ASSESSMENT OF THE MOST ADEQUATE PRE-TREATMENTS AND WOODY BIOMASS SOURCES INTENDED FOR DIRECT CO-FIRING IN THE U.S.

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There is increasing interest in replacing coal with woody biomass in co-firing plants for electrical power. A variety of pre-treatments can be used to make biomass more suitable for co-firing. This research presents a model that evaluates the delivered costs of various pre-treated biomass sources, electricity production costs, and constraints, and calculates a least cost mix. Results of the scenario presented indicate that wood chips are the most economical co-firing option for delivering biomass to direct-fired boilers. Apart from potential feeding and processing issues, the wood-chips options of forest residues present the lowest cost of electricity production for small-scale co-firing applications. From the options that will ensure minimum processing issues in the co-firing cycle, wood pellets from southern yellow pine represent the most economical choice. Based on coal displacement from the facility, torrefied wood pellets from southern yellow pine is a preferred option as compared to other choices evaluated. An alternative to torrefied wood pellets from southern yellow pine is dark torrefied *Eucalyptus benthamii*, providing similar electricity production costs while reducing coal utilization.

Keywords: *Direct Co-firing; Eucalyptus; Southern pine; Forest residues; Economic assessment; Wood pellets; Torrefied wood pellets*

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INTRODUCTION

Domestic and international concerns over carbon emissions have increased the interest and potential utilization of biomass for power generation (Evans and Perschel 2009; Kim *et al.* 2009). In the United States, 30 states currently have renewable portfolio standards (RPS) for electrical power generation, requiring utilities to generate a portion of their electricity from renewable sources (wind, solar, biomass, hydroelectric, thermal, *etc.*)

The costs of producing liquid and gaseous biofuels from cellulosic biomass are currently not competitive with fossil fuel sources. The conversion of biomass to biofuel technology is still largely under development (Worldwatch Institute 2007). Unlike liquid and gaseous biofuels, solid biofuels require fewer technological resources.

Pre-treatments for solid bioenergy vary from very simple, direct size-reduction of the biomass (*i.e.* chipping and grinding), to the increase in density through an extrusion processes (pelletization and briquetting), and the more advanced pyrolysis of biomass (torrefaction). Pre-treatments for solid bioenergy can open its utilization for several industries by drastically improving handling and transportation characteristics of the biomass.

In the area of power generation, three types of pre-treatments currently represent the most relevant options: chipping, pelletization, and torrefaction. Chipping of wood biomass is a common practice and can be done in the forest when the timber is harvested and then transported directly to power plants. Pelletization of woody biomass is a proven technology with expanding markets in Europe. Torrefaction is still in the early stages of development and holds the promise of delivering a product with a high energy density and ease of handling. In addition, a combination of pre-treatments such as torrefaction and pelletization holds the potential of improved energy density and handling advantages versus typical woody biomass (Bergman 2005).

For existing coal fired electrical power plants, an attractive alternative to using straight biomass as a fuel substitute is using some combination of biomass and coal to reduce carbon emissions. It can be argued that some configuration of biomass, pre-treatments, feeding systems, boilers, and turbines may actually provide an adequate substitution of coal, producing considerable reductions in carbon emissions.

In order to identify the best coal/biomass fuel mix for coal-fired power plants, different types of biomass must be evaluated in terms of technical and economic aspects, considering variables such as heating value, energy density, bulk density, delivered price of the biofuel (including production costs, transportation, further processing at the power plant), and other factors. Adding to the complexity of the problem, the energy production efficiency of traditional coal fired electrical generation facilities is influenced by the percentage of coal substituted and the biomass used, since various biomass and pre-treatments differ in moisture content, ash content, and heating value.

The objective of this project was to identify and assess different pre-treatments and woody biomass sources that are deemed suitable for co-firing in existing power plants in the U.S. This will determine the capacity by which power production costs and coal utilization would be reduced, through the evaluation of different variables, such as the delivered cost of biofuel, transportation, further processing required prior to combustion, and inherent characteristics of the delivered biofuel.

METHODS

In order to assess woody biomass types and the various pre-treatments for suitability for use in conjunction with coal for co-firing electrical power plants, a comprehensive framework is illustrated in Fig. 1.

Coal

Coal is a fossil fuel, composed mainly of carbon, hydrogen, and oxygen, formed from vegetation that has been consolidated between rock strata and altered by the combined effects of pressure and heat over millions of years (World Coal Institute 2009). Medium bituminous coal (typically utilized in power plants) contains an average of 32.247 MJ/Kg (13,840 Btu/lb., Engineering ToolBox 2010), with an average price of $159.2/ton (U.S. Energy Information Administration, EIA 2012).

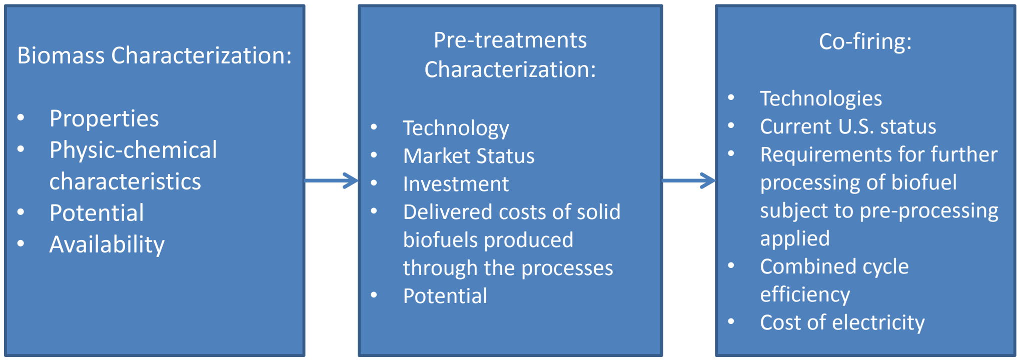

Fig. 1. Methodology for assessing biomass and pre-treatments options for co-firing in U.S. power plants

Over the next 20 years, there is expected to be a 53% increase in coal demand for electrical generation. Currently, coal generates approximately 45% of the electricity in the U.S., being the most important fuel source for electricity generation (Gruenspecht 2012; Quarterly Coal Report 2012). With the current projected demand, there are 118 years left before known U.S. coal reserves are depleted (World Coal Institute 2009).

Types of Biomass Selected for Analysis

Four species of woody biomass were selected for this study based on current and potential availability and are described below:

Southern yellow pine

Southern yellow pine comprises several pine species allocated in the southern U.S., from New Jersey to Texas (USDA-FS 2000). It is estimated that over 63 million acres of pines are planted every year (Cassidy and Zophy 2004), with average yields of 6.48 green tons per acre per year (McClure 2006). The recent decline in pulp, paper, and wood products manufacturing has produced a large surplus of planted southern pines, with many biomass facilities acquiring these available resources for solid fuels production (Carolina Pacific LLC 2009; Conrad *et al.* 2011; Green Circle Bio Energy Inc. 2011). Due to its availability, well-understood supply chain logistics, and current utilization in the bioenergy industry, southern yellow pine presents favorable characteristics that make its evaluation in co-firing economically viable (Southern Pine Council 2011).

Natural hardwood biomass

Hardwood chips from natural forests represent another important available source of biomass for bioenergy production. Historically, hardwood chips have been sold to pulp mills as well as to manufacturers of secondary wood industry products such as oriented strand board (OSB); however, the hardwood chip market demand has decreased during the last ten years, as fewer pulp mills remain in operation (Nicholls *et al.* 2009). This situation has left an increased availability of hardwood chips, which can be utilized for energy production, mostly through direct firing. In the U.S., facilities have realized the potential of its hardwood biomass utilization from natural stands for co-generation of electricity (Wiltsee 2000).

Forest biomass waste (softwood residues, and pocosin biomass)

Mixed sources of forest biomass, such as forest thinnings and harvest residues, have been utilized for bioenergy production in the U.S., especially in the manufacturing of solid sources such as pellets and briquettes (Marinescu and Bush 2009). The main reason for considering forest residues for bioenergy is its availability at a relatively low cost. The U.S. Department of Agriculture indicates that most regions and counties in the Eastern and Southeast U.S. have more than 25 thousand dry tons/year of forest residues available (Milbrandt 2005). In the Southern United States, such as Virginia and North Carolina, there is an increasing availability of Pocosin biomass, defined as all biomass unsuitable for high-value wood products, extracted from conventional forest harvest areas with fire-adapted evergreen shrubs and trees such as Swamp Bay and Pond Pine (denominated Pocosins) (Carter 2010).

These forest harvest residues have the potential for providing and expanding biomass availability for bioenergy production in the U.S. (Perlack *et al.* 2005). Large amounts of these forest materials have been identified by the Forest Service as needing to be removed to improve forest health and reduce fire hazards (USDA-FS 2003; Miles 2004). This removal requires that the residue be utilized or disposed of, thus having the bioenergy industry as a key element for its utilization can be economically viable.

Eucalyptus

Eucalyptus plantations can be found in some southern U.S. states including South Carolina, Florida, Georgia, Alabama, Texas, Mississippi, and Louisiana. A large number of trials and pilot plantations have been installed to evaluate characteristics such as freeze tolerance, rotation length, wood properties, and disease resistance, amongst others (Wright 2010; Gonzalez *et al.* 2011a, 2011b; Pirraglia *et al.* 2012d). *Eucalyptus* has attracted recent interest for bioenergy (Gilbert 2007), although it is rarely mentioned in current literature as a potential biomass feedstock. With continuous advances in hardwood silviculture, genetics, and species varieties, a strong case for reconsidering alternative hardwood plantations for bioenergy in the U.S. is currently being evaluated for pellet production. These eucalypt wood pellets have the possibility of generating electricity through co-firing with coal or gasification, offering alternatives that make bioenergy production economically viable in the Southeastern U.S. (Dougherty and Wright 2012). This opportunity has been recognized by the U.S. Department of Energy, as *Eucalyptus* and other hardwood varieties have been added to the "Growing Bioenergy and Carbon Cycling Portfolio" (Gilbert 2007). In 2011, the complete genome of *Eucalyptus* was sequenced as part of this effort (specifically, *Eucalyptus grandis*; The Joint Genome Institute 2011). This sequencing opens opportunities for the improvement of biomass from eucalypts in the U.S., and for the production of renewable bioproducts (University of Pretoria 2011).

The interest generated in the U.S. toward the potential utilization of eucalypts for bioenergy must be addressed and supported with research that demonstrates whether eucalypts are suitable for energy generation in economic and technical terms. In this sense, Dougherty and Wright (2012) highlight that rapid biomass growth, along with a guaranteed supply of high-quality feedstock throughout the year, is a key element in making hardwoods such as eucalypts worthy of consideration for energy production in the Southern U.S. In the present project, the species *Eucalyptus benthamii* was used based on its availability from trial plantations and analysis of its properties (Pirraglia *et al.* 2012a).

Pre-treatments Selected for Analysis

Size reduction of biomass is one of the basic pre-treatments (chipping) that can be combined with other advanced technologies, such as pelletizing (a form of densification) and torrefaction processing, which are described in the next paragraphs.

Size reduction (chipping/grinding)

Size reduction in wood is performed through cutting action using machines with sharp knives that have the ability to vary the size of the chips in order to meet end-user requirements. Grinding can be typically performed on or near the forest, which helps optimize transportation and form the biomass for some end-uses, such as wood boilers, co-firing, *etc.* However, according to Kofman (2006), chips used as fuel in boilers require constant monitoring of moisture content, particle size distribution, bulk density, dust and fungal spores' level, and ash content, which can make grinding a less effective option than chipping.

Pelletization

Transportation, handling, and utilization of solid biomass can be improved through a densification process such as pelletizing. Pelletizing is defined as compressing cylindrical particles of biomass to a diameter of 6 to 12 mm, a length of approximately four times the diameter, and moisture content lower than 8% (PiR 2006). The advantage of pellets versus green wood chips resides in a high energy density, improving material handling and combustion efficiency (Moran *et al.* 2004). The process involves particle reduction of the biomass to less than 3 mm in size, drying the material, and extrusion through a set of dies and rollers, typically using the extractives and binders of the biomass in order to form the material together.

This solid biomass has several applications for commercial, industrial, and domestic heating and power generation, with many high-efficiency stoves and boilers available for the residential market, providing a competitive heating source as compared to oil or natural gas (Overend 2004). Specifically, pelletization has become a proven technology for the conversion of biomass into industrial heat and power, especially in several European Union (EU) countries, Canada, and the U.S. (Pirraglia *et al.* 2010a). A number of countries in Asia including China, Korea, and Japan are also evaluating an increased use of wood pellets for electricity generation. The main reason for the increase in pellets utilization resides in it being an attractive fuel for power stations, since pellets are composed of small particles that can be readily crushed and used in fuel burners in a similar manner as coal (Hoque *et al*. 2006).

Torrefaction

Biomass torrefaction is a process that consists of heating the biomass in an inert environment (without the presence of oxygen) at relatively low temperatures (up to 400°C), making it a slow-rate pyrolysis. During this process, water and volatile components are driven out of the solid biomass. Heavier components with higher heating values remain in the biomass, resulting in high energy content and yield. Important properties that torrefaction improves in the biomass are: mass/energy yield, reduction in volatiles and moisture content, and increase in fixed carbon content (Bezzon and Dilcio Rocha 2000; Green *et al*. 2000). Depending on the process conditions and the biomass type, a torrefaction unit can render 25% to 40% of the fixed carbon content, with an overall yield of 70% to 90% (Bezzon and Dilcio Rocha 2000). In the case of woody biomass, the torrefied biomass can range from brown to dark black in color, at which point it approaches the properties of coal (Bergman and Kiel 2005). In addition to improvements in biomass properties, torrefaction also allows a low-energy input technology, since a torrefaction unit only requires a start-up source of energy, with no additional external inputs since the pyrolysis gases being recirculated supply enough internal energy to continue the process (Bezzon and Dilcio Rocha 2000).

Solid biomass utilization in heat and power generation requires biomass of small, uniform particle sizes in order to efficiently feed it to fuel burners. In torrefaction, the reactions cause the biomass to become completely dried and lose most of its fibrous structure, decreasing the energy required for particle reduction (grinding) and feeding of the biomass (Bergman and Kiel 2005), making torrefied material very suitable for co-firing technologies. Additional advantages of torrefied biomass for energy generation through co-firing are (Battacharya 1990):

- Hydrophobic nature: the torrefied material does not absorb water; which improves its characteristics for storage and preservation
- Higher calorific value and less smoke when burnt
- It can be used in the steel industry and also in gasification and combustion processes

Despite several identified advantages of torrefaction, the potential of this technology remains mostly unexplored. Torrefaction is still considered as a new development for woody biomass upgrading and is not available commercially, although some early efforts for its commercialization were performed in the 1980's (Bergman and Kiel 2005). Since these early efforts, other technologies and concepts have been proposed (Arcate 2002; Duijn 2004), though none have developed beyond the technical demonstration stage. Bergman and Kiel (2005) stated that the application of torrefaction as a new pre-treatment technology becomes financially interesting if it leads to reductions in costs on the overall biomass-energy conversion.

Torrefaction/pelletization

Integration of torrefaction with other technologies has also been proposed and investigated. The properties and advantages of torrefied biomass can be further improved by combining torrefaction with pelletization, producing a very energy-dense fuel (Bergman and Kiel 2005). Some authors have even stated that the future of the wood pellets industry will rely on switching to torrefied wood pellets technologies, inserting the torrefaction process into an existing process that already has an established supply chain, equipment, and marketing channels (Lipinsky *et al.* 2002). This combination is in an advanced stage of development in some European countries (Kiel 2007), as part of the IEA Bioenergy Task 32, regarding advances and goals in Biomass Combustion and Co-firing (IEA Bioenergy 2011). Such interest in the combined pelletization-torrefaction process has arisen for its potential utilization for biomass firing and co-firing in coal plants. Torrefaction causes the biomass to lose its fibrous structure, making it very suitable for coal mills; this gives the opportunity for significant increases in the biomass/coal ratio in power plants (IEA Bioenergy 2009). The benefits of a combined torrefaction-pelletization processes are:

- Requires approximately the same energy as an alternative pelletization plus transportation logistics
- The energy density of the torrefied pellets is higher, resulting in more efficient transportation
- Pellets of torrefied material contain lower moisture content than traditional wood pellets.
- Since only a small fraction of the energy needed for torrefaction will come from external energy sources, a net efficiency of 70% to 90% is comparable to the efficiency of drying and pelletizing of regular wood pellets (IEA Bioenergy 2009).

These benefits have attracted the attention of many institutions and companies in the U.S. Trials for the production of torrefied wood pellets are already underway and are expected to be in operation during 2012 (Melin 2011). Some preliminary results of a semi-industrial process for torrefied pellets indicate that the pelletization can be achieved with low energy input, but the quality of the pellets highly depends on the pelletization conditions, including correct selection of biomass and machinery (Boerrigter 2006; Kiel 2007). In this sense, previous work performed by the authors indicate the necessity of adding either steam conditioning (treatment selected for the torrefied pellets described in this research due to its lower production costs), or binders (Distillers Dried Grains, feed corn, soybeans, *etc.*) in order to manufacture durable pellets that are adequate for transportation (Pirraglia *et al.* 2012c), increasing the production costs of this pre-treatment. The characteristics of this new technology and its combination with a pelletization process must be carefully assessed in its economic and technical aspects, as well as evaluating the selection of biomass for such a product. Furthermore, research in this combined technology is part of the 2011 Department of Energy Biomass Program (Sokhansanj 2011) in an effort to determine technical parameters and barriers (temperatures, times, particle sizes, feeding systems, *etc.*) as well as economic aspects (gains in energy compared to mass losses, integration in a continuous process, calculation of mass and energy balances, and cost-benefit analyses for turnkey operations). All these aspects are of critical importance for the near-term commercialization of this technology.

Considerations and Variables for Determining the Suitability of Pre-treatments and Biomass Types for Co-firing

Cost of pre-treatment at factory gate

Based on previous literature (Pirraglia *et al.* 2010b) and current models being developed (Pirraglia *et al.* 2012b; 2012c), the costs for producing wood chips, wood pellets, torrefied wood, and torrefied wood pellets have been assessed, and these costs include transportation (delivered cost) of the biomass to the facilities with a maximum transportation distance of 50 miles. Considerations for economies of scale are taken into account with the calculation of each production cost at factory gate. The cost of wood chips at the forest site (hardwood, softwood, and/or forest residues) is maintained constant since this pre-treatment can be usually performed at the forest, and trucks can be immediately loaded at surrounding roads. Every type of biomass considered for the study is initially assessed as debarked roundwood, since the inclusion of bark, tree limbs, leaves, *etc*. carry a typically higher ash content, and thus, is not rendered suitable for co-firing. More advanced pre-treatments (pelletization, torrefaction, and torrefaction/ pelletization) require substantial capital investment and dedicated facilities, having different production costs depending on the manufacturing volume.

Transportation considerations

A detailed calculation of transportation costs was performed based on previous work by Brechbill and Tyner (2008). They assumed a fixed cost of $15/truck of biomass for a truck loaded to full weight capacity; otherwise, the cost becomes a function of load size. A variable cost of $0.12/mile/ton was also used. In addition, an average loading and unloading cost of $5/truck was added to the transportation cost, which was based on estimates of Mahmudi and Flynn (2006) and is adjusted to $/ton of loaded/unloaded biomass, depending on the amount transported per truck. Transportation to the power facility was considered with a maximum hauling distance of 50 miles and utilizing walking-floor trucks with a maximum volumetric capacity of 80 cubic meters (Kofman 2007), or maximum weight capacity of 36.3 tons (80,000 pounds), whichever occurs first, due to legal weight restrictions (U.S. Department of Transportation, USDOT 2000). These are characteristic of the trucks commonly utilized in the biomass industry, and the constraints imposed by law are important considerations that determine if transportation of certain pre-treated biomass is limited by weight or by volume, with impacts on the final delivered costs of biomass to power facilities. The decision of limiting the transportation of pre-treated biomass by weight or by volume is performed based on the bulk density of each pre-treatment and has an important effect on the biomass transportation costs.

Further pre-processing prior to co-firing

According to Kofman (2006), biomass fed to power plants for co-firing requires uniformity and very specific particle sizes. Each type of pre-treatment considered for this project delivers a biomass with different particle sizes and grinding ability characteristics. In addition, the moisture content of the biomass entering the co-firing units influences grinding ability and efficiencies (Hoadley 2000), and requires a proper design of systems to handle the biomass. Hardwood and softwood chips, as well as forest residues, require two particle reduction stages before feeding the particles to the boiler (Grinding and hammermilling), while wood pellets, torrefied wood, and torrefied wood pellets require only a fine grinding stage (hammermilling). Energy required for first-stage grinding of hardwood and softwood chips, and forest residues, is taken from previous literature (Arrieche *et al.* 2011).

Energy consumption for the fine grinding (hammermilling) of wood pellets is taken from DiGiacomo and Taglieri (2008), while the energy consumption required for fine grinding of torrefied wood and torrefied wood pellets is a fraction of that required for wood pellets, as stated by Repellin *et al.* (2010), establishing this energy as 10% of the original requirements for fine grinding of regular wood pellets.

Relevant information for the capital costs and consequent depreciation of equipment influencing the fuel costs in pre-processing (hammermills, grinders, miscellaneous equipment, and building space) was obtained from Pirraglia *et al.* (2010b) and the Biomass Energy Resource Center (BERC 2011), while estimates for building requirements (receiving and unloading zone, storage area for wood chips or pellets, and building required for pre-processing depending on the biomass received) were estimated based on recommendations by Campbell (2007). This information allows calculating the cost of grinding and/or hammermilling operations in the biomass prior to feeding it to the boiler.

Co-firing

Co-firing can be defined as the production of energy in (typically) coal-fired power plants through partial substitution of the original fuel (coal) with biomass feedstock (Maciejewska *et al.* 2006; IEA 2009). Co-firing of coal and biomass has already been evaluated in most of its economic and technical details for several types of biomass in Europe (Wieck-Hansen *et al.* 2000; Brem 2005; Maciejewska *et al.* 2006; Livingston 2008; Al-Mansour and Zuwala 2010) and in its effect on emissions reduction (Veijonen *et al.* 2003; Lako 2010).

Different types of co-firing techniques have been developed with the most common being direct co-firing, parallel co-firing, and indirect co-firing. In the U.S., direct co-firing is the preferred technological choice. From the approximately 40 co-firing plants currently operational in various stages of development (pilot tests, ramp-up production, commercial operation, *etc.*), 39 of the 40 utilize a direct co-firing system (IEA Co-firing database 2009), making direct co-firing the most common and preferred technological choice. Direct co-firing incorporates biomass and coal entering the boiler simultaneously (Maciejewska *et al.* 2006). This option has several variants:

- Blending of the biomass with coal on the fuel receiving yard, then utilizing regular coal processing and combustion equipment to feed the mix. This option is the most straightforward and has lowest cost with the potential problems of inconsistent mixing and/or differences in the feedstock and limited application to conventional wall or corner-fired furnaces; in addition, some types of biomass, like herbaceous crops, may not be fed this way (Livingston 2005; Kiel 2005; Maciejewska *et al.* 2006).

- Separate milling and feeding of the biomass. This option allows separately milling the biomass and feeding it to the combustion chamber, allowing the coal and biomass to mix downstream in the coal mills. This option increases capital investment, but has less impact in the coal feeding system, as compared to the biomass blending system (Maciejewska *et al.* 2006; Livingston 2008). In addition, co-firing different types of biomass creates unique combustion issues. For a system feeding blended coal-biomass, the maximum blend of biomass is about 4%, while for a system feeding biomass separately to the boiler this percentage can reach 20% (Sondreal *et al.* 2001; Belosevic 2010).
- The installation of dedicated biomass processing units (milling and burners) has the advantage of being highly flexible regarding the type of biomass that can be fed to the boiler. By having a separate processing stream for biomass, it can be adapted to biomass with different properties and homogenize those properties, making them adaptable for feeding into the boiler. This, however, is the most expensive and complex option and only a few projects in Europe are currently utilizing it (Maciejewska *et al.* 2006).

For analysis purposes, the preferred option in direct co-firing is the one that requires the least amount of modifications to the boiler and feeding system, which is the separate milling and feeding of the biomass. This option also represents the one with the least additional capital investment and eliminates some of the feeding issues present in some of the other choices. A process flow of the analyzed co-firing option is presented in Fig. 2 (Modified from U.S. Department of Energy, USDOE 2011).

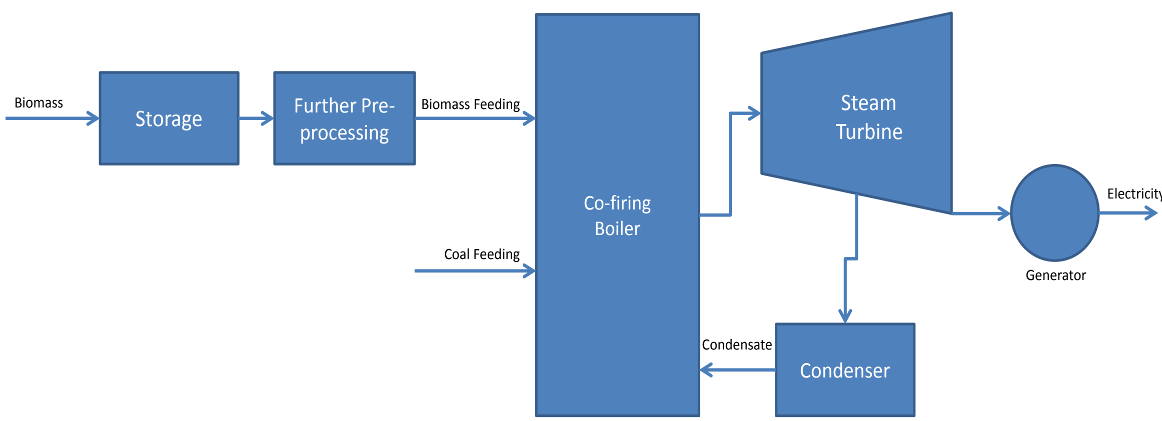

Fig. 2. Schematic of the analyzed co-firing process

In this process configuration for direct co-firing, all the different combinations of biomass and pretreatments evaluated are milled and fed separately in the process denominated Further Pre-processing, ensuring that the feeding is composed of uniform biomass particles, between 1 and 3 mm. in length, and reducing combustion issues (loss of efficiency, non-uniform combustion, *etc*.).

Based on the configuration (pre-treatment), biomass (type), and the aforementioned co-firing process, efficiencies for the boiler, turbine, and combined cycle were calculated (further described in the results section). The model considers the high heating value and usable heating value delivered to the boiler, along with the moisture content of the biomass, for the calculation of different efficiencies of the system and the associated cost of electricity ($/Kwh).

An additional parameter considered for the evaluation of the co-firing process is the amount of blend (biomass plus coal) that must be fed into the cycle in order to produce the required electrical output. This property is evaluated through a case study in which a power plant producing 100 MWh is considered, since this is a typical plant capacity in the U.S., with all of the different combinations of biomass and pre-treatments evaluated. Further details are provided in the case study section.

RESULTS AND DISCUSSION

Calculations for the most suitable pre-treatment and type of biomass intended for direct co-firing for electricity generation in the U.S. are divided into two sections. The first section considers the cost of a biomass pretreated and delivered to the boiler feeding system, which includes transportation, short-term storage, further processing at the power plant, and additional analyses of potential feeding and handling issues for the most suitable biomass and pre-treatment. The second section considers the cost of electricity generated and the biomass/coal blend requirements (tons/hour) for a particular case study.

With transportation costs and further pre-processing costs added to the initial biomass delivered costs for each biomass type and pre-treatment, it is possible to calculate the cost of biomass delivered to the boiler unit and calculate the cost per energy unit of biomass delivered ($/MJ Delivered). Table 1 summarizes the properties (MC, HHV, LHV, UHV, and Energy Density) and delivered costs ($/ton and $/MJ delivered) of the biomass depending on the type of biomass and pre-treatment applied.

Table 1. Main Properties and Calculated Costs of the Biomasses and Pre-Treatments Evaluated *

Biomass species and pre-treatment	MC	Bulk Density (kg/m^3)	HHV (MJ/Kg)	LHV (MJ/Kg)	UHV (MJ/Kg)	Energy Density (MJ/m^3)	$/ton Product	$/MJ Delivered
Southern Yellow Pine Chips	25%	157	19.73	18.37	13.15	2065	66.5	5.1
Eucalyptus *benthamii* Chips	25%	210	18.53	17.17	12.25	2573	63.4	5.2
Pocosin Biomass Chips	25%	150	19.62	18.26	13.07	1960	49.9	3.8
Softwood Residues Biomass Chips	25%	150	20.52	19.16	13.74	2061	75.3	5.5
Hardwood Chips	25%	210	18.50	17.14	12.23	2568	87.3	7.1
(Light) Torrefied Southern Yellow Pine	5%	230	23.68	22.32	21.07	4847	185.8	8.8
(Medium) Torrefied Southern Yellow Pine	3%	265	25.33	23.97	23.18	6131	199.1	8.6

Table 1. Continued

Biomass species and pre-treatment	MC	Bulk Density (kg/m^3)	HHV (MJ/Kg)	LHV (MJ/Kg)	UHV (MJ/Kg)	Energy Density (MJ/m^3)	$/ton Product	$/MJ Delivered
(Dark) Torrefied Southern Yellow Pine	1%	304	26.60	25.24	24.96	7593	205.0	8.2
(Light) Torrefied Eucalyptus *benthamii*	5%	230	24.50	23.14	21.86	5027	185.8	8.5
(Medium) Torrefied Eucalyptus *benthamii*	3%	265	26.22	24.86	24.03	6357	199.1	8.3
(Dark) Torrefied Eucalyptus *benthamii*	1%	304	27.53	26.17	25.88	7872	205.0	7.9
(Light) Torrefied Pocosin Biomass	5%	230	23.54	22.18	20.95	4818	217.8	10.4
(Medium) Torrefied Pocosin Biomass	3%	265	25.19	23.83	23.04	6095	222.0	9.6
(Dark) Torrefied Pocosin Biomass	1%	304	26.45	25.09	24.82	7548	225.8	9.1
(Light) Torrefied Softwoods Residues	5%	230	24.62	23.26	21.98	5054	217.8	9.9
(Medium) Torrefied Softwoods Residues	3%	265	26.35	24.99	24.16	6391	222.0	9.2
(Dark) Torrefied Softwoods Residues	1%	304	27.67	26.31	26.02	7914	225.8	8.7
Southern Yellow Pine Pellets	8%	689	19.73	18.37	16.70	11506	140.2	8.4
Eucalyptus *benthamii* Wood Pellets	8%	689	18.53	17.17	15.60	10745	140.2	9.0
Pocosin Biomass Pellets	8%	689	19.62	18.26	16.60	11436	199.4	12.0
Softwood Residues Biomass Pellets	8%	689	20.52	19.16	17.43	12007	199.4	11.4
Torrefied Wood Pellets Southern Yellow Pine	5%	800	33.20	31.84	30.12	24097	227.0	7.5
Torrefied Wood Pellets Eucalyptus *benthamii*	5%	800	24.50	23.14	21.86	17486	227.0	10.4
Torrefied Wood Pellets Pocosin	5%	800	23.54	22.18	20.95	16759	313.1	14.9
Torrefied Wood Pellets Softwood Residues Biomass	5%	800	24.62	23.26	21.98	17580	313.1	14.2
Medium-Volatile Bituminous Coal	10%	793	32.25	31.16	27.79	22040	159.2	5.7

* All acronyms are defined together in a table in the appendix.

Information in Table 1 was researched from different sources. The bulk densities of the softwood and hardwood (dried) chips were obtained from the Scandinavian Pulp, Paper, and Board Testing Committee (1992), and the bulk density of forest residues were from Phanphanich and Mani (2009). The bulk density of "premium" wood pellets was obtained from standards developed by the Pellet Fuel Institute (PFI 2011). The bulk density of torrefied wood and torrefied wood pellets was obtained from Bergman (2005).

Heating values from the different biomass options and the respective pre-treatments were obtained from several literature reports and from experimentation in the Department of Forest Biomaterials, North Carolina State University with an adiabatic bomb calorimeter. Values for southern yellow pine and hardwood chips were consulted from Arrieche *et al.* (2011). Values for *Eucalyptus benthamii*, Pocosin biomass, softwood forest residues, and torrefied *Eucalyptus benthamii* were obtained from previous experiments (Carter 2010; Pirraglia *et al.* 2012a; Pirraglia *et al.* 2012c). Values for intense torrefaction treatments (medium and dark torrefaction) for each of the species was estimated as a percentage increase from the original HHV of the biomass according to data from James (2009), with the exception of *Eucalyptus benthamii*, for which there was experimental data available (Pirraglia *et al.* 2012a). For calculation of the heating value effectively delivered to the boiler (Usable Heating Value, UHV), the relation proposed by Oliveira Rodrigues and Rousset (2009) was used:

$$UHV(\text{MJ/Kg}) = LHV * (1-MC) - 2.51 * (MC) \tag{1}$$

LHV represents the Lower Heating Value of the biomass, and is calculated as a function of the Higher Heating Value as follows:

$$LHV(\text{MJ/Kg}) = HHV - 1.36 \tag{2}$$

With this information, the model calculates the energy density of each delivered biomass/pre-treatment (Tons/m^3). Based on these calculations, torrefied wood pellets of southern yellow pine (24,097 MJ/Kg and 22,040 MJ/Kg) represent the most energy-dense biomasses.

A further step is the calculation of energy costs delivered to the boiler. Biomass costs of forest residues were obtained from Estcourt and Jack (2012) and McNeel *et al.* (2010), and account for $28.78/BDT, when considered as combined activity with saw timber production. Biomass costs of softwood (Loblolly Pine) and hardwood (*Eucalyptus*) chips were taken from Gonzalez *et al.* (2011b), excluding the transportation costs from their model and adapting the biomass cost to biomass with a 25% moisture content. Costs for wood pellets, torrefied wood, and torrefied wood pellets were taken from Pirraglia *et al.* (2012b-c), in which the cost for the production of durable, transportable, torrefied wood pellets includes a pre-processing cost for steam conditioning before pelletization. The moisture content of the wood chips from different biomasses was established at 25%; this moisture content is lower than what is typically required by a small or medium-size power plant (Kofman 2007).

In the present work, it is considered that by choosing direct co-firing and separate feeding of biomass and coal, the facility will require the least amount of additional investment (only requiring investment in biomass handling equipment), and that the facility is already able to handle dust formation from the biomass with existing dust filters. Transportation costs, grinding costs (if grinding is needed), and hammermilling costs are added depending on the pre-treatment option considered. Table 2 shows the unit costs for each pre-treatment and summarizes these previously described costs and energy consumption.

Table 2. Transportation Costs, Grinding and Hammermilling Costs, and Energy Consumption of Different Pre-treatments

Type of Pre-Treatment	Total Transportation Costs ($/ton)	Energy for Grinding (Kwh/ton)	Cost of Grinding ($/ton)	Energy for Hammermilling (Kwh/ton)	Cost of Hammermilling ($/ton)
Softwood Chips	$ 9.38	32.5	$ 2.26	49	$ 3.41
Forest Residues chips	$ 8.98	28.0	$ 1.95	56	$ 3.90
Hardwood Chips	$ 8.91	37.5	$ 2.61	57	$ 3.97
Premium Wood Pellets	$ 6.55	N/A	N/A	20	$ 1.39
Torrefied Wood	$ 7.09	N/A	N/A	2	$ 0.14
Torrefied Wood Pellets	$ 6.55	N/A	N/A	2	$ 0.14

With the information described above, it is possible to calculate the delivered cost of biomass at the boiler, shown in column 8 of Table 1. This information allows, in combination with the energy density of the pre-treated biomasses, the energy costs of delivering different options of biomasses and pre-treatments, in $/MJ delivered. This information is presented in column 9, Table 1.

Based on the calculated results, the delivery of chips from Pocosin (3.8 $/MJ), southern yellow pine (5.1 $/MJ), *Eucalyptus benthamii* (5.2 $/MJ), softwood residues (5.5 $/MJ), and mixed hardwood (7.1 $/MJ) represent the most economical choice per Mega joule of delivered biomass.

From the most advanced options of pre-treatments, torrefied wood pellets of southern yellow pine (7.5 $/MJ) and dark torrefied wood of *Eucalyptus benthamii* (7.9 $/MJ) represent the most economical options for delivering energy to the boiler, with the additional advantages of providing higher loads per truck (improving transportation) and a higher energy density, requiring a smaller amount (tons) of biomass and coal fed to boilers. The analysis, in terms of quantity of biomass and amount of coal required, is dependent on the plant capacity and level of electricity produced (in MWh). A case study with a comprehensive analysis of this aspect is presented in the case study section of this report.

For the feeding of biomass and coal to the boiler, certain aspects of the model (such as biomass-to-coal ratio, efficiencies, and variation of efficiencies in boilers and turbines based on the type of biomass being fed, mostly due to the moisture content of the biomass) have to be described and represent the base for the calculation of the effective electrical energy that can be obtained with each combination.

The approximate rate of biomass-to-coal substitution in direct-fired boilers is about 20% weight/weight (Belosevic 2010). This ratio is used in the model since it allows for the fewest required changes in burner settings, feeding systems, and dedicated equipment or replacement of traditional equipment for biomass combustion. As a general guideline, biomass fed at a weight ratio greater than 20% to 30% requires additional modifications and capital investment and may produce certain limitations on the types of biomass that can be fed (Gast *et al.* 2007). Furthermore, biomass substitution in boilers decreases its nominal efficiency. It has been suggested that boiler efficiencies for a blending of coal with biomass is reduced approximately 1% for every 10% substitution of coal with biomass for traditional coal-burning boilers (Canalis *et al.* 2003). The rate of 20% substitution minimizes the loss in efficiency.

The type of coal selected for this analysis was medium-volatile bituminous coal, having an average heating value of 32.247 MJ/Kg (13,840 Btu/b, Engineering ToolBox, 2010). This type of coal is the most common form of coal in the U.S. and the primary type of coal used for electricity generation in coal-fired plants (Stokes 2003). In addition, this type of coal contains a high average ash content (10%) and volatile content of approximately 25%, producing a difference between its HHV and LHV of 1.09 MJ/Kg (470 Btu/lb.; World Coal Institute 2007), with an average bulk density of 793 Kg/m^3 (Engineering ToolBox 2010). The current delivered price of coal for the electric power sector, also known as steam coal (as of September 30th, 2011), is $144.44/short ton ($159.22/metric ton; U.S. Energy Information Administration, EIA 2012).

Boiler efficiency is defined as the percentage of the fuel energy that is converted to steam energy (U.S. Environmental Protection Agency, EPA 2007), and in the model presented, the boiler efficiency is considered to be 80.7%, following results obtained by Good *et al.* (2006) on a grate boiler with a 100% heat load, calculated by the direct determination method. It is suggested that steam turbine efficiencies for electric generation are close to 40% (Council of Industrial Boiler Owners 2003). This efficiency, combined with the boiler efficiency, results in combined cycle efficiency of 32.3% with coal with a 10% moisture content which is a value similar to those reported on combined cycles by several authors (Valero 2003).

These efficiencies, however, represent nominal efficiencies when considering feeding biomass with less than 10% moisture content. Moreover, the addition of biomass with elevated moisture content further reduces the efficiency of the boiler. For the purposes of the model, in which some biomasses were fed with moisture contents as high as 25%, a decrease in efficiency was expected. The model deals with this characteristic by using a relationship between the moisture content of the biomass entering the boiler and the resulting decrease in efficiency produced. From the work of Levi *et al.* (2006) it can be inferred that efficiency decreases approximately 4.4% (with the base being coal with 10% moisture content) for every 10% increase in moisture content. This type of approximation is useful in determining the influence of the biomass feed moisture content on the combined cycle efficiency. In the case of feeding wood chips (hardwood, softwood, pocosin, and softwood residues), this effect is negative, reducing the overall efficiency, which is contrary to the case of pellets and torrefied biomass, which increase the overall efficiency.

Based on this information, the model calculates the combined cycle efficiency for each type of pre-treated biomass. Using equations described by the World Coal Institute (2007), the model combines the cycle efficiency with the energy entering the cycle, converting Megajoules of biomass/coal blend to MWh of thermal energy, and ultimately, to KWh of electricity, as follows:

1 MWh Thermal Power = 3600 MJ (3)

1 MW (electrical power) [MWe] = approximately 1 MW (thermal power)/3 (4)

Utilizing Equations (3) and (4), along with the combined costs of biomass/coal blend, the model calculates the cost of electricity produced with each different type of biomass and pre-treatment. Table 3 summarizes the combined cycle efficiency and reports the cost of electricity generated ($/KWh) with each biomass option.

Table 3. Efficiencies and Unit Costs of Electricity Calculated for Each Biomass and Pre-Treatment

Biomass Species and Pre-Treatment	Combined Cycle Efficiency	$ cents per Kwh Generated
Medium-Volatile Bituminous Coal*	34.0%	5.7
Southern Yellow Pine	31.8%	6.4
Eucalyptus benthamii	31.8%	6.4
Pocosin Biomass	31.8%	6.3
Softwood Residues Biomass	31.8%	6.3
Hardwood Chips	31.8%	6.7
(Light) Torrefied Southern Yellow Pine	32.5%	6.9
(Medium) Torrefied Southern Yellow Pine	32.5%	6.9
(Dark) Torrefied Southern Yellow Pine	32.6%	6.8
(Light) Torrefied *Eucalyptus benthamii*	32.5%	6.9
(Medium) Torrefied *Eucalyptus benthamii*	32.5%	6.8
(Dark) Torrefied *Eucalyptus benthamii*	32.6%	6.8
(Light) Torrefied Pocosin Biomass	32.5%	7.2
(Medium) Torrefied Pocosin Biomass	32.5%	7.1
(Dark) Torrefied Pocosin Biomass	32.6%	7.0
(Light) Torrefied Softwoods Residues	32.5%	7.1
(Medium) Torrefied Softwoods Residues	32.5%	7.0
(Dark) Torrefied Softwoods Residues	32.6%	6.9
Southern Yellow Pine Pellets	32.3%	6.8
Eucalyptus Benthamii Wood Pellets	32.3%	6.8
Pocosin Biomass Pellets	32.3%	7.3
Softwood Residues Biomass Pellets	32.3%	7.2
Torrefied Wood Pellets Southern Yellow Pine	32.5%	6.9
Torrefied Wood Pellets *Eucalyptus benthamii*	32.5%	7.2
Torrefied Wood Pellets Pocosin Biomass	32.5%	8.0
Torrefied Wood Pellets Softwood Residues Biomass	32.5%	7.9

*Medium-Volatile Bituminous Coal Data utilized as reference and for calculations of the combined co-firing costs and quantities.

Table 3 shows that the most economical option for producing electrical power (besides pure coal) is the utilization of residues (Pocosin and softwood residues at 6.3 $ cents/Kwh). A disadvantage that cannot be accounted for in this analysis is the availability of these types of residues required for large scale facilities, making this an option that may be useful for only small-scale power plants. Furthermore, the ash content of these types of biomasses may become another disadvantage of its utilization. Considering that for large-scale power plants sufficient availability is required, southern yellow pine and *Eucalyptus* chips represent the most attractive biomass for this application.

Considering the more advanced pre-treatments, wood pellets and dark torrefied wood from southern yellow pine and *Eucalyptus benthamii*, along with medium torrefied wood from *Eucalyptus benthamii*, represent the most economical choices, at $6.8 cents/Kwh each. The current cost of electricity is placed (on a national average) at $6.96 cents/Kwh for the industrial sector, $10.39 cents/Kwh for the commercial sector, and $11.79 cents/Kwh for the residential sector, making these biomasses/coal blends competitive for the three end-user electricity sectors. It must be noted that the already operating cycle would require additional capital investment (boiler, turbine, condenser, *etc.*), which must be added to this analysis, along with a minimum profit analysis in order to enhance the accuracy of the analysis performed on this project. The required additional capital investment is specific to a particular facility; since cycles in current operation with coal switching to biomass/coal blends have depreciation periods that have already been accounted for in their income statements, they would require an adjustment based on the depreciation time period left. This type of analysis can only be included if the project is considering a new facility and/or substitution and installation of new dedicated equipment and building space.

A case study is presented to provide further information for the assessment of biomass and pre-processes for co-firing. This approach considers more aspects of the production of electricity from each biomass/pre-treatment for a better assessment of costs of production per hour ($/hour) and changes in required amounts of biomass and coal (tons/hour) due to differences in the intrinsic usable energy of each biomass/coal blend.

Case Study

A case study that evaluates the production of electricity through co-firing of biomass in a 20% to 80% ratio is presented below. A plant size of 100 MWe was selected, as this is the most common size facility in the U.S. (Co-firing database, IEA 2009). The case study evaluates the amount of biomass and coal (20%/80% proportion) necessary to produce 100 MWh of electric power, depending on the characteristics of the pre-treatment and biomass fed to the system. In addition, it calculates the production costs of each option (in $/hour). Figures 3 and 4 present the electricity production costs in $/hour and the total amount of blend (tons of biomass and coal) required for each considered biomass option in order to produce 100 MWh of electrical power; acronyms used for this and subsequent figures are defined in the Appendix.

Figure 3 demonstrates that the utilization of Pocosin biomass chips is the most economical option, being $147/hour less expensive than the next option (southern yellow pine Chips). Pocosin biomass availability at the required rate (9.13 tons/hour, Fig. 4), however, may hinder its potential utilization. This may be the same case of softwood residues, requiring 9.08 tons/hour (Fig. 4). Assuming that the power plant runs all year without downtime, the requirements for Pocosin or softwood residues are in the order of 79,760 tons/year and 79,323 tons/year, respectively. This may require hauling of residues from several different sources and greater distances than the initially considered 50 miles; thus, this type of biomass is recommended for smaller power plants than the one proposed in this case study.

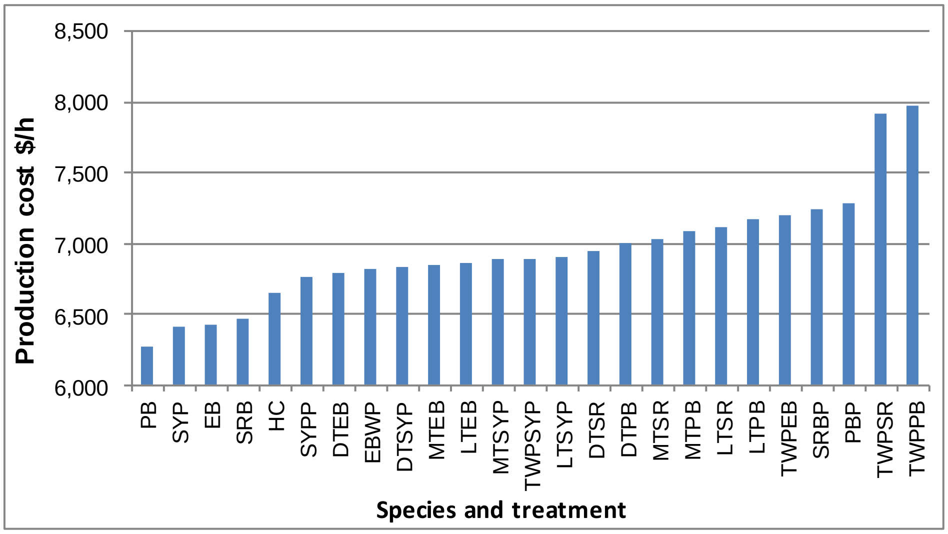

Fig. 3. Hourly production costs of electrical power from each different biomass source and pre-treatment in a 100 MWh power plant

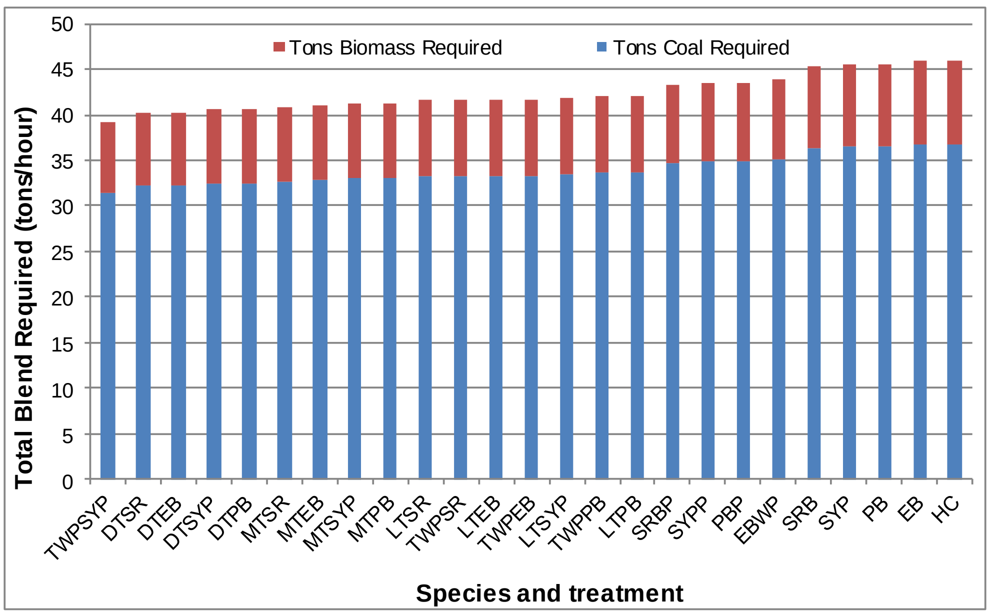

Fig. 4. Biomass and coal (blend) utilization for each different biomass source and pre-treatment in order to produce 100 MWh in a power plant

Many regulations indicate that a main objective of a power facility in the next few years should be to displace the consumption of fossil fuels (coal in this case). Based on a pure coal utilization reduction, the best biomass option (from Fig. 4) is represented by torrefied wood pellets of southern yellow pine, requiring 31.4 tons/hour of coal and 7.85 tons/hour of biomass to produce 100 MWh. This leads to a reduction of carbon utilization by more than 5 tons/hour as compared to utilizing regular wood chips from any of the biomasses described.

Southern yellow pine and *Eucalyptus benthamii* chips are the next recommended options in terms of electricity production costs (6,414 and 6,433 $/ton, respectively), requiring also similar quantities of biomass (9.12 and 9.19 tons/hour, respectively, Fig. 4). One of the shortcomings of chip utilization in direct-fired boilers is related to the high moisture content that these chips usually carry. This MC may generate grinding and feeding issues (such as the one presented in Fig. 5) and storage degradation of the biomass, reducing the overall efficiency of the cycle and creating potential operational problems in the boiler.

Fig. 5. Overloading and bundling caused by high moisture chips entering a hammermill chamber (Arrieche 2010)

The more advanced pre-treatment options aid in reducing these potential problems by providing a biomass with a lower moisture content and more homogeneous characteristics. From the more advanced options, southern yellow pine pellets represent the most economical (at $6,764/hour), followed closely by dark torrefied *Eucalyptus benthamii* (at $6,787/hour). The main difference between these two options is the total amount of biomass/coal blend required; while southern yellow pine pellets will require a combined 43.52 tons/hour, dark torrefied *Eucalyptus benthamii* will require 3.21 tons/hour less (40.31 tons/hour of blend), totaling 28,042.56 tons/year less material entering the boiler. This substantial difference also has a large impact on storage and logistics of the power plant if storage of the biomass is limited, making dark torrefied *Eucalyptus benthamii* a preferred choice if the feeding systems and or/storage capacity of the power plant represent a limitation.

It is noteworthy that for any of the torrefied biomasses evaluated, the severe treatment (dark) is preferred over the medium and light treatments, since its cost in $/hour per MWh generated is lower than the medium and light torrefaction options. This may become an important characteristic of the pre-treatment when torrefaction becomes more economically feasible in the near future.

CONCLUSIONS

An evaluation of delivered costs of biomass and pre-treatments for direct co-firing in power plants in the U.S., along with a case study, was conducted. The main conclusions from this work indicate that:

1. Considering a biomass production-cost approach, wood chips (southern yellow pine and eucalyptus) and forest residues (Pocosin and softwood residues) delivered to the boiler are the most economical biomass and pre-treatment options, considering transportation, handling, and further pre-processing of the biomass.
2. As torrefaction becomes a preferred pre-treatment for biomasses intended for co-firing, the more severe treatments (dark torrefaction) represent more economical options in terms of production cost per MWh generated.
3. The cost of producing electricity ($/Kwh) from a Pocosin chips/coal blend is a preferable choice; however, its utilization requires larger amounts of biomass and coal being fed to the boiler limiting its potential utilization for smaller size power plants (less than 100 MWh).
4. The cost of electricity production from wood chips (southern yellow pine and *Eucalyptus benthamii*) represents the most economical option for power plants equal to or larger than the one presented in the case study, due to the availability of the wood chips. Potential storage degradation, feeding issues of biomass with a high moisture content, and potential boiler and combustion issues, however, may hamper its potential and make other choices more preferable even with the favorable increment in production costs.
5. Based on coal displacement from the power plant, the utilization of torrefied wood pellets from southern yellow pine represent the best option, being able to displace more than 5 tons/hour as compared to the utilization of traditional wood chips from any of the biomasses evaluated.
6. With current U.S. conditions and considering the options that would minimize potential feeding and combustion issues, wood pellets of southern yellow pine present the most adequate biomass/pre-treatment combination in an electricity production-cost basis.
7. A second choice, dark torrefied hardwood (*Eucalyptus benthamii*), represents an interesting alternative to wood pellets of southern yellow pine, since it considerably reduces the amount of biomass/coal blend required without severely increasing the cost of production. This is an adequate option for systems with limited storage capacity and leads to a reduction in the feeding system load.

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APPENDIX

Definition of Acronyms	
TWPSYP	Torrefied Wood Pellets Southern Yellow Pine
DTWSR	(Dark) Torrefied Softwoods Residues
DTEB	(Dark) Torrefied *Eucalyptus benthamii*
DTSYP	(Dark) Torrefied Southern Yellow Pine
DTPB	(Dark) Torrefied Pocosin Biomass
MTSR	(Medium) Torrefied Softwoods Residues
MTEB	(Medium) Torrefied *Eucalyptus benthamii*
MTSYP	(Medium) Torrefied Southern Yellow Pine
MTPB	(Medium) Torrefied Pocosin Biomass
LTSR	(Light) Torrefied Softwoods Residues
TWPSR	Torrefied Wood Pellets Softwood Residues Biomass
LTEB	(Light) Torrefied *Eucalyptus benthamii*
TWPEB	Torrefied Wood Pellets *Eucalyptus benthamii*
LTSYP	(Light) Torrefied Southern Yellow Pine
TWPPB	Torrefied Wood Pellets Pocosin Biomass
LTPB	(Light) Torrefied Pocosin Biomass
SRBP	Softwood Residues Biomass Pellets
SYPP	Southern Yellow Pine Pellets
PBP	Pocosin Biomass Pellets
EBWP	*Eucalyptus benthamii* Wood Pellets
SRB	Softwood Residues Biomass
SYP	Southern Yellow Pine
PB	Pocosin Biomass
EB	*Eucalyptus benthamii*
HC	Hardwood Chips