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Biomass for Power Generation in the EU-27: Estimating Potential Demand, CO_2 Abatements and the Biomass and CO_2 Breakeven Prices for Co-firing

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Keywords: Biomass, Electricity Production, Co-Firing, Switching Price, EU ETS.

This work has been presented at the conference "Développement agricole et forestier vers une société sobre en carbone" of Paris-Dauphine University (Paris, June 2013). The authors would like to thank Philippe Delacote (LEF-INRA and Climate Economics Chair), Frédéric Lantz (IFP-School), Julien Rousseau (Sofiprotéol), Raphaël Trotignon (Climate Economics Chair) and two anonymous referees for insightful comments and suggestions on earlier versions of this work. Any remaining errors are ours.

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Biomass for Power Generation in the EU-27: Estimating Potential Demand, CO_2 Abatements and the Biomass and CO_2 Breakeven Prices for Co-firing[†]

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Abstract

This paper gives an overview on the potential of using biomass in the European power sector. First, we introduce the main questions related to this topic. Next, we present a method that enables us to estimate the potential volumes of biomass which may be used in the European power generation. We also derive the biomass and CO_2 switching prices, which make profitable the biomass co-firing in different types of coal plants. Finally, we rely on recent literature to figure out what are the potential biomass feedstocks in the EU countries, and we compare those resources with results of our estimations. Results indicate that the potential biomass demand from the power sector may be quite high compared with the potential biomass supply. We also identify that the biomass co-firing can produce high volumes of CO_2 abatements, which may account for more than two times the potential abatements from the coal-to-gas fuel switching. Our economic analysis about biomass and CO_2 breakeven prices shows that co-firing can remain profitable with very high biomass prices, when the carbon price is high enough. Hence, the carbon price appears as an important driver of co-firing, which can make a high share of the potential biomass demand from the power sector being economically profitable, even with high biomass prices. However, as biomass stocks are limited, such a situation would result in potential conflicts between different biomass usages.

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1. Introduction

In adopting the 2001 Directive (2001/77/EC) to increase the share of renewable electricity in total electricity consumption, the European Union demonstrated its interest in promoting renewables in Europe. This emphasis was confirmed in 2008, with the Climate and Energy Package, which extends the EU's climate policy beyond 2012. The package includes three "20 targets" to be attained by 2020: reducing greenhouse gas (GHG) emissions by 20% compared to the 1990 level, achieving 20% of renewable energy in total energy consumption, and increasing energy efficiency by 20%. In addition, the EU has also committed itself to reaching 10% of energy from renewable resources in transportation by 2020.[1]

There is a growing interest in using biomass in energy. Biomass is increasingly acknowledged as an important renewable energy source (RES), which can make a very significant contribution to achieve the EU targets. The use of biomass would not only increase the share of RES in the energy balance, but also reduce the carbon footprint, since biomass does not raise CO_2 concentrations in the atmosphere (or very slightly, compared with fossil fuels).[2] Furthermore, as with other RES, a further advantage of biomass is that it reduces energy dependency.

However, there are also a number of concerns about the sustainability of bioenergy, including the potential impacts on food and feed production, changes in land-use, and reduced biodiversity. While, in general, such negative externalities cannot be completely eliminated, most of them can be considerably reduced through the use of lignocellulosic biomass. Among the positive effects of lignocellulosic biomass, is the fact that it does not enter into competition with food (or indirectly, through land-use), in contrast to other energy crops such as sugar beet, sugar cane, maize, potatoes, etc. Lignocellulosic biomass can also alleviate concerns about land-use, since a large proportion of those feedstocks come from agricultural and forestry residues. Moreover, any remaining land-use concerns should potentially be addressed through certifications schemes similar to those used in the forestry industry (ECF et al., 2010).

Biomass is of particular interest in power generation, since it is not subject to problems of intermittency when used to generate electricity as opposed to other RES. This increases reliability and lowers the cost of managing production, by allowing power producers

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[1] The Climate and Energy Package, which was first discussed in 2008, entered in force in 2009 through adoption of the Directive 2009/28/EC. In the case of biomass, the EU objectives have been further defined in the biofuels Directive (2003/30/EC), and in the Biomass Action Plan of 2005.

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

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 thermal power-plants, which provides great opportunities for increasing the share of renewable electricity in the near-term, with no or little investments. Biomass co-firing in coal plants enables power producers to reduce CO_2, SO_2 and NO_X emissions. Regarding CO_2 emissions, co-firing can be 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).[3]

As there is a great number of coal-fired power plants in Europe, a substantial technical potential for biomass co-firing exists in much of the EU countries. To date, very few papers have investigated the question of how much biomass can be used in the existing European power stations. Among them, Berggren et al. (2008) investigate the technical potential for biomass co-firing in the Polish coal power stations. More specifically, this paper focuses on matching the potential biomass supply in Poland with estimated opportunities for biomass co-firing in the existing coal plants. Moreover, the authors derive the CO_2 abatements associated with co-firing. Hansson et al. (2009), propose an estimation of the technical potential biomass demand for co-firing in the existing coal-fired power plants in the EU-27 countries. However, as opposed to Berggren et al. (2008) for Poland, the authors do not provide an extensive comparison of the estimated technical biomass demand with the potential biomass supply in Europe. Moreover, the CO_2 abatements associated with co-firing are not computed.

Our paper extends these previous contributions by matching the potential biomass supply in the EU-27 with estimations of the technical potential biomass demand from the existing power plants in the European power sector. As opposed to the aforementioned papers, we take into account both biomass co-firing in coal plants and power generation from dedicated biomass power plants. We rely on literature to figure out what are the potential biomass feedstocks in the EU-27 countries. Comparing the potential biomass supply with our estimated potential demand, we shed light on how biomass market may be impacted by biomass demand from the European power sector. Furthermore, we compute the CO_2 abatements associated with the estimated potential opportunities for co-firing in the EU-27.

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[3] 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.

In addition to our analysis of the technical potential for biomass in the European power sector, we provide an original method that enables us to estimate the marginal cost of co-fired electricity and the associated biomass and CO_2 breakeven prices for co-firing. These values reflect the economic conditions that make profitable the biomass co-firing in different types of coal plants. To the best of our knowledge, no previous work has provided such analysis. This allows us to discuss potential consequences of biomass demand from the power sector regarding competition between different usages for the biomass resources.

In summary, compared to the previous literature, our contribution is threefold. First, we estimate the technical potential biomass demand from the existing power plants in the European power sector, considering both biomass co-firing in coal plants and power generation from dedicated biomass power plants. Second, we match our estimates with the potential biomass supply in Europe, and we compute the CO_2 abatements associated with co-firing opportunities in the EU-27. Third, we provide a simple and original method that enables us computing the biomass and CO_2 breakeven prices for co-firing.

The remainder of the paper is organized as follows. In section 2, we give an overview of questions related to using biomass in power generation. Section 3 present our estimations of the technical potential biomass demand from the European power sector, and the associated CO_2 abatements. We also derive the biomass and carbon switching prices for co-firing. Section 4 focuses on matching biomass supply in the EU-27 countries with potential biomass demand from our estimations. Section 5 concludes.

2. Key issues and economic considerations in biomass power generation

In this section we present the key issues related to the use of biomass for power generation and the economics of co-firing. The technological options for using biomass in power generation and the pre-treatment of biomass will then be described, followed by a review of the economic advantages and drawbacks of biomass co-firing.

2.1 Key issues: Why use biomass in power generation?

2.1.1 Reducing CO_2 emissions and energy dependency

Contrary to fossil fuels, biomass is a renewable green carbon resource that can replace non-renewable black carbons such as coal, oil and gas. It is considered as a carbon neutral fuel because the CO_2 emissions associated with its combustion were previously fixed in the material as it grew, and will once more be fixed as planted replacement crops grow. However, it is often pointed out that defining biomass fuels as carbon neutral is fundamentally wrong, because it neglects up-stream emissions. The overall CO_2 emissions associated with the use of biomass depend on many factors, such as processing (transport modes and distances), and – in the case of dedicated energy crops – on cultivation, harvesting and possible land-use change effects. Taking into account these indirect emissions can increase the biomass emission factor from zero to about 0.01-0.03 $kgCO_2/KWh$ (15 to 38% due to transport), depending on the biomass type (DECC-SAP, 2011). This is still much lower than CO_2 emissions from fossil fuels.[4]

Ancillary benefits from using biomass in energy may also include a reduced dependency on imported fossil fuels, and there may be the potential to develop local biofuel supply chains, which can benefit local rural economies. Furthermore, unlike other RES (e.g. solar, wind), biomass-based power generation can be made available whenever it is needed. Hence, power producers can dispatch biomass units as conventional power plants, which increases reliability and lowers the cost of managing power generation.

2.1.2 Fostering the penetration of RES

To foster the penetration of renewable energy, each EU country proposes different support schemes to promote them.[5] Thus, power producers can take advantage of these economic means to reduce their costs of production and make this production profitable.

On the one hand, there is **regulation**. The goal is to create incentives that are not compulsory. Thus, electricity suppliers for instance, do not have to include a minimum share of renewable energy in their bids. Similarly, there is no regional or municipal constraint on use or renewable energy production. However, we can have constraints on the technology or the type of biomass used. For example, some countries support biomass only if it is used in CHP-plants and some countries do not support co-firing of biomass with fossils fuels (e.g. Netherlands, Germany and France).

On the other hand, we find support-schemes divided into three categories. The first one is **the feed-in-tariffs (FIT)** where renewable energy production benefits from the purchase-obligation defined by law. Any generation under this mechanism is sold, transported

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[4] Whereas those indirect emissions are often mentioned for biomass, they are consistently ignored when fossils fuels are concerned. However, CO_2 emissions associated with transport and processing also exist in this case, and can be more substantial than with biomass. For instance, taking into account the overall emissions, the emission factor of hard coal can reach 0.385 $kgCO_2/KWhp$ (DECC-SAP, 2011) compared with the 0.339 value provided by IPCC (2006).

[5] For an extended literature review of support scheme in France, see Le Cadre et al. (2011).

and distributed, except when this production undermines the security of the network. Through this system, the renewable facilities are not dependent on market conditions. Fourteen member states use a FIT as the main support scheme (Austria, Bulgaria, Cyprus, France, Greece, Hungary, Ireland, Latvia, Lithuania, Luxembourg, Portugal, Spain, UK), while four others offer the choice between FIT or Feed-In-Premium (Slovenia, Finland, Germany, Czech Republic).

The second support scheme is the **call for tenders**, used for higher capacities (e.g. in France or Portugal). There is a broad range of conditions concerning plant size, combustion, type of biomass and level of biomass support. Every call for tenders is an opportunity to specify new performance criteria that need to be met. For example, they can highlight security for using heat, which maximizes energy efficiency projects, and biomass supply plans. Calls for tenders for biomass power plant construction thus adjust specifications to technological advances, the maturity of the industry and the biomass sources availability.

The third support scheme is **green certificates.** The RECS (Renewable Energy Certificate System) is a harmonized European system of traceability and certification of renewable electricity. It is a subset of the European Energy Certificate System (EECS) from a private initiative which aims to draw electricity in Europe. Six countries have a quota system (Belgium, Italy, Sweden, UK, Romania and Poland). The RECS is administered in each country (geographical area) by a single issuing bank (Observ'ER in France). After opening an account with the issuing institution, the producer sends a certificate request to the central bank no later than three months after the production of electricity subject to the certification request. In France, according to Observ'ER, the application must be accompanied by proof of the production realized by the manager of transmission or distribution. The statements are verified by Observ'ER. Once the application is approved, Observ'ER will give credits to the producers of green electricity. Facilities under obligation to purchase at fix feed-in-tariffs can enhance the electricity generated by issuing RECS certificates. Currently, this system is the basis for the green tenders made by some suppliers of electricity to individual and industrial customers. The Directive 2009/28/EC imposes conditions on systems' evolution to guaranty the electricity comes out from renewable sources. It is about finding a solution to avoid duplication emissions (the national guarantee of origin and certificates RECS) and articulates the certification of electricity with feed-in tariffs.

In addition to these financial supports, one can also mention: tax credit for sustainable development, eco-zero interest loans, tax exemptions and accelerated or exceptional depreciation. Systems to ensure the production of electricity from renewable sources also cover systems of guarantee of origin, demonstration funds, reduced VAT rates, support for electricity generation from off-grid renewable systems and Energy Performance Plans for farms. In conclusion, a large panel of support schemes has been implemented in Europe to promote RES and the biomass used to produce heat and power. However, progress needs to be made to harmonize them.

2.2 Technological options for using biomass in power generation

Current options for generating power from biomass are dedicated biomass power plants, Combined Heat and Power plants (CHP) and biomass co-firing with fossil fuels in large power boilers. These different technologies are presented in what follows.

2.2.1 Combustion in dedicated power plants and cogeneration

The most straightforward way to generate electricity from biomass is to burn it in a power plant that is especially designed for this purpose. In addition to electricity, heat is generated. Biomass is combusted to heat water, generating steam that is conveyed to a turbine to produce electricity. When this heat is used for other purposes (e.g. heating), simultaneously with power generation, a CHP-system is created.

Dedicated biomass and CHP plants have to be adapted to the characteristics of fuel, and limitations in the biomass supply. Accordingly, the typical size of these plants is smaller than that of coal plants (1-100 MW, which is about ten times smaller than coal plants), because of the scarce availability of local feedstock and the high transportation costs. The small size strongly increases the investment costs per KW and results in lower conversion efficiency compared with co-firing in coal plants. In Europe, the investment cost of biomass plants varies from USD 3000-5000/KW, depending on the plant technology and size (IEA, 2007). This is about three to ten times more than the investment cost for retrofitting coal plants for co-firing (excluding the indirect co-firing configuration, which is much more expensive). The investment cost can even reach Euros 9000/KW for CHP plants. In this case, the higher investment costs result in higher overall efficiency of the energy conversion chain. Moreover, some countries have adopted specific support policies for biomass when it is used in CHP plants (EURELECTRIC, 2011). This lowers the investment cost.

2.2.2 Co-firing in coal-power stations

Co-firing is the simultaneous combustion of biomass and coal in the same coal power station. It is the least expensive option for using biomass in power generation, and is expected to play an important role in the future. A wide variety of biomass can be used, including herbaceous and woody materials, wet and dry agricultural residues and energy crops. Currently, the typical conversion efficiency for a dedicated biomass power plant is 25-30% (Ecofys, 2010), while the average conversion efficiency for conventional coal-fired power plants (so-called subcritical pulverized plants) is around 36% in OECD countries, with new state-of-the-art plants reaching at least 43% (Wicks and Keay, 2005). Biomass co-firing is expected to decrease the generation efficiency of coal plants, due potential sources of efficiency losses associated with biomass (e.g. presence of non-preheated air in biomass, increased moisture content, etc). However, the impact on conversion efficiency from low levels of biomass co-firing is judged to be modest (IEA-IRENA, 2013) which leads to higher conversion efficiency compared with dedicated biomass power plans. Accordingly, biomass co-firing represents a promising way to convert biomass with high electrical efficiency. It offers one of the best short- and medium-term opportunities for reducing GHG emissions from power generation. However, it can only happen in countries where coal-based electricity represents a significant share of power generation.

There are three basic co-firing options, and all have been demonstrated on an industrial scale:

- **Direct co-firing:** is the cheapest and simplest co-firing configuration. Biomass and coal are burned in the same boiler, using the same or separate mills and burners. This is by far the most commonly applied co-firing configuration as it enables co-firing percentages of up to approx 3% on an energy basis, without significant investment costs (Al-Mansour and Zuwala, 2010).
- **Indirect co-firing:** this is a less common option in which a gasifier converts the solid biomass into a fuel gas that can be burned with coal in the same boiler. This approach is more expensive because of the additional equipment required for the gasifier. However, it allows for a greater variety and higher percentages of biomass to be used. The fuel gas can also be cleaned prior to combustion, which allows minimizing the impact on the performance and integrity of the boiler.
- **Parallel co-firing**: it is also possible to install a separate biomass boiler that supplies the same steam cycle. As with indirect co-firing, this method allows for high biomass percentages and greater fuel flexibility, but it requires much more investment than simple direct co-firing.

The investment cost for retrofitting a coal plant for co-firing is in the range of USD 430-S500/KW for direct co-firing, USD 760-900/KW for parallel co-firing, and USD 3000-4000/KW for indirect co-firing (IEA-IRENA, 2013). It depends on the plant capacity and service (i.e. power generation only or CHP), the quality of the biomass to be used, and the type of existing boilers. Apart from indirect co-firing, these costs are always significantly lower than the cost of investing in a dedicated biomass power plant.[6] This is explained by the large pre-existing infrastructures in case of co-firing, and the small size of dedicated biomass power plants.

Co-firing is also associated with difficulties and constraints that limit utilization of biomass in coal pants. These limitations include problems of modifications of combustion behavior, possible reduction in conversion efficiency, deposit formation (slagging and fouling), corrosion, erosion and resulting changes in equipment life-time related to the quality of the biomass.[7] For instance, though herbaceous biomass has been co-fired in several power plants worldwide, its higher inorganic matter content results in higher potential problems of slagging and fouling. Actually, only moderate biomass levels can be co-fired without any major problems of corrosion, slagging and fouling). Nevertheless, a significant part of those difficulties can be overcome through different pre-treatments that make it possible to improve biomass quality, while increasing the quantity of biomass that can be included in coal plants. Indeed, evidently, the higher the quality of biomass is, the higher the quantity of biomass that can be co-fired in coal plants. The coal plant technology and the co-firing option are also important. Although direct co-firing is the cheapest option for co-firing, it causes more severe problems of efficiency losses, corrosion and deposit formation than other co-firing configurations. Hence, the co-firing percentage is typically lower with direct co-firing compared with other options. The boiler technology also influences the quantity of biomass that can be use in co-firing. In general, fluidized bed boilers can substitute higher levels of coal with biomass than fixed bed or pulverized coal boilers (Maciejewska et al., 2006; Leckner, 2007; IEA-IRENA, 2013).

2.3 Pre-treatment of raw biomass

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[6] Investment costs for indirect co-firing are about ten times higher than for direct co-firing. However, this configuration allows for the use of cheaper waste fuels with impurities, which can strongly decrease operating costs related fuel consumption.

[7] The constraints associated with co-firing also depend on the boiler technology of coal plants. In general, limitations to co-firing are less stringent with fluidized bed than with fixed bed or pulverized coal boilers (Maciejewska et al., 2006; IEA-IRENA, 2013).

Most of the constraints related to co-firing originate from fuel properties. Raw biomass fuels usually have high moisture content and chemical composition that reduce the conversion efficiency of coal plants, and generate potential problems of corrosion. Various pre-treatments can be applied to raw biomass in order to avoid or reduce these problems. Pre-treatment can also lower the costs of handling, storage and transportation of biomass. Furthermore, pre-treatment can create new opportunities for long distance trades. Finally, pre-treatment could reduce the need to invest in complex and expensive co-firing technologies.[8]

Several options exist for biomass pre-treatment, which correspond to more or less sophisticated solutions. Common basic pre-treatments include drying, chipping and grinding. There are also more advanced options that produce biomass fuels with higher quality. These pre-treatments include pelletisation, torrefaction and pyrolysis. Pelletisation is a process that densifies fine biomass particles into compact and low-moisture capsules by applying pressure and heat. Torrefaction is thermo-chemical pre-treatment that consist of biomass heating in the absence of oxygen. Temperatures between 200 and 300°C are needed, which produces a solid uniform product (torrefied biomass) with very low moisture content and high energy density. Torrefied biomass contains around 70-90% of the initial weight and 80-90% of the original energy content (Uslu et al., 2008). The remaining of the initial weight is converted into gas containing a part of the original energy content. As torrefaction, pyrolysis is a thermo-chemical pre-treatment performed in absence of oxygen. Temperatures employed in pyrolysis are 400-800°C, and the products are gas, liquid (bio-oil) and solid (char).

The cost of pre-treatment can significantly vary from one option to another, but it is usually high.[9] However, it can be compensated by better operability of fuel (e.g. handling, storage and transportation), reduced co-firing constraints and higher conversion efficiency of coal plants. Some recent studies point out that the cost of pre-treatment can reach more than 50% in case of torrefied wood pellets (KEMA, 2012; IEA-Bioenergy, 2012). However, when taking into account the benefits of pre-treatment on the whole supply chain, up to the point of combustion, torrefied wood pellets yield better economic performances than simple wood pellets (IEA-Bioenergy, 2012).[10]

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[8] For a wide overview of biomass pre-treatments and economic issues related to co-firing, see Maciejewska et al. (2006) and Le Cadre (2012).

[9] See Maciejewska et al. (2006) for cost estimations of different pre-treatment options.

[10] Uslu et al. (2008) evaluate torrefaction, pyrolysis and pelletisation in terms of their energy and economic performances on the whole biomass-to-energy supply chain for power generation and biofuel production. Results indicate that torrefaction is more advantageous than pelletisation, while pyrolysis has drawbacks in terms of energy and economic efficiency when compared to other pre-treatments. When torrefaction is combined with pelletisation, this results in the optimal supply chain from an energy and economic perspective.

2.4 The economic advantages and drawbacks of co-firing

2.4.1 A higher fuel cost than coal

Power plant operating costs are, in general, higher for biomass than for coal, due to the higher delivered cost of the fuel. Even when the biomass is nominally free at the point of production, for instance in the case of some dry agricultural residues, the costs associated with collection, transportation, preparation, and on-site handling can increase the cost per unit of input to the boiler to a point where it rivals, and often exceeds, the cost of coal.

2.4.2 Comparison with other RES

When compared to alternative RES, biomass co-firing is normally significantly cheaper, and has the advantage that it can be implemented relatively quickly (Al-Mansour and Zuwala, 2010). Hartmann and Kaltschmitt (1999) show that in comparison to wind, hydro and photovoltaics (PV), the use of biomass is very promising in terms of non-renewable energy consumption (in MWh_{prim}/MWh_{elec}), CO_2 and SO_2 emission-equivalents per MWh_{elec}. Moreover, the fact that most RES cannot be dispatched when required, as they strongly depend on weather conditions, prevents them from constituting a reliable base-load solution. Contrary to PV and wind power, the technologies based on biomass are not subject to problems of generation intermittency. Despite their short setup periods and zero fuel requirements, PV and wind often suffer from resource unavailability. In this respect, biomass has a great advantage compared with other RES, and it can be used as a buffering capacity when wind or PV are not available. Moreover, the resource can be stored and used during peak hours.

2.4.3 Supply security and fuel flexibility

In addition to requiring relatively small changes at the power plants, biomass co-firing also holds the advantage of uncertain biomass supplies not jeopardizing the fuel supply for power plant owners, who can manage a temporary loss on the biomass supply side (or short-term biomass price volatility) by increasing the share of coal in the fuel mix (Hansson et al., 2009). Biomass as a fuel provides a hedge against price increases and supply shortages of coal. In co-firing, biomass can be viewed as an opportunity fuel, used only when the price is favorable.

There is currently no large European or national biomass market, which creates uncertainty with respect to supply and price.[11] Implementation of co-firing should therefore be

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[11] The European biomass market has substantially grown in the last few years and is still developing. Organized marketplaces have emerged, with spot and future transactions. Standardized contracts for wood pellets are now

a comparatively low-risk path for power-generating companies, as they can then still rely on the use of fossil fuel as base fuel in case of disturbances on the biomass supply side.

2.4.4 Reducing the cost of GHG emissions and other pollutions

Apart from direct savings in fuel cost, other financial benefits can be expected from co-firing. Indeed, co-firing can reduce the net SOx, NOx and heavy metal emissions and the plant could claim the applicable pollution-reduction incentives offered by government agencies. Replacing coal by biomass in an existing boiler will also reduce CO_2 emission from the plant. Moreover, the use of biomass to displace fossil fuel can be eligible for special tax credits from many governments.

3. Biomass in the current European power generation: Potential demand, associated abatement, and cost estimates

In this section we propose a simple and original method, that enables us to estimate the potential biomass demand, and associated CO_2 abatements from using biomass in the European power sector. The quantities obtained represent technical potentials, which do not necessarily coincide with results given by economic optimization. Our aim is to figure out the volumes that are technically attainable, regardless of economic decisions. By contrast, our estimations of the co-firing cost, and associated biomass and CO_2 breakeven prices, reflect economic conditions that make biomass co-firing in different types of coal plants profitable.

3.1 Potential biomass demand and associated CO_2 abatements

3.1.1 Overview of coal and dedicated biomass capacities in the European power mix

In order to get first intuitions about biomass potential in the European power sector, we begin with a short overview of coal and dedicated biomass capacities in the EU countries. This is summarized in Fig. 1, which represents, for each technology (coal or dedicated biomass) in each country in 2011, the ratio between the installed capacity in the country and the EU average installed capacity.[12] Thus, for a given type of power plant (coal or dedicated

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available in exchanges such as IceEndex (www.iceendex.com). The interested reader can also refers to Argus (www.argusmedia.com), which provides data from OTC transactions of wood-pellets and wood-chips delivered to ports of North-West Europe.

[12] For instance, the ratio for coal capacities in Germany corresponds to the German coal capacities divided by the EU average of coal capacities.

biomass), a ratio higher than one means that the country has more installed capacities than the EU average (and vice versa).

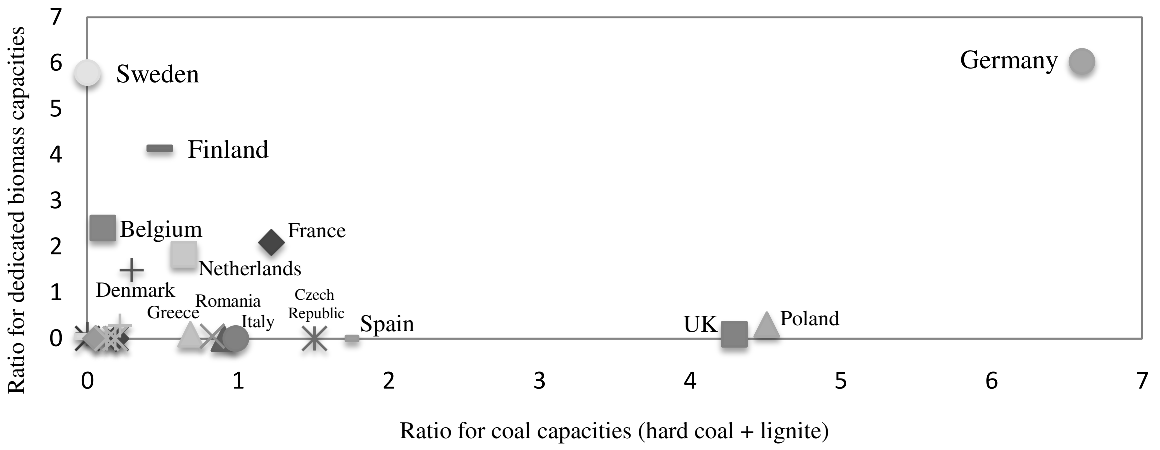

Figure 1: Installed capacities for coal (hard coal + lignite) and dedicated biomass power plants in the EU countries. Values are ratios between capacities of each country and the EU average capacity. Data provided by ENTSO-E (www.entsoe.eu).

Fig. 1 enables us to distinguish between countries with many dedicated biomass and few coal plants (Sweden and Finland), many coal and few dedicated biomass plants (Poland and the UK), and both many coal and dedicated biomass plants (Germany).

3.1.2 Estimation method for potential demand and associated abatements

The method consists in determining the amount of primary energy associated with observed production of power plants. This enables us to deduce how much biomass can be used in power generation. In the case of coal plants, one can derive the volumes of biomass entering the boiler, given a percentage of biomass in the biomass-coal blend (on energy basis). We call this the incorporation rate. Finally, once quantities of coal and biomass associated with electricity production are known, we estimate the resulting CO_2 emissions of coal plants by applying primary energy emission factors. Emissions are derived with and without co-firing, which allows us to compute CO_2 abatements. Basically, the method encompasses three steps, which are summarized in Box 1.

Box 1: Three-step estimation method

Step 1: Estimating the quantity of primary energy associated with observed production

$Q_c^i = \frac{Y_c}{\eta_c^i}$ is the quantity of primary energy (MWh_{prim}) in coal plants of type c, with c = {Hard-Coal (HC), Lignite (L)} and i = {co-firing (cf), no co-firing (nocf)}. Y_c represents the production of coal plants c (MWh_{elec}), and η_c^i is the efficiency rate of coal plants c under i cycle (MWh_{elec}/ MWh_{prim}). Using the same method, we also compute the quantity of primary energy entering in dedicated biomass power plants.

We model the efficiency rate of coal plants under co-firing using the following equation: $\eta_c^{cf} = \eta_c^{nocf} - \rho_b \, inc_{c,b}$, where subscript b denotes the type of biomass. ρ_b is a coefficient measuring possible losses 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.

Step 2: Estimating the quantity of biomass entering in the boiler, in case of co-firing

Under co-firing, $Q_c^{cf} = Q_{c,c}^{cf} + Q_{c,b}^{cf}$, where $Q_{c,c}^{cf}$ and $Q_{c,b}^{cf}$ are, respectively, the quantity of coal and the quantity of biomass in the blend. $Q_{c,b}^{cf} = inc_{c,b} \times Q_c^{cf}$ and $Q_{c,c}^{cf} = (1 - inc_{c,b}) \times Q_c^{cf}$.

Step 3: Estimating the CO_2 emissions and associated abatement

$E_c^i = e_c \, Q_{c,c}^i$ represents CO_2 emissions of coal plants c under i cycle (tCO_2), where e_c is the primary energy emission factor (tCO_2/ MWh_{prim}). In case of co-firing, $Q_c^{nocf} \equiv Q_{c,c}^{nocf}$. Then, we get co-firing abatements as follows: $A_c = E_c^{nocf} - E_c^{cf}$.

In order to figure out a range of values in which we can situate the potential biomass demand and the CO_2 abatements, we consider two extreme cases in our estimations, reflecting minimal and maximal values. Thus, we get a lower (min case) and a higher (max case) range (Tab.1).

Table 1: Lower and higher range for potential biomass demand and CO_2 abatements.

Cases to estimate	Biomass type	Incorporation rate	Losses coefficient
Min case (lower range)	Low quality = Raw biomass (RAW)	5%	$\rho_{RAW} = 0.05$
Max case (higher range)	High quality = Torrefied pellets (ToP)	50%	$\rho_{ToP} = 0$

Regarding incorporation rates and losses coefficients, the values in Tab. 1 reflect differences induced by variations in the quality of biomass. Indeed, the higher the quality of biomass, the higher the incorporation rate is. This translates into higher incorporation rates for ToP than for RAW.[13] Thus, we assume incorporation rates of 5 and 50%, reflecting the Min case and the Max case, respectively.[14] Losses on the coal plants efficiency rates also depends on the type of biomass. Hence, the value of the losses coefficient increases when the biomass quality decreases. As a limit case, we assume a zero loss coefficient for ToP.

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 (Box 1). According with Ecofys (2010), we assume a linear relationship between the efficiency losses and the incorporation rate. [15] This is not a very strong assumption, because this only affects estimations in the Min case ($\rho_{ToP} = 0$ in the Max case), in which the efficiency losses are to be small because of the 5% incorporation rate. Indeed, several studies on co-firing have reported very few efficiency losses (or even none) for incorporation rates 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 $\eta_c^{cf} = 0.378$, which corresponds to a loss in conversion efficiency of 0.66%. Baxter (2005) 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 $\rho_b = 0.05$, the loss in conversion efficiency spans from 0.66% ($inc_{c,b} = 0.05$) to 6.58% ($inc_{c,b} = 0.5$).

3.1.3 Estimation results for potential demand and associated abatements

Before turning to results, we first present data. We use 2011 yearly power production data of hard coal, lignite and dedicated biomass power plants in the EU-27. Data are provided by

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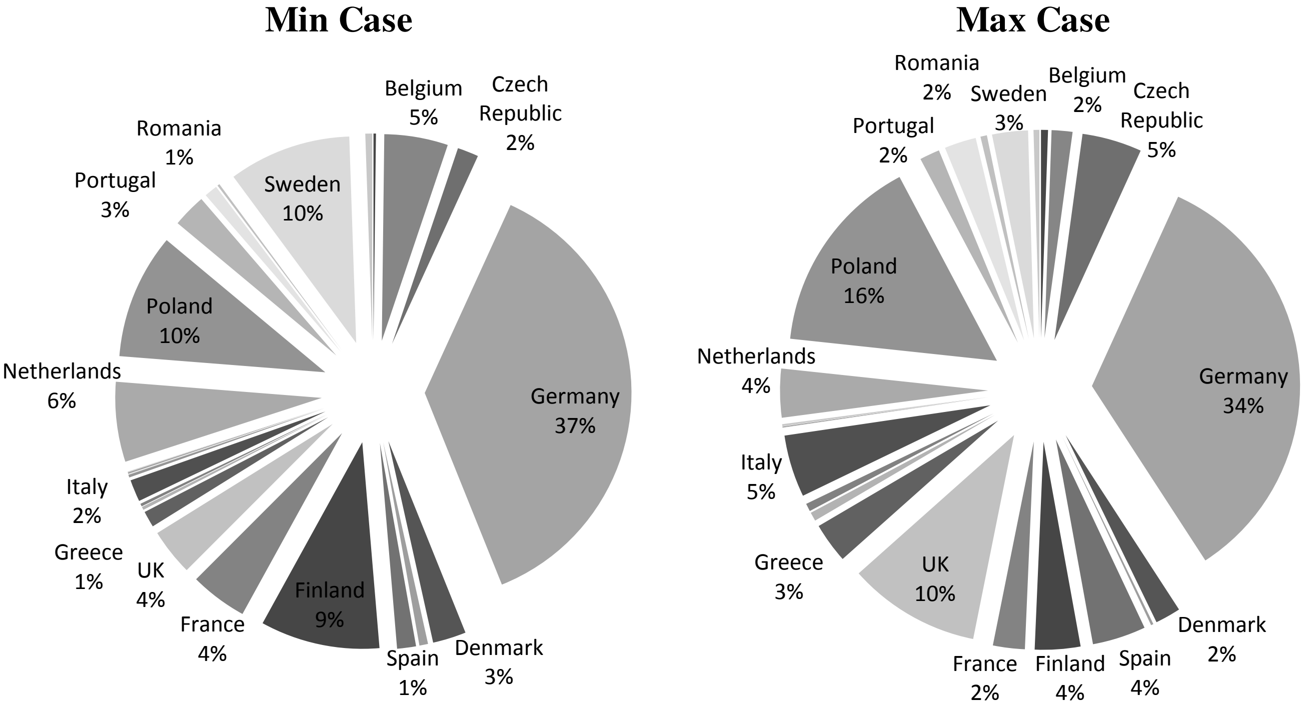
[13] Co-firing is currently feasible with incorporation rates of 20%, and sometimes almost 50%. With pre-treatments, incorporation rates can reach more than 50%. However, in practice, actual incorporation rates rarely exceed 10% (IEA-IRENA, 2013). Interested readers can also refer to IEA data-base about co-firing, available at http://www.ieabcc.nl/database/cofiring.php.

[14] Note that Berggren et al. (2008) and Hansson et al. (2009) assumed incorporation rates ranging from 10 to 15%, in order to fit what is most often observed in current practices. By contrast, we assume a large range of incorporation rates, reflecting a wide a range of possible cases from very conservative (5%) to the most prospective (50%) values. Moreover, as opposed to the aforementioned papers, we take into account the effects of efficiency losses related to the incorporation rate and the biomass quality (see equation for η_c^{cf} in Box 1).

[15] 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.

ENTSO-E, the European Network of Transmission System Operators for Electricity. We assume efficiency rates of 30, 34, and 38%, for dedicated biomass, lignite, and hard coal power plants, respectively.[16] The CO_2 emission factors for primary energy (tCO_2/MWh_{prim}) are provided by IPCC (2006): 0.357 for lignite, 0.339 for hard coal, and zero for biomass.


Min Case

Max Case

Figure 2: The EU countries' shares in the total EU potential biomass demand from the power sector (co-firing + dedicated biomass plants).

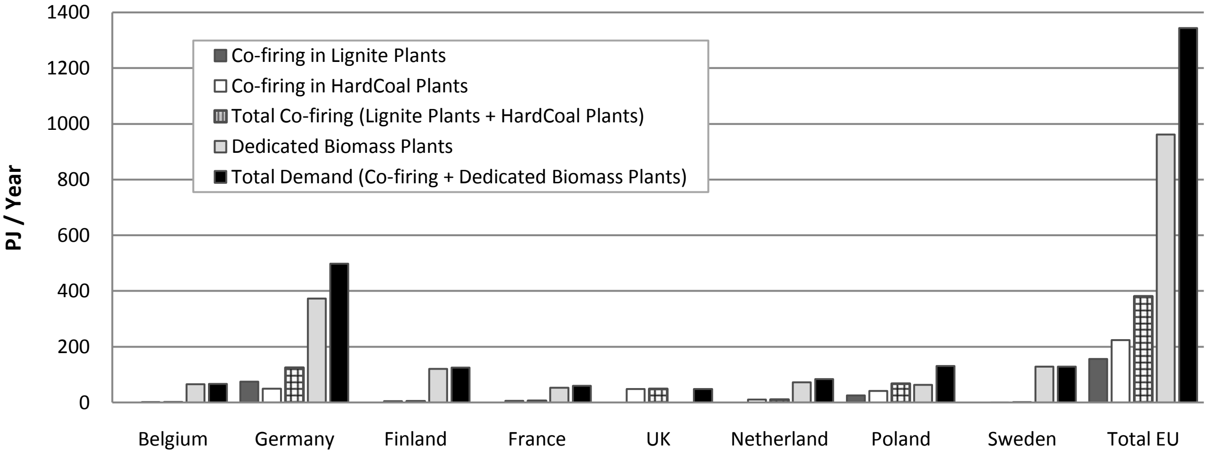


Figure 3: Potential biomass demand (per country and type of power plant) in the min case.

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[16] We consider both co-firing in hard coal and lignite plants in our estimations. Indeed, 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 high moisture content. See ECF et al. (2010).

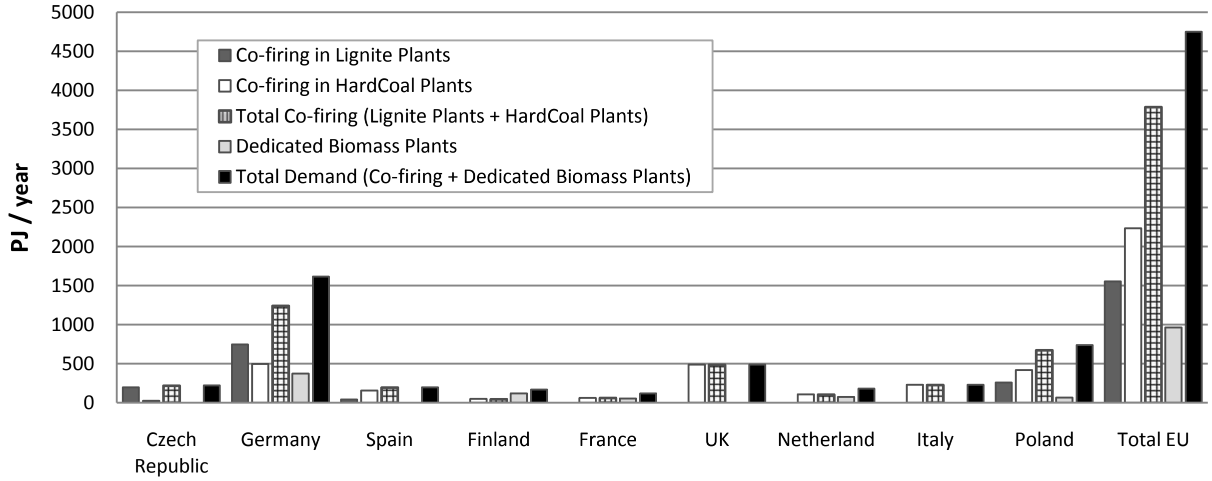

Figure 4: Potential biomass demand (per country and type of power plant) in the max case.

Results indicate that the EU potential biomass demand ranges from 1344 to 4739 PJ a year (381 to 3787 for co-firing alone).[17] In all cases, Germany has the highest potential demand with 498 to 1618 PJ (125 to 1243, co-firing alone). For instance, this is much higher than that of Poland, the second biggest demand potential with 132 to 738 PJ (68 to 675, co-firing alone). Moving from the min to the max case, we observe a change in distribution of quantities among countries. The demand share from coal plants increases, while that of dedicated biomass plants decreases (Fig. 3 and 4). Hence, the share of countries with many coal-fired plants and few dedicated biomass plants in their power mix increases (e.g. Poland and the UK, see Fig. 1 and 2). On the other hand, countries with many dedicated biomass plants and few coal plants represent a smaller share of the whole EU demand (e.g. Finland and Sweden, see Fig. 1 and 2). In between, the share of Germany is high and stable in all cases. This is because there are both many coal and dedicated biomass plants there.

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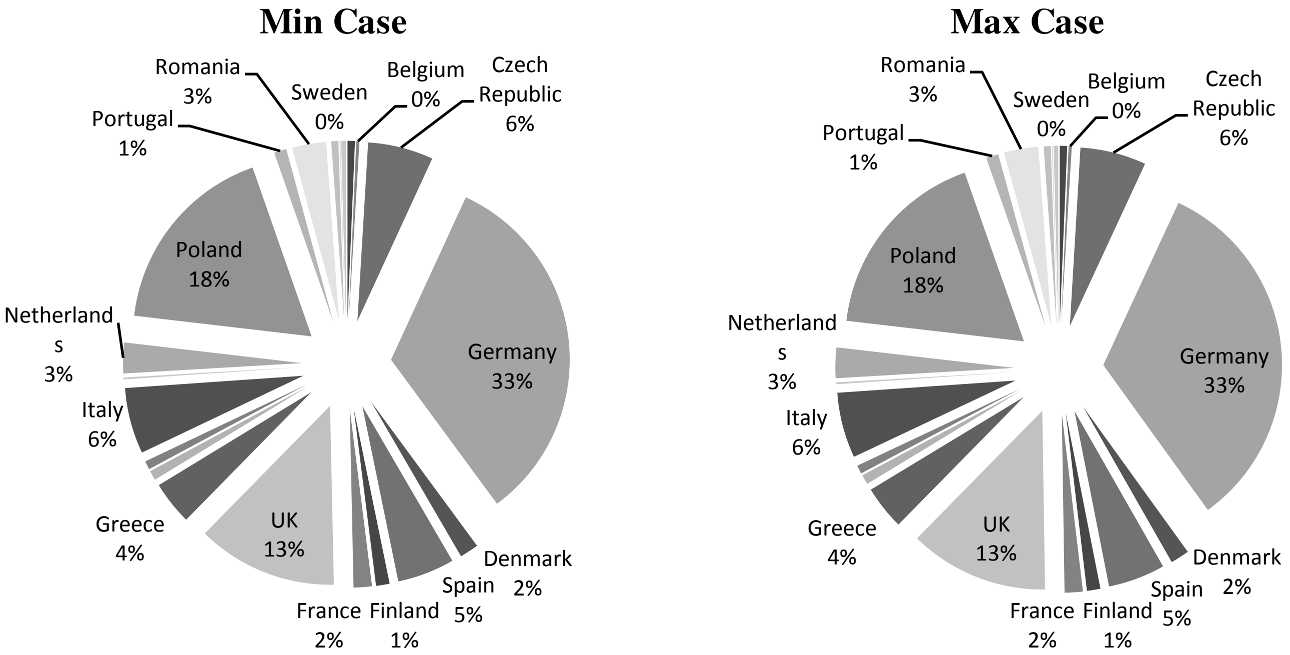
[17] Assuming incorporation rates ranging from 10 to 15% (on energy basis), Hansson et al. (2009) find a potential biomass demand from co-firing of approximately 500 to 900 PJ per year in the EU-27.


Min Case

Max Case

Figure 5: EU countries' shares in the total EU abatement potential from co-firing (hard coal + lignite).

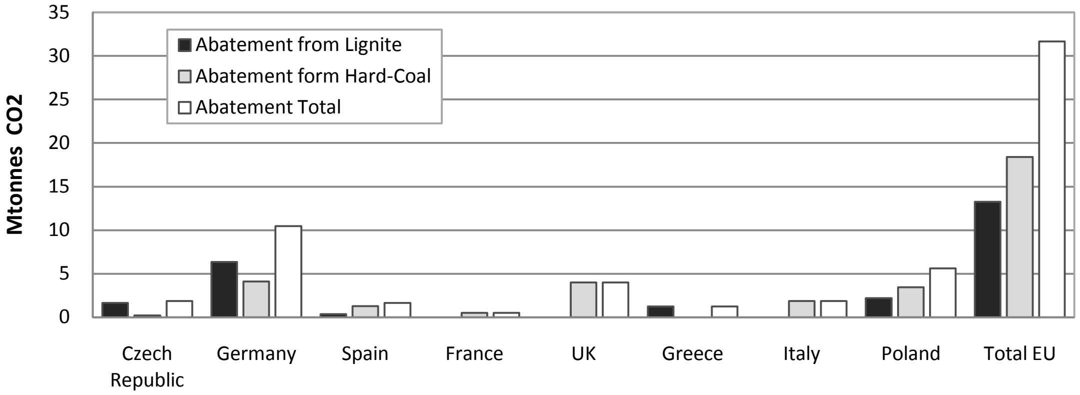


Figure 6: Estimated CO_2 abatements (per country and type of power plant) in the min case.

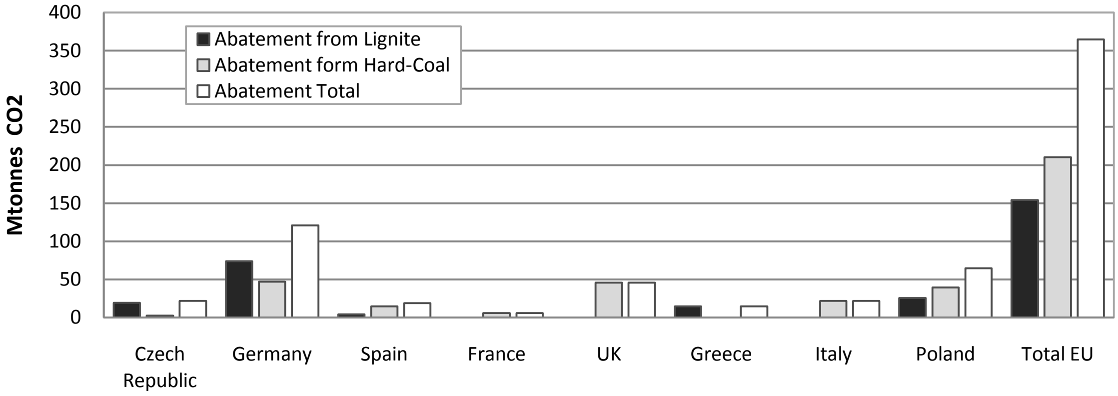


Figure 7: Estimated CO_2 abatements (per country and type of power plant) in the max case.

Regarding CO_2 abatements, results indicate that the total EU potential ranges from 31.6 to 364.6 Mt a year.[18] Here again, Germany has the highest share with 10.4 to 120.8 Mt. Poland and the UK also have a great potential, due to the importance of coal-based electricity in these countries.[19] As opposed to what we observe with biomass quantities, there is no change in the geographical distribution of abatements when we move from the min to the max case (Fig. 5). Indeed, the contribution of each type of coal plant to abatements is not modified when the incorporation rate increases (Fig. 6 and 7), whereas we observe a reduced share for the potential demand of dedicated biomass power plants (Fig. 3 and 4). When the incorporation rate increases, this translates into the same percentage of increase in every coal plant, whatever the country and the type of coal. Hence, only the abatement volumes are increased, and the distribution is not modified.

3.2 Cost of electricity under co-firing and switching prices

In this section, we briefly present the economic background in which situates this analysis. This provides non-familiar reader with a short overview of literature on which our methodology relies on. Next, the analytical framework is introduced.

3.2.1 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 has generated a wide literature including 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).[20] The basic idea is that with a high enough CO_2 price, coal plants switch places with gas plants in the merit order.[21] Without a CO_2 price, coal plants are usually brought on line first, because of

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[18] This corresponds to between 0.7 and 7.7% of the EU GHG emissions in 2010, which accounted for 4721 $MtCO_2e$ (EEA, 2012). In comparison, coal-to-gas fuel switching, which is often considered as one of the main abatement option in the EU ETS, offers a maximal potential of about 150 $MtCO_2$ a year (Delarue et al., 2012).

[19] Assuming incorporation rates around 10% (on energy basis), Berggren et al. (2008) find that about 4 Mt of CO_2 per year can be abated through co-firing with biomass in Polish coal plants. We find that about 5Mt of CO_2 per year can be abated through co-firing when a 5% incorporation rate is assumed. This difference in results may be explained by the data. Indeed, we use data reflecting power generation in 2011, whereas Berggren et al. (2008) use data from 2004.

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

[21] 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.

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 the 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.

Relying on literature about coal-to-gas fuel switching, 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. This framework 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).[22]

3.2.2 Estimation method for switching prices

Equalizing expressions of marginal costs of electricity with and without co-firing, we derive values of carbon and biomass prices for which power producers are indifferent between co-firing and classical cycle. They are the carbon switching price and the biomass switching price, which correspond to prices that make coal plants equally attractive under co-firing or classical conditions. These switching prices reflect biomass and CO_2 prices which are compatible with a profitable co-firing.

The first step consists in determining expressions of the marginal cost of electricity, with and without co-firing. The switching prices can then be derived using these expressions. There are several factors influencing the marginal cost of electricity under co-firing. First of

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[22] As the biomass and carbon switching prices are computed for different types of coal plants reflecting different positions in the merit order, one can consider that the different switching prices implicitly refer to different horo-seasonal segments. Nevertheless, a full representation of all the switching prices for all the horo-seasonal segments is beyond the scope of this paper. This deserves further investigations.

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 (see section 2). In order to account for this, we model the efficiency rate (MWh_{elec}/MWh_{prim}) of coal plants c under co-firing using the equation for η_c^{cf}, as given in Box 1. Then, the higher the losses coefficient (ρ_b) 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. This is accounted for with the influence of $inc_{c,b}$, the incorporation rate, on η_c^{cf}.[23]

Marginal cost of electricity under co-firing

Using the equation for η_c^{cf} given in Box 1, 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:

$$MC_c^{cf} = q_{c,c}^{cf}\, C_c + q_{c,b}^{cf}\, B_b + e_c^{cf}\, EUA, \qquad \textbf{(1)}$$

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

In equation **(1)**, $h_c^{cf} = 1/\eta_c^{cf}$ is the heating rate (MWh_{prim}/MWh_{elec}) of coal plants c under co-firing. It is computed given η_c^{cf}, the efficiency rate of coal plants c under co-firing (MWh_{elec}/MWh_{prim}), as given in Box 1. Thus, h_c^{cf} corresponds to the quantity of primary energy (MWh_{prim}) 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,

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[23] 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.

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/MWh_{elec}). It is computed given e_c, the primary energy emission factor of coal c (tCO_2/MWh_{prim}). 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:

$$MC_c^{nocf} = h_c^{nocf}\, C_c + e_c^{nocf}\, EUA, \qquad \textbf{(2)}$$

where $h_c^{nocf} = 1/\eta_c^{nocf}$ and $e_c^{nocf} = e_c \times h_c^{nocf}$ are, respectively, the heating rate (MWh_{prim}/MWh_{elec}) and the emission factor (tCO_2/MWh_{elec}) 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 (MWh_{elec}/MWh_{prim}), and the primary energy emission factor of coal c (tCO_2/MWh_{prim}). Note that, when assuming $inc_{c,b} = 0$ and $\rho_b = 0$, equation **(1)** is equivalent to equation **(2)**. 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 **(1)** and **(2)** are equivalent.

Biomass and carbon switching prices

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

$$EUA_{c,b}^{SW} = \frac{q_{c,b}^{cf}\, B_b - \left(h_c^{nocf} - q_{c,c}^{cf}\right) C_c}{e_c^{nocf} - e_c^{cf}} \text{ and } B_c^{SW} = \frac{C_c\left(h_c^{nocf} - q_{c,c}^{cf}\right) + EUA\,(e_c^{nocf} - e_c^{cf})}{q_{c,b}^{cf}}, \qquad \textbf{(3)}$$

where $EUA_{c,b}^{SW}$ is the carbon switching price ($Euros/tCO_2$) associated with using biomass b in coal plants c, and B_c^{SW} is the biomass switching price ($Euros/MWh_{prim}$) associated with using biomass in coal plants c.

$EUA_{c,b}^{SW}$ is calculated given the prices of biomass b and coal c. It corresponds to the increased fuel cost of co-firing which enables power producers to abate one tonne of CO_2.[24] Accordingly, co-firing is cheaper than using coal plants in classical cycle if the additional fuel cost associated with co-firing ($q_{c,b}^{cf}\, B_b - \left(h_c^{nocf} - q_{c,c}^{cf}\right) C_c$) is smaller than the cost of increased CO_2 emissions in the case of classical cycle ($EUA(e_c^{nocf} - e_c^{cf})$). In other words, switching to co-firing will (will not, respectively) occur if $EUA_{c,b}^{SW} < EUA$ ($EUA_{c,b}^{SW} > EUA$, respectively), where EUA denotes the observed price of EUAs. Hence, $EUA_{c,b}^{SW}$ reflects the CO_2 price from which it becomes profitable to include biomass b in coal plants c.

B_c^{SW} is calculated given the prices of coal c and of CO_2. It corresponds to the benefit associated with including one MWh_{prim} of biomass in coal plants of type c. This arises from reduced costs of coal consumption ($C_c\left(h_c^{nocf} - q_{c,c}^{cf}\right)$) and of CO_2 emissions ($EUA(e_c^{nocf} - e_c^{cf})$). Hence, B_c^{SW} can be considered as the benefit of one MWh_{prim} 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 $B_b < B_c^{SW}$ ($B_b > B_c^{SW}$, respectively). Hence, B_c^{SW} reflects the biomass price beyond which including biomass in coal plants of type c is no longer profitable.

3.2.3 Estimation results for switching prices

In order to compute the biomass and carbon switching prices, we use price data for lignite, hard coal and different types of biomass. For simplicity, we use annual prices. Values and references are summarized in Tab. 2. Regarding, efficiency rates of coal plants and emission factors for primary energy, we assume the same values as in section 3.1.

Table 2: Fuel prices (Euro/MWh_{prim}) as delivered to power plants.

Fuel	Prices – Euros/MWh_{prim} (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)

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[24] 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 this case, the constraints associated with co-firing are less stringent, which tends to decrease the cost of managing power generation to reducing CO_2 emissions.

In all our calculations, we assume an incorporation rate of 10%. As we already mentioned, this corresponds to incorporation rates frequently encountered in practice.[25] Furthermore, we split the different biomass types of Tab. 2 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 that are quite similar to the ones of raw wood (Maciejewska et al., 2006; Acharya et al., 2012). This enables us to apply a higher losses coefficient to the NOPT category, reflecting the lower quality of this biomass type (see Tab. 3).

Table 3: Estimated carbon switching prices (using price data from Tab. 2) as given by equation **(3)**.

$EUA_{c,b}^{SW}$	**Pre-Treatment ($\rho_{PT} = 0$)**		**No Pre-Treatment ($\rho_{NOPT} = 0.05$)**	
	Low biomass price	High biomass price	Low biomass price	High biomass price
$EUA_{L,ToP}^{SW}$	36.88	41.64	(51.36)[a]	(53.66)[a]
$EUA_{HC,ToP}^{SW}$	55.11	60.12	(68.51)[a]	(70.89)[a]
$EUA_{L,WP}^{SW}$	22.88	39.68	(34.35)[a]	(54.65)[a]
$EUA_{HC,WP}^{SW}$	40.38	58.06	(51.54)[a]	(71.90)[a]
$EUA_{L,WC}^{SW}$	(-9.60)[a]	(28.48)[a]	-3.13	41.51
$EUA_{HC,WC}^{SW}$	(6.19)[a]	(46.27)[a]	12.17	58.33
$EUA_{L,AR}^{SW}$	(-10.44)[a]	(-2.32)[a]	-4.44	5.40
$EUA_{HC,AR}^{SW}$	(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 have defined the carbon switching price as the increased fuel cost of co-firing, which enables power producers to abate one tonne of CO_2. More precisely, two effects have to be considered when switching to co-firing. On the one hand, the fuel cost of biomass ($q_{c,b}^{cf}\ B_b$) increases (since no biomass was used before). On the other hand, the cost of coal consumption ($\left(h_c^{nocf} - q_{c,c}^{cf}\right)C_c$) decreases. Thus, defining the carbon switching price as an increased fuel cost is equivalent to considering that the effect of biomass is greater than that of coal. It is worthwhile mentioning these two effects to interpret the results of Tab. 3.

Results of Tab. 3 show that the carbon switching price associated with using biomass in lignite plants is always cheaper than that of hard coal plants, whatever the situation we consider. This is because, in the price data we use, the lignite price is higher than the price of

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[25] Whereas the effect of modifying the losses coefficient is straightforward, it is difficult to disentangle in case of the incorporation rate. In fact, we estimated that modifying the incorporation rate induces two opposite effects for the co-firing cost, and the net effect is undetermined for the carbon and biomass switching prices. Results are available from the authors upon request.

hard coal. Thus, each time a $\mathrm{MWh_{prim}}$ of biomass is included in a coal plants, it comes with a higher avoided cost for coal consumption in the case of lignite. This translates into a lower carbon switching price 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, Tab. 3 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). It is explained by the price difference between pre-treated and non pre-treated biomass. Indeed, in the 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.[26] Note that an exception comes from the carbon switching prices associated with the high WC price, 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 Tab. 3 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 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.

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

$B_{c,b}^{SW}$	**Carbon price**				
	Euros 5/tCO_2	Euros 10/tCO_2	Euros 20/tCO_2	Euros 50/tCO_2	Euros 100/tCO_2
$B_{L,NOPT}^{SW}$	15.88	17.40	20.45	34.68	52.54
$B_{HC,NOPT}^{SW}$	11.29	12.76	15.71	28.55	45.23
$B_{L,PT}^{SW}$	18.61	20.40	23.97	29.58	44.81
$B_{HC,PT}^{SW}$	13.00	14.69	18.09	24.54	39.28

Similarly to the carbon switching price, results of Tab. 4 indicate that co-firing is cheaper in lignite plants. Indeed, we observe that the biomass switching price has higher values in the

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[26] Results of Tab. 3 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.

case of co-firing in lignite plants. This reflects the higher benefits associated with including one MWh_{prim} 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 MWh_{prim}, it would be profitable switching to co-firing in lignite plants, but not in hard coal plants. One may say that the biomass co-firing profitability-band is larger with lignite plants than with hard coal.

We also observe in Tab. 4 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.

Finally, the results of Tab. 4 illustrate that co-firing can remain profitable with a very high biomass price, if the carbon price is high enough. For instance, assuming a Euros 50 CO_2 price, co-firing would be profitable in lignite plants with a biomass price of about Euros 25-35 per MWh_{prim} (about Euros 40-50 per MWh_{prim} with a Euros 100 CO_2 price), depending on the situation. Hence, the carbon price can be an important driver of co-firing, which can make the switching profitable even with high biomass price.

4. Matching European biomass supply with potential demand from the power sector: Uncertainties on supply and competition for biomass resources

This section focuses on matching biomass supply with potential biomass demand estimations of previous section. We rely on literature to figure out what the potential biomass feedstocks in the EU countries are. Comparing potential supply and demand, we want to shed light on how the biomass market may be impacted by biomass demand in the power sector. Results indicate that potential demand may be high compared with supply, which may induce conflicts with other biomass usages.

In order to carry out a relevant comparison between potential supply and demand, we focus on papers covering the same geographical area as in section 3. We identify three main references that provide an extensive overview of potential biomass supply for energy production in the EU-27: Ericsson and Nilsson (2006), Renew (2006) and Panoutsou et al. (2009).[27] Renew (2006) consider projected estimates for 2020 with high (S1) and low (S2) biomass production. Starting Point reflects the biomass potential for the years 2000-2004. In Ericsson and Nilsson (2006), scenarios 1, 2 and 3 refer to periods 2015-2025, 2025-2045, and beyond 2045, respectively. The letters in the scenario names indicate low (a) and high (b) biomass supply. Panoutsou et al. (2009) provide estimates for the biomass supply in 2000, 2010 and 2020.

Ericsson and Nilsson (2006), Renew (2006) and Panoutsou et al. (2009) use basically the same classification for biomass feedstocks, which facilitates comparisons. Accordingly, we split lignocellulosic biomass into four groups as follows:

- **Agricultural residues**. These products include a wide range of plant material produced along with the main product of the crop. Cereal straw, fruit tree prunings, corn stems, cobs, etc, are some examples of agricultural residues that can be used for energy purposes.
- **Forestry Wood**. This category includes wood fuel and residues from logging and forest thinning (branches, sawdust, stumps and roots, etc).
- **Wood industry by-products**. These residues are produced mainly in forest-related industries like sawmills and paper. This includes materials like sawdust, husks, kernels or black liquor.
- **Energy crops**. Woody or herbaceous crops that are grown specifically for their fuel value. This includes short rotation (e.g. willow, poplar, eucalyptus) and perennial crops (e.g. miscanthus, switchgrass, reed canary grass).

Fig. 8 gathers different biomass potential supply scenarios elaborated by the three aforementioned papers. Thus, we obtain a set of biomass potentials for five time horizons (2000, 2010, 2020, 2025-2045, and beyond 2045), which are compared to the biomass potential demand in the power sector, as estimated in the previous section.

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[27] These papers are based on a large number of studies using data from country level reports and European statistics. This provides us with a wide overview of the potential biomass supply in the EU countries.

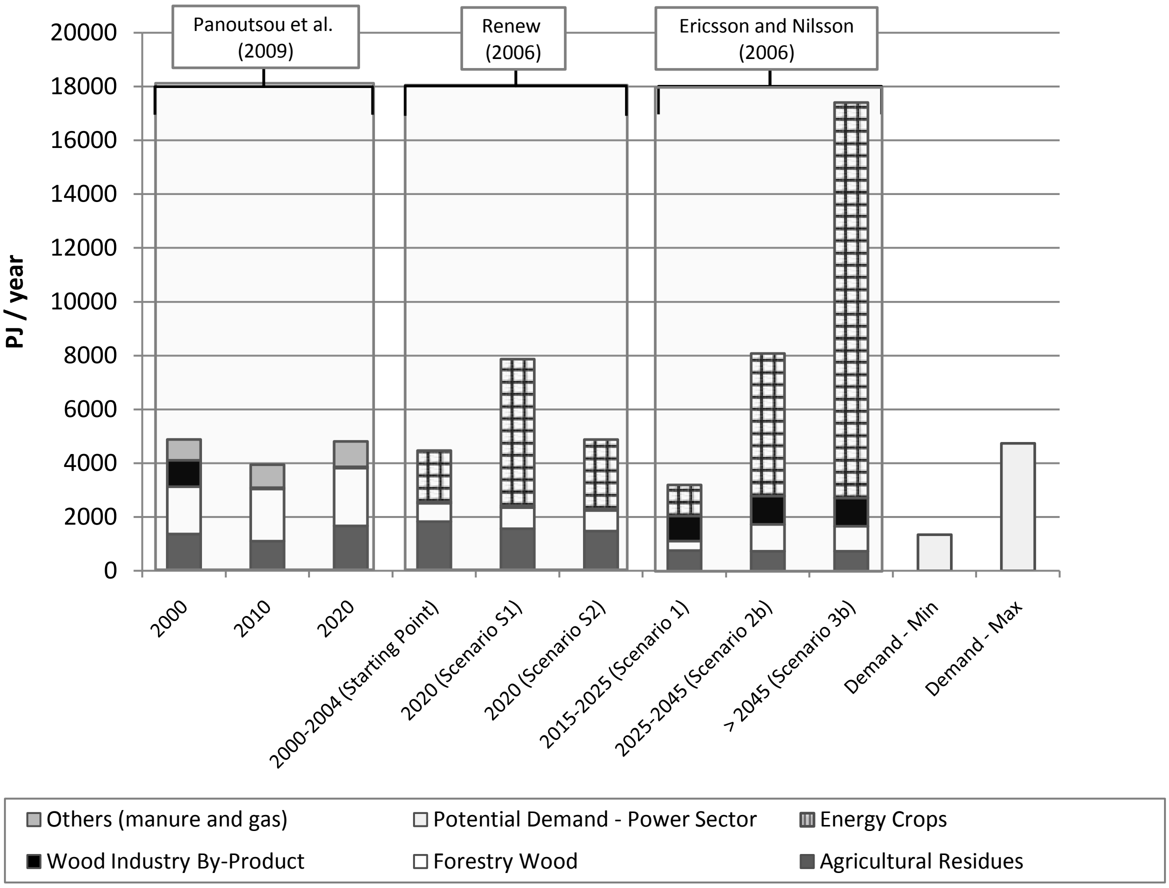

Figure 8: Potential biomass supply assessment in EU-27.

Fig. 8 indicates that there may be strong differences in potential supply estimates from one study to another. For instance, considering forestry wood, agricultural residues and wood-industry by-product for 2020, the estimated resource varies from 2000 (Ericsson and Nilsson, 2006) or 2350 (Renew, 2006) to almost 4000 PJ a year (Panoutsou et al., 2009). There may also be significant differences in the same study, when considering different scenarios for the same year. For instance, for the same time horizon of 2020, Renew (2006) estimates an overall potential varying from 4900 to almost 8000 PJ a year. This induces strong uncertainties about the actual biomass potential. This strong discrepancy in estimates is explained by the heterogeneity of biomass resources. Moreover, biomass production can be heavily dependent on the region where it is produced. Hence, different hypotheses about land availability, agronomic or weather conditions can substantially impact the results. The question of potential conflicts between different biomass usages can also influence estimates. For instance, the question of how much agricultural biomass can be used in energy without impacting other biomass usages.

Regarding energy crops, there are strong uncertainties about the share they will represent in lands in the future. Potential detrimental effects related to changes in land-use or reduced biodiversity may constitute barriers to their development.[28] The evolution of yields is also an important unknown parameter. Even though yields have increased in Europe during the last decades, we cannot be sure that this rise will continue with the same rate in the future. Renew (2006) anticipates an increase in yields from 10 to 30% by 2020 in their intensive production scenario, and from 7 to 20% in another scenario in which agricultural practices are less intensive. The share of energy crops also differs from one scenario to another.

Results also depend on hypotheses about availability factors for energy purposes of forestry, wood industry and agricultural residues. Even though the same availability factors are assumed in general for all the European countries, the value can differ from one study to another. For example, Panoutsou et al. (2009) retain a uniform availability factor of 30% for agricultural residues in all the European countries. Ericsson and Nilsson (2006) and Renew (2006) distinguish between the availability factor of maize (25%) and other cereals (22%).

The heterogeneity of hypotheses induces significant differences in the share of each biomass source in the overall biomass supply (Fig. 8). Globally, literature indicates that energy crops offer the most important potential source of biomass supply, with 1150 to 14000 PJ a year. The following category can be forestry, wood industry or agricultural residues, depending on the scenario and other hypotheses.

Despite uncertainties in the supply side, when comparing the EU biomass supply estimates from literature with potential biomass demand from the power sector, we observe that demand may be quite high compared with supply and sometimes higher (Fig. 8 and 9).[29] This may induce potential tensions in the biomass market.

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[28] See Ben Fradj (2013) for an economic analysis of potential effects induced by changes in land-uses due to development of energy crops in France.

[29] In Fig. 9, the Baseline Supply Potential refers to the average of values provided in the Renew (2006) Starting Point and in the Panoutsou et al. (2009) EP 2000. The 2020 Supply Potential is the average of values in the Renew (2006) S1 and S2, the Ericsson and Nilsson (2006) scenario 1, and the Panoutsou et al. (2009) EP 2020.

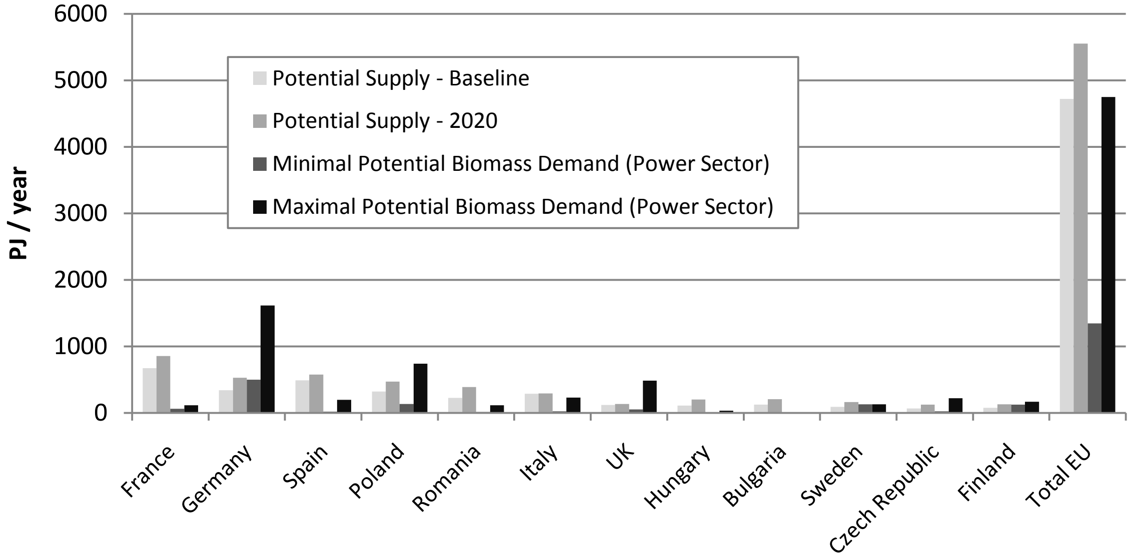

Figure 9: Comparison between potential biomass supply and demand in the ten EU countries with the highest potential supply.

Actually, our results indicate that the EU27 potential demand could cover between 8% (min potential demand with the Ericsson and Nilsson (2006) Scenario 3b) and 148% (max potential demand with the Ericsson and Nilsson (2006) Scenario 1) of the biomass production in Europe.[30] This may significantly increase biomass prices. As pointed out in the previous section, a high enough carbon price can make co-firing profitable even with very high biomass prices. Hence, high biomass prices can be affordable in the power sector, whereas this can constitute barriers for other competing biomass usages.

When comparing situations of different EU countries, Fig. 9 indicates that there are great differences in the balance between potential demand and supply. While some countries have a heavily positive balance (e.g. France, Spain), meaning that they can produce more than the potential demand from inland power generation, others countries have a significantly negative balance (e.g. Germany, the UK). Hence, one may conclude that a lot of trading opportunities could exist between the EU countries, in which countries with large positive balance may become net suppliers. For instance, France would export a substantial part of its biomass resources to Germany.[31] While, in general, feedstock costs are relatively low in the

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[30] Note that we used 2011 data to estimate potential demand from the power sector. Thus projected potential demand for 2020 would be substantially higher compared with our estimates, if considering investments in new power plants using biomass. Those investments would be supported by the different European schemes to promote biomass in energy. Regarding co-firing, investments in new highly efficient coal plants would be triggered by Carbon Capture and Storage (CCS) technologies, which can result in negative CO_2 emissions (i.e. net removal of CO_2 from the atmosphere) when associated with biomass (IEA-IRENA, 2013).

[31] Remember that we refer to quantities that are technically possible, but that do not necessarily reflect the current situation. Hence, a country with a positive balance in our estimations may import large volumes of

case of biomass, additional costs related to logistics and transportation may be much more significant (Hamelinck et al., 2005). However, as pointed out in section 2 of this paper, several pre-treatments can be applied to raw materials in order to densify biomass and save transport and handling costs. This would facilitate biomass trading among European countries and beyond.

5. Conclusion

This paper provides estimations of the technical potential biomass demand from the existing power plants in the European power sector, considering both biomass co-firing in coal plants and power generation from dedicated biomass power plants. Furthermore, we match our estimates with the potential biomass supply in Europe, and we compute the CO_2 abatements associated with co-firing opportunities in the EU-27. We also investigate the cost of biomass co-firing in European coal power stations, and we derive a simple and original method that enables us computing the biomass and CO_2 breakeven prices for co-firing.

Results indicate that the potential biomass demand from the power sector may be quite high compared with the potential biomass supply in the EU-27 (sometimes higher). Co-firing offers the highest potential with up to 80% of the overall technical biomass demand. Co-firing can also produce high volumes of CO_2 abatements, which may account for more than two times the potential abatements from the coal-to-gas fuel switching.

Our economic analysis regarding biomass and CO_2 breakeven prices indicate that the co-firing profitability depends on the quality of biomass and on the type of coal plants involved. In particular, we show 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 some cases, considering biomass prices that reflect the current market conditions, we find that co-firing can be profitable in lignite plants with a zero or very low carbon 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 MWh_{prim} of biomass in lignite plants, due to greater coal cost savings with a higher lignite price.

Comparing our estimations for the potential demand from the power sector with the potential biomass supply in Europe, we see that the biomass demand from power generation

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biomass in practice. This would be explained by shortfall in the current local biomass resource compared with what is needed. However, taking into account the whole potential supply, including non-exploited resources from forest and residues, the potential local biomass resource exceeds the need, which results in a positive balance.

may generate tensions in the biomass market if a high share of potential demand turns out to be economically profitable. Interestingly, we also derive from our framework that a profitable co-firing remains possible with very high biomass prices, when the carbon price is high enough. Hence, a high enough carbon price can induce a strong biomass demand in the power sector (and in other carbon dependant sectors), even with a substantial increase in biomass prices compared with their current levels. However, as biomass stocks are limited, such a situation would result in potential conflicts between different biomass usages.

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