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Switching to biomass co-firing in European coal power plants: Estimating the biomass and CO2 breakeven prices

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Abstract

This paper investigates the cost of biomass co-firing in European coal plants. We propose an original method to get expressions of biomass and CO2 breakeven points: carbon switching price and biomass switching price. They correspond to carbon and biomass prices that make coal plants equally attractive under co-firing or classical conditions. The carbon switching price is the carbon price from which it becomes profitable to include biomass in coal plants (i.e. if the actual carbon price is higher than the carbon switching price, co-firing is profitable). The biomass switching price is the biomass price beyond which including biomass in coal plants is no longer profitable (i.e. if the actual biomass price is lower than the biomass switching price, co-firing is profitable). We run sensitivity analyses to see the effect of varying quantity and quality of biomass in coal plants' boilers. Results show that the carbon switching price associated with using biomass in lignite plants is always cheaper than that of hard-coal, due to higher lignite price. We also find that the biomass switching price is higher with lignite. This reflects the greater benefit when including biomass in lignite plants, due to greater coal cost saving. Finally, results indicate that the carbon switching price increases, and the biomass switching price decreases, when the biomass quality falls, due to greater conversion efficiency losses. However, we observe no influence when the biomass quantity varies.

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1. Introduction

Increasing the use of biomass in energy would not only increase the share of renewable energy source (RES) in the energy balance, but also reduce the carbon footprint, since biomass does not contribute to increase the CO_2 concentration in the atmosphere (or very few, compared with to fossil fuels).[1] In power generation, biomass is of particular interest. Indeed, as opposed to other renewables, biomass is not subject to problems of intermittency when used to generate electricity. This increases reliability and lowers the cost of managing production, by allowing power producers to dispatch biomass units, as with conventional power plants. Another very promising feature of biomass in electricity is that it can be used in existing coal power stations, which provides great opportunities to increase the share of renewable electricity in the near-term, with no or very few investments. Biomass co-firing in coal plants is also sometimes considered as the most effective abatement measure in the European Union Emission Trading Scheme (EU ETS), because it substitutes biomass, with zero emissions under the scheme, for coal, which produces the highest CO_2 emissions per MWh of electricity (Al-Mansour and Zuwala, 2010).[2]

To date, a large literature has developed to investigate technical considerations related to biomass co-firing in coal plants (*e.g.* Macejewska *et al.*, 2006; ECF *et al.*, 2010; Saidur *et al.*, 2011; IEA-IRENA, 2013). However, a few papers have provided rigorous treatment of the economics of co-firing in power generation (Santisirisomboon *et al.*, 2001; Berggren *et al.*, 2008; Le Cadre *et al.*, 2011; Le Cadre *et al.*, 2012). These papers use simulation models, taking into account the biomass-coal co-firing option, to compute the optimal dispatch of power plants that minimizes the overall cost of generating electricity. Thus, the potential co-fired electricity is estimated, as well as the cost for implementing the co-firing, and the avoided CO_2 emissions. Contrary to these papers, we do not simulate the optimal dispatch of power plants, with the associated biomass quantities and CO_2 emissions. By contrast, we propose a simple and original method that enables us to get expressions of the biomass and CO_2 switching prices that make profitable the biomass co-firing in different types of coal plants. We rely on literature about *fuel switching*, which describes the ability of European power producers to reduce their CO_2 emissions by switching fuels from coal to gas in electricity generation. Thus, a *fuel switching price* is derived, which reflects the CO_2 price that is compatible with a profitable fuel switching. To the best of our knowledge, no previous work has provided such analysis of switching in case of co-firing.

This paper aims to fill this gap in literature, by introducing a flexible framework which allows computing the biomass and CO_2 breakeven prices of co-firing: *carbon switching price* and *biomass switching price*. They correspond to carbon and biomass prices that make coal plants equally attractive under co-firing or classical conditions (*i.e.* when coal is the only input). The carbon switching price is the carbon price from which it becomes profitable to include biomass in coal plants (*i.e.* if the actual carbon price is higher than the carbon switching price, co-firing is profitable). The biomass switching price is the biomass price beyond which including biomass in coal plants is no more profitable (*i.e.* if the actual biomass price is lower than the biomass switching price, co-firing is profitable). These switching price expressions can serve as a dash board, which expresses, at every point in time, how advantageous co-firing is, given the coal, biomass, and CO_2 prices.[3] We also run some

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[1] See ECF *et al.* (2010) for discussions about actual CO_2 emissions from burning biomass.

[2] According with the Directive 2003/87/EC (establishing the EU ETS and related rules) and the Decision 2007/589/EC (establishing guidelines for the monitoring and reporting of greenhouse gas emissions), emissions from burning biomass are exempted from surrendering corresponding allowances. This is equivalent to a zero emission factor applied to biomass. See Bertrand *et al.* (2013) for an estimation of the European abatement potential from biomass co-firing in coal power stations.

[3] Standardized contracts for biomass have increasingly developed in the last few years, and thus, more and more reliable price data are available. For instance, IceEndex (www.iceendex.com) and Argus (www.argusmedia.com)

sensitivity analyses to investigate the effect of modifying the quantity and the quality of biomass entering in boilers of coal power stations. Results indicates that the carbon switching price associated with using biomass in lignite plants is always cheaper than that of hard-coal plants, due to a higher lignite price. In the same way, we find that the biomass switching price has higher values in case of co-firing in lignite plants. This reflects the greater benefits associated with including one MWhp of biomass in lignite plants, due to greater coal cost savings with a higher lignite price. Results also indicate that the carbon switching price increases, and the biomass switching price decreases, when the biomass quality decreases, due to greater losses in conversion efficiency of coal plants, *ceteris paribus*. However, we observe no significant influence when varying the incorporation rate, reflecting the quantity of biomass in coal plants.

The remainder of the paper is organized as follows. Section 2 introduces the economic background and the theoretical model we use. Section 3 presents empirical results, and some sensitivity analyses are included in section 4. Section 5 concludes.

2. Cost of electricity under co-firing and switching prices

2.1. Switching prices and co-firing: Economic background

The usual matter of switching prices in the European power sector is to describe the power producers' ability to substitute (cleaner) gas-fired plants for (dirtier) coal-fired plants in power generation, thereby reducing CO_2 emissions. This phenomenon is known as *fuel switching*, and it has produced a wide literature with both empirical and theoretical works (*e.g.* Sijm *et al.*, 2005; Kanen, 2006; Delarue and D'haeseleer, 2007; Delarue *et al.*, 2008; Carmona *et al.*, 2009; Bertrand, 2010; Delarue *et al.*, 2010; Bertrand, 2012; Lujan *et al.*, 2012).[4] The basic idea is that with a high enough CO_2 price, coal plants switch places with gas plants in the merit order.[5] Without a CO_2 price, 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 CO_2 price, gas plants may be preferable to coal plants, due to their lower carbon intensity, and thus it may be cheaper to switch between coal and gas plants. If such switching occurs, CO_2 emissions are reduced because coal plants are brought on line for shorter periods. In this case, the CO_2 price that makes fuel switching profitable is known as *fuel switching price*. It is computed by equalizing the marginal cost of coal and gas power plants, including the cost of CO_2. This allows deriving the breakeven points, which express how advantageous fuel switching is at a certain point in time, given the fuel and CO_2 prices.

The method we present here enables us to compute switching prices which highlight economic conditions that make profitable the biomass co-firing in coal-fired plants. More precisely, they correspond to prices that make coal plants equally attractive under co-firing or classical conditions (*i.e.* when coal is the only input). Equalizing expressions of marginal costs of electricity with and without co-firing, we derive values for which power producers are indifferent between co-firing and classical cycle. These values are breakeven points for co-firing. We call them, *carbon switching price* and *biomass switching price*.

provide price data from spot and futures transactions of wood-pellets and wood-chips delivered to ports of North-West Europe.

[4] See Bertrand (2011) for a review of this literature.

[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 plants to production as demand increases.

2.2. Theoretical model

There are several factors influencing the marginal cost of electricity under co-firing. First of all, it depends on the fuel and CO_2 prices. In this way, the coal and biomass types impact the marginal cost of electricity. Indeed, the price of lignite is not the same as the price of hard-coal. Likewise, the price of biomass varies from one quality to another. The marginal cost of co-fired electricity also depends on changing combustion behavior of coal-fired station, due to adding biomass in the boiler. More precisely, biomass may induce slight losses in conversion efficiency of coal plants. Potential sources of efficiency losses include presence of air in biomass, and the increased moisture content of the biomass-coal blend for co-firing (Baxter, 2005). In order to account for this, we use a coefficient measuring losses in the efficiency rate of coal plants under co-firing. Then, the higher the losses coefficient is, the higher the loss in conversion efficiency. This increases the cost of co-firing. Furthermore, modifying the quantity of biomass entering in the boiler may also affect losses in conversion efficiency and the cost of co-firing. Accordingly, we include in our analysis a variable reflecting the percentage of biomass in the biomass-coal blend for co-firing. We call this incorporation rate.[6]

Marginal cost of electricity under co-firing

In case of co-firing with biomass, we express the efficiency rate of coal plants c using the following equation:

$$\eta_c^{cf} = \eta_c^{nocf} - \rho_b \, inc_{c,b} \, , \qquad \textbf{(1)}$$

where subscript b denotes the type of biomass, and index cf stands for co-firing. ρ_b is the losses coefficient measuring possible decreases in the efficiency rate of coal plants under co-firing with biomass b, and $inc_{c,b}$ represents the incorporation rate of biomass b in coal plants c.[7] Finally, η_c^{nocf} is the efficiency rate (MWhelec/MWhp) of coal plants c without co-firing.

The way we model η_c^{cf}, enables us to represent the effect of different incorporation rates on the efficiency losses, for a given losses coefficient. According with Ecofys (2010), we assume a linear relationship between the efficiency losses and the incorporation rate.[8] This is not a very strong assumption, because, at the 5-10% incorporation rate, efficiency losses are small.[9] Indeed, several studies on co-firing have reported very few efficiency losses (or even none) for incorporation rate of about 5-10% (Baxter, 2005; Ecofys, 2010; IEA-IRENA, 2013). Hence, using this setting, we get higher efficiency losses for higher losses coefficients, and, for a given losses coefficient, higher efficiency losses when the incorporation rate increases. As an illustration, let us assume a co-firing situation with the following values: $\eta_c^{nocf} = 0.38$, $\rho_b = 0.05$, and $inc_{c,b} = 0.05$. In this case we get $\eta_c^{cf} = 0.3775$, which corresponds to a loss in conversion efficiency of 0.66%. Baxter (2005)

[6] Whereas the effect of modifying the losses coefficient is straightforward, it is difficult to disentangle in case of the incorporation rate. In fact, modifying the incorporation rate induces two opposite effects for the co-firing cost, and the net effect is undetermined. See section 4 .

[7] Note that the losses coefficient and the incorporation rate depend on the type of biomass. This is because losses in conversion efficiency tend to increase when the biomass quality decreases. In the same way, the higher the quality of biomass is, the higher the possible incorporation rate is. Accordingly, the losses coefficient and the incorporation rate are supposed to depend on the biomass quality.

[8] Whereas some studies find a linear relationship between these variables (*e.g.* Ecofys, 2010), others report non-linear relationship (*e.g.* Mann and Spath, 2001). This probably deserves further investigations.

[9] Co-firing is currently feasible with incorporation rates of 20%, and sometimes almost 50%. With pre-treatments, incorporation rates can reach more than 50%. However, in practice, actual incorporation rates rarely exceed 10% (IEA-IRENA, 2013).

indicates that, if all the efficiency losses associated with co-firing were allocated to only the biomass fraction of energy input, they would represent a 0-10% loss in conversion efficiency. In our case, assuming $\rho_b = 0.05$ and $\eta_c^{nocf} = 0.38$, the loss in conversion efficiency spans from 0.66% ($inc_{c,b} = 0.05$) to 6.58% ($inc_{c,b} = 0.5$).

Using the above equation for η_c^{cf}, we can express the marginal cost of one MWh of electricity generated in coal plants *c* under co-firing. Then we get the following expression:

$$MC_c^{cf} = q_{c,c}^{cf}\, C_c + q_{c,b}^{cf}\, B_b + e_c^{cf}\, EUA, \qquad \textbf{(2)}$$

where B_b is the price of biomass *b* (Euros/MWhp) and C_c is the price of coal *c* (Euros/MWhp), with *c* = {*HC (Hard-Coal), L (Lignite)*}.[10] EUA denotes the price of European Union Allowances (Euros/tCO_2), the CO_2 certificates from the EU ETS.

In equation **(2)**, $h_c^{cf} = 1/\eta_c^{cf}$ is the heating rate (MWhp/MWhelec) of coal plants *c* under co-firing. It is computed given η_c^{cf}, the efficiency rate of coal plants *c* under co-firing (MWhelec/MWhp), as given by equation **(1)**. Thus, h_c^{cf} corresponds to the quantity of primary energy (MWhp) in the biomass-coal blend which allows power producers to generate one MWh of electricity under co-firing. Hence, once h_c^{cf} and $inc_{c,b}$ are known, one can compute the quantities of coal and biomass needed to generate one MWh of co-fired electricity as follows: $q_{c,b}^{cf} = inc_{c,b} \times h_c^{cf}$ and $q_{c,c}^{cf} = (1 - inc_{c,b}) \times h_c^{cf}$. $q_{c,b}^{cf}$ ($q_{c,c}^{cf}$, respectively) denotes the quantity of biomass *b* (quantity of coal *c*, respectively) entering in the biomass-coal blend, h_c^{cf}, allowing to generate one MWh of co-fired electricity in coal plants of type *c* (*i.e.* $h_c^{cf} = q_{c,c}^{cf} + q_{c,b}^{cf}$).

Finally, $e_c^{cf} = e_c \times q_{c,c}^{cf}$ is the emission factor of coal plants *c* under co-firing (tCO_2/MWhelec). It is computed given e_c, the primary energy emission factor of coal *c* (tCO_2/MWhp). Note that in equation we use for e_c^{cf}, emissions arise from the coal fraction of energy input only. This reflects the zero emission rate applied to biomass in the EU ETS.

Marginal cost of electricity without co-firing

Under a classical cycle, when coal is the only input, we define the marginal cost of one MWh of electricity generated in coal plants of type *c* as follows:

$$MC_c^{nocf} = h_c^{nocf}\, C_c + e_c^{nocf}\, EUA, \qquad \textbf{(3)}$$

where $h_c^{nocf} = 1/\eta_c^{nocf}$ and $e_c^{nocf} = e_c \times h_c^{nocf}$ are, respectively, the heating rate (MWhp/MWhelec) and the emission factor (tCO_2/MWhelec) of coal plants *c* without co-firing. As before, η_c^{nocf} and e_c represent, respectively, the efficiency rate of coal plants *c* without co-firing (MWhelec/MWhp), and the primary energy emission factor of coal *c* (tCO_2/MWhp). Note that, when assuming $inc_{c,b} = 0$ and $\rho_b = 0$, equation **(2)** is equivalent to equation **(3)**. Indeed, in this case, $q_{c,c}^{cf} = h_c^{cf}$ (since $q_{c,b}^{cf} = 0$) and $\eta_c^{cf} = \eta_c^{nocf}$. Therefore, $h_c^{cf} = h_c^{nocf}$ and $e_c^{cf} = e_c^{nocf}$, so that equations **(2)** and **(3)** are equivalent.

[10] The co-firing potential of hard-coal and lignite plants is broadly the same. Slight differences can exist in certain cases, because hard-coal plants generally require high-quality biomass, while lignite plants can more easily burn biomass with pretty high moisture content. See ECF *et al.* (2010).

Biomass and carbon switching prices

Equalizing the marginal costs of electricity with and without co-firing, we get:

$$EUA^*_{c,b} = \frac{q^{cf}_{c,b}\, B_b - \left(h^{nocf}_c - q^{cf}_{c,c}\right) C_c}{e^{nocf}_c - e^{cf}_c} \text{ and } B^*_c = \frac{C_c\left(h^{nocf}_c - q^{cf}_{c,c}\right) + EUA\,(e^{nocf}_c - e^{cf}_c)}{q^{cf}_{c,b}}, \quad \textbf{(4)}$$

where $EUA^*_{c,b}$ is the *carbon switching price* (Euros/tCO_2) associated with using biomass *b* in coal plants *c*, and B^*_c is the *biomass switching price* (Euros/MWhp) associated with using biomass in coal plants *c*.

$EUA^*_{c,b}$ corresponds to the increased fuel cost from co-firing which enables power producers to abate one tonne CO_2.[11] Accordingly, co-firing is cheaper than using coal plants in classical cycle if the additional fuel cost associated with co-firing $(q^{cf}_{c,b}\, B_b - \left(h^{nocf}_c - q^{cf}_{c,c}\right) C_c)$ is smaller than the cost of increased CO_2 emissions in case of classical cycle $(EUA(e^{nocf}_c - e^{cf}_c))$. In other words, switching to co-firing will (will not, respectively) occur if $EUA^*_{c,b} < EUA$ ($EUA^*_{c,b} > EUA$, respectively), where *EUA* denotes the observed price of EUAs. Hence, $EUA^*_{c,b}$ reflects the CO_2 price from which it becomes profitable to include biomass *b* in coal plants *c*.

B^*_c corresponds to the benefit associated with including one MWhp of biomass in coal plants of type *c*. This arises from reduced costs of coal consumption $(C_c\left(h^{nocf}_c - q^{cf}_{c,c}\right))$ and of CO_2 emissions $(EUA(e^{nocf}_c - e^{cf}_c))$. Hence, B^*_c can be considered as the benefit of one MWhp of biomass entering in coal plants *c*, whereas B_b (the observed price of biomass *b*) is the cost. Therefore, including biomass *b* in coal plants *c* is a profitable (not profitable, respectively) option as long as $B_b < B^*_c$ ($B_b > B^*_c$, respectively). Hence, B^*_c reflects the biomass price beyond which including biomass in coal plants of type *c* is no longer profitable.

3. Empirical results

In order to compute the biomass and carbon switching prices, we use price data for lignite, hard-coal and different types of biomass. Values and references are summarized in Table 1. Moreover, we assume efficiency rates of 34, and 38%, for lignite, and hard-coal power plants, respectively. The CO_2 emission factors for primary energy are provided by the Intergovernmental Panel on Climate Change. They account for the quantity of CO_2 (in tonnes) per MWhp of lignite (0.357), hard-coal (0.339), and biomass (zero).

Table 1: Fuel prices (Euro/MWhp) as delivered to power plants.

Fuel	Prices – Euros/MWhp (as delivered to power plants)	Sources
Lignite	16.8	www.kohlenstatistik.de
Hard-Coal	11.3	www.kohlenstatistik.de
Torrefied Pellets (ToP)	30 – 31.7	ECF *et al.* (2010), KEMA (2012)
Wood Pellets (WP)	25 – 31	ECF *et al.* (2010), Argus (2011), KEMA (2012)
Wood Chips (WC)	13.4 – 27	ECF *et al.* (2010), Argus (2011)
Agricultural Residues (AR)	13 – 16	ECF *et al.* (2010)

[11] Note that, as opposed to fuel switching with coal and gas plants, co-firing does not necessarily entail changes in the dispatch of power plants. More precisely, if co-firing does not modify the merit order of power plants, there is no change in the dispatch.

In all our calculations, we assume an incorporation rate of 10%. As we already mentioned, this corresponds to incorporation rates frequently encountered in practice. Furthermore, we split the different biomass types of Table 1 into two categories: Pre-Treatment (PT), and No Pre-Treatment (NOPT). While we consider ToP and WP as high quality pre-treatments lying in the PT category, we include WC in NOPT. We choose this division because WC exhibits energy contents which are quite similar to the ones of raw wood (Maciejewska *et al.*, 2006; Acharya *et al.*, 2012). This enables us to applying a higher losses coefficient to the NOPT category, reflecting the lower quality of this biomass type (*cf.* Table 2).

Table 2: Estimated carbon switching prices (using price data of Table 1) as given by equation **(4)**.

$EUA^*_{c,b}$	**Pre-Treatment ($\rho_{PT}=0$)**		**No Pre-Treatment ($\rho_{NOPT}=0.05$)**	
	Low biomass price	High biomass price	Low biomass price	High biomass price
$EUA^*_{L,ToP}$	36.88	41.64	(51.36)[a]	(53.66)[a]
$EUA^*_{HC,ToP}$	55.11	60.12	(68.51)[a]	(70.89)[a]
$EUA^*_{L,WP}$	22.88	39.68	(34.35)[a]	(54.65)[a]
$EUA^*_{HC,WP}$	40.38	58.06	(51.54)[a]	(71.90)[a]
$EUA^*_{L,WC}$	(-9.60)[a]	(28.48)[a]	-3.13	41.51
$EUA^*_{HC,WC}$	(6.19)[a]	(46.27)[a]	12.17	58.33
$EUA^*_{L,AR}$	(-10.44)[a]	(-2.32)[a]	-4.44	5.40
$EUA^*_{HC,AR}$	(5.01)[a]	(13.85)[a]	10.81	21.00

a: Values associated with losses coefficients which do not reflect the quality of the considered biomass type.

So far we defined the carbon switching price as the increased fuel cost of co-firing, which enables power producers to abate one tonne CO_2. More precisely, two effects have to be considered when switching to co-firing. On the one hand, the fuel cost of biomass ($q^{cf}_{c,b}\ B_b$) increases (since no biomass was used before). On the other hand, the cost of coal consumption ($(h^{nocf}_c - q^{cf}_{c,c})C_c$) decreases. Thus, defining the carbon switching price as an increased fuel cost is equivalent to weighing the effect of biomass compared with coal costs. It is worthwhile mentioning these two effects to interpret results of Table 2.

Results of Table 2 show that the carbon switching price associated with using biomass in lignite plants is always cheaper than that of hard-coal plants. This is because, in price data we use, the lignite price is higher than the price of hard-coal. Thus, each time a MWhp of biomass is included in a coal-fired station with lignite, it comes with a higher avoided cost for coal consumption. This translates into a lower carbon switching prices in lignite plants compared to hard-coal. Accordingly, one can conclude that switching to co-firing is cheaper in lignite plants, and it can be profitable with lower CO_2 prices. In addition, Table 2 shows that the carbon switching price associated with using non pre-treated biomass (WC and AR) is cheaper than that of pre-treated biomass (ToP and WP). Indeed, in price data we use, pre-treated biomass is so expensive that it is associated with a higher carbon switching price than non pre-treated biomass, even taking into account the lower losses coefficient of pre-treated biomass.[12] One exception is the carbon switching prices associated with the high WC price,

[12] Results of Table 2 indicate that the carbon switching price is an increasing function of the losses coefficient. That is, the higher the losses coefficient is, the higher the loss in conversion efficiency is. This increases the additional fuel cost needed to abate one tonne of CO_2 under co-firing, and thus the carbon switching price. See section 4 for further details.

which are higher than those associated with the high WP price. In this case, the price difference of biomass is so small that it produces a weaker effect on the carbon switching price than the difference of losses coefficients.

Interestingly, we also observe in Table 2 that the carbon switching price of lignite plants turns out to be negative in several cases, meaning that switching to co-firing is a profitable option even for a zero CO_2 price. The negative carbon switching prices arise from circumstances in which the considered biomass type is so cheap that, combined with the higher lignite price, the additional cost of biomass under co-firing is lower than the coal cost saving. Hence, power producers can make money by switching to co-firing so as to abate one tonne of CO_2, even neglecting the CO_2 cost saving.

Table 3: Estimated biomass switching prices (using price data of Table 1) as given by equation **(4)**. Subscripts PT and NOPT only reflect the different values we use for losses coefficient (as given in Table 2).

B_c^*	**Carbon price**		
	Euros 5/tCO_2	Euros 10/tCO_2	Euros 20/tCO_2
$B_{L,NOPT}^*$	15.88	17.40	20.45
$B_{HC,NOPT}^{SW}$	11.29	12.76	15.71
$B_{L,PT}^*$	18.61	20.40	23.97
$B_{HC,PT}^*$	13.00	14.69	18.09

Similarly to the carbon switching price, results of Table 3 indicate that co-firing is cheaper in lignite plants. Indeed, we observe that the biomass switching price has higher values in case of co-firing in lignite plants. This reflects the higher benefits associated with including one MWhp of biomass in lignite plants, due to greater coal cost savings with a higher lignite price. Accordingly, the zone in which biomass prices are compatible with a profitable co-firing is larger with lignite plants than with hard-coal. For instance, in the case of non pre-treated biomass with a Euros 5 CO_2 price, results indicate that co-firing in lignite plants is a profitable option as long as the biomass price is not more than Euros 18.61. The same breakeven value is Euros 13 with hard-coal plants. Assuming a biomass price of Euros 15 per MWhp, it would be profitable switching to co-firing in lignite plants, but not in hard-coal plants.

We also observe in Table 3 that the biomass switching price always has a higher value when reflecting pre-treatment. This is explained by the lower losses coefficient we use in this case. This translates into lower losses in conversion efficiency, and thus lower cost for co-fired electricity. Consequently, co-firing produces better outcomes in this case, which appears in the higher biomass switching prices.

4. Sensitivity analysis

Modifying the value of the losses coefficient (ρ) and of the incorporation rate (inc) may affect the cost of co-firing and switching prices. We already mention this in previous sections. We go further here, by running a series of sensitivity analysis to see how switching prices are affected when changing the value of ρ and inc. We use the same data as in section 3. However, as a simplification, we assume a single biomass price of Euros 23.4 per MWhp. This corresponds to the average of the biomass price values reported in Table 1. Moreover, we also assume a single CO_2 price of Euros 5 per tonne.

As indicated in Table 4, when increasing the value of the losses coefficients, carbon switching price increases and the biomass switching price decreases. This is because the cost of co-firing increases when ρ increases, *ceteris paribus*.

Table 4: Effect of changing losses coefficient (*ceteris paribus*).

inc	ρ	η_L^{cf}	η_{HC}^{cf}	effect 1		effect 2		EUA_L^*	EUA_{HC}^*	B_L^*	B_{HC}^*
				h_L^{cf}	h_{HC}^{cf}	e_L^{cf}	e_{HC}^{cf}				
10%	0	0.340	0.380	2.941	2.632	0.945	0.803	18.40	35.66	18.61	13.00
10%	0.01	0.339	0.379	2.950	2.639	0.948	0.805	20.39	37.52	18.07	12.66
10%	0.05	0.335	0.375	2.985	2.667	0.959	0.814	29.70	46.11	15.88	11.29
10%	0.1	0.330	0.370	3.030	2.703	0.974	0.825	45.70	60.29	13.14	9.58

Two reasons can explain the rise in the cost to switch to co-firing as ρ increases, and the resulting higher (lower, respectively) carbon switching price (biomass switching price, respectively). First, more primary energy is needed for each switched MWh of electricity (effect 1, Table 4). Second, CO_2 emissions per MWh of co-fired electricity increases (effect 2, Table 4), and thus the CO_2 abatements per switched MWh decrease. Therefore, more switched MWhs are required to get one tonne of CO_2 abatements.

Effects 1 and 2 show unambiguously that the additional fuel cost which enables power producers to abate one tonne CO_2 under co-firing increases with ρ. Hence, the higher the losses coefficient is, the higher the carbon switching price. Likewise, these two effects explain the decrease in the biomass switching price as ρ increases. Both indicate that the cost of one MWh of co-fired electricity increases, due to the greater cost for fuel (effect 1) and CO_2 (effect 2). In other words, each switched MWh of electricity provides power producers with fewer CO_2 cost saving, and greater additional fuel cost. This explains that each MWhp of biomass entering in coal plants has a lower value, and thus the biomass switching price decreases.

Table 5: Effect of changing incorporation rate (assuming different losses coefficients, *ceteris paribus*).

inc	ρ	η_L^{cf}	η_{HC}^{cf}	effect 1		effect 2		EUA_L^*	EUA_{HC}^*	B_L^*	B_{HC}^*
				h_L^{cf}	h_{HC}^{cf}	e_L^{cf}	e_{HC}^{cf}				
50%	0.05	0.315	0.355	3.175	2.817	0.567	0.477	29.70	46.11	15.88	11.29
5%	0.05	0.338	0.378	2.963	2.649	1.005	0.853	29.70	46.11	15.88	11.29
50%	0.10	0.290	0.330	3.448	3.030	0.616	0.514	45.70	60.29	13.14	9.58
5%	0.10	0.335	0.375	2.985	2.667	1.012	0.859	45.70	60.29	13.14	9.58
50%	0.30	0.190	0.230	5.263	4.348	0.939	0.737	509.80	294.29	2.19	2.74
5%	0.30	0.325	0.365	3.077	2.740	1.044	0.882	509.80	294.29	2.19	2.74

Table 5 shows that moving from 5 to 50% incorporation rate does not impact the carbon and biomass switching prices, whatever the value of ρ we use. As with the losses coefficient, modifying the incorporation rate induces two effetcs. However, unlike what happens with the losses coefficient, those two effects work in opposite directions, and the net effect of increasing the incorporation rate is undetermined.[13]

As before, effect 1 indicates that more primary energy is needed to generate one switched MWh of electricity when inc increases (*e.g.* we move from 2.963 to 3.175 MWhp of

[13] This result may depend on assumptions of the model. This is an important question, which deserves further investigations.

lignite per MWhelec, when $\rho = 0.05$). This tends to increase the fuel cost per switched MWh of electricity, and thus the additional fuel cost needed to abate one tonne of CO_2. However, simultaneously, the CO_2 emissions per MWh of co-fired electricity decreases (effect 2), because more biomass is included in the blend for co-firing. Thus, the CO_2 abatements per switched MWh increase, so that fewer switched MWhs are required to get one tonne of CO_2 abatements. This tends to decrease the additional fuel cost needed to abate one tonne of CO_2 under co-firing. Therefore, modifying the incorporation rate induces two opposite effects for the carbon switching price, and we cannot conclude on the net effect. In the same way, the net effect on the biomass switching price is undetermined because increasing *inc* tends to increase the fuel cost per MWh of co-fired electricity, while the CO_2 cost saving increases simultaneously.

5. Conclusion

This paper investigates the cost of biomass co-firing in European coal power stations. Relying on literature about coal-to-gas *fuel switching* in power generation, we propose a simple and original method that enables deriving expressions of the biomass and CO_2 switching prices that make profitable the biomass co-firing in different types of coal plants. These values correspond to breakeven points for co-firing, and we call them *carbon switching price* and *biomass switching price*. To the best of our knowledge, no previous work has provided such analysis of switching in case of co-firing.

Results indicates that the carbon switching price associated with using biomass in lignite plants is always cheaper than that of hard-coal plants, due to a higher lignite price. The carbon switching price of lignite plants is even negative in several situations, meaning that switching to co-firing is profitable even for a zero CO_2 price. This arises from circumstances in which the considered biomass type is so cheap that, combining with the high lignite price, this translates into situations where the additional cost of biomass under co-firing is lower than the coal cost saving. Hence, power producers can make money by switching to co-firing so as to abate one tonne of CO_2, even neglecting the CO_2 cost saving. In the same way, we find that the biomass switching price has higher values in case of co-firing in lignite plants. This reflects the greater benefits associated with including one MWhp of biomass in lignite plants, due to greater coal cost savings with a higher lignite price. Accordingly, the zone in which biomass prices are compatible with a profitable co-firing is larger with lignite plants than with hard-coal.

We also investigate the effect of modifying the quantity and the quality of biomass entering in boilers of coal power stations, through different sensitivity analyses. According to results, the carbon switching price increases, and the biomass switching price decreases, when we increase the value of the coefficient measuring the efficiency losses of coal plants under co-firing, *ceteris paribus*. This reflects higher cost for co-firing when associated with lower biomass quality, because of greater losses in conversion efficiency of coal plants. However, we observe no significant influence when varying the incorporation rate. Indeed, modifying the incorporation rate induces two opposite effects for the co-firing cost, and the net effect is undetermined for both the biomass and carbon switching prices.

This paper provides a flexible framework which allows us to derive the biomass and CO_2 breakeven prices of co-firing, in different situations. These expressions of the biomass and carbon switching prices can serve as a dash board, which expresses the advantages of co-firing given the coal, biomass, and CO_2 prices. Moreover, this method offers several perspectives for further research. An avenue for future research consists in using these expressions as basis for econometric estimations investigating the impact of the CO_2 price on biomass prices, or to assess the influence of different co-firing drivers on biomass consumption of power producers.

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