BIOMASS CO-FIRING AS AN ALTERNATIVE TECHNOLOGY FOR A CLEAN COAL ELECTRIC GENERATION IN BRAZIL

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Abstract: *The mitigation of greenhouse gases emission is one of the important issues in combustion engineering. Biomass is a potential renewable source but with limited use in large scale energy production because of the relative smaller availability as compared to fossil fuels, mainly to coal. Besides, the costs concerning transportation must be well analised to determine its economic viability. An alternative for the use of biomass as source of energy is the co-firing, that is the possibility of using two or more types of fuels combined in the combustion process. Biomass can be co-fired with coal in a fraction between 10 to 25% in mass basis (or 4 to 10% in heat-input basis) without seriously impacting the heat release characteristics of most boilers. Another advantage of cofiring, besides the significant reductions in fossil* CO_2 *emissions, is the reduced emissions of* NO_x *and* SO_x*. As a result, co-firing is becoming atractive for power companies worldwide. This paper presents a review on the sucessfull use of biomass in co-firing worldwide, discussing the benefits and issues reported on using this kind of technology. Important data on the brazilian energy matrix are presented and analysed. It is made an attempt to identify the most suitable types of biomass for co-firing with coal in Brazil.*

Keywords: *Co-firing, biomass, coal, clean energy, electric generation.*

1. INTRODUCTION

In view of an increasingly industrialised world, energy production is becoming the great challenge to be dealt with. The challenge is even higher knowing that main energy sources are not renewable, so the development of technologies for using renewable sources at commercial level is needed. In this scenario, Brazil has a relatively comfortable position among other countries, because its large experience regarding conversion of biomass into energy. Additionally, several many researchs and projects concerning the use of biomass as an energy source are currently taking place in Brazil, as showed by Lora & Andrade (2009).

Coal is by far away the most abundant fuel in nature. Proven reserves at the end of 2005 amounted to around 909 billion tonnes, equivalent to 164 years at current production rates, IEA (2006). Coal will be a dominant energy source for many decades to come, because there is no ready substitute for this fuel, in the quantities required, at this time and for the foreseeable future, Tillman (2000). Dispite of that, coal is considered a non-environmental friendly fuel, because its expressive level of pollutants emission.

On the other hand, biomass is the third largest primary energy resource in the world, after coal and oil, and is one of the major sources of energy in developing countries, where it provides 35% of all the energy requirements, Werther et al. (2000).

The environmental image of coal can be enhanced by co-firing or co-combustion, that is the possibility of using two or more types of fuels combined in the combustion process, with biomass, since biomass combustion has the potential to be CO_2 neutral (during the growth period, plants removes CO_2 from atmosphere and released it again in the combustion). Biomass fuels such as wood wastes, short-rotation woody and herbaceous crops, agricultural wastes and many other materials are the most suitable for co-firing with coal. Typically, these fuels are modest in heat content, ranging from 16-21 MJ/kg, and low in sulfur. Wood materials tend to be low in nitrogen and ash content while the agricultural materials can have high nitrogen and ash contents. All of these fuels are highly volatile with volatile/fixed carbon ratios in the order 3.5-5, and can be co-fired at 10 to 25% in mass basis (or 4 to 10% in heat-input basis) without seriously impacting the heat release characteristics of most boilers, Tillman (2000).

Some advantages regarding co-firing coal and biomass are:

- Job creation in biomass logistics, enhancing local economy.

- Reduction in airborne emissions (including NO_x and SO_2).
- Possibility to diversify fuel sources.
- Meets most renewable portfolio standards.
- Can be considered green power.
- Increase in the externalities associated with green energy generation.

Some disadvantages are:

- Deficiencies in facilities for storing, feeding and pulverizing the fuel.
- Adverse fireside impacts on flame stability.
- Some biomass tends to increase ash fouling, slagging and corrosion.
- High biomass costs in many cases.
- Increase in the emission of chlorine and potassium compounds.
- Potential problems with selective catalytic reduction technology.

Dispite of that, it is clear that all advances in combustion technology will only be adopted when they reduce cost and can be implemented with acceptable technical risk. This way, the choice of fuel and generating technology for new power plants is influenced by an increasingly complex combination of interrelated factors, identified by Sondreal et al. (2001):

- Current and future governmental polices on restructuring and deregulation of utilities, and environmental regulations that in the future could include taxes on carbon emissions.
- Macroscopic factors such as proximity to load centers, electrical transmission lines, plant capital investment, delivered fuel cost, and fuel price stability.
- The state of development of new generating and environmental control technologies and the associated benefits and risks involved in their deployment, which are strongly related to fuel properties.

This paper presents a a review on the use of biomass in co-firing worldwide, discussing the benefits and issues reported on using this kind of technology. Important data on the brazilian energy matrix are presented and analysed, with special attention to brazilian coal. Also is made an attempt to identify the most suitable types of biomass for co-firing with coal in Brazil. Finally, are showed some potential issues reported in literature that must be faced for conducting a co-firing project.

2. CO-FIRING WORLDWIDE

First researchs regarding co-firing coal/biomass have been reported in the last few years, suggesting that co-firing is a new research theme. With driving forces such as the Kyoto protocol, that imposes environment regulations for lowering pollutant emissions in a foreseeable future, co-firing is becoming an atractive technology for thermoelectric generation companies worldwide, as shown in Wieck-Hansen et al. (2000) and Gold & Tillman (1996).

Hughes & Tillman (1998) listed 15 co-firing tests in full-size utility coal-fired boilers in USA between 1987 and 1996, where biomass such as sander dust, forest debris, waste wood and switchgrass were used. They also listed 19 additional studies that had been conducted between 1985 and 1996, including laboratory combustion tests, cold-flow biofuel performance testes, fuel characterizations, processing characterizations, resource characterizations, and co-firing case study conceptual engineering evaluations and cost estimates.

Jenkins et al. (1999) investigated the potential for using leached rice straw through co-firing in three existing biomass power plants: a stoker-fired traveling grate (which uses forest-derived wood as fuel), a circulating fluidized bed (urban wood and agricultural wood, shells and pits), and a suspension fired unit (rice hulls). In each case, the straw was blended in a percentage between 20 to 25% of total heating value. No adverse effects due to slagging or fouling were observed, and no bed agglomeration occurred in the circulized fluidized bed. NO_x emissions did not increased in the suspension unit, but increased for the grate and the fluidized units due to the higher nitrogen content of the straw, and required increased ammonia injection for control. The specific deposition rate on deposit probes decreased. Silica and chlorine concentrations increased and alkali and sulfur concentrations decreased in the deposits. The major difficulty concerned with the suspension fired unit was related with grinding the rice straw to an acceptable particle size and feeding the boiler through equipment designed for hulls.

Gold & Tillman (1996) conducted a research co-firing wood with coal in a pulverized coal power plant. They say that the boiler thermal efficiency decreases from 89.2% to 88.0%

comparing the case where only coal is used and the case where wood share of 15% (heat basis) was co-fired with coal. A decrease of 19.1% in SO_2, 10.0% in NO_x and 24.6% in HCl emissions was also found. They concluded that co-firing at 10-15% heat input has a minimal impact upon boiler efficiency and flame temperature and, consequently, does not require a change in unit operation.

Wieck-Hansen et al. (2000) made a research in an existing 150 MW_e pulverized coal-fired power station, that was modified for co-firing coal and straw (triticale and miscantus), where 4 of the 12 burners were converted to combi-burners. They said that co-combustion has increased the need for sootblowing compared to normal operation and there had been some slagging especially at 20% straw share (heat input basis). The unburned carbon in the bottom ash was higher performing co-combustion (up to 20%) than firing coal alone, as a result of insufficient residence times for some of the straw particles, but this does not affect the boiler efficiency significantly. By co-firing 10% straw in heat basis the corrosion rate of superheaters and reheaters was at the same level as normally seen by combustion of coal alone (2 mm/100,000 h), but for a 20% straw share the corrosion rate increased by a factor of 2-3 at moderate temperature, achieving the upper limit for low-corrosive coals. The authors concluded: “The results do not show any considerable corrosion risks by introduction of co-combustion of 10% straw at plants with high steam temperatures – up to 580^{o}C”.

To obtain an overview of the many deposit probe samples collected, Andersen et al. (2000) developed a procedure for visual analyses in a 150 MW_e pulverized coal boiler modified for co-firing coal and wheat straw, in which the physical appearance of the deposits were evaluated and divided into five classes with increasing amount and tenacity. Based upon the visual analyses of the upstream deposits, it was found that the deposit amount and tenacity increased with increased exposure time, increased straw share, increased flue gas temperature and increased load during experiments with higher ash amount coal (south american), but were alike the pure coal ash deposits for lower ash amount coal (north american).

Boylan et al. (2000) conducted a research to evaluate the feasibility, costs and benefits of co-milling and direct injection co-firing of switchgrass with coal as a potential renewable energy source. The study consisted of four phases, which look at farm production issues, pilot co-milling, pilot combustion tests and full-scale demonstration. Reduction up to ~55% in the NO_x emission in a pilot scale facility burning coal with switchgrass was obtained.

Battista Jr. et al. (2000) performed full-scale tests co-firing sawdust with coal, ranging from 0% to almost 7% biomass share in heat basis, and finded a maximum decrease lower than 1% in boiler efficiency. SO_2 emissions decreased proportional to the co-firing percentage on a heat input basis, so reaching 7%. NO_x emissions decreased dramatically when co-firing sawdust, according to the authors, because “biomass floods the combustion region with volatiles, creating more substantial fuel staging at the base of the flame”.

An overview of the combustion of agricultural residues was presented by Werther et al. (2000). The objective was to give more information related to the effect of physical and chemical properties of the residues on their processing as well as the combustion and emission characteristics, through the discussion of: densification of agricultural residues, the effect of the high volatile contents in agricultural residues on the combustion process, problems related to the low melting point of the ashes of some agricultural residues, the emission characteristics of agricultural residues, design considerations for mono-combustion systems for agricultural residues, and the co-combustion of agricultural residues with coal (in this last topic, are presented useful information about modification requirements in furnaces; combustion and emission characteristics; fouling, corrosion and slagging behaviour; and experience from large-scale plants). They concluded that the combustion and emission characteristics are not negatively affected during co-firing, but a possible negative impact of co-firing is the expected increase in fouling and corrosion due to the presence of compounds with low melting point in the ash.

In a review of advances in combustion technology and biomass co-firing, Sondreal et al. (2001) reports that the Energy and Environmental Research Center (EERC), from University of North Dakota, recently completed some co-firing tests on a rice straw lignin, that is the waste residue from a experimental process to produce ethanol called Arkenol. The tests were performed in both a bench-scale facility and a pilot-scale pf-fired combustor, on blends of 5% and 10% dried lignin with a subbituminous coal. The lignin was received as a paste containing 79% moisture, and then it was air-dried to 19% moisture and pulverized in a hammer mill to a size circa 60% minus 200 mesh. The combustion gave excellent carbon burnout and easily maintained the desired furnace exit gas temperature. However, the very high sodium content of the lignin resulted in rapid deposit growth for both 5% and 10% lignin blends, forming much larger deposits than for firing coal alone.

3. COAL IN BRAZIL

Internal energy offer in Brazil in 2007 reached 238.8 million tonnes of oil equivalent (toe). Biomass responds for 66,475,000 toe, consolidated as the second main energy source, while coal responds for 14,356,000 toe, being the fifth main energy source, accoding to MME (2008).

Electric energy matrix in Brazil in 2009 reached 111,665 MW, with biomass responding for 5,094 MW, being the fourth main source, and coal for 1,455 MW, being the seventh main source, according to ANEEL (2009). Biomass fuels used are sugarcane bagasse, biogas, charcoal, rice hulls, black liquor and wood residues, and almost all electric energy production from this fuels is for self consumption.

Figure 1 shows a comparison between the brazilian internal energy offer by source in 2007, according to MME (2008), and the brazilian electric energy matrix by source in 2009, according to ANEEL (2009).

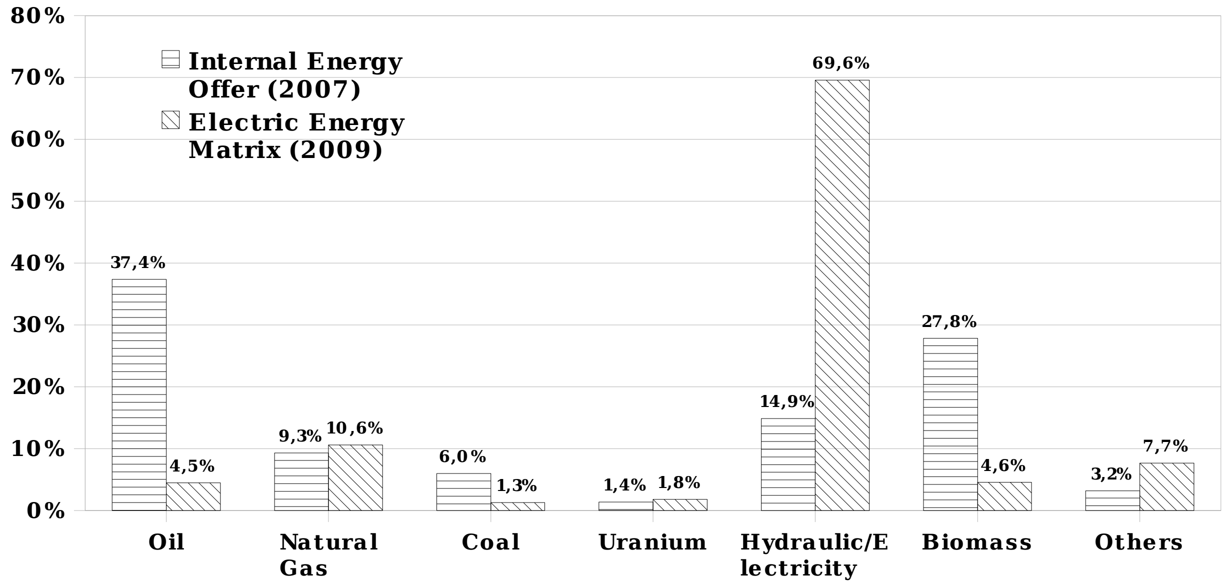

Figure 1: Brazilian comparison between internal energy offer in 2007 and the electric energy matrix in 2009, from MME (2008) and ANEEL (2009).

Brazilian coal is characterized as having low heating value and high ash and sulfur contents, varying its composition according to the site. Brazilian coal reserves are estimated in 32.3 billion tonnes, MME (2008), and 99.98% of it is located in the south region states of Rio Grande do Sul (89.25%), Santa Catarina (10.41%) and Paraná (0.32%). The state of São Paulo has the remaining 0.02%.

Coal is mainly used for power generation in Brazil. In 2007, an amount of 5,153,000 tonnes of coal were used for electric generation in Brazil, and coal power plants were responsible for 1.7% of the total amount of electric energy produced, MME (2008). It is estimated that the reserves can cover the demand for over 200 years. An average annual increase for coal demand of 1.7% is expected from 2004 to 2030 in Brazil, IEA (2006).

Table 1 shows all brazilian coal power plants in operation, under construction and granted, in the year of 2009, with data taken from ANEEL (2009).

Table 1: Brazilian coal power plants situation in 2009, ANEEL (2009).

Name	Power [MW]	Owner	City/State
Running units			
Charqueadas	72	Tractebel Energia	Charqueadas/RS
Figueira	20	Copel Geração	Figueira/PR
Jorge Lacerda A	232	Tractebel Energia	Capivari de Baixo/SC
Jorge Lacerda B	262	Tractebel Energia	Capivari de Baixo/SC
Jorge Lacerda C	363	Tractebel Energia	Capivari de Baixo/SC
Presidente Médici A/B	446	CGTEE	Candiota/RS
São Jerônimo	20	CGTEE	São Jerônimo/RS
Alunorte	40.1	Alumina do Norte do Brasil	Barcarena/PA
Total	**1,455.1**		
Under construction			
Alumar	75.2	Consórcio Alumar	São Luís/MA
MPX	700	MPX Energia	Caucaia/CE
Presidente Médici C	350	CGTEE	Candiota/RS
Total	**1,125.2**		
Granted units			
Barcarena	600.1	Vale	Barcarena/PA
Concórdia	5	Sadia	Concórdia/SC
Jacuí	350.2	Tractebel Energia	Charqueadas/RS
Meio do Mundo	153	DSL	Santana/AP
Porto do Itaqui	360.1	UTE Porto do Itaqui	São Luís/MA
Seival	542	UT Seival	Candiota/RS
Sepetiba	1,377	Itaguaí Energia	Itaguaí/RJ
Sul Catarinense	440.3	UT Sul Catarinense	Treviso/SC
Total	**3,827.7**		

4. AGRICULTURAL RESIDUES PRODUCTION IN BRAZIL

Brazilian largest annual crops that results in considerable amount of organic residues are soy, corn, rice, manioc, wheat, cotton, beans and sugarcane. Table 2 lists brazilian data from these crops production, acreage and yield concerning the year of 2005, MAPA (2005).

Table 3 lists residues data from crops listed in table 2. The residues yield considered was the lower values from range reported by Nogueira & Lora (2002). It is difficult to determine reasonably values for this parameter because residues are not collected in the harvesting period. This way, the purpose using the lower values was to do a conservative analysis. Nevertheless, by using this values the total amount of each residue calculated is quite different from that reported by Lora & Andrade (2009). The heating value was obtained from Cuiping et al. (2004), Pattiya et al (2006) and Woodgas (1998). Dispite the qualitative tendency of this table, can be observed that Brazil has a huge energy potential from agricultural residues. For comparing purposes, taking the listed total energy potential of 3,707,554,000,000 MJ and considering an average lower heating value for brazilian coal of 18.8 MJ/kg, the total energy potential of these residues listed in table 3 are equivalent to 197,210,301,000 kg of coal, which is 38.3 times the amount of coal used for electric generation in Brazil in 2007, according to MME (2008).

Table 2: Data regarding major Brazilian crops in 2005, MAPA (2005).

Crop	Production [ton]	Acreage [ha]	Yield [ton/ha]
Soy	51,182,000	22,949,000	2.23
Corn	35,134,000	11,559,000	3.04
Rice	13,192,000	3,916,000	3.37
Manioc	27,636,000	1,944,000	14.22
Wheat	4,659,000	2,361,000	1.97
Cotton	3,666,000	1,258,000	2.91
Bean	3,021,000	3,748,000	0.81
Sugarcane	455,272,000	6,172,000	73.76
Total	**593,762,000**	**53,907,000**	**--**

Table 3: Energy potential from major Brazilian agricultural residues in 2005.

Residue	Acreage [ha]	Yield [ton/ha][(1)]	Production [ton]	HV [MJ/kg]	Energy potential [PJ]
Soy straw	22,949,000	3.0	68,847,000	16.96[(2)]	1,167.65
Corn stalk	11,559,000	5.0	57,795,000	16.64[(2)]	961.71
Rice straw	3,916,000	4.0	15,664,000	14.66[(2)]	229.63
Manioc stalk	1,944,000	6.0	11,664,000	17.58[(3)]	205.05
Wheat straw	2,361,000	4.5	10,624,500	16.56[(2)]	175.94
Cotton stalk	1,258,000	7.0	8,806,000	17.91[(2)]	157.72
Bean stalk	3,748,000	1.0	3,748,000	16.31[(2)]	61.13
Sugarcane bagasse	6,172,000	7.0	43,204,000	17.33[(4)]	748.73
Total	**53,907,000**	**--**	**220,352,500**	**--**	**3,707.55**

(1): Nogueira & Lora (2002).
(2): Cuiping et al. (2004).
(3): Pattiya et al (2006).
(4): Woodgas (1998).

Considering an average heating value of 16 MJ/kg for agricultural residues, recovering 0,27% or 595,000 tonnes of the total residue production listed in table 3 would be enough for co-firing biomass in a 10% heat basis with coal in all brazilian coal power plants over one year.

Dispite this huge potential, major agricultural residues producing regions in Brazil are away from coal sites, so any project for new co-firing power plants must include an economic study verifying its viability (residues costs for collecting, transportation and handling). For regions away from coal sites but with huge agricultural residues production the solution, obviously, can be the development of biomass burning dedicated power plants. But unfortunately in this case the major problem to be dealt is the seasonality of crops.

5. COAL AND BIOMASS CHARACTERIZATION

Table 4 shows the proximate and ultimate analysis of one brazilian coal and the agricultural residues listed in table 3, for comparing purpouses. Data was taken from Crnkovic et al. (2004), Cuiping et al. (2004), Pattiya et al (2006) and Woodgas (1998). The coal listed is a typical one from the city of Criciúma, in Santa Catarina state, and is called CE 4500 (the number 4500 is related to the expected heating value of the coal, that is 4,500 cal/g).

Table 4: Proximate and ultimate analysis of some materials.

Material	HV [MJ/kg]	Proximate analysis [%]				Ultimate analysis [%]				
		Mois.	Ash	Vol.	FC	N	C	S	H	O
Coal (CE 4500)[(1)]	18.83	0.81	44.50	19.25	35.44	0.90	50.59	5.14	3.52	7.93
Soy straw[(2)]	16.96	9.34	6.08	68.95	15.62	0.95	43.16	0.20	6.90	44.76
Corn stalk[(2)]	16.64	9.31	13.12	62.74	14.83	0.99	42.69	0.21	6.16	42.69
Rice straw[(2)]	14.66	8.11	15.25	61.10	15.54	0.69	38.52	0.29	6.13	39.28
Manioc stalk[(3)]	17.58	15.54	6.01	79.90	14.09	0.67	51.12	0.10	6.87	41.34
Wheat straw[(2)]	16.56	8.63	12.45	63.96	14.96	0.58	42.11	0.32	6.53	40.51
Cotton stalk[(2)]	17.91	7.66	6.41	67.36	18.57	1.09	46.10	0.26	6.85	43.35
Bean stalk[(2)]	16.31	7.62	5.03	68.44	18.90	0.97	42.16	0.24	6.13	45.28
Sugarcane bagasse[(4)]	17.33	--	11.27	73.78	14.95	0.38	44.80	0.01	5.35	39.55

[(1)]: Crnkovic et al. (2004).
[(2)]: Cuiping et al. (2004).
[(3)]: Pattiya et al (2006).
[(4)]: Woodgas (1998).

From data in table 4 can be easily identified that biomass has at least 3.5 times the amount of volatiles present in coal. This is particularly important because it is believed that this is responsible for dramatically decreasing NO_x emissions when co-firing coal with biomass, according to Battista Jr. et al. (2000). Through co-firing, it is also possible a reduction in emission of sulfur compounds, since the amount of sulfur in biomass is expressively lower than coal.

Ash content of biomass listed in table 4 are in the range of 6-15%. When co-firing these biomass with a low ash content coal, like anthracite, some troubles may take place. In brazilian case, however, biomass presents a very low ash content compared with coal, so the behaviour is inverse, and is expected that co-firing will reduce the ash issues experienced in combustion.

6. CO-FIRING CHALLENGES

According to Sondreal et al. (2001), co-firing provides a more practical and cost-effective means of utilizing biomass by taking advantage of the relatively high efficiency of large utility boilers without incurring a large capital investment. Nevertheless, co-firing different types of biomass containing a variety of mineral constituents not found in coal along with a diversity of coal types creates unique combustion problems that must be identified and corrected to avoid discrediting biomass co-firing as a practical utility option.

Chemical composition of agricultural residues are directly linked with the soil, the fertilizer composition/amount used, and the weather conditions. Since sources of this fuel are heterogeneous, so do their chemical composition. This can result in technical problems concerning chemical products formed in combustion.

Biomass usually have more chlorine content than coal, and this result in more emission of chlorine compounds, that may become an environmental problem. But from the corrosion point of view, it is better to form HCl than KCl, because first one is carried out in flue gas and the last one can result in deposition and corrosion problem.

Crop farms located near oceans produce residues with a high chlorine content, specially if a dry summer takes place, that also increases the potassium content. This happens because rain can wash out potassium and chlorine, as stated by Wieck-Hansen et al. (2000). These authors say that “the differences in the straw composition are interesting in relation to corrosion, slagging and fouling, and the impact on fly ash. The variation in straw ash composition also depends on the field where it is grown, this means that a lot of analyses are required to get an exact description of the fuel burned”.

Another problem regarding biomass is that there is a maximum moisture limit which must not be exceeded. “High moisture content can lead to poor ignition, reduce the combustion temperature, which in turn hinders the combustion of the reaction products and consequently affects the quality of combustion”, Werther et al. (2000). High moisture levels requires large amounts of energy for drying the fuel before grinding. This way, biomass transportation and specially storage becomes important parameters, since organic compounds are hygroscopic.

Also, an important limit is the fraction of biomass that can be fed through pulverizers in a pulverized coal-fired plant, which is less than 4% by mass, or about 2% by heat input for a plant using bituminous coal. Higher percentages of co-firing require a separate feed system for feeding biomass directly into the boiler through separate injection ports, according to Sondreal et al. (2001).

As said before, in the brazilian case the ash content of biomass is benefical since brazilian coal has a higher amount of ash compared to biomass. But as stated by Werther et al. (2000): “A peculiar ash problem, which is normally experienced during the combustion of some agricultural residues, is the low melting properties of the ash. This is due to the presence of very high contents of potassium oxide (K_2O) in some residues. The problems attributed to low melting temperatures of the ashes from these residues are bed agglomeration in fluidized bed as well as fouling, scaling and corrosion of the heat transfer surfaces”.

Agricultural residues present high content of volatile matter. This means that they are easier to ignite and to burn, but the combustion is fast and difficult to control. The high volatile matter content of the biomass burns off quickly in a boiler, and the time required for complete combustion is short compared to that for a coal particle of similar size. For biomass dedicated power plants, the consequence is cited by Werther et al. (2000): “The implication of this is that the design and operation principles normally adopted for coal combustion systems may not be applied for the combustion of agricultural residues”. However, for co-firing, the high content of coal and the high volatile content of biomass can compensate each other and provide a better combustion process than for individual fuels.

Agricultural residues have very low bulk densities when compared to coal. This results in high costs for transportation, and also complicates the processing, storage and firing. The solution for this is the densification of biomass through baling, briquetting or pelleting, however, the basic problem is its cost, that may become the use of biomass not economically feasible. Additionaly, it is difficult to process and reach an ideal size for biomass particles aiming co-firing. The consequence of co-firing larger biomass particle sizes than ideal with coal, as studied by Lu et al. (2008), is that this led to a slight delay in the ignition of the fuel. Kostamo (2000) reports feeding issues using coal mills for simultaneous milling of coal and sawdust, and said: “the co-firing tests were successful in many ways, but the behaviour of the coal mills caused some problems, and therefore the simultaneous feed might not be the solution in a long-term use”. Also, Sondreal et al. (2001) say that “guidelines for complete combustion derived from laboratory combustion studies indicate that biomass char burnout may become a problem for top sizes greater than 3 mm and fuel moisture contents exceeding 40%”.

Concerning the construction sector, a recent study on the properties of concrete containing wood-coal fly ash reported no significant detrimental effects on strength, workability, permeability, or setting time due to the presence of the wood ash, according to Sondreal et al. (2001).

Dispite all benefits by using biomass in co-firing, the major barrier for its use is economic, as said by Hughes (2000): “The most critical terms in the cost of a cofiring operation are the fuel cost and the capital cost of the modifications to the power plant to enable biomass fuel to be cofired with the coal”.

7. CONCLUSIONS AND DISCUSSION

This work presented co-firing biomass with coal as a promising alternative for clean electric generation in Brazil. A review was made on the use of biomass in co-firing worldwide, discussing its benefits and issues reported. An attempt to identify the most suitable types of biomass for co-firing with coal in Brazil was also done. It was showed that the yearly brazilian agricultural residues production is huge, and the recovery of a little fraction of it is enough for co-firing purposes.

Generally, combustion and emission characteristics are not negatively affected during co-firing, but a possible negative impact of co-firing is the expected increase in fouling and corrosion due to the presence of compounds with low melting point in the ash. So special attention must be given to which kind of biomass will be used in co-firing.

Literature reports issues concerning feeding systems, and it is suggested that the fraction limit of biomass that can be fed through coal pulverizers is about 2 % in a heat input basis. For higher percentages of co-firing, a separate feed system for biomass is required.

Dispite many literatures have reported experimental studies in the last years, first modelling approaches using CFD are currently being carried out. Nevertheless, co-firing is currently at its infancy, and the major challenge is the development of technologies that are suitable for its peculiarities.

Unfortunately, there is not yet a notice of co-firing units operating in Brazil, but the Jorge Lacerda Thermoelectric Complex, a coal power plant complex located in Capivari de Baixo, Santa Catarina state, is currently developing a research for co-firing coal with rice straw in a 50 MW power plant. The unit, originally coal-fired, will be modified for burning up to 30% share of biomass in heat basis. An economic study was already made verifying the viability of the project, since the complex is located in a region with many rice farms. It is expected the development of a computational fluid dynamics (CFD) model of the co-firing combustion process, that will be validated with some *in loco* experimental measurements.

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9. REFERENCES

Andersen, K. H.; Frandsen, F. J.; Hansen, P. F. B.; Wieck-Hansen, K.; Rasmussen, I.; Overgaard, P.; Dam-Johansen, K. *Deposit Formation in a 150 MWe Utility PF-Boiler during Co-combustion of Coal and Straw*. **Energy and Fuels**, v.14, p.765-780, 2000.

ANEEL - Agência Nacional de Energia Elétrica, 2009. **Banco de Informações de Geração** . Available at: <http://www.aneel.gov.br/area.cfm?idArea=15&idPerfil=2>. Date of access: March 15, 2009.

Battista Jr., J. J.; Hughes, E. E.; Tillman, D. A. *Biomass Cofiring at Seward Station*. **Biomass and Bioenergy**, v.19, p.419-427, 2000.

Boylan, D.; Bush, V.; Bransby, D. I. *Switchgrass Cofiring: Pilot Scale and Field Evaluation*. **Biomass and Bioenergy**, v.19, p.411-417, 2000.

Crnkovic, P. M.; Polito, W. L.; Filho, C. G. S.; Milioli, F. E.; Pagliuso, J. D. *O Efeito da Granulometria na Decrepitação durante a Decomposição Térmica de Calcários e Carvão* . **Química Nova**, v.27, p.58-61, 2004.

Cuiping, L.; Chuangzhi, W.; Yanyongjie; Haitao, H. *Chemical Elemental Characteristics of Biomass Fuels in China*. **Biomass and Bioenergy**, v.27, p.119-130, 2004.

Gold, B. A.; Tillman, D. A. *Wood Cofiring Evaluation at TVA Power Plants*. **Biomass and Bioenergy**, v.10, p.71-78, 1996.

Hughes, E. *Biomass Cofiring: Economics, Policy and Opportunities*. **Biomass and Bioenergy**, v.19, p.457-465, 2000.

Hughes, E. E.; Tillman, D. A. *Biomass Cofiring: Status and Prospects 1996*. **Fuel Processing Technology**, v.54, p.127-142, 1998.

IEA - International Energy Agency, 2006. **World Energy Outlook 2006**. Available at: <http://www.iea.org/>. Date of access: March 15, 2009.

Jenkins, B. M.; Williams, R. B.; Bakker, R. R.; Blunk, S.; Yomogida, D. E.; Carlson, W.; Duffy, J.; Bates, R.; Stucki, K.; Tiangco, V. *Combustion of Leached Rice Straw for Power Generation*. **Proceedings of the Fourth Biomass Conference of the Americas**, p.1357-1363, 1999.

Kostamo, J. A., 2000. **Co-firing of Sawdust in a Coal Fired utility Boiler**. Available at: <http://www.journal.ifrf.net/published-articles.html>. Date of access: April 27, 2009.

Lora, E. S.; Andrade, R. V. *Biomass as Energy Source in Brazil*. **Renewable & Sustainable Energy Reviews**, v.13, p.777-788, 2009.

Lu, G.; Yan, Y.; Cornwell, S.; Whitehouse, M.; Riley, G. *Impact of Co-firing Coal and Biomass on Flame Characteristics and Stability*. **Fuel**, v.87, p.1133-1140, 2008.

MAPA - Ministério da Agricultura, Pecuária e Abastecimento, 2005. **Agricultura Brasileira em Números - Anuário 2005**. Available at: <http://www.agricultura.gov.br>. Date of access: February 23, 2009.

MME - Ministério de Minas e Energia, 2008. **Balanço Energético Nacional - Ano Base 2007**. Available at: <http://www.mme.gov.br>. Date of access: March 12, 2009.

Nogueira, L. A. H.; Lora, E. E. S., 2002. **Wood Energy: Principles and Applications**. Available at: <http://www.nest.unifei.edu.br/english/pags/downloads/downloads_en.html>. Date of access: March 23, 2009.

Pattiya, A.; Titiloye, J. O.; Bridgwater, A. V., 2006. **Fast Pyrolysis of Agricultural Residues from Cassava Plantation for Bio-Oil Production**. Available at: <http://www.energy-based.nrct.go.th/Article/Ts-3%20fast%20pyrolysis%20of%20agricultural%20residues%20from%20cassava%20plantation%20for%20bio-oil%20production.pdf>. Date of access: April 06, 2009.

Sondreal, E. A.; Benson, S. A.; Hurley, J. P; Mann, M. D.; Pavlish, J. H.; Swanson, M. L; Weber, G. F.; Zygarlicke, C. J. *Review of Advances in Combustion Technology and Biomass Cofiring*. **Fuel Processing Technology**, v.71, p.7-38, 2001.

Tillman, D. A. *Cofiring benefits for coal and biomass*. **Biomass and Bioenergy**, v.19, p.363-364, 2000.

Werther, J.; Saenger, M.; Hartge, E.-U.; Ogada, T.; Siagi, Z. *Combustion of Agricultural Residues*. **Progress in Energy and Combustion Science**, v.26, p.1-27, 2000.

Wieck-Hansen, K.; Overgaard, P.; Larsen, O. H. *Cofiring Coal and Straw in a 150 MWe Power Boiler Experiences*. **Biomass and Bioenergy**, v.19, p.395-409, 2000.

Woodgas, 1998. **Proximate and Ultimate Analyses**. Available at: <http://www.woodgas.com/proximat.htm>. Date of access: April 06, 2009.