service in the business as usual (BAU) case and thereby diminishes the gas-fired capacity that is available to substitute for coal when the CO_2 price is high enough to induce switching.

Figure 3 presents (a) the corresponding 3D representation and (b) the contour plot of the abatement. In these figures, the extent to which CO_2 abatement changes with load and EUA price can be seen by drawing a straight line from any point on the appropriate axis.

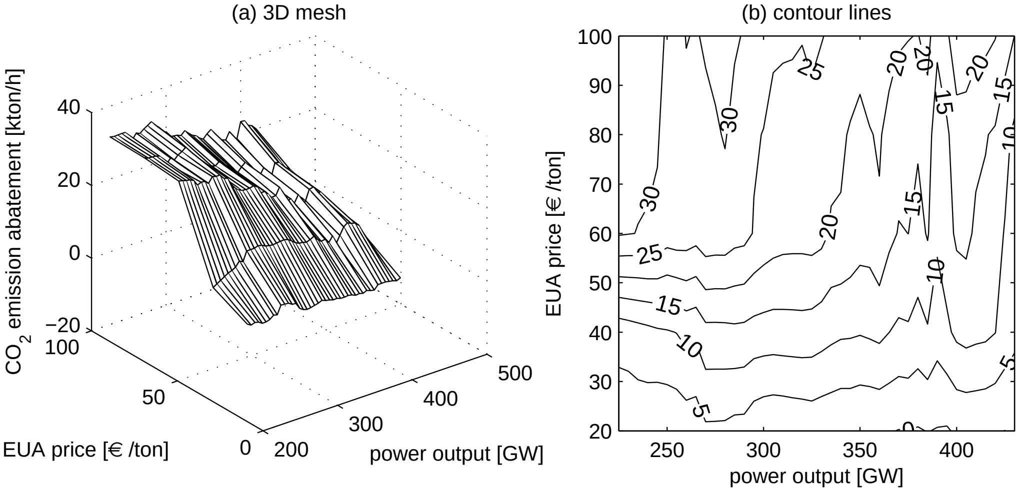

Figure 3. (a) 3D mesh of the power output, EUA price and abatement relationship; (b) corresponding contour lines of the abatement [kton/hour].

Given typical fuel price relationships and the historical configuration of plant types, a carbon price will have its greatest effect at relatively low load levels, when gas capacity is available for switching. For any given CO_2 price, the amount of abatement will diminish as load increases. This tendency is particularly pronounced when CO_2 price levels are high enough to trigger significant switching at low load levels.

Figure 4 presents these relationships in the MACC form, that is, in two-dimensional space with load represented as shifts of the curve, in both absolute and percentage levels. Each of the curves in **Figure 4** (a) reflects a vertical line drawn from the corresponding power output in **Figure 3** (b). The inward shifts of the MACCs reflect the diminished abatement potential that occurs when gas-fired capacity is called into service to meet increasing load. The shift is even greater visually when expressed in percentage terms, as in **Figure 4** (b) since the denominator representing what emissions would be in the absence of a CO_2 price, diminishes with load.

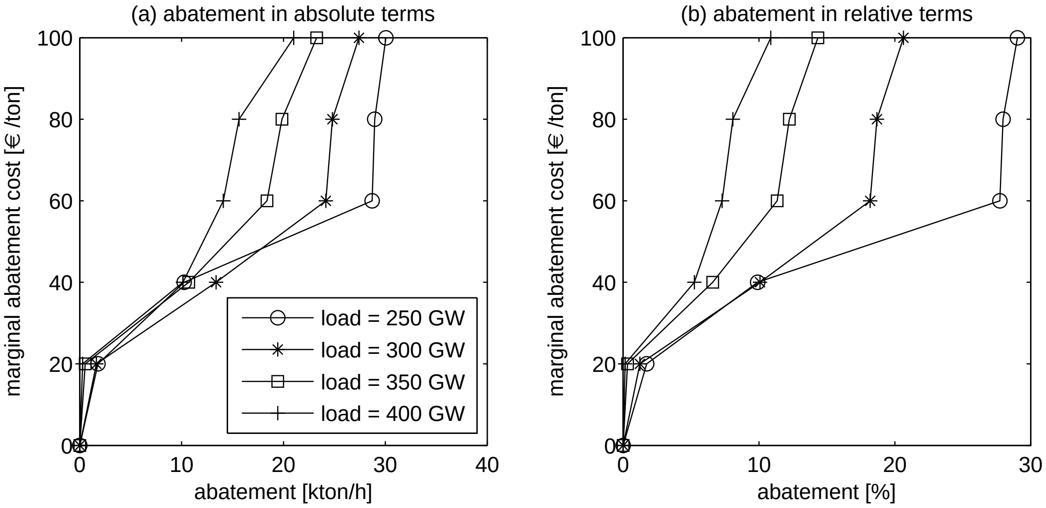

Figure 4. MACCs for different load levels, with fixed (average) fuel prices. Abatement is expressed in (a) absolute terms and (b) relative terms.

The MACC's presented in **Figure 4** show the relationship only for hours at which the load is as indicated. A more meaningful way to present a MACC would be to assume an expected load as it varies through diurnal and seasonal cycles in a given year. This would be closer to the longer term relationship represented in MACCs as encountered in the literature. **Figure 5** presents such a MACC constructed with the results of (full year) simulations at CO_2 prices ranging from zero, which reflects BAU conditions, to 100 €/ton.

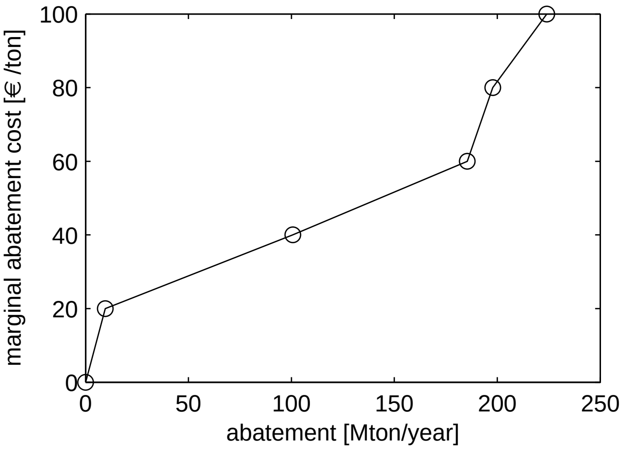

Figure 5. MACC as a result of full year simulation, with fixed (average) fuel prices (abatement is expressed in absolute terms).

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The general shape of this expected annual MACC is similar to those shown in **Figure 4**, but very unlike the smoothly convex MACCs derived from CGE models, which are largely a reflection of the assumed convexity in the production functions. The additional abatement produced by a given increment in price is very little at low and high price levels and much greater at an intermediate level ranging in this case from 20 € to 60 € per ton of CO_2. This characteristic shape is largely explained by the interaction of the CO_2 price with prevailing fuel prices and the configuration of the electricity generating system. A low CO_2 price will not overcome the fuel cost advantage of coal and thereby provide enough incentive to switch; however, once the CO_2 price is high enough, a switching band is entered in which more and more natural gas units are substituted for coal units until most of the available fuel switching capacity has been activated. Thereafter, higher CO_2 prices will not elicit much additional abatement from fuel switching.

The exact placement of this annual MACC will depend not only upon the geographic and temporal distribution of load during the year, but also on the capital stock in place for the year and the fuel price relationships that obtain during the year. Generally speaking, the length of the “switching band,” the range in which additional CO_2 price increases have a relatively large effect on abatement, will be determined by the existing capital stock and relative fuel prices, while the vertical placement of this segment of the MACC depends on plant efficiencies and relative fuel prices. These relationships are the subject of the next section of this paper.

4 THE EFFECT OF FUEL PRICES

For the purposes of this paper, fuel and carbon prices are taken as exogenously determined. Several papers have shown some influence of oil or natural gas prices on the EUA price, but this effect is weak and there are other factors that also influence EUA prices[6]. Recall, however, that the aim of this paper is to demonstrate the sensitivity of MACCs to the different conditions and parameters under which these are developed.

In analyzing the effect of fuel prices on abatement through fuel switching, the “switching band” needs to be explained in more detail. We then proceed to a consideration of the

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[6] For a more extensive discussion of this complicated relationship, see Mansanet-Bateller et al. [21], Bunn and Fezzi [22], and Alberola et al. [23].

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effects of fuel prices on abatement when load is held constant.

4.1 *Development of the switching band*

The EUA price required to switch a certain coal and gas plant in the merit order depends on each plant's fuel cost, efficiency and emission rate as shown in the following illustrative example[7]. Let η_c be a coal plant's efficiency; η_g be a gas plant's efficiency; FC_c the fuel cost for coal [€/GJ]; FC_g the fuel cost for gas [€/GJ]; EF_c the emission factor of coal [ton CO_2/GJ]; and EF_g the emission factor of gas [ton CO_2/GJ]; then the allowance cost necessary to switch both plants in the merit order, ACs [€/ton CO_2], becomes:

$$ACs = \frac{\eta_c \cdot FC_g - \eta_g \cdot FC_c}{\eta_g \cdot EF_c - \eta_c \cdot EF_g} \qquad (1)$$

As the prices of coal or natural gas vary, the allowance cost necessary to effect the switch from the coal plant to the gas plant changes proportionally. Given plant efficiencies and emission factors, the allowance cost that would justify switching from a coal plant to a gas plant can be expressed as a ratio of the natural gas to coal price.

Let $x = \frac{FC_g}{FC_c}$, then substituting this ratio into Eq. (1) gives:

$$ACs = \frac{(\eta_c x - \eta_g) FC_c}{\eta_g \cdot EF_c - \eta_c \cdot EF_g} = a \cdot x + b \qquad (2)$$

The relationship between the gas/coal price ratio, x, and the switching price is presented in **Figure 6** for several combinations of natural gas and coal plant efficiencies[8].

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[7] While the discussion in this paper tends to focus on coal and natural gas, it must be noted that switching also occurs between gas and oil, oil and coal, and between lignite and hard coal, albeit in much smaller quantities.

[8] In this section, the gas price will be varied to vary the fuel price ration between gas and coal. A ratio from zero to 5 is considered. A ratio of zero in fact means a gas price equal to zero. This limit is rather hypothetical, although the price of natural gas in fact has been zero, for example, in the UK during several days in 2006, due to problems with the interconnector with mainland Europe.

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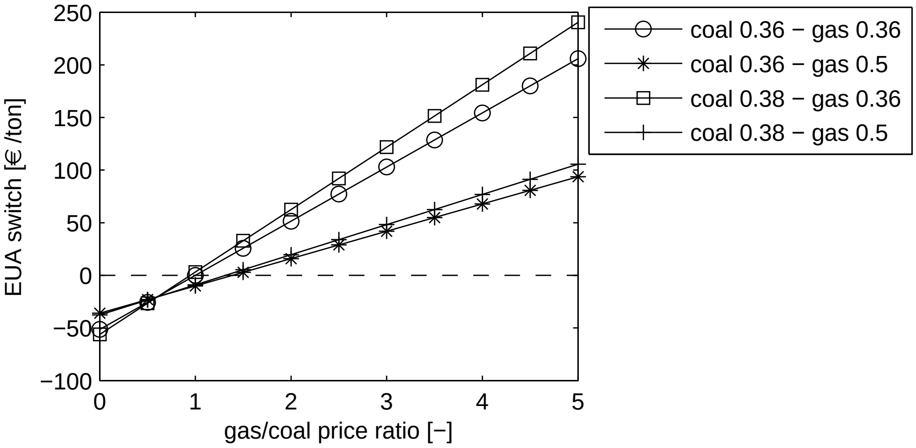

Figure 6. Relationship between gas/coal price ratio and allowance price required for switching, depicted for different combinations of efficiencies.

Figure 6 illustrates equation (2) for various pairs of coal and gas plants with the indicated, assumed efficiencies[9]. The two lines with the lower slope reflect the switching points when efficient combined-cycle gas units (η_g=0.5), substitute for less efficient coal units. Intuitively, these substitutions would be the first to occur as CO_2 prices rise and these lines define one end of the switching band. The other two lines in Figure 6 represent the switching points when less efficient single cycle gas units (η_g=0.36) substitute for coal units of approximately the same efficiency. These substitutions would be the last to occur and they signal that most of the abatement through fuel switching has been achieved. Hence, the switching segment of the MACC can be defined as the range of EUA prices that would occasion switching for any given gas/coal price ratio. For instance in Figure 6, if the gas price was twice the coal price, there would be no switching without a carbon price; however, a carbon price of 15.9 €/ton would switch the most efficient available gas plant for the least efficient coal plant in service and progressively more switching would occur until most opportunities are exhausted at an EUA price of 62.5 €/ton.

The vertical placement of the switching band is also indicated by this interaction between fuel prices and generation efficiency. The initial nearly vertical segment of the MACC in **Figure 5** corresponds to the distance between the start of the switching band and the dashed line indicated a zero carbon price. As shown, the higher the gas price relative to the coal price, the greater the CO_2 price must be to induce switching from the least efficient coal units in service to the most efficient gas units not in service. In the same

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[9] Most current European power plants are included within these ranges. Very efficient plants, whether gas (55%) or coal (45%) are present only in very limited numbers.

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manner, the top lines in Figure 6 indicate the end of the switching band and the resumption of a nearly vertical segment of the MACC when little additional abatement can be expected from higher CO_2 prices.

Furthermore, Eq. (2) and Figure 6 illustrate an important point: switching from coal to natural gas can occur even if there is no carbon cost. This will occur whenever the value of ACs in equation (2) is non-positive. So long as the value of the denominator in equation (2) is positive, as will typically be the case (since the natural gas plant has lower emissions than the coal plant) and coal has a positive price (i.e., $FC_c \geq 0$), there is a gas/coal price ratio x (or alternatively a price of natural gas) that is low enough to justify dispatching the natural gas plant in place of the coal plant even without a CO_2 price. This price ratio can be shown to be $x = \frac{\eta_g}{\eta_c}$, the ratio of the efficiency of the gas plant to the coal plant. In the examples given in **Figure 6**, the fuel price range that would trigger switching with no carbon price starts at 1.39 (= 0.50/0.36) and ends at 0.95 (= 0.36/0.38), as illustrated by the dashed horizontal line. A positive carbon price allows this switching to occur at higher fuel price ratios. For instance, for the examples given in Figure 6, and at an EUA price of 20 €/ton, the switching range extends from 2.16, when the most efficient available gas plant displaces the least efficient operating coal plant, to 1.28, when all switching opportunities are exhausted.

4.2 *Abatement as a function of the fuel price ratio*

The preceding discussion highlights an important aspect of CO_2 emissions reduction by switching: it occurs only over certain price intervals defined by fuel and allowance prices. In general, there always exists a gas/coal price ratio that is either high enough or low enough for the abatement potential from fuel switching to be zero. A very low fuel price ratio will cause all available gas plants to be in service and, for any given CO_2 price, there always exists a high enough fuel price ratio to make switching economically unattractive. In order to describe this interval, a load must be assumed. The diurnal load cycles for four representative days during the year are given in Figure 7 (a) below and the simulated CO_2 emissions associated[10] with those 96 hours is presented in Figure 7 (b) in a similar way as in **Figure 1**.

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[10] Fuel prices used for this figure are the same as the ones used in the previous section, i.e., the 2005 average.

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Each successive 24-hour period in **Figure 7** (a) represents respectively,

- A winter week day
- A summer week day
- A winter weekend day
- A summer weekend day

As can be seen in **Figure 7** (b), emissions for these 96 representative hours span the whole spectrum shown earlier in **Figure 1**.

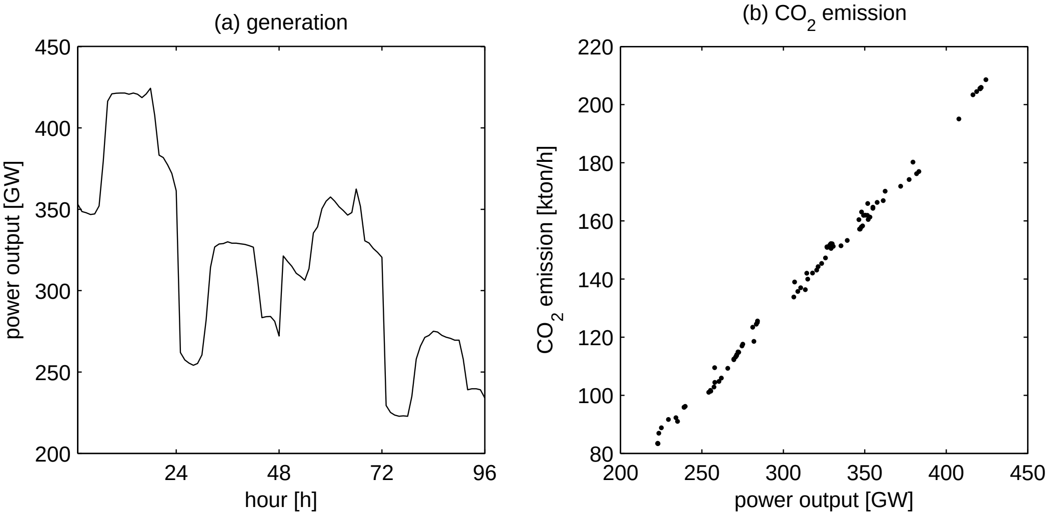

Figure 7. (a) Generation in the four representative days; (b) corresponding CO_2 emission for every simulated hour (96 in total).

Figure 8 presents load-averaged CO_2 emissions for these four representative days as a function of the fuel price ratio for different EUA price scenarios, together with the corresponding abatement. The top-most line in **Figure 8** (a) shows the effect of the fuel price ratio on emissions with no carbon price. With very low natural gas prices, EU emissions for an average hour would be 125 kton or lower[11] but as the natural gas price rises, coal would substitute for gas generation and emissions would rise until they reach a peak of about 142 kton when the natural gas price approaches twice the coal price.

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[11] The emissions at a zero gas/coal price are higher than a ratio of 0.5, since in this case, with no cost for CO_2, using natural gas is actually free of cost, and therefore gas is used wherever possible. This point, therefore, should be interpreted with caution.

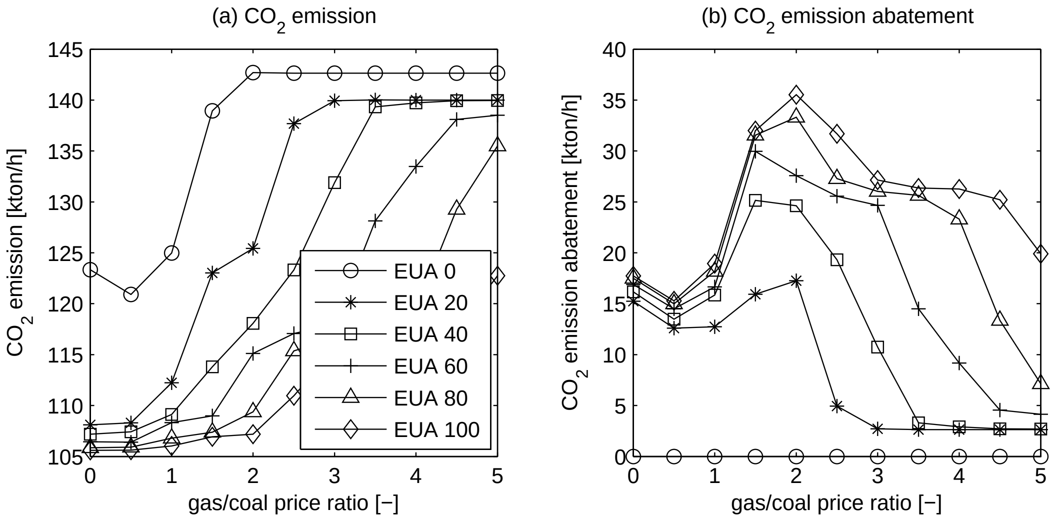

Figure 8. (a) CO_2 emission and (b) corresponding abatement, averaged over load, under different fuel an EUA prices.

As a progressively higher EUA price is imposed, the lines representing emissions in **Figure 8** (a) are pushed down and stretched out to the right. The distance between the zero-price line and the other lines, shown on **Figure 8** (b) indicates the abatement that would be achieved by that CO_2 price over the range of fuel price ratios. Those abatement profiles have a characteristic shape: the emission reduction associated with any given carbon price rises, peaks, and then falls as the fuel price ratio increases.

This characteristic shape reflects the interaction between the switching opportunities created by the fuel price ratio as it increases and the exploitation of those opportunities that can be economically justified by the carbon price. When the capital stock is fixed, higher fuel price ratios cause less gas and more coal capacity to be in service, thereby creating opportunities for switching and thus abatement with an appropriate CO_2 price. For any given CO_2 price, a technical maximum exists, which is higher for higher CO_2 prices[12]. Once the technical maximum is reached, abatement falls as still higher fuel price ratios reduce the number of available switching opportunities that can be economically justified at the assumed carbon price.

As was the case when variations in load were considered, the complexity of these

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[12] This technical maximum will be determined by the lesser of 1) the amount of coal-fired generation that is activated at the fuel price ratio, or 2) the amount of unused but available gas-fired generation that could substitute for the coal-fired generation at the given fuel price ratio.

relationships can be more presented in three-dimensional form as is done in Figure 9.

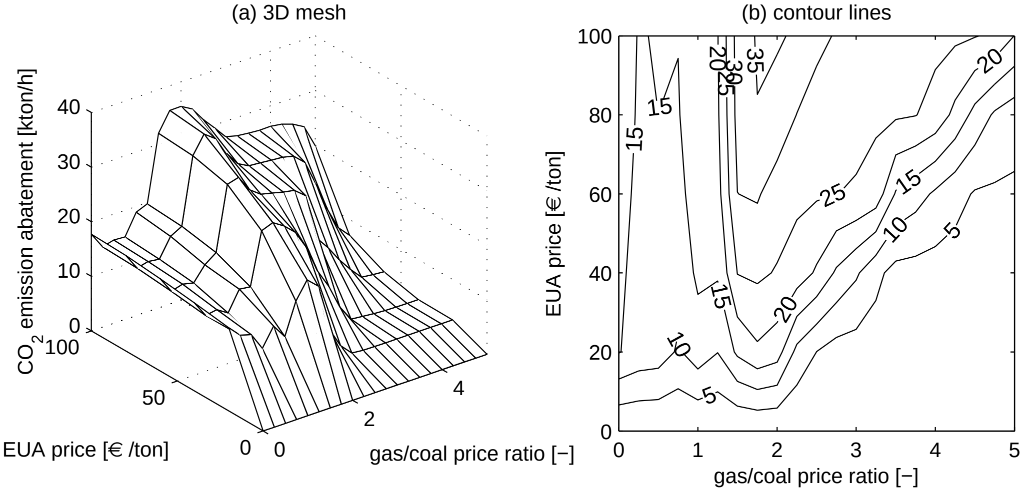

Figure 9. CO_2 emission abatement, averaged over load, under different fuel an EUA prices; (a) 3D mesh; (b) corresponding contour lines.

A more inclusive weighting of availability during the year than the four representative days used here could be done, but the result would be only a variation on the case presented above. For any given configuration of plants and load, higher fuel price ratios increase potential abatement from switching up to a point, defined by the distinct “ridge” in Figure 10, after which higher fuel price ratios diminish abatement in response to a given CO_2 price.

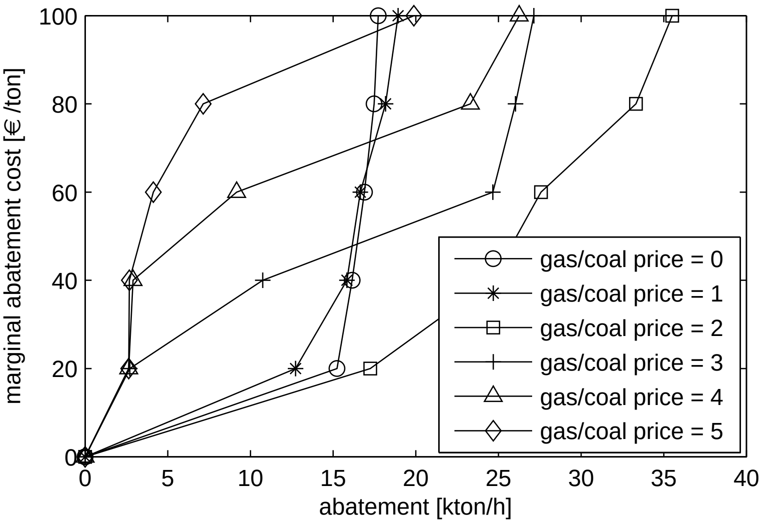

Figure 10. MACCs for different fuel price ratios, at average system load (abatement is expressed in absolute terms).

These relationships can also be presented as MACCs as is done in **Figure 10** for 6 different fuel price ratios. As can be readily seen, the shifts of the MACC occasioned by different fuel price ratios are significant. A distinction can be made between the ‘low’ ratios (0 - 1), the ‘mid’ ratio (2) and the ‘high’ ratios (3 - 5). The MACCs for the low price ratios are characterized by limited abatement and a very steep slope reflecting the small switching capability that exists when all or most available gas units are already in service due to the low gas price. The mid price ratio of 2 offers the greatest abatement opportunities. It is enough to put the coal plants into service in the absence of a CO_2 price, but not so great as to require a high CO_2 price to justify switching. At higher fuel price ratios, the switching capacity is available but a higher CO_2 price is required to make switching economically attractive.

5 COMBINING LOAD AND FUEL PRICE EFFECTS

When the effects of load and fuel prices are considered together, the quantity of abatement that will be obtained for any given CO_2 price will tend to resemble a hill. **Figure 11** presents this “abatement hill” in the case of an allowance cost of 60 €/ton (power output is averaged out in steps of 25 GW) for the 96 hours of the four simulated typical days (Section 4.2) sorted according to load.

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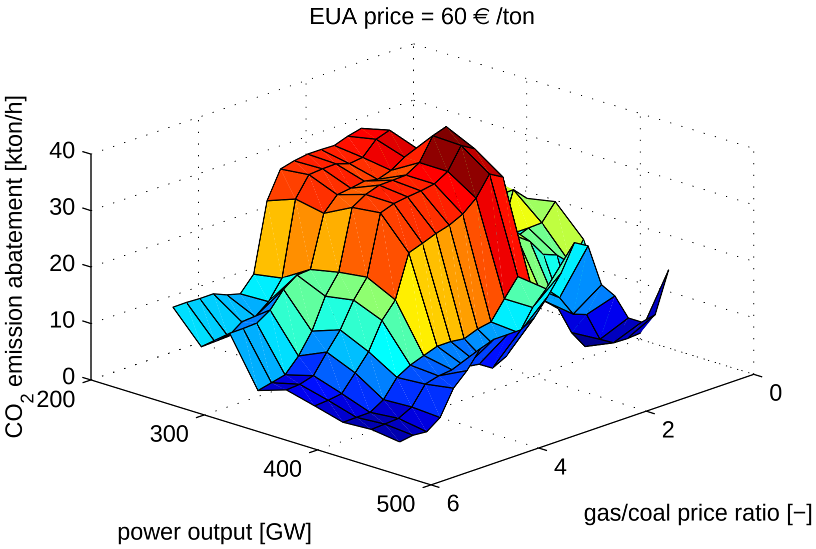

Figure 11. Abatement as function of power output and fuel price ratio, for a EUA price of 60 €/ton.

The contours of this hill are determined by the given configuration of plants and the three factors that have been discussed: load, fuel price ratio, and CO_2 price. At the hypothetical extremes of load and fuel price ratios (which are for the most part outside the range of actual experience in the European electrical system), no abatement would occur at any CO_2 price, but as one moves away from these hypothetical limits to more realistic combinations, there will be an abatement response to a CO_2 price. The steepness of the sides of the hill and the height of its summit are determined by load and the fuel price ratio.

Figure 12 presents the abatement contour lines, corresponding to figures like **Figure 11**, now for EUA prices ranging from 20 €/ton up to 100 €/ton (the 80 €/ton case is not presented for the sake of simplicity). The complex topography reflects, in this instance, the characteristics of the European power system, but certain features persist and are clearly related to CO_2 prices. A zone of maximum abatement potential—the plateau of the abatement hill—can be clearly distinguished situated at the lower load levels. This zone starts at a gas/coal price ratio a little above 1 and higher CO_2 prices not only raise the elevation of the plateau but expand its area to include higher fuel price ratios. The CO_2 price also influences the elevation of the surrounding plains, representing high load levels and/or very low or very high gas/coal prices, but these areas always feature less abatement than the plateau for the reasons explained in previous sections.

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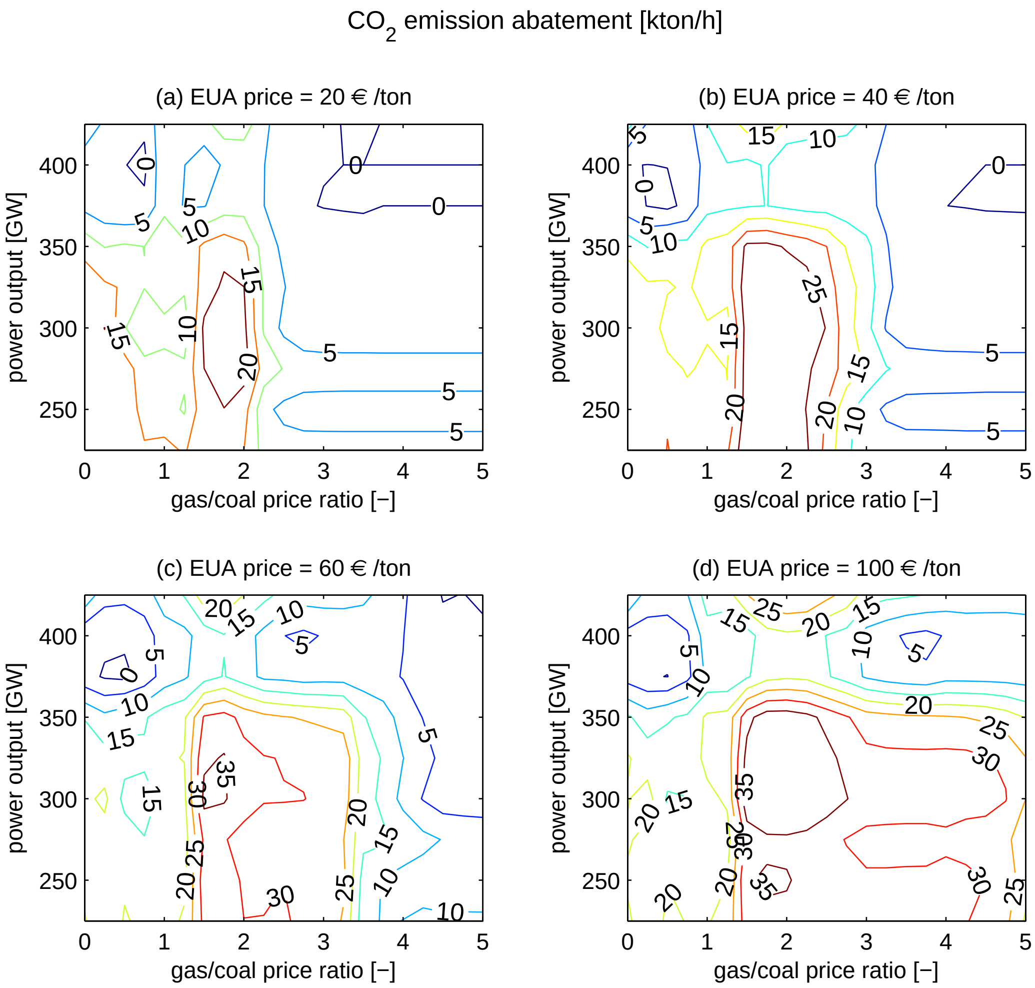

Figure 12. Contour lines of CO$_2$ emission abatement, expressed in [kton/hour], as function of power output and fuel price ratio. (a) EUA price = 20 €/ton; (b) EUA price = 40 €/ton; (c) EUA price = 60 €/ton; (d) EUA price = 100 €/ton.

In seeking to understand the variations in abatement potential of the high load areas of these diagrams, it must be remembered that more efficient generation will get dispatched sooner regardless of the CO$_2$ price. Thus, at high load levels, the cheapest switching opportunities—those associated with high efficiency gas units—are unavailable. Consequently, a higher CO$_2$ price is required to make switching to the remaining lower efficiency gas plants economic.

Two-dimensional MACCs can be created from this complex topography by plotting the abatement associated with any given combination of load and fuel price ratio in each of the diagrams in Figure 12 against the CO$_2$ price. As an example, **Figure 13** plots eight such

MACCs corresponding to four different load levels for two different price ratios in the two panels.

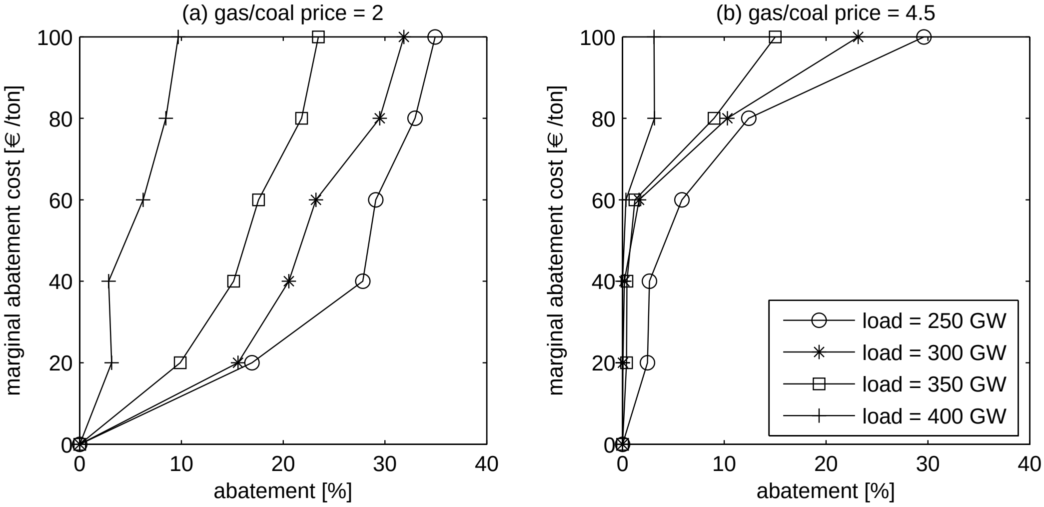

Figure 13. MACCs for different load levels, at (a) a gas to coal price ratio of 2 and (b) a gas to coal price ratio of 4.5 (abatement is expressed in relative terms).

The influence of the fuel price ratio on the robustness of these MACCs is clearly evident (panel (a) versus panel (b)). Load also makes a difference but it is not as great, especially at high fuel price ratios. The extreme sensitivity of the placement of the MACCs to the fuel price ratio is not surprising since the CO_2 price acts only to modify this ratio. If the gas price is very high relative to that for coal, fuel switching and the consequent abatement will occur only at the relatively high CO_2 prices needed to overcome the fuel cost advantage of the higher emitting fuel. However, when the fuel price ratio is more reasonable (and closer to the historic average) as depicted in panel (a), the potential for abatement through fuel switching in the European power system can be considerable, nearly 20% of emissions at a price of 20 €/ton when load is at its lowest.

6 CONCLUSIONS

The title of this paper raises the question of whether MACCs reflecting abatement opportunities through fuel switching in the power sector are robust. The answer is certainly in the negative if one has in mind the simple two-dimensional description that is common in the literature. MACCs can be derived for any given combination of load and fuel price relations for a given hour or for any given period based on some expectation of

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load and fuel prices, but the MACC will look very different in other hours or as a result of significant deviations from the ex-ante expectations, especially those relating to fuel prices.

Our purpose in this paper has been to provide an alternative, more complex, but still reasonably simple depiction of the fuel switching response to a carbon price. The reduction in emissions over some period of time in response to any given price of CO_2 will be the integration of the abatement that obtains during the high frequency intervals (hourly in our model) in which load and fuel prices interact. This integration can be thought of as the summation of the points indicated by rapidly shifting MACCs, but we would suggest that it may be easier to visualize the more complex topography of the "abatement hill" and to imagine the summation of the abatement points as the power system moves onto the plateau, wanders around on it, then goes down one side, and perhaps moves along one of the slopes, or even stays in the plain. In either case, the analyst is well advised to remember that there is no simple relationship between price and abatement, at least for this important component of the more comprehensive response to climate policy.

Two general conclusions emerge from this research. First, as stated above, the relationship between CO_2 price and abatement is highly complex. For any given hour with given load and fuel prices, the expected monotonically rising (although not necessarily convex) relationship between price and abatement can be observed. However, when hours are aggregated into days, weeks, months, and years, the constancy of the relationship will be completely lost. Whatever the aggregation, the amount of abatement will depend as much upon load and fuel price relationships as it will upon the price of CO_2. When using MACCs, one should therefore be extremely cautious, as these MACCs are derived under a specific set of conditions.

A second general conclusion concerns the longer term implications: a larger amount of available gas capacity will increase the amount of abatement in response to a CO_2 price when the fuel price relationships make the use of coal more economic in the absence of a carbon price. The analysis presented here provides a cautionary warning that, even with a price on carbon, the price of natural gas relative to that of coal might reach levels that would make switching unattractive. Still, at the price relationships that have heretofore prevailed only long periods, the pronounced variations in load over daily, weekly, and seasonal cycles would lead to increased switching if more gas capacity were available. The extent to which additional investment in gas capacity would be justified given expected fuel and CO_2 prices over the life of the intended investment is the very essence

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of any investment decision. The analysis in this paper demonstrates that this decision must take into account the highly complex relationships between load, fuel and EUA prices in judging whether the expected utilization of any new plant would warrant the investment.

The presented methodology and corresponding graphs are useful in future analyses relating to the effects of fossil fuel price shocks, changes in demand for electricity (e.g., due to economic downturn), etc. on the abatement of CO_2. As an example, the obtained results can serve as a further basis to investigate the possible beneficial effects of smart metering, as this might induce shifts in demand, which will have an impact on possible CO_2 mitigation, as demonstrated in this analysis.

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8 REFERENCES

[1] Criqui P, Mima S, Viguir L. Marginal abatement cost of CO_2 emission reductions, geographical flexibility and concrete ceilings: an assessment using the POLES model. Energy Policy 1999;27(10):585–601.

[2] Ellerman AD, Decaux A. Analysis of Post-Kyoto CO_2 Emissions Trading Using Marginal Abatement Curves. MIT Joint Program on the Science and Policy of Global Change Report 40, October 1998. Available on: < http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt40.pdf >

[3] Morris J, Paltsev S, Reilly J. Marginal Abatement Costs and Marginal Welfare Costs for Greenhouse Gas Emissions Reductions: Results from the EPPA Model. MIT Joint Program on the Science and Policy of Global Change Report 164, November 2008. Available on: < http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt164.pdf >

[4] Klepper G, Peterson S. Marginal abatement cost curves in general equilibrium: The influence of world energy prices. Resource and Energy Economics 2006;28(1):1-23.

[5] Jacoby, HD. The Uses and Misuses of Technology Development as a Component of Climate Policy. MIT Joint Program on the Science and Policy of Global Change Report 43, November 1998. Available on: < http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt43.pdf >

[6] Chen W, Wu Z, He J, Gao P, Xu S. Carbon emission control strategies for China: A comparative study with partial and general equilibrium versions of the China MARKAL model. Energy 2007;32(1):59-72.

[7] Delarue E, Voorspools K, D’haeseleer W. Fuel switching in the electricity sector under the EU ETS: review and prospective. Journal of Energy Engineering ASCE 2008;134(2):40-46.

[8] Delarue E, Ellerman D, D’haeseleer W. Short-term CO_2 abatement in the European power sector: 2005 and 2006. Submitted to Environmental and Resource Economics 2008.

[9] Voorspools K. The modelling of the power generation of large interconnected power systems in the framework of emission reduction strategies and the liberalization of the market. Doctoral thesis, K.U.Leuven, Applied Mechanics and Energy Conversion, Leuven, 2004. . Available on: < http://www.mech.kuleuven.be/tme/resources/docs/doct/voorspools.pdf >

[10] Voorspools K, D’haeseleer W. Long-term Unit Commitment optimization for large power systems: unit decommitment versus advanced priority listing.

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Applied Energy 2003;76(1-3):157-167.

[11] Voorspools K, D’haeseleer W. The modelling of electric generation of large interconnected systems: How can a CO_2 tax influence the European generation mix. Energy Conversion and Management 2006;47(11-12):1338-1358.

[12] Delarue E, Lamberts H, D’haeseleer W. Simulating greenhouse gas (GHG) allowance cost and GHG emission reduction in Western Europe. Energy 2007;32(8):1299-1309.

[13] Eurelectric, Union of the electricity industry. Statistics and prospects for the European electricity sector (1980-1990, 2000-2030) EURPROG 2006. 2007.

[14] ENTSO-E, European Network of Transmission System Operators for Electricity website. Available on: </ http://www.entsoe.eu/ >

[15] Energinet.dk, Electricity and gas transmission infrastructure operator Denmark website. 2007. Available on: < http://www.energinet.dk/en/menu/Frontpage.htm >

[16] Fingrid Oyj, Electricity transmission system operator Finland website. 2007. Available on: < http://www.fingrid.fi/portal/in_english/ >

[17] Statnett, Electricity transmission system operator Norway website. 2007. Available on: <http://www.statnett.no/default.aspx?ChannelID=1001 >

[18] National Grid, Electricity transmission system operator England and Wales website. 2007. Available on: < http://www.nationalgrid.com/uk/ >

[19] Soni, Electricity transmission system operator Northern Ireland website. 2007. Available on: < http://www.soni.ltd.uk/ >

[20] Eirgrid, Electricity transmission system operator Ireland website. 2007. Available on: <http://www.eirgrid.com/EirgridPortal/ >

[21] Mansanet-Bateller M, Pardo A, Valor E. CO_2 prices, energy and weather. The Energy Journal 2007;28(3):73-92.

[22] Bunn D, Carlo F. Interaction of European carbon trading and energy prices. FEEM Nota di Lavoro 63, 2007. Available on: < http://www.feem.it/NR/rdonlyres/FD3881DB-58D9-4530-9E7B-C567E13DDDC4/2355/6307.pdf >

[23] Alberola E, Chevallier J, Chèze B. Price drivers and structural breaks in European carbon prices 2005-2007. Energy Policy 2008;36(2):787-797.