Biomass waste co-firing with coal applied to the Sines thermal power plant in Portugal

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Abstract

Environmental issues raised by the use of fossil fuels lead to the search for alternatives that promote the reduction of emissions of greenhouse gases. CO_2 has been identified as being the most important and urgent to control. Co-firing is a technique that allows the simultaneous combustion of different types of fuels, for example coal and biomass, combining the advantages of both. This study characterizes the advantages of the system and the possibilities of using waste biomass as fuel in a coal-fired thermal power plant. For this, co-firing biomass waste, from forestry operations, with bituminous coal was simulated. Then reductions in CO_2 emissions into the atmosphere from Sines Thermal Power Plant in Portugal were calculated, showing a reduction of more than 1,000,000 tons/year of CO_2. Also it was verified that although environmentally advantageous, co-firing is still not economically viable due to the high cost of the residual biomass, combined with its low-energy density and high transportation costs.

Keywords: Co-firing, residual biomass, CO_2 emissions, energy costs

1. Introduction

The environmental advantages of using biomass and other renewable energy forms as alternative energy sources to fossil fuels are the basis that sustains initiatives for the use of these resources, in all their variants, to increase its penetration into energy markets [1].

Unfortunately, these advantages are accompanied, in general, by inherently problematic properties (stationary, low-energy density, scattering, competition with other uses, etc.) that characterize these power sources and, more particularly, biomass waste. These features are closely related to the final costs of its use, delaying its incorporation into the energy markets, and ensuring that its current use remains far below expectations in terms of its expected potential [2].

In any case, to increase the consumption of residual biomass for energy production, as well as to put into practice actions and support tools, cost reduction and improved efficiency of procedures for collecting and processing these energy resources should be promoted [3].

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In this study we analyse a technology that could allow an increase in the contribution of biomass energy in the Portuguese energy scenario, especially residual biomass, such as waste from forestry operations, through its co-firing with coal, and an estimation of CO_2 emissions was conducted in order to demonstrate the environmental advantages of using biomass waste in energy production, despite the economic disadvantage that still exists due to low coal prices and to the high collection and transportation costs related to biomass waste.

This brief introduction, where a contextualization is made, is followed by a description of the co-firing technology and the state-of-the-art concerning test realized internationally. After comes the simulation of residual biomass co-firing at Sines Thermal Power Plant in Portugal, divided in description of the plant; the co-firing of biomass; the CO2 emissions; and the economic feasibility, followed by the conclusions.

2. Co-firing in conventional coal power plants

An interesting and promising alternative for the production of electricity from biomass is through its co-firing in conventional coal power plants already in operation. This is a relatively recent technological development, and consists in replacing part of the coal used in the plant with biomass, with a maximum of 20% in energy potential, but 15% being the most common value achieved in tests performed in many thermal power plants in the EU and USA. Although this percentage is small, due to the large size of the plants, the end result is the production of a very substantial amount of electrical energy with this renewable fuel [4].

In addition, as well as the significant advantages of using biomass instead of fossil fuels, co-firing has other, no less important advantages when compared with the exclusive use of biomass in plants that are only equipped for this purpose.

For example, much lower investment is required per unit of installed capacity, because co-firing biomass can use much of the existing infrastructure in each plant (steam cycle, electrical systems, cooling system, and at least part of the boiler), which is reflected in a drastic reduction in the investment, despite the pre-treatment facilities being usually more complex than in a power plant that is used exclusively for biomass [5].

The generation of electricity with higher performance is not feasible, because the use of low-density biomass resources implies that, to achieve significant electrical potential, the collection should encompass too large an area, which would entail high transportation costs. Therefore, and by a simple matter of economy of scale, the promoters of a biomass thermal plant find themselves forced to decide between getting a high performance and a high cost per installed kW, or reducing this investment by reducing performance. This last option is the most frequently chosen to ensure the economic viability of the project. Thus, in a biomass thermal plant (usually less than $20MW_e$), performance hardly reaches 30%, whilst in coal thermal power plants of large dimensions (500 MW_e or more), where co-firing takes place, performance can reach 36% [6]. This possibility also allows much greater flexibility in operation, because a co-firing plant allows great flexibility and easy adaptation to the availability of biomass at a precise moment. A biomass plant would have to face the possibility of stopping or reducing production in certain periods due to either a shortage of resources or an increase in situational prices. However, a co-firing plant, even with these situations, could continue in full operation using the fuel which has been projected, in a greater proportion or even exclusively [7]. And, a very important environmental advantage would be the reduction in NO_x emissions due to the lower nitrogen content of biomass and synergistic effects between biomass and coal. This is an advantage that should be proven and quantified at each plant where co-firing may be conducted, because there may be significant differences among them [8].

Thus, co-firing becomes an easy and economical way to increase the short-term consumption of biomass in place of fossil fuels. However, this technology also has certain drawbacks and uncertainties, such as operating costs, because the pre-treatment of biomass co-firing is more costly (in facilities already in operation), especially in the case of co-firing in a pulverized coal thermal power plant. However, this increase in cost can be compensated, at least partially, by the fact that these power plants already have specialized personnel, which reduces both the cost of manpower [9] and uncertainty regarding the behaviour of the boiler due to a mix of fuels for which it was not designed [10].

Furthermore, although the concept of co-firing is relatively simple and has already been tested successfully in many power plants around the world, particularly in the USA and EU, there are many aspects (such as ideal pre-treatment, place of introduction of biomass, etc.) that should be studied in detail for each case: type of boiler, type of coal and type of biomass [11-20].

Although co-firing can be applied to all types of thermal power plants, the possibilities are greater in those that have installed pulverized fuel boilers, not for technical reasons, but because this technology is more widespread. In these boilers, finely pulverized coal with reduced moisture content is introduced, achieving high performance with very low residence times. These aspects require that biomass should present similar capabilities, and therefore before combustion it must undergo pre-treatment that, although varying from case to case, consists primarily of drying (natural or forced) to reduce the moisture content to values generally under 20% [21], and on grinding to reduce the particle size usually to less than 3 mm [22].

Regarding the type of coal used in the case of Portugal, mainly bituminous coal from Colombia, but also from other sources, such as South Africa and the USA, Table 1 shows the characteristics of this type of coal, as well as biomass waste [23].

"See Table 1 at the end of the manuscript".

The majority of the co-firing experiments were carried out with coal with an energy density higher (anthracite type) than that of biomass. However, the heating value of bituminous coal used in Portugal, although higher, is not much higher, as anthracite is, than that of biomass waste, as can be seen in Table 1. This may imply a considerable reduction in the investment necessary because there is the possibility of using biomass in the same systems as those designed for feeding coal to the boiler, especially burners. Additionally, it is possible to introduce the biomass in a simple way, at the centre of the flame generated by the coal, and it is technically feasible to use a particle size bigger than that of coal. This involves a reduced pre-treatment cost compared to other types of co-firing [24].

3. Residual biomass co-firing at Sines thermal power plant

3.1. Sines Thermal Power Plant

The thermal power plant is located in the municipality of Sines (SW Portugal), near the harbour of Sines, where the coal that feeds the plant is unloaded. The plant consists of four groups of identical generators which have an independent autonomy able to contribute an electrical capacity of 314 MW each. The construction of the plant began in early 1979 and its first generator went into operation in 1985, with the rest following in 1986, 1987 and 1989 [25].

Each group of generators which makes up the plant system includes a steam natural circulation group (GGV), a turbo alternator (GTA) and one main transformer. The supply of coal that fuels the plant comes mainly from Colombia, but also from South Africa and the USA. Transport is by sea and discharge takes place in the harbour of Sines to the coal storage park, which has a capacity of 1,500,000 tons. Transport to the storage park is carried out by conveyor belts and transfer towers [26].

In the coal park four active batteries are formed with 150,000 tons each and a stack of 700,000 tons liability. The total capacity of coal in the thermal power plant park grants autonomy to the plant operation at full capacity for about five months [27].

Via a set of conveyor belts, coal is carried to the metal silos which are located near the steam generator. Once in the silos, coal is discharged into a hopper, and from there to the mill where the grinding is carried out. Then the pulverized coal is transported to the boiler where it is burned ensuring complete combustion in the combustion chamber. The average energy production at the power plant in the years 2008-2011 [28] was calculated as approximately 7,210 GWh.

3.2. Atmospheric emissions of CO_2

Sines Thermal Power Plant has an internal continuous monitoring system, which controls atmospheric emissions to the environment. Currently the system consists of five monitoring stations that control all the pollutants generated, including heavy metals and suspended solid particles. There are also dust collection units in the chimneys of the plant contributing to a reduction of generated dust emissions [29].

Gases, and some solid waste resulting from this process, are treated to reduce SO_2 content released into the atmosphere through the two 225 metre chimneys, which ensure the atmospheric dispersion of particles [30].

The analysis of the model used in this study is based on the average value of electricity generation in recent years, presented in the previous section, and with it a value for the amount of CO_2 emitted into the atmosphere was estimated [31].

Using the reference value of CO_2 emissions factor of 0.980 kg/kWh_e for bituminous coals [32], and for the total amount of energy production used in this model, the thermal power plant emits approximately 7,065,800 tons of CO_2 annually into the atmosphere, making it by far the largest source of CO_2 in Portugal [25].

3.3. Emissions reduction with biomass co-firing

The innumerable recent experiments performed with co-firing of biomass have showed that, despite the environmental advantages presented by energy production from biomass compared to its production with fossil fuels, foremost of which is the CO_2 balance of virtually nil, the use of this renewable source in boilers designed for other fuels can cause increased emissions of other contaminants [33].

These contaminants were monitored in real time in many of the experiments performed, and were compared with the data obtained for the combustion of coal only, in the same boilers, and in most cases no differences were found in the emission of particles or other contaminants [34].

Furthermore, in these studies it was also shown that, as would be expected, given the characteristics of the new fuel (sulphur percentage much lower than coal), SO_2 emissions decreased and also a decrease in NO_x emissions was detected [35].

The model under analysis in this study started from the assumption that 15% of the average amount of energy produced in recent years in the Sines Thermal Power Plant could be replaced.

Resorting to a lower calorific value of 2.80 kWh/kg very often referred to in studies concerning equivalent forms of biomass waste [36] from forest clearing operations, it was estimated that it would take approximately 400,000 tons/year of waste biomass to replace the 1,082 GWh equivalent to 15% substitution by renewable fuel.

The combustion of the residual biomass for power generation releases 0.018 kg/kWh_e of CO_2 into the atmosphere [37], so the combustion of 400,000 tons/year releases about 19,500 tons/year of CO_2, from a combined total of 6,025,430 tons/year CO_2, saving 1,040,370 tons/year of CO_2. On Table 2, a summary of the obtained calculations is presented.

"See Table 2 at the end of the manuscript".

3.4. Economic feasibility

The results analysed in different experiments conducted mainly in the USA and EU countries found that the investment required to adapt an existing pulverized coal thermal plant to co-firing technology may be lower than initially expected. The reasons for this lower need for investment are, on the one hand, that it can be used to supply biomass for some of the equipment projected for coal, especially the burners [38], and on the other hand, the possibility of introducing biomass without forced drying.

If the dryer is not needed, the cost of pre-treatment decreases, along with the operation costs, due to not requiring auxiliary fuel for this equipment [39].

Nevertheless, the low investment and operation costs are not sufficient to ensure the economic viability of co-firing since, currently, even before the required cleaning operations, the cost of forest biomass, the low density of which implies high transportation costs, is higher than the cost of coal. Therefore, for this technology to be economically viable, it would be necessary to rely on incentives applicable to electricity generated using biomass waste. These incentives already apply to exclusive biomass thermal power stations but, currently, it is not foreseen that they will be applied to co-firing [40].

Figure 1 presents a graphic comparing the price per kWh of bituminous coal from Colombia and of residual biomass. For the residual biomass, a constant value over the past 12 months was assumed for the best market price, which was obtained through direct consultation with suppliers; this was 15.00 €/ton for biomass resulting from forestry operations, supplied as woodchips, with an average size of 30x15x15 mm and a moisture content of 30% and a cost of shipping from 10.00 €/ton, predicting a maximum distance of 200 km to the Sines Thermal Power Plant, as the maximum limit for the supply area of residual biomass to the plant.

"See Fig. 1 at the end of the manuscript".

In the 45-60 km Sines thermal power plant surrounding region, it is estimated that there is an annual biomass generation capacity of about 32 tons/year (wet basis), or about 72 tons/day (dry basis), resulting from the forestry operation of 107,000 ha of forest area, composed mainly of eucalyptus forests (39,000 ha) and pine forests (68,000 ha). However, this capacity of residual biomass is grossly inadequate for the coefficient of coal replacement of 15 % treated in this study. For this reason, it was necessary to extend the collection area up to 200 km, covering the whole of the Alentejo region, which has a capacity of annual generation of waste biomass of about 1,000,000 tons/year, in order to achieve the fuel needs calculated in this study [41].

Several studies state that, to be viable the supply of biomass to a given consumption place, the collection point should not exceed 45-60 km radius. However, in the case of this study, this was not possible due to lack of necessary resources in that area of 45-60 km [42].

4. Conclusions

From the analysis of the results obtained in numerous experiments performed internationally and the several studies carried out, including the one described here, it can be stated that the co-firing of biomass in power plants that use pulverized coal is technically feasible and can increase the contribution of renewable energy, satisfying the demand for primary energy, while maintaining the environmental advantages of using biomass over the use of fossil fuels.

Although this technology is applicable to all types of pulverized coal plants, it is more efficient when using biomass resources with lower calorific coals, such as bituminous coal, rather than others with higher calorific value, such as anthracite. Due to the similarity in some of its properties, it is possible to considerably reduce the investment necessary and the cost of operation and maintenance, since it is possible to take advantage of the existing power systems and fuel, even avoiding the need for forced drying of the biomass.

Nevertheless, the high cost of residual biomass means that, even taking into account the economic advantages mentioned, the penetration of co-firing technology is not at present economically viable. Something similar happens with the biomass plants, even in this case counting the incentives for the produced energy. This is one of the reasons why there are so few biomass power plants in Portugal using as fuel a mixture of biomass waste from forestry operations and wood logs, especially pine, in order to try to reduce the fuel cost.

On the other hand, if an incentive was defined for electricity produced from biomass through co-firing, this technology would be economically viable at the current market prices of residual biomass, which would enable much more extensive use of this renewable fuel. Such incentives are justified by the significant environmental benefits that the use of biomass (or any other source of renewable energy) presupposes, compared to the use of fossil fuels, benefits that are, of course, shared by co-firing, as shown in the reduction of CO_2 emissions of 1,000,000 tons/year, calculated in this study, which is significant.

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References

[1] Cherubini, Francesco. "The biorefinery concept: Using biomass instead of oil for producing energy and chemicals". Energy Conversion and Management 51.7 (2010): 1412-1421.

[2] García-Frapolli, Eduardo, et al. "Beyond fuel wood savings: Valuing the economic benefits of introducing improved biomass cook stoves in the Purépecha region of Mexico". Ecological Economics 69.12 (2010): 2598-2605.

[3] Saidur, R., et al. "A review on biomass as a fuel for boilers". Renewable and Sustainable Energy Reviews 15.5 (2011): 2262-2289.

[4] De, S., and M. Assadi. "Impact of cofiring biomass with coal in power plants–A techno-economic assessment". Biomass and Bioenergy 33.2 (2009): 283-293.

[5] Lintunen, Jussi, and Hanna-Liisa Kangas. "The case of co-firing: The market level effects of subsidizing biomass co-combustion". Energy Economics 32.3 (2010): 694-701.

[6] Al-Mansour, Fouad, and Jaroslaw Zuwala. "An evaluation of biomass co-firing in Europe". Biomass and Bioenergy 34.5 (2010): 620-629.

[7] Berndes, Göran, et al. "Strategies for 2nd generation biofuels in EU — Co-firing to stimulate feedstock supply development and process integration to improve energy efficiency and economic competitiveness". Biomass and Bioenergy 34.2 (2010): 227-236.

[8] McIlveen-Wright, D. R., et al. "A techno-economic assessment of the reduction of carbon dioxide emissions through the use of biomass co-combustion". Fuel 90.1 (2011): 11-18.

[9] Tumuluru, Jaya Shankar, et al. "A review on biomass classification and composition, co-firing issues and pretreatment methods". Proceedings of the 2011 ASABE annual international meeting. Louisville, Kentucky, USA. 2011.

[10] Basu, Prabir, James Butler, and Mathias A. Leon. "Biomass co-firing options on the emission reduction and electricity generation costs in coal-fired power plants". Renewable Energy 36.1 (2011): 282-288.

[11] Nicholls, David L., and John I. Zerbe. Co-firing biomass and coal for fossil fuel reduction and other benefits: Status of North American facilities in 2010. US Department of Agriculture, Forest Service, Pacific Northwest Research Station, 2012.

[12] Molcan, Peter, et al. "Characterisation of biomass and coal co-firing on a 3MWth Combustion Test Facility using flame imaging and gas/ash sampling techniques". Fuel 88.12 (2009): 2328-2334.

[13] Wang, Xuebin, et al. "Experimental investigation on biomass co-firing in a 300MW pulverized coal-fired utility furnace in China". Proceedings of the Combustion Institute 33.2 (2011): 2725-2733.

[14] Teixeira, Paula, et al. "Evaluation of slagging and fouling tendency during biomass co-firing with coal in a fluidized bed". Biomass and Bioenergy 39 (2012): 192-203.

[15] Zuwala, Jaroslaw, and Marek Sciazko. "Full-scale co-firing trial tests of sawdust and bio-waste in pulverized coal-fired 230t/h steam boiler". Biomass and Bioenergy 34.8 (2010): 1165-1174.

[16] Dong, Changqing, et al. "Numerical modeling of the gasification based biomass co-firing in a 600MW pulverized coal boiler". Applied Energy 87.9 (2010): 2834-2838.

[17] Abreu, P., C. Casaca, and M. Costa. "Ash deposition during the co-firing of bituminous coal with pine sawdust and olive stones in a laboratory furnace". Fuel 89.12 (2010): 4040-4048.

[18] Zulkepli, I. I., et al. "Numerical study of co-firing biomass with coal in cyclone combustor". IOP Conference Series: Earth and Environmental Science. Vol. 16. No. 1. IOP Publishing, 2013.

[19] Steer, Julian, et al. "Biomass co-firing trials on a down-fired utility boiler". Energy Conversion and Management 66 (2013): 285-294.

[20] Kazagic, A., and I. Smajevic. "Synergy effects of co-firing wooden biomass with Bosnian coal". Energy 34.5 (2009): 699-707.

[21] Wils, Andrea, et al. "Reduction of fuel side costs due to biomass co-combustion". Journal of Hazardous Materials 207 (2012): 147-151.

[22] Bridgeman, T. G., et al. "An investigation of the grindability of two torrefied energy crops". Fuel 89.12 (2010): 3911-3918.

[23] Nunes, L. J. R., J. C. O. Matias, and J. P. S. Catalão. "Energy recovery from cork industrial waste: Production and characterisation of cork pellets". Fuel 113 (2013): 24-30.

[24] Clements, B. R., et al. "Ignition characteristics of co-fired mixtures of petroleum coke and bituminous coal in a pilot-scale furnace". Fuel 97 (2012): 315-320.

[25] Gerbelová, Hana, et al. "The effect of retrofitting Portuguese fossil fuel power plants with CCS". Applied Energy 101 (2013): 280-287.

[26] Gerbelová, H., C. Ioakimidis, and P. Ferrão. "A techno-economical study of the CO2 capture in the energy sector in Portugal". Energy Procedia 4 (2011): 1965-1972.

[27] Carneiro, Júlio F., Dulce Boavida, and Ricardo Silva. "First assessment of sources and sinks for carbon capture and geological storage in Portugal". International Journal of Greenhouse Gas Control 5.3 (2011): 538-548.

[28] Apolinario, Isabel, Liliana Ferreira, and Pedro Verdelho. "Introduction of a decoupled entry-exit tariff system in the Portuguese natural gas sector". European Energy Market (EEM), 2012 9th International Conference. IEEE, 2012.

[29] Gerbelová, Hana, et al. "The effect of retrofitting Portuguese fossil fuel power plants with CCS". Applied Energy 101 (2013): 280-287.

[30] Lyko, H. "Membrane technology for CO2 emission-free power plant operation". Filtrieren und Separieren 2 (2012): 44.

[31] Sujatha, K., et al. "Intelligent parallel networks for combustion quality monitoring in power station boilers". Advanced Materials Research 699 (2013): 893-899.

[32] Whitaker, Michael, et al. "Life cycle greenhouse gas emissions of coal-fired electricity generation: Systematic review and harmonization". Journal of Industrial Ecology 16.S1 (2012).

[33] Basu, Prabir, James Butler, and Mathias A. Leon. "Biomass co-firing options on the emission reduction and electricity generation costs in coal-fired power plants". Renewable Energy 36.1 (2011): 282-288.

[34] Bertrand, Vincent. "Switching to biomass co-firing in European coal power plants: Estimating the biomass and CO2 breakeven prices". Economics Bulletin 33.2 (2013): 1535-1546.

[35] Aris, Mohd Shiraz, Hussain H. Al-Kayiem, and Chin Yee Sing. "Experimental investigations on the characteristics of biomass and coal-biomass fuel briquettes". Advanced Materials Research 683 (2013): 246-249.

[36] Saikia, M., et al. "Prospect of bioenergy substitution in tea industries of North East India". International Journal of Modern Engineering Research (IJMER) 3.3 (2013): 1272-1278

[37] Mills, Evan. "From carbon to light". Prepared for the United Nations Framework Convention on Climate Change, Clean Development Mechanism Executive Committee, Small-Scale Working. 2010.

[38] Anderson, Nathaniel, et al. "A comparison of producer gas, biochar, and activated carbon from two distributed scale thermochemical conversion systems used to process forest biomass". Energies 6.1 (2013): 164-183.

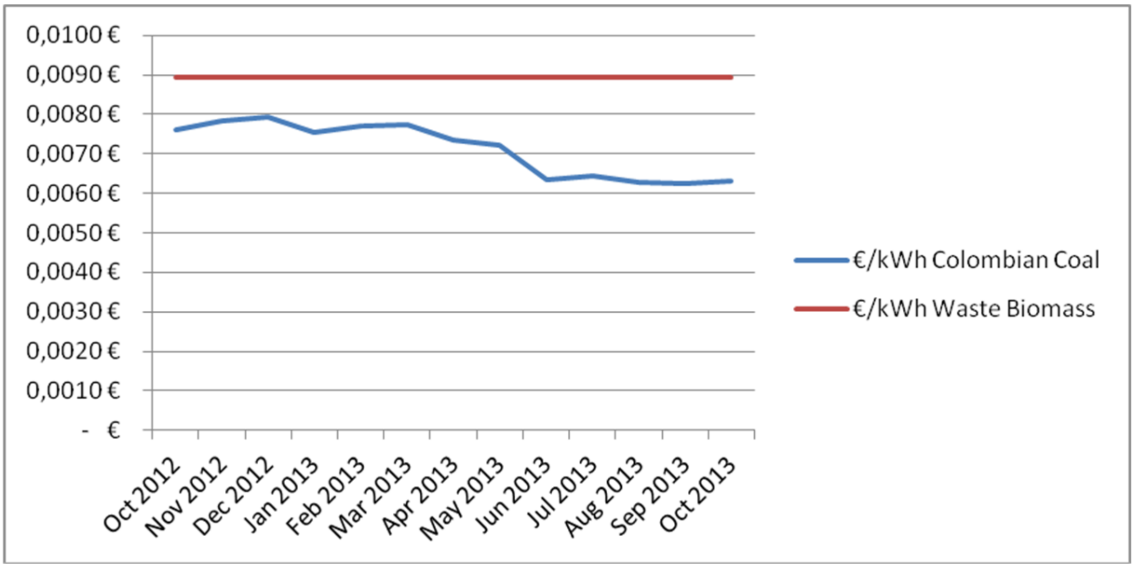
[39] Yin, Chungen, Lasse Rosendahl, and Søren K. Kær. "Towards a better understanding of biomass suspension co-firing impacts via investigating a coal flame and a biomass flame in a swirl-stabilized burner flow reactor under same conditions". Fuel Processing Technology 98 (2012): 65-73.

[40] Suik, H., T. Pihu, and A. Molodtsov. "Wear of the fuel supply system of CFB boilers". Oil Shale 25.2 (2008): 209-216.

[41] Viana, H., et al. "Assessment of forest biomass for use as energy. GIS-based analysis of geographical availability and locations of wood-fired power plants in Portugal." Applied Energy 87.8 (2010): 2551-2560.

[42] Butnar, Isabela, et al. "Life-cycle assessment of electricity from biomass: Case studies of two biocrops in Spain." Biomass and bioenergy 34.12 (2010): 1780-1788.

Figure captions



(prices of bituminous Colombian coal were researched in www.indexmundi.com)

Fig. 1. Comparison of prices of bituminous coal and residual biomass.

Tables

Table 1

Characteristics of bituminous coal of Colombian origin, used in Portugal and residual biomass (adapted from [23])

	Bituminous coal *	Biomass waste	Units
LHV	7.85	2.80	kWh
Ashes	< 11	< 3	%
Moisture	< 5	< 30 **	%

* data obtained from EDP - Gestão da Produção de Energia, S.A.

** after 2 months of cutting and stored in a sheltered location.

Table 2

Data and calculations

	Data and Calculations
The average energy production at the power plant in the years 2008-2011	7,210 GWh
Amount of energy production to be replaced (15%)	1,082 GWh
Bituminous coal CO_2 emissions factor	0,980 kg/kWh$_e$ of CO_2
Residual biomass CO_2 emissions factor	0.018 kg/kWh$_e$ of CO_2
Biomass lower calorific value	2.80 kWh/kg
Amount of biomass to replace coal (15%)	400,000 tons/year
CO_2 production burning biomass	19,500 tons/year
CO_2 production burning 100% coal	7,065,800 tons/year
CO_2 production burning 85% coal and 15% residual biomass	6,026,430 tons/year
CO_2 emissions reduction	1,040,370 tons/year