ABSTRACT

PIRRAGLIA TUNEZ, ADRIAN. Assessment of the Most Adequate Pre-treatments for Woody Biomass (Solid Biofuels) Intended for Direct Co-firing in the U.S. (Under the direction of committee Co-chairs Drs. Daniel Saloni and Joseph Denig).

Ligno-cellulosic biomass is regarded a potential and competitive source for bioenergy due to rising fossil fuel costs, concerns over the environment, and mandates on renewable energy. Biomass conversion into bioenergy has attracted countless research projects in recent years. In this sense, thermal conversion (burning of solid biofuels) is especially useful for power generation. Most promising products and technologies in this category include densified (pellets), and thermally pretreated products (torrefied wood). Despite this interest, little comparative research exists on determining which form of solid biofuel is more profitable, efficient, and feasible to produce electrical energy through direct co-firing, technology that has the potential to mitigate fossil fuels utilization for electricity.

The challenge of determining the most adequate solid biofuels requires a complete assessment of economic, technical, and physic-chemical characteristics of the pre-treatments and biomasses. In this project, the subject of selecting adequate woody biomasses and pre-treatments for co-firing is investigated in six studies.

First study: fuel properties of two freeze-tolerant *Eucalyptus* species (*E. benthamii* and *E. macarthurii*) were studied, and wood pellets were manufactured with binders. Results indicate that wood density and heating values of these species are comparable to softwoods and hardwoods naturally occurring in southern U.S., with both species being adequate for biofuel utilization. Some binder-wood combinations enhance the heating value of the pellets, while increasing the ash content (weight/weight, w/w).

Second study: the same eucalyptus species were processed in a torrefier, and wood pellets were manufactured with binders. Fuel properties were analyzed. Compared to results from the first study, the heating value of the eucalypts and pellets was enhanced by 19%, while moisture and volatiles content were drastically reduced, leading to an increase in the amount (w/w) of carbon. Thus, torrefaction is useful for improving heating value of biomass, and properties for transportation and handling.

Third study: a techno-economic model for determining production costs of wood pellets for U.S. manufacturers was developed, considering the most important technical and financial factors affecting pellet production. Results indicate profitability for U.S. manufacturers and distributors/retailers, with biomass and labor costs being the most sensitive variables, followed by energy and CAPEX.

Fourth study: a technical and economic model for the production of ligno-cellulosic torrefied biomass for U.S. manufacturers was developed. Results indicate that production of torrefied biomass can be profitable, subject to a high sensitivity on biomass cost, CAPEX, and technology affordability for large-scale production. Additional results indicate that carbon credits may positively influence profitability based on analyses of net present value and internal rate of return.

Fifth study: a techno-economic model for a torrefaction-pelletization process was developed, considering important economic and production parameters. Results indicate that biomass delivered costs and depreciation are the most significant factors influencing production costs, with CAPEX being the most sensitive variable due to high investments in torrefaction reactors. Selection of different torrefaction technologies, adequate binders, and carbon credits, may represent a major improvement in a project's feasibility, drastically reducing capital costs.

Sixth study: delivered costs of various pre-treated biomasses (from previous studies), electricity production costs, co-firing technology, and other variables are input into a model that calculates a least cost mix for electricity production. Results indicate that forest-residues wood chips present the lowest electricity production cost in small-scale co-firing applications, with potential feeding and processing issues. From the options that ensure minimum processing issues in the co-firing cycle, wood pellets from southern yellow pine represent the most economic choice. Based on coal displacement (w/w) from the facility, torrefied wood pellets from southern yellow pine is a preferred option as compared to other choices, followed by dark-torrefied *Eucalyptus benthamii*, providing similar electricity production costs while reducing coal utilization.

Assessment of the Most Adequate Pre-treatments for Woody Biomass (Solid Biofuels) Intended for Direct Co-firing in the U.S.

by
Adrian Pirraglia Tunez

A dissertation submitted to the Graduate Faculty of
North Carolina State University
In partial fulfillment of the
Requirements for the degree of
Doctor of Philosophy

Forest Biomaterials

Raleigh, North Carolina

2012

APPROVED BY:

_____	_____
Daniel Saloni Committee Co-chair	Joseph Denig Committee Co-Chair
_____	_____
Richard Lemaster	Dennis Hazel

DEDICATION

A Santiago, quien en su breve paso por este mundo, nos enseñó el valor de la vida. Nos demostraste lo unidos que debemos estar ante la adversidad, y la falta que nos hace estar juntos como familia. Tu breve estancia a nuestro lado nos demostro la resistencia, y a la vez fragilidad de la vida. Papá, donde quiera que se encuentren, cuida bien de el. Los extrañamos a los dos.

To Santiago, who is his brief crossing through our world, taught us the value of life. You showed us how united we must be against adversity, and how much we miss being with each other as a family. Your brief stay by our side gave us a lesson on the resilience, and at the same time, fragility of life. Dad, wherever you two are now, please take good care of him. We miss you both.

BIOGRAPHY

Adrian Pirraglia Tunez was born on November 29, 1982 in Caracas, Venezuela. After finishing his high school education at “Unidad Educativa Colegio La Salle T.H”, he joined “Universidad Catolica Andres Bello” (UCAB) to pursue the Industrial Engineering Bachelor’s degree. While pursuing the completion of his bachelor’s degree in 2005, he began working at CANTV, the main telecommunications company from Venezuela, as a Consultant for the Human Resources Planning and Development Management. In 2007, Adrian is accepted at N.C. State University as a student on the Integrated Manufacturing Systems and Engineering Master’s program, and began to work as research assistant supported by the Department of Wood and Paper Science with Dr. Daniel Saloni. After finishing his master’s degree in 2009, Adrian continued his studies joining the doctorate program at the Forest Biomaterials Department, North Carolina State University, under the direction of Drs. Daniel Saloni and Joseph Denig. During his doctoral studies, Adrian researched and evaluated several conversion pathways of woody biomass to bioenergy, along with projects on Lean Manufacturing, Process Improvement, and Green Manufacturing in the wood industry.

ACKNOWLEDGMENTS

The author would like to deeply thank to all the people that helped make this achievement a reality. Many people have helped me along the way, to all of them, I would like to express all my gratitude. However, there is a select group of them that I want to include here.

My advisors: Drs. Daniel Saloni, and Joseph Denig who have been more than just excellent advisors to me. Thank you both, for believing in me, and guiding me all the way here. I would have never made it without your guidance.

Dr. Richard Lemaster, for all his support and advice, and for always having his door open, and receiving me whenever I needed it. Thank you.

My friends and research partners, Guillermo and Ronalds, for all their support, advice, and friendship. You have always been here for me, without you guys, I would not have made it.

My friends back home, even the distance was not able to separate us: Luis Carlos, Yarana, Jose Manuel, and Mayrene. You are always there for me, thanks for all the joy and companionship you have given me; I feel lucky to have you in my life.

My girlfriend, friend, and companion Schauren, for all her support and understanding through the rough times, and her love and smile through the happy moments. I would not be here without you.

Finally, I would like to thank my family. My brother Javier, for being my role model, thank you for being my brother, my friend, and a father. Mary and my nieces, for always being there for me, for all your support, for all the moments we have shared together, I cannot wait to see you again dear sister. Carmen, for being the best mother any son could ask for. For the endless nights talking on the phone, and listening to each other's problems. For always being a friend, and for always being a guide for me, you are the most amazing woman in the universe. I love you mom. My father, Nicola, wherever you are now, I know you are looking out for us. Thank you for showing me the value of hard work, and for being a fighter even in the darkest hours. Thank you dad, I will always miss you.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

Biomass has been the most prevalent source of energy, mainly for use in heat generation (Hohenstein and Wright, 1994; Fritsche et al. 2006; Scientific American, 2009), and now holds the promise as a replacement for fossil fuels in the industrial world. Biomass can be defined as carbon-based material that is derived from living or recently living organisms, composed of organic molecules containing hydrogen, oxygen, nitrogen, and small amounts of other chemicals (Biomass Energy Centre, 2011). If properly managed biomass can be a renewable and a sustainable source of food and energy. According to the U.K. Biomass Energy Centre (2011) biomass can be classified into five basic categories of materials: virgin wood, energy crops, agricultural and agricultural residues, food and food waste, and industrial waste and co-products.

Recent interest in biomass is mainly due to rising fossil fuel costs and concerns over carbon emissions, and has driven a worldwide search for alternative energy sources (Evans and Perschel, 2009; Kim et al. 2009). The lure of biomass is that it uses a sustainable cycle to produce energy, having carbon dioxide drawn from the atmosphere, and when the biomass is converted to energy, this carbon dioxide is released, being available for the production of new biomass, producing little or no net addition of carbon to the atmosphere (Oak Ridge National Laboratory, 2011).

The use of biomass for energy has increasingly gained worldwide attention during recent years (Evans and Perschel, 2009). The Wood Institute for the Environment (2007) argues that biomass has one of the highest potentials for providing clean energy, while reducing dependence on petroleum and strengthening agricultural economies (Phipps et al. 2007). Several authors indicate that the interest generated by bioenergy will further increase in the near future (Demirbas, 2009; Wopienka et al. 2009; Wopienka, 2011). During the 1970’s there was a similar interest in renewable energy due to energy crisis, but it rapidly declined as oil prices decreased (Ragauskas et al. 2006; Rice and Burton, 2010). However, this current interest in alternative energy sources is predicted to have a deeper impact than its predecessor, since fossil fuel reserves are further depleted, oil prices are high (between $83 and $116 per barrel during 2011; IndexMundi, 2011), and global consumption of oil has

tripled since 1970 (Lovis et al. 2004). This trend should continue with developing countries predicted to increase their energy needs by 80% by 2020 (Exxon Mobil, 2004), and a global energy consumption that has increased almost 23-fold in the last century (Demirbas and Demirbas, 2007). In this sense, industrialized countries have recognized the need to develop alternative energy sources, including biomass (Ragauskas et al. 2006). Some authors indicate that industrialized countries have identified the need to develop alternative sources of energy, due to limited crude oil reserves, which are predicted to be depleted in 50 years at the present rate of consumption (Sheenan et al.1998), potentially creating a foreign exchange crisis, and dependence on imported oil (Demirbas, 2005; Senthilkjumar and Gunasekaran, 2005). This drive has led to establish aggressive energy policies and goals, steering government perception towards renewable energy sources, transforming industries, creating renewable energy-related jobs, and boosting renewable energy policies in more than a hundred countries (REN21, 2010).

The increase in bioenergy usage can be clearly seen through recent years. The Renewable Energy Policy Network for the 21st Century (REN21, 2006) stated that all forms of bioenergy supplied 10 percent of the world's primary energy demand by 2006, representing about 90 percent of the contribution of all renewable energy. In 2009, the growth of renewable energy contribution was unprecedented despite the global financial crisis, lower oil prices, and slow progress in establishing climate policies, increasing from 10% to 13% (IEA, 2009). Other sources report higher increases of 14% by 2008, with 13% of this energy generation coming from direct firing of biofuels from biomass. One can postulate that much of this increase was driven by a higher commitment from governments and institutions to reduce dependence on non-renewable hydro carbons (REN21, 2010), highlighting the importance that energy from biomass may achieve in the near future, and creating the need to further develop energy conversion processes applicable to biomass.

Biomass can be converted into energy using two broad types of conversion strategies: thermal conversion, in which heat is generated from burning biomass, being the dominant conversion form, or chemically converting the biomass so it can be used as fuel. Biofuels are further defined as solid (bio-char, pellets, briquettes), liquid (bioethanol, biodiesel, and vegetable oil), or gaseous fuels (biogas, syngas) derived from biomass (Kong et al. 2008;

Demirbas, 2008a; Balat, 2008a; Demirbas, 2008b; Balat, 2009; Demirbas, 2009). Biofuels differ from direct use of biomass for energy (burning) in the fact that they are typically more refined fuel sources to produce bioenergy, requiring certain processes or pre-treatments in order to facilitate transportation, handling, and ease the energy extraction.

First generation biofuels are those produced from food and fodder crops, while second generation biofuels can be produced from the whole cellulosic material of plants; by utilizing the whole plant material, second generation biofuels allow to obtain more fuel per unit of agricultural land use, and less energy input required per production (Tranport Biofuels, 2007; House of Commons, Environmental Audit Committee, 2008; European Biofuels Technology Platform, 2009). Second generation biofuels may help overcome the deficiencies of first generation biofuels, especially in areas of controversy such as the utilization of food crops for energy purposes (Balat, 2008b; Demirbas, 2008c; Demirbas, 2008d), in which many authors have argued that biofuels derived from food crops are driving higher food prices and may affect land availability for food (Rice and Burton, 2010). With the technology for first-generation biofuels limiting its use over food sources, and the development of economically feasible large-scale technology for second-generation biofuels in the horizon of medium-term future (Ragauskas et al. 2006; IEA RETD, 2010), much interest in bioenergy is shifting towards second generation biomass sources and fuels, (Lovins et al. 2004; Parikka, 2004). However, replacing conventional fossil fuels with biomass deem certainly difficult to accomplish by only relying in first generation biofuels. In this sense, second generation biofuels could provide a better solution to replace conventional fuels (Ragauskas et al. 2006). Furthermore, even with the current state of technology for second generation biofuels, less than half of the energy from the original feedstock is recovered when manufacturing liquid biofuels (bioethanol, biodiesel) (Samson et al. 2008), leading to substantial loss in energy yield compared to the original dried material. A better solution for fuel replacement with biomass, especially for power generation, is the manufacturing of solid biofuels, which retain most of the energy yield of the original biomass, and improves handling and transportation (Zwart et al. 2006).

According to Kaltschmitt and Weber (2006), solid biofuels can be defined as fuels subject to a thermal and/or mechanical treatment that densifies or concentrates the original

biomass energy content, and are especially suitable for heat and power generation in industrial facilities. The most promising products and technologies in this category are densified products such as pellets and briquettes, and thermal pretreated products such as torrefied wood and bio-char. Even though these products have been available, at different stages of commercialization, there has been little comparative work on determining which form of solid biofuel is more profitable, efficient, and feasible in terms of technical issues, supply, handling, storage, and overall economics to produce electrical energy, especially through direct firing and co-firing.

Direct firing is defined as the combustion of biomass for energy production through heat, or combined heat and power generation (Overend, 2004). Co-firing can be defined as the combustion of finely grinded biomass material blended with coal, carried out in large pulverized coal power boilers (Van Loo and Koppejan, 2008; Hunt and Tennant, 2009). The utilization of solid biofuels for co-firing has been given special research attention in recent years; several authors state that biomass co-firing has the highest potential for commercial applications in large-scale facilities, and is one of the most readily available options for displacing fossil fuels utilization in the present and near-term future, also presenting a low-risk, low-cost, sustainable, and renewable energy option that will allow for reductions in CO_2, SO_x, and NO_x emissions (Grammelis, 2011). Co-firing of solid biofuels can provide thermal energy, which is one of the most needed forms of energy for commercial and industrial sectors, thus having the potential to mitigate and displace fossil fuels utilization for thermal energy (Samson, 2008).

However, woody biomass sources must be transformed into an energy efficient, and economically sound biofuel in order to justify and expand its utilization. Several authors indicate that power and heat applications using woody biomass is key to the success of solid biofuels (Bringezu et al. 2009), and it can be achieved through biofuels suitable for direct burning and co-firing in power plants (those with low moisture content, adequate shape, heating value, and enough availability for large applications). Samson (2006) states that solid biofuels produced from a densification process represents the best biofuel cycle in terms of energy, land use, and economics for heat and power generation, since it provides a product that can be easily produced, transported, and fed into power generation systems. Though,

since different pre-treatment options for densification are available today, and some others are being developed, the most appropriate type of pre-treatment must be assessed, in order to further improve the economics, efficiency, and energy content of solid biofuels. Authors differ when it comes to determine which pre-treatment is the most suitable process depending on the biomass utilized and other key parameters, and few efforts have been conducted in order to directly compare and determine the most adequate conversion processes for biomass, given current economical U.S. conditions; thus, additional information is needed in order to make accurate decisions in biomass selection, and conversion technologies, that will assure the best profitability for U.S. producers.

The challenge of determining the most adequate solid biofuels pre-treatments requires a complete assessment of the main economic and technical characteristics of the processes, as well as the physical-chemical characteristics of the most adequate biomass for each process. Since further research needs to be conducted in this area, and many companies, institutions, and governments are pondering the best utilization of biomass resources for bioenergy production, the need for evaluating in a holistic manner current and new technologies for solid biofuels becomes both, a great research opportunity and a challenge, and represents the main focus of this project.

1.1. Statement of Objectives

The objective of this research is to evaluate different pre-treatments levels and woody biomasses for solid biofuels intended for direct co-firing in electric power plants. Technical and economic aspects, as well as mass and energy balances, will be considered. The assessment will include technical requirements for the pre-treatment, production costs, final fuel characteristics, and transportation costs to final point of use.

1.2. Specific Objectives

- Identify currently available pre-treatments of solid biofuels in the U.S.

- Assess, compare, and describe the physical-chemical characteristics of a range of woody biomasses in terms of energy content and suitability for solid biofuels production.
- Perform technical and economic evaluations, through process and financial models with defined boundaries, of the selected pre-treatments in order to determine profitability, critical variables for each process, and sensitivity of the variables to changes in the market.
- Identify and establish a method and/or measurement unit that allows to directly comparing the utilization of selected pre-treatments in co-firing, considering the boundaries of the models previously developed, considering different scenarios, the types of biomass evaluated and characterized, and additional variables that may affect the evaluation criteria of the pre-treatments, such as production volumes, supply chain considerations (transportation, storage, logistics, etc.).

2. BACKGROUND AND LITERATURE REVIEW

2.1. Background

Biomass has been the main source for food, energy, and the main constituent of all man-made products throughout human history. Special importance has had biomass for energy production, mainly through the combustion of wood for heat (Hohenstein and Wright., 1994; Green et al. 2000; McKendry, 2002; Fritsche et al. 2006), which is still the main source of energy in many countries. Until the mid-1800s, biomass remained as the main supply of energy and fuel's needs in the world, and its usage only declined with the beginning of the fossil fuels era (Klass, 1998; Green et al. 2000).

During the 1970's, oil prices increased to unprecedented levels, creating a worldwide oil crisis for over a decade. This crisis unveiled the need for alternative energy sources that could replace oil and other hydrocarbons as a main energy source. In the midst of this crisis, biomass was considered again as a source that could provide a sustainable supply of energy, and also provide environmental and economic benefits. This first interest in biomass declined when oil prices declined and reached more affordable levels.

However, during this period, it was observed that for an efficient utilization of biomass as a fuel, the biomass would require physical, morphological, and/or chemical modifications to make it suitable for energy production. These changes are necessary due to the fact that biomass has a low heating value and low density for a fuel, especially when compared to solid fuels such as coal, reason why its usage as energy source was displaced by the use of fossil fuels in the majority of industrialized countries (Green et al. 2000).

Such initial changes produced in the biomass are called pre-treatments, and the products obtained are called biofuels, which are more suitable products for energy production, denominated bioenergy. The conversion of biomass into biofuels is useful not only for improved energy generation, but also for optimizing supply chain aspects of bioenergy, such as enhanced transportation and storage, proper shape to optimize capital and operational costs, reduction in biomass delivered cost, etc. Figure 1 shows a simplified scheme of energy production from biomass sources.

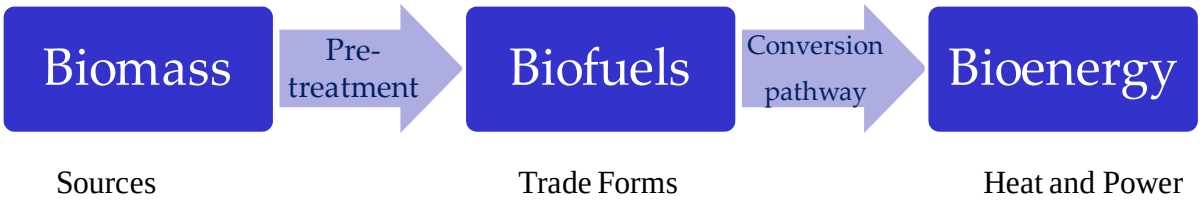


Figure 1.1. Simplified production chain of bioenergy (Food and Agriculture Organization of the United Nations, FAO, 2004)

The previous figure shows in three simple elements how biomass is transformed into energy. This simplified diagram is useful for defining, in order of appearance, the three most important concepts in bioenergy production: Biomass, Biofuels, and Bioenergy itself.

2.2. Concepts and definitions

2.2.1 Biomass

Biomass is defined as the organic material that stems from plants, including all land and water-based vegetation. This plant material is derived from the reaction between the CO_2 in the air, water, and sunlight, producing carbohydrates, which forms biomass' building blocks (McKendry, 2002). Ramamurthi and Bali (2000) broadened this definition by stating that biomass is a general term for all materials whose origins are directly related to photosynthesis, and includes all new plants grown, residues and wastes, and biodegradable organic effluents from industries. The importance of this concept relies in the fact that biomass represents stored solar energy (Green et al. 2000), thus, through adequate technologies and treatments, this stored energy can be extracted and utilized. Energy released from a biomass source is referred to as bioenergy, and will be further defined. Biomass has the potential for becoming a large source of sustainable energy if properly managed (Chynoweth et al. 1993), through conversion to solid, liquid, and gaseous fuels (Wise., 1981; Jerger and Chynoweth., 1987; Smith et al. 1988; Smith and Frank, 1988).

2.2.1.1 Types of biomass

A classification system is an important element that must be identified when researching biomass properties, characteristics, or end-uses. Rosillo-Calle et al. (2007) states that there are many ways of classifying biomass, and the classification may depend on the objective, aim, or particular interest of the researcher/author, however, they state that whatever method is used, it must be clearly specified. In their "Biomass Assessment Handbook", they adopt an eight-category classification system, dividing biomass into natural forest/woodlands, forest plantations, agro-industrial plantations, trees other than forests and woodlands, agricultural crops, crop residues, processed residues, and animal wastes. Other classification systems have been described by other authors, such as Panoutsou, (2011), who established a simple three-categories classification, agricultural, forestry, and waste-based biomass, Klass (1998) who established a broad categorization of biomass by dividing it between virgin biomass and waste biomass, arguing that this classification allows to determine (in the case of virgin biomass) approximate land area required to produce sufficient biomass and a given annual yield, to meet particular fuel demands in a determined country, or to identify sources of biomass waste and assess the potential impact of energy production from these sources Another simple classification was proposed by the Biomass Energy Centre (2011), which classifies the types of biomass as virgin wood, energy crops, agricultural residues, food waste, and industrial waste and co-products. The Worldwatch Institute (2007) classified biomass according to their conversion technology into energy. According to the Institute, biomass feedstocks can be grouped into two categories, first-generation feedstocks that are harvested for their sugar, starch and oil content, and can be converted into liquid fuels using conventional technology, and "next-generation" feedstocks, that are harvested for its total biomass, and can only be converted into liquid fuels by advanced processes. These next-generation feedstocks include woody biomass, and have a much greater potential for expanding the supply of liquid and gaseous fuels for energy.

Despite the different classification systems described, all authors generally separate biomass between woody biomass and non-woody biomass (including herbaceous crops) (Rosillo-Calle et al. 2007). For the purposes of this research project, the classification proposed by McKendry (2002) is adequate, since it separates the biomass types in four main

categories: woody biomass, herbaceous biomass, aquatic plants, and manures, from which the “woody biomass” category is of particular importance for the objectives of the project, and is further described below.

2.2.1.2 Woody Biomass

In general, woody biomass contains, in descending order, varying amounts cellulose, hemicelluloses, and lignin, along with small amount of other extractives. The high concentration of cellulose gives woody plants the “cellulosic biomass” denomination. Woody plants in particular are typically characterized by slow growth, and are composed of tightly bound fibers, giving it its typical hard surface (McKendry, 2002). On the contrary, herbaceous plants (usually perennial) have more loosely bound fibers, indicating a lower proportion of lignin content. The relative proportion of cellulose and lignin is one of the key factors in determining the suitability of plant species for conversion into energy. Woody biomass can be categorized further in softwoods and hardwoods (Hoadley, 2000). Further information about softwoods, hardwoods, and species of particular interest for biomass to energy, and forest residues is provided in the following paragraphs.

2.2.1.3 Species of Interest

Softwoods and hardwoods differ in many characteristics, such as cellular structure, anatomy, and a higher average density, and also have differences in properties for biofuels manufacturing, being the heating value one of the most distinctive features. Literature indicates that average heating values for hardwoods ranges from 18.6 to 19.8 MJ/Kg, and its bark ranges from 17.2 to 22.8 MJ/Kg. For softwoods, heating values range from 20.0 to 22.1 MJ/Kg, and the bark ranges from 20.4 to 25.1 MJ/Kg, having both a higher range of HHV than hardwoods (Resch, 1989). Typical North American softwoods are southern yellow pine, Douglas-fir, Western Hemlock, Eastern Spruce, Redwood, and Eastern White Pine.

Hardwoods include around 22 families in the U.S., being Oak, Black Locust, Black Walnut, Cherry, Gum, Cottonwood and Chestnut the most common. Hardwoods have been an important wood resource for lumber and furniture applications, and play an important role for the production of pulp and paper. In recent years, several fast-growing hardwood species

that have been traditionally used in the paper industry have attained attention for its potential use for energy production, and additional species have been introduced in plantations for bioenergy.

Is of particular interest for the objectives of this research the description of eucalyptus species (hardwood) and southern yellow pine (softwood), along with mixed sources of woody biomass, specifically hardwood chips and forest residues, which are further defined below.

2.2.1.3.1 Southern Yellow Pine

Southern yellow pine has a substantial economic importance in the U.S., with more than ten species being native to Southeastern U.S., spread through several states (Peter, 2008). One of the most common species, loblolly pine, is considered as an excellent model for economics and genetic studies due to its particular economic importance (Lev-Yadun and Sederoff 2000).

Pine plantations in the U.S. comprises more than half of the world's industrial forest plantations (Wear and Greis 2002; Siry et al. 2006), being pulp and paper, wood composites, and lumber industries the main end-use of these plantations (Peter, 2008). More than 50 years of research in the southeastern U.S. has led to an extensive body of literature in southern pines, including growing systems, tree improvement programs, seed germination, nursery, forestry, logistics, and field trials, highly improving the productivity of southern pine plantations (Fox et al. 2004; Fox et al. 2007). However, since the prices of sawlog timber mark the utilization of southern pines for other industries, few studies have been reported for southern pines biomass conversion into energy. The study of planting southern pines as a short rotation energy crop is relatively new, with one of the first trials evaluated by Rockwood and Dippon (1989), with harvesting at 8 years, obtaining rather low biomass yield with first-generation material; this yield is not expected to highly improve throughout time, since southern pines do not regenerate by coppicing, and logistics (harvesting and transportation) issues have not been resolved for small-diameter southern pines (Peter, 2008). Typically southern pines are planted with rotations ranging from 20-35 years, due to its utilization in traditional wood industries. Despite not having the flexibility of a short rotation

energy crop, southern yellow pine is becoming an important source of biomass, due to its availability and vast plantation areas. Another important factor influencing the interest of southern yellow pine for bioenergy is decline in competitiveness in the pulp and paper industry, which has reduced the demand of small diameter pulpwood, increasing drastically the availability of southern pines for other applications, and pushing growers to look for new markets (Peter, 2008). These characteristics, along with very well established tree improvement programs and genetic resources, make the southern pine a very strong potential source of biomass for energy production (Peter, 2008).

According to several authors, two conversion strategies exist for the southern pine biomass-to-energy industry, aside from its utilization in ethanol production, the first is an integrated forest refinery, that produces fuels from the biomass and converts it into energy, as a side operation to cellulose-based products such as pulp and paper (Stuart, 2006; Van Heiningen, 2006; Chambost et al. 2007a; Chambost et al. 2007b; Towers et al. 2007), and the second strategy is to convert southern pine biomass into heat and/or power through co-firing with coal and/or wood pellets, in stand-alone facilities dedicated only to this activity (Peter, 2008). Proof of the importance that southern pine is achieving is the fact that more than six biomass-to-energy facilities have been proposed or already exist in the U.S. that rely in the solely utilization of southern yellow pine plantations (Southern Environmental Law Center, 2011). In this sense, Green Circle Bio Energy Inc. (2011) has been producing for several years around 500 thousand tons per year of wood pellets from southern yellow pine, having the biggest pellets operation in the world, mainly for the export market, showing the potential that this biomass source can have for energy production in the U.S.

2.2.1.3.2 Eucalyptus

Biomass productivity for the energy sector heavily depends on the characteristics of the species that are being grown. Rockwood (2000) states that the ideal woody species to grow for bioenergy, among other attributes, should have the following characteristics:

- Rapid early growth
- Tolerance to climate conditions and sites

- Responsiveness to site amendment
- Tolerance of planting density and vegetative competition
- And coppicing ability

Eucalyptus species have been considered as a very valuable source for power generation due to the fact that it contains the attributes previously mentioned (Wijayatunga et al. 2005). It is expected that short-rotation woody biomass such as eucalyptus and its hybrids will be planted for bioenergy on sites that enable high productivity and proximity to processing factories (Hinchee et al. 2009). By the end of the 20th century, eucalyptus species became the most widely planted hardwood in the world (Turnbull, 1999; Patzek and Pimentel, 2005) mainly due to its utilization in the pulp and paper industry. As of the year 2000, Brazil possessed 6 million hectares, supplying about half of the world's eucalyptus pulp (Rothman and Furtado, 2000); published reports suggest that by the beginning of the 21st century existed 17.8 million hectares of planted eucalyptus (IUCN, 2001). This high utilization of eucalyptus denotes its importance for several industries and countries, and many efforts have been performed in order to increase the productivity and quality of already existing plantations (Patzek and Pimentel, 2005). For more than 30 years, Eucalyptus species have been evaluated in Florida for species potential. Early studies in the 1980's show that E. *Grandis* was one of the most productive species for southern Florida , with *E. Camaldulensis* and *E. tereticornis* showing promising resistance to freezes (Rockwood and DeValerio, 1986; Reddy and Rockwood, 1989). Authors also have stated that woody biomass production can be maximized by using short rotation intensive culture systems (SRIC), such as Eucalyptus, which can, and have been, developed by comprehensive research programs, especially in Florida (Rockwood et al. 1985; Rockwood and Prine. 1988; Rockwood. 2000). Further evidence of high productivity of eucalyptus species can be found in a number of studies performed by several universities and institutions, finding that some eucalyptus varieties are among the most productive woody species available for energy cropping (Rockwood et al. 1993). Eucalyptus also offers several advantages when compared to other short-rotation woody crops, such as hybrid poplar, offering higher yields, and shorter rotation periods for

bioenergy production (8-10 years for hybrid poplar, 4-5 years for eucalyptus) (Worldwatch Institute, 2007; Wright, 2010).

2.2.1.3.3 Mixed Sources and Residues: Hardwood Chips and Forest Residues

Wood residues are defined as by-products from wood-related activities, such as harvesting, and manufacturing. These residues can be classified as logging, saw-milling, plywood and particleboard production, and perennial plantations residues (Koopmans and Koppejan, 1998).

Residues generated from forest operations (logging and perennial plantations) typically include thinning, trees of undesirable species, quality, potential growth, pruning and harvest residue including treetops and limbs, and understory material that increases the risk of fire damage. Residues can represent as much as 40% of a tree (Fung et al. 2002). Increasing the markets for forest residues through use of the material for bioenergy would improve forest management, and may justify the investment in removing them from the forests. In this sense, densified fuels from forest residues, such as pellets and briquettes, can provide with the necessary economic impulse to remove and process such residues (Fung et al. 2002). For this reason, its utilization in bioenergy generation must be further assessed and evaluated.

Hardwood chips represent another important available source of biomass for bioenergy production. Historically, high value hardwood chips have been sold to pulp mills, however, the chips 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.

2.2.2 Biofuels

Biofuels can be defined as “fuels with a minimum of 80% content by volume of materials derived from living organisms harvested within 10 years of its manufacture” (Uhlenbrook, 2007). These fuels are renewable sources of energy, intended to satisfy or alleviate the escalating global energy needs (Somerville, 2006).

2.2.2.1 Conversion pathways for biofuels

In addition to classifications systems for raw biomass, it is necessary to establish and differentiate the types of biofuels that can be produced, in order to assess and describe characteristics, properties, technological status, and end-use of the biofuel. A system proposed by the FAO (2004) classifies biofuels in three categories: woodfuels, agrofuels, and municipal by-products. This classification system is useful, since it differentiates biofuels by the type of biomass used for its production, instead of differentiating by the conversion technology used. For example, pellets, briquettes, and ethanol are different conversion processes, and are intended for different end uses, however, they can be produced with either an agricultural crop, or woody biomass; is of particular interest of this project to evaluate certain types of biofuels technologies only considering its production with woody biomass, being in concordance with the biomass classification system previously selected.

McKendry states that the right choice of a biomass, in terms of species, depends on the end-use of the energy, or feasible biomass conversion pathway (combustion, gasification, pyrolisis, fermentation, etc.). Some plant species are flexible enough for its use in different conversion technologies: e.g. sugarcane can be processed through combustion, fermentation, or gasification. Finding an optimal energy application for a determined biomass is more challenging than only determining that different conversion technologies can be applied to the same type of biomass. Such is the case of woody biomass, in which the biomass breakdown through fermentation is more complex and expensive than for agricultural crops, making it more suitable and readily available for direct or co-firing applications than for chemical or biochemical conversion. Since the theoretical amount available for a given biomass is the same regardless of the conversion process, the ideal technology will be the one that allows recovering the highest amount of stored energy in the biomass (McKendry, 2002).

So far, costs of producing liquid fuels from woody (cellulosic) biomass are not competitive as compared to fossil fuels (Worldwatch Institute, 2007). Unlike liquid fuels production from biomass, heat and power generation through co-firing has already well-established and widely used technologies; moreover, while advances in liquid biofuels production are being made, technologies efficiencies are being improved in co-firing, making

biomass conversion into electricity even more competitive (Fritsche, 2006, as cited by the Worldwatch Institute, 2007). Converting cellulose into glucose, and glucose into alcohol is more easily and economically performed with high cellulose content biomass, such as perennial grasses, than with lignin-rich biomass, such as woody plants, which are not easily converted (Coombs, 1996; McKendry, 2002). Inherent properties of the biomass determine the most adequate conversion pathway for energy production, in the same sense that the selection of a given type of biomass over others is influenced by the form in which the energy is required. These two aspects interplay and can provide equally flexibility or subsequent processing issues if the correct biomass is not selected. Depending on the energy conversion process selected, particular properties of the biomass are important in biofuels processing, such as:

- Moisture content
- Calorific value
- Proportion of fixed carbon and volatile matter
- Ashes/residues content
- Alkali metal content
- Cellulose/lignin ratio

In the case of “dry” biomass conversion, the first four properties are of critical importance, while for “wet” conversion processes, the first and last properties mentioned are of critical importance (McKendry, 2002). Conversion processes for biofuels should be intended to provide clearly defined fuel characteristics, ensuring technically simple and robust conversion into useful energy, in order to reduce issues in meeting energy supplies efficiently (Food and Agriculture Organization of the United Nations, FAO, 2004). However, different conversion processes are suitable for a variety of energy options. The possible conversion pathways developed until now, and its potential and actual energy applications are depicted in Figure 2.1.

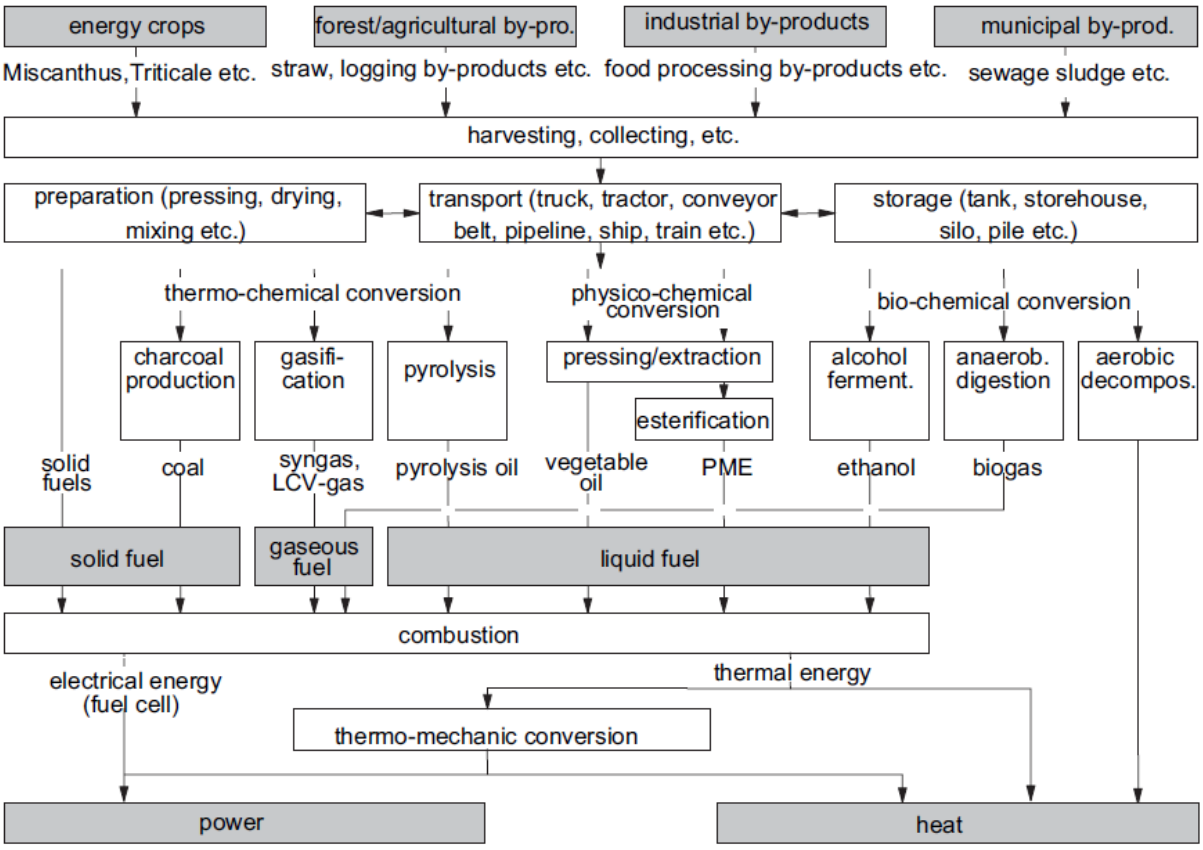


Figure 2.1. Possible conversion pathways, fuels from biomass, biomass sources, and energy form obtained (Food and Agriculture Organization of the United Nations, FAO, 2004)

Notice from Figure 2.1 that every source of biomass and conversion pathway selected can be used to produce power and heat; however, the most direct conversion pathway is represented by solid fuels, used through combustion to generate heat, power, or a combination of both, thus, optimizing and understanding the options to produce solid fuels for such direct conversion is of great importance.

2.2.2.2 Solid Biofuels

The production of power and heat from solid biomass, as depicted previously, is one of the most important and direct bioenergy generation pathways, experiencing an average increase of 2.7% of the total bioenergy production sector since 1990 (Silveira, 2005). Hence, it is important to understand and improve the process design, economics, and biomass

sources for solid biofuels production. According to Hoadley (2000), the calculations for the potential use of woody biomass for combustion have two basic considerations: the stove efficiency and the moisture content of the material. Additionally, in the use of biofuels for bioenergy, is important to properly design systems to handle biomass and feedstocks. Typically the raw biomass has a low bulk energy density (defined as the amount of energy contained in a given volume of raw biomass), and requires pre-treatments for its utilization in energy generation. Size reduction of biomass is one of the basic pre-treatments (chipping), which can be combined with some other more advanced technologies, such as pelletizing and briquetting (two forms of densification), and torrefaction, processes that are described in the next paragraphs.

2.2.2.2.1 Wood pellets

Transportation, handling, and utilization of solid biofuels can be highly improved through a densification process, such as pelletizing. Pelletizing is defined as compressed cylindrical particles of biomass, with a diameter from 6-12 mm, a length of approximately four times the diameter, and moisture content lower than 8% (PiR, 2006). This process produces a fuel that has a volumetric density between 800 -1200 kg/m^3, resulting in an energy density of around 0.05 m^3/GJ. The process involves a particle reduction of the biomass to less than 3 mm, and to dry the material (often an obligatory step). Then the material is densified using (typically) the natural waxes and extractives of the biomass in order to bind the material together in a high pressure system of dies, and with a high mass and energy production efficiency (over 95%, Overend, 2004) . Pelletized biomass has an enhanced volumetric density and calorific value per unit of volume, improving material handling and combustion efficiency (Moran et al. 2004).

This solid biofuel has several applications, for commercial, industrial, and domestic heating and power generation, having many high-efficiency stoves and boilers on the market, providing a competitive heating source as compared to oil or natural gas (Overend, 2004). Specifically, pelletization has become a proven technology for conversion of biomass into heat and power, becoming an increasing, mature energy market in several European Union countries, and Canada and the U.S. The main reason for the increase in pellets utilization

resides in 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 the same sense as coal (Hoque et al. 2006).

2.2.2.2.2 Torrefaction

When woody biomass is heated well above the boiling point of water, chemical degradation starts to occur. At higher temperatures or with longer heating time the wood will darken, and eventually convert into char. If oxygen is present, the wood will ignite above 500°F. If oxygen is not present in the reaction, the gases trapped inside the wood are driven off the material, in a process known as destructive distillation, or pyrolysis, giving a charcoal-like product (Hoadley, 2000).

According to Bezzon and Dilcio Rocha (2000), biomass torrefaction is a process that consist of heating up the biomass in an inert environment (without the presence of oxygen), with low heating rates (up to 300°C), making it a slow-rate pyrolysis. During this process, only water and some volatile components are driven out of the solid biomass. Heavier components with higher heating value remain in the biomass, resulting in high energy content and yield. Important properties that torrefied biomass have are: i) yield: the ratio of torrefied material weight to dry input material, ii) volatiles content: is the weight lost per unit of dry torrefied material, as compared to original dry biomass, and iii) fixed carbon content: the dry torrefied mass weight minus the weight of volatiles and ashes, per unit of weight of torrefied material (Green et al. 2000). Depending on the process conditions and the biomass type, a torrefaction unit can render 25 to 40% of fixed carbon content, with an overall yield of 70 to 90% (Bezzon and Dilcio Rocha, 2000), and in the case of woody biomass, the torrefied biomass can range from brown to dark black in color, and approaches the properties of coal (Bergman and Kiel, 2005). In addition to improvements in the biomass, a torrefaction process also provides with a low-energy input technology for biomass upgrading, since a torrefaction unit only requires a start-up source of energy, with no additional external inputs, since pyrolysis gases are recirculated, supplying enough internal energy to continue the process (Bezzon and Dilcio Rocha, 2000).

As discussed previously, solid biomass utilization in heat and power generation requires that the biomass has a small, uniform particle size in order to efficiently feed it to fuel burners. In torrefaction, the reactions causes the biomass to become completely dried, and to lose most of its fibrous structure, improving 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 use in energy generation through co-firing are (Battacharya, 1990):

- Hydrophobic nature: the torrefied material does not absorb water; which also 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;
- Similar density and mechanical strength compared to the initial biomass

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 early efforts for its commercialization were performed in the 1980's by the company Pechiney, in France, which produced 12 thousand tons per year of torrefied material (Bergman and Kiel, 2005). Since these early efforts, other technologies and concepts have been proposed (Arcate, 2002; Duijn, 2004), without any of them having developed beyond the technical demonstration stage. Bergman and Kiel (2005) stated that the application of torrefaction as a new pre-treatment technology becomes only interesting if it will lead to reductions in costs on the overall biomass-energy conversion, since torrefaction has still not achieved the commercial technology status. This reason increases the need for research in technical and economics of torrefaction in the near future. In order to address the limitations of commercial availability of this technology, the Energy Research Center of the Netherlands (Boerrigter et al. 2006) has proposed the first combined torrefaction and pelletization process (TOP) for woody biomass, with the intention of commercialize it in the near future, Figure 2.2 shows the Process Diagram proposed by this institution for the development of this technology.

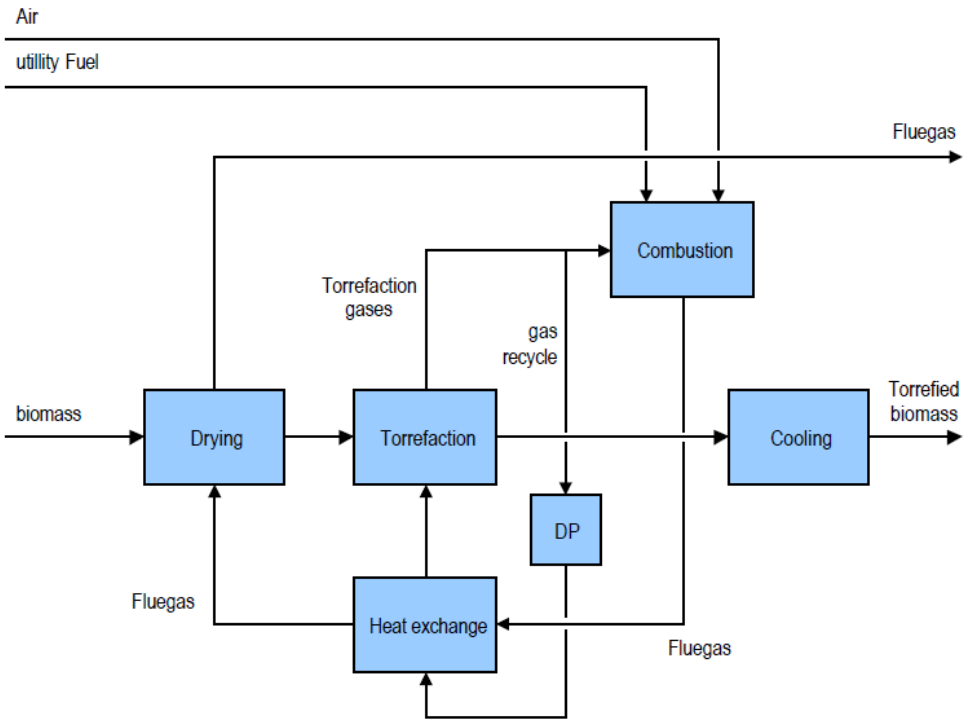


Figure 2.2. Process Diagram for the proposed TOP technology, with detail on the integrated drying-torrefaction process. (Bergman and Kiel, 2005)

This TOP process is one of the first attempts to understand and assess the technical and economic aspects of manufacturing torrefied woody biomass, determining that the process may render savings between 30-70% as compared to traditional pelletization of wood. However, economic and technological aspects of this process need further investigation

2.2.3 Bioenergy

Biomass can be depicted as organic matter in which solar energy is stored in chemical bonds. When these bonds are broken by chemical or physical processes (digestion, combustion, decomposition), the biomass releases the stored chemical energy, denominated bioenergy (Klass, 1998). Bioenergy has the advantage (over fossil fuels) of having a very wide spectrum of availability, depending on the different agro-climatic conditions (Bakthavatsalam, 2000), meaning that in different countries or regions (for which there may

not exists local sources of fossil fuels) different locally-grown, and readily available sources of biomass can be used for bioenergy generation. Particular advantages of bioenergy production also includes: it can be organized in small scales, from 1 to 100 MW, allowing slow and modular increments in energy supply, minimizing the risks of large-scale investments (Silveira, 2005).

Biomass can be converted into three basic forms of bioenergy:

- Electricity/heat energy
- Transport fuel (ethanol, biodiesel)
- Chemical feedstock

Typically, biofuels intended for transportation bioenergy are in liquid or gaseous form, while for its use in direct firing or co-firing for industrial, residential, and commercial applications, the fuel must be in a solid state. In this sense, woody biomass is more economically suited for production of solid biofuels, thus being more adaptable for heat and electricity generation, mostly through direct co-firing (McKendry, 2002).

There has been a great deal of interest in bioenenegy programs in many European Union countries, including the Netherlands, Sweden, United Kingdom, and Denmark (Silveira, 2005). In the U.S. the forest products industry has been actively investigating strategies that are economically feasible for the development of integrated forest biorefineries (Amidon 2006; Larson et al. 2006; Van Heiningen 2006; Chambost et al. 2007a; Chambost et al. 2007b; Towers et al. 2007), along with stand-alone facilities for the production of wood pellets, wood gasification, and bioconversion of wood to ethanol (Kotra, 2007; Peter, 2008).

Bauen (2005) mentions that two fundamental issues arise when considering the development of bioenergy options from woody biomass: i) what biomass conversion technologies and end-uses present the most favorable economic, technical and environmental options in the future energy mix, and ii) the availability of the biomass resources that is compatible with the different options. Among the most important conversion technologies, Bauen (2005) mentions biomass firing and co-firing

2.2.3.1 Direct Firing and Co-firing

Combustion is the most common application of biomass for energy, producing heat, power (electricity), or combined heat and power (Overend, 2004), and among its advantages are that it helps achieve easy start-up for boilers, provides greater combustion efficiency, and reduces overall greenhouse gas emissions (Green et al. 2000). During modern times, heat and power generation in factories has been mostly provided through the burning of coal and oil, and it was not until the oil crisis of the 1970's that biomass was considered as a potential source of fuel for industrial facilities. According to Walter et al. (2000), co-firing refers to "the combined use of biomass and fossil fuels in power plants as well as in industrial steam boilers", and has been considered in some countries as the first step for enhancement of biomass use in power generation. Utilization of biomass for co-firing in previously coal-based energy generation was not seriously considered as an alternative energy source. However, recent interest in this technology has brought new advances in the utilization, end-use, and optimization of large scale applications for biomass burning, making it a commercially available technology, and a reality in many European countries, and the U.S. (Walter et al. 2000). Recent studies show that blending biomass with coal simplify the operation of indirectly heated gasifiers and turbines, lowering capital and operational costs, and providing a greater flexibility in feedstock choices (Green et al. 2000). Other authors also state that a significant advantage of co-firing is that it requires a low capital investment, and provides with an efficiency that can equal that of coal at over 34% biomass-coal ratio (EPRI, 1997; Tillman, 2000).

In co-firing, the amount of biomass to be burned along with coal depends on detailed economic and technical assessments, such as biomass availability and cost, biomass hauling distance, plant performance and efficiency, upgrading and maintenance of boilers, and/or addition of new boilers, (Anderl and Mory, 1998; Walter et al. 2000). The emergence of gas turbines as the most efficient way to transform heat into mechanical energy has direct many advances in fuels blending for co-firing in the recent past, with the objective of producing adequate fuels for advanced gas turbines (Green, 1986, Gigler et al. 2002). In this sense, recent advances in biomass burning can now result in the transfer of 65-80% of the heat

content of the wood into hot air, steam or hot water for bioenergy generation (Green et al. 2000).

In addition, the use of biomass for co-firing without a modification on its physical properties, or a pre-treatment, is not feasible, since coal is typically pulverized and burned in the boilers, thus requiring the biomass to have this same physical shape, with uniform and homogeneous particle sizes. In order to address this limitation of biomass, and make it feasible for use in co-firing, several technical pre-treatments have been proposed and developed. One of the simplest ideas involves drying and grinding of the biomass, and an adaptation to the boiler that allows for simultaneous burning of coal and biomass (Walter et al. 2000). Raw woody biomass can be converted into pellets or briquettes, processes in which moisture is normally removed, the material is densified, and the particle size is significantly reduced. Torrefaction process is another option, which produces a charcoal-like material from the biomass, with improved energy properties that significantly enhances grinding characteristics of the biomass, delivering more uniform particle sizes, with lower energy consumption (Bezzon and Dilcio Rocha, 2000; Bridgeman et al. 2010; Phanphanich and Mani, 2011).

2.3. Literature review: Importance and Research justification

With large amounts of information on biomass, bioenergy, and conversion processes available, it becomes difficult to provide with an objective and consistent body of literature that justifies the research that is being performed in these areas. Information is often contradictory, and data is sometimes unverifiable or not thoughtfully collected. In the following paragraphs, the author compiles the most relevant an reliable information found on current bioenergy, biomass, and conversion processes and trends, building the case that makes the selection of biomass and processes adequate for this research project, and justifying the current efforts being performed in these areas, with actual and potential advantages and challenges.

2.3.1 Bioenergy from Biomass

The reality of energy production from renewable sources is that despite all efforts and advances in several areas, and the rapid growth of alternative energy in several regions, fossil fuels annual addition to the world energy supply and demand are still much larger in absolute terms (Silveira, 2005). It is clear that it will require more than a single source of alternative energy to displace the majority of fossil fuels. Finding the balance of different energy sources, and the most suitable application for each source is both a challenge and a long term goal that must be assessed through several short-term goals in every renewable-energy area. In this sense, challenges and opportunities for bioenergy production must be thoughtfully assessed, in order to respond to an increased demand for fossil fuels displacement from the market.

The Food and Agricultural Organization of the United Nations (2004) states that in order to correctly asses biomass potential and utilization, three needs must be developed and understood: first, the need for concerted statistics and indicators, in order to measure the adequacy and success of a given biomass source for energy, second, bioenergy balances, in order to measure the required energy inputs for production of the biomass and its consequent transformation into energy, vs. the final energy output produced from that biomass source, and a final trade aspect, which comprises the form and end-use of a given biomass source for biofuels.

During recent years, biomass as an energy source had experienced an increased revival of interest, with new technical advances that are showing the competitiveness of this sector (Rosillo-Calle et al. 2000). The Worldwatch Institute (2007) indicates that biomass fuels represents the only near-term substitute for fossil fuels, standing as a potential solution to issues such as rising oil prices, climate instability, and deepening in poverty in agricultural areas. The main reasons for this renewed world-wide interest in biomass for energy production are (according to McKendry, 2002):

- Technological advancements in conversion processes, and crop optimization and production, promises several improvements in energy from biomass and its applications, with lower costs and higher conversion efficiencies.

- The agricultural sector in Western Europe and in the U.S. has experienced food surplus production, which has led to a policy in which land is underused, in order to reduce the surplus. This reduction has brought as a consequence the de-population of rural areas, and payments of governmental subsidies to keep land fallow. This situation makes the introduction of alternative non-food crops for energy production desirable, since the demand for energy could provide an enormous market for energy crops in these surplus lands.
- The potential harm caused by climate change, and the strong political interest has become a driving force towards obtaining "cleaner" energy sources, that reduces the emissions of greenhouse gases (GHG) generated by fossil fuels. In theory, biomass utilization can mitigate some of the effects of climate change, since the CO_2 released when utilizing the biomass is (theoretically) taken up during re-planting and growth of the biomass, therefore not contributing to a CO_2 build-up.

Other reason for interest in biomass as an energy source are that biomass is (typically) an indigenous energy source, which is available in almost every country, and has several different applications, which can diversify not only the fuel source portfolio, but also the energy end-use, leading also to a more secure energy supply. Biomass production can also generate local sources of employment, providing local benefits (McKendry, 2002), and Domac et al. (2005) indicate that positive socio-economic impacts of biomass utilization are the main drivers for implementing bioenergy projects. In the U.S. specifically, local reasons for the recent interest and development of biomass production for bioenergy have been the following:

- Forest industries' need for residue disposal and increased utilization of tree resources;
- A desire to find and use alternative energy sources to reduce dependence on fossil fuels;
- Solid waste disposal issues related to resource utilization, recycling, and reduction of solid waste landfills;
- Concerns with global environmental issues related to climate change; (Frank and Smith., 1993; Schroeder, 2000).

As of the year 2000, biomass was estimated to contribute to 10-14% of the world's energy supply (McKendry, 2002), with heat and power generation (thermal conversion) having a growth rate of 2.5% annually (Sims and El Bassam, 2004). There is a general perception that biomass energy can only deliver small amounts of energy, and is highly inefficient, having only a marginal contribution to total energy requirements of a determined region, and that the technology for conversion is quite expensive (Bakthavatsalam, 2000). According to Domac et al (2005), the change towards a more widespread use of biomass for energy is necessary, but the economic benefits of such transition are generally poorly assessed and communicated. These misconceptions provide momentum for research to demonstrate the technical and economic feasibility of biomass utilization for different energy sectors.

An important aspect to secure an increased use of bioenergy, at relatively constant costs and with long-term access to energy supplies in the near future, is the diversity of feedstocks, or biomass types for energy production (Domac et al. 2005).

2.3.1.1 Biomass Selection

Selection of the adequate feedstock or biomass type is crucial for the development of secured and sustainable bioenergy markets. In this sense, authors have several characteristics that are desirable in an ideal biomass-for-energy crop, and which depend on the conversion technology used (McKendry, 2002):

- High yield (measured as maximum production of dry matter per hectare)
- Low energy input to produce the crop
- Low cost
- Chemical composition with the least amount of contaminants
- Low nutrient requirements

According to McKendry (2002), some other desirable characteristics will also depend on local conditions, such as climate and soil. Water consumption can become a constraint in many areas worldwide, making a drought-resistance factor of critical importance.

Several authors agree that cellulosic biomass from wood and forestry is expected to significantly expand the availability, quantities, and conversion technologies available for biofuels (Worldwatch Institute, 2007). In the near future, it is expected that a substantial share of the world's energy requirements will be met by means of cellulosic biomass. But it still remains as an uncertainty how much of that need can be actually met at an economical cost, and also anticipating that different energy uses and applications for woody biomass will also compete, requiring even more accurate technical and economic assessments and research, in order to keep profitability of energy production. In order to further develop this aspect of bioenergy production, detailed technical and economic analyses have to be researched, aiming to understand the suitability of different biomasses for certain conversion pathways, and the feasibility of each feedstock source (Marinescu and Bush, 2009). For the development of this project, several types of cellulosic biomass were selected, based on several aspects that make each type of biomass important for the development of solid biofuels.

2.3.1.1.1 Southern Yellow Pine

Southern pines have traditionally been the number one choice for many wood products manufacturers and many applications in the U.S., from structural components in construction, to flooring, furniture, lumber, material handling, decorative objects, and even for pulp and paper (Southern Pine Council, 2011). Recently, the decline of many wood products manufacturers, and the housing and pulp and paper industry have produced a large surplus of planted southern pine, with decreased prices and availability of timberland (Conrad et al. 2011), which is being mostly acquired by biomass facilities for solid biofuels production such as pellets (Green Circle Bio Energy Inc., 2011), and briquettes (Carolina Pacific LLC, 2009). Many producers prefer to utilize softwoods (such as pine), since they are easier to chip and mill, due to its lower density (Marinescu and Bush, 2009). For such fuels, transportation, availability, and capital costs are limiting factors in feedstock selection (Marinescu and Bush, 2009); since sources of southern pine are readily available at the present moment, its technical and economic evaluation for solid biofuels production renders necessary. In addition, with pine pulpwood chips prices decreasing systematically; there is

evidence that currently there is little or no competition between forest industry mills and wood-to-energy facilities (Conrad et al. 2011), being yet another reason for its utilization in the biomass to bioenergy industry.

Southern pine utilization for biomass has gathered attention in the southeast of the U.S., creating many projects for the development of high-productivity, and low-cost supply and logistics systems for southern pine energy plantations, in an effort to provide the lowest delivered cost of biomass (Auburn University, 2011). Since several efforts are being conducted in the areas of supply chain, delivered costs, and productivity, it deems necessary to also evaluate the potential energy obtained from processing southern pine biomass into biofuels, its ratio to the amount of energy utilized in processing it, the economics of its processing, and the most adequate conversion pathways for such biomass.

2.3.1.1.2 Eucalyptus

Hardwood trees are expected to provide with substantial feedstock for the bioenergy industry, depending on the biofuel produced (cellulosic ethanol, pellets, biodiesel, etc.) (Merkle and Cunningham, 2011). In this sense, hybrid poplars are typically mentioned when discussing biomass to energy plantations (Tuskan, 1998), mainly due to its availability (Tuskan et al. 2006), and more recently, eucalyptus has also attracted high interest as a hardwood for bioenergy (Gilbert, 2007). However, hybrid poplars still have to be proven suitable as bioenergy plantations in the southeast of the U.S., since climatic conditions in the region may severely affect productivity (Tschaplinski et al. 1998). In this sense, eucalyptus presents the advantage over poplar of being freeze-tolerant, and fast-growing (Wright, 2010).

Hardwoods, and more specifically eucalypts, are rarely mentioned in current literature as potential feedstock for cellulosic biomass (Merkle and Cunningham, 2011). However, as far back as the 1970’s and 1980’s, the U.S. Department of Energy Short-Rotation Woody Crops program intended to identify potential candidates for biomass to bioenergy plantations, with many hardwoods tested at the time (Steinbeck and Skinner 1985, Tuskan 1998). During the 1990’s, the Department of Energy eliminated many candidates, narrowing the focus of the program (Tuskan 1998). With continuous advances in hardwood silviculture, genetics, and forestall varieties, a strong case for reconsidering alternative hardwoods for bioenergy in

the U.S. exists in the present (Merkle and Cunningham, 2011). Some hardwoods are currently being evaluated for pellets production, having the possibility of generating electricity through co-firing with coal, or gasification, offering powerful advantages to make bioenergy production economically viable in the southeastern U.S. (Merkle and Cunningham, 2011). This opportunity has been recognized by the U.S. Department of Energy in recent years, by adding eucalyptus and other hardwood varieties to the "Growing Bioenergy and Carbon Cycling Portfolio" (Gilbert, 2007), and in 2011, the complete genome of eucalyptus was deciphered as part of this effort (specifically, Eucalyptus Grandis) (The Joint Genome Institute, 2011). This sequencing opens many opportunities for the improvement of biomass from eucalyptus in the U.S., and for the production of renewable bioproducts (University of Pretoria, 2011). The interest generated in the U.S. towards the potential utilization of eucalyptus 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, Merkle and Cunningham (2010) highlight that rapid biomass growth, along with a guaranteed supply of high-quality feedstock throughout the year are key elements to make hardwoods such as eucalyptus worthy of consideration for energy production in southern U.S.

2.3.1.1.3 Mixed Sources

Mixed sources of forest biomass, such as forest thinnings, harvest residues, and hardwood chips, have been considered and widely utilized for bioenergy production in the U.S., especially in the manufacturing of solid biofuels such as pellets and briquettes (Marinescu and Bush, 2009). The main reason for the utilization of forest residues for bioenergy is the availability, at a relatively economic cost, of such. A recent report by the U.S. Department of Agriculture indicates most regions and counties in the east and southeast states of the U.S. have more than 25 thousand dry tons/year of forest residues available (Milbrandt, 2005). These residues have the potential to provide and expand biomass availability for bioenergy production in the U.S. (Perlack et al. 2005), and aid in the goal of reaching a sustainable 1-million tons of biomass supply per year.

One of the common problems when dealing with forest residues and chips for bioenergy, is the identification, separation, and suitability of these resources for bioenergy, since it can include rotten wood, tree tops and limbs, and other undesirable biomass that may significantly affect the quality of the biofuels manufactured, generating the need to characterize these residues, in order to accurately utilize them for bioenergy, being able to generate products with homogeneous characteristics and quality. This characterization and economic analysis is necessary, since 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), and its removal require that it be utilized in other activities, or disposed for, having the bioenergy industry as a key element for its utilization.

An additional reason for the evaluation of forest residues and hardwood chips is the projected increase in forest inventory throughout the year 2050. Current removals of U.S. forest standing inventory are far less than the total standing inventory, and by the year 2050, forest inventories are projected to increase relative to removals, significantly increasing the availability of residues, but also the fire hazards (Perlack et al. 2005). This scenario creates an ideal ground for a bioenergy industry based on forest residues for the medium to long term, increasing the necessity to evaluate its suitability and economic aspects for biofuels production.

2.3.2 Analysis of Selected Solid Biofuels

The selection of an adequate conversion process for biomass to bioenergy is as critical as the correct biomass selection. Many technologies are currently available or under development, with cellulosic ethanol and solid biofuels (pellets, briquettes, and torrefied wood) being among the most important currently. Cellulosic ethanol is a technology that still requires optimization, and is currently not competitive cost-wise with fossil fuels (Merkle and Cunningham, 2010). On the contrary, solid biofuels, with the exception of torrefied wood, have been in the market for decades, allowing the technology for its production to evolve and become more efficient, improving quality and costs. However, these biofuels were always reduced to a small sector of the bioenergy market, mainly in European

countries, and in few industrial applications in the U.S. The recent worldwide increment in prices in the energy sector, and the creation of many policies for carbon emission reduction, and fossil-fuels displacement in many countries has significantly increased the demand of these fuels. The global production of wood pellets has almost doubled during the period of 2007-2009, and projections indicate that Europe will reach a consumption of more than 50 million tons per year by 2020, being a 6-time fold increase in market (Pirraglia et al. 2010).

An important reason for this increase and interest in solid biofuels is it capability for being used in direct co-firing for industrial facilities. Biomass presents certain characteristics that make its direct use for bioenergy not viable in a large scale, especially for co-firing applications. These characteristics are:

- Capital and operational costs of biomass gasifiers, turbines, and boilers are high
- Cultivated biomass feedstock (in most locations in the U.S.) cost more than coal, which has been the traditional fuel for burning applications
- Biomass availability may be seasonal
- Low biomass density limits its economic transportation range
- High oxygen/carbon ratio of biomass leads to gaseous sub-products with low heating value
- Green biomass requires drying, high moisture content is not tolerated in many power generation applications
- Properties of the ashes from biomass can lead to low melting points, which can affect boilers performance (Green et al. 2000).

Many of these non-desired characteristics can be modified or eliminated through densification or torrefaction processes, which delivers a more homogeneous product, highly suitable for applications in stoves, boilers, and industrial burners; hence, it is important to evaluate its economics and technical aspects for U.S. production.

2.3.2.1 Wood Pellets

Wood pellets have gathered a substantial importance as an alternative fuel in the U.S. during recent years. Between 2005 and 2007, pellet fuel production increased by 25% in the United States (Bowyer 2008), and currently, the United States ranks in the top three, along with Sweden and Canada, in annual pellet production (Peksa-Blanchard et al. 2007). Even more noticeable is the increase from 2002 through 2007, in which U.S. production increased more than 200% (Pirraglia et al. 2010). This increase in production is due to the opening of many new facilities, especially in the Southern U.S., expanding the capacity of the U.S. for exports, mainly to European countries. In addition to exports, internal consumption of wood pellets has also increased significantly reaching more than 1 million residences and businesses currently using pellets for heating (PFI, 2011). This increase in both the internal market and the exports market requires a well-balanced supply of pellets from both, large producers, and small, local producers. This characteristic indicates that a variety of biomass sources and factory configurations will be used in order to satisfy the demand, and the economics and technical aspects of this must be correctly assessed, if a sustainable and mature market is to be developed.

Moreover, the Pellet Fuel Institute (PFI, 2011) also cites the main reasons and benefits to continue research and development of wood pellets; these are:

- Typical U.S. homeowners use 3 tons of pellets per heating season at a cost of about $825. With an average retail price of $250/ton, pellets offer a fuel cost per million BTU of $19.05. To offer a fuel cost of $19.05 per million BTU, # 2 fuel oil and propane would have to be priced at $2.05/gal and $1.36/gal, respectively.
- Direct thermal conversion of 3 million tons of wood pellets, at an efficiency level of approximately 80% displaces the equivalent of almost 8.5 million barrels of Number 2 fuel oil; that is 356 million gallons.
- Pellet stoves have extremely low particulate emissions due to their high burn efficiency and the density of the fuel (<1 gm/hr).
- Every ton of pellets used vs. oil reduces CO2 emissions by about 1.5 tons. Total emissions offset this year (2011) will be nearly 4.5 million tons of CO2.
- Pellet distribution costs less than the cost of distributing wood chips.

- Wood pellets have a fossil energy ratio (net energy output/fossil energy used) of 12:1.
- As of 2009, pellet manufacturing directly employs approximately 2,300 people in the U.S. and supports thousands of industry-related jobs in fields such as transportation and logging. (Spelter and Toth, 2009)
- Location of ports, better road infrastructure, and year-round harvesting makes the U.S. a more ideal exporter for European countries than Canada (Pirraglia et al. 2010)

2.3.2.2 Torrefaction

Torrefaction has been regarded as one of the most promising technologies for biomass processing into biofuels (Lipinsky et al. 2002). Torrefaction as a pre-treatment has the benefit that it would turn a low-energy density material, with high moisture content and hygroscopicity, and that will decay during storage, into a material that is hydrophobic, achieves a equilibrium moisture content around 3%, reduces the biomass weight by 20 to 30%, is easy to store, and will not decay, while retaining around 90% of the wood's original energy content (Lipinsky et al. 2002). Such characteristics of the process have created expectations and drawn attention to its commercialization. At this point, torrefaction is a technology under development, and has not reached commercial stage. With more than 13 patent applications for this technology in the U.S. only, and more than 22 projects for the next 3 years in development of a commercial torrefactor (Melin, 2011), this technology is expected to be available in the near-term future, making critical its evaluation of success and challenges factors, Especially since this technology is expected to provide a solution for a substitution or displacement of coal in direct firing and co-firing operations (Lipinsky et al. 2002).

Some efforts in identifying potential and success factors for torrefied biomass have been recently performed. The Food and Agriculture Organization (2004, modified from Smith et al. 2001)) has assessed the potential and differences for several biomass conversion processes (Table 2.1), based on Feedstock, Conversion Technique, and System Aspects, evaluating the production of charcoal-like material (torrefied) for energy production.

Table 2.1. Assessment of promising biofuels in terms of feedstock, technology, and system aspects (Smith et al. 2001)

	Charcoal prod. & use for heat production.	Syngas production & elect. generation	Pyrolysis oil prod. & use in engines	Vegetable oil prod. & transport. use	Veg. oil esterification & transport use	Alcohol production & transport use	Biogas production & elect. generation
Feedstock							
By-products	++	+++	+++				++
Energy Crops	+++	+++	+++	+++	+++	+++	+
Conversion Technique							
Technology	+++	++	+	+++	+++	+++	++
System Technology	+++	+	+	+++	++	++	++
System Aspects							
System Integration	+	+++	+++	+	+++	+++	++
Environmental Benefits	++	+++	+++	+++	+++	+++	++
Costs	++	+	+	+	+	+	+
Cost Red. Potential	+	+++	+++	+	+	+	++

Evaluation: + less promising; ++ promising; +++ very promising

Source: Smith, K.R.; Kaltschmitt, M.; Thrän, D. 2001 [19]

This preliminary study indicates that the production of charcoal-like biofuels are very promising, especially with the utilization of energy crops (such as eucalyptus plantations), with enhanced environmental benefits and costs. However, this study also indicates the need to further study the cost reduction potential (economic factor), and the system integration (technical factor) of producing this type of solid biofuel. In addition, other technical concerns exist, regarding maintenance and costs of the machinery (Melin, 2011), making necessary to further evaluate the many aspects of implementing this technology in a large scale, and with the correct types of biomass.

2.3.2.3 Combined Torrefaction-Pelletization

System integration of torrefied biomass with other technologies has also been proposed and investigated, stating that properties and advantages of torrefied biomass can be further improved by a combination of the torrefied material with densification (e.g. pellets), producing a very energy-dense fuel (Bergman and Kiel, 2005). Some author have even stated that the future of the wood pellets industry will rely in switching to torrefied wood pellets technologies, since it is a matter of inserting the torrefaction process into an existing enterprise, which 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 arises for its potential utilization for biomass firing and co-firing in coal plants. Torrefied biomass has lost the fibrous structure, making it very suitable for coal mills; this gives the opportunity for significant increases in biomass/coal ratio in power plants (IEA Bioenergy, 2009a). Among the benefits of a combined torrefaction-pelletization processes are:

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

All 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 torrefied pellets indicate that the pelletization can be easily achieved, with low energy input required, but the quality of the pellets highly depends on the pelletization conditions, including the correct selection of biomass and machinery (Kiel, 2007). 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 product. The future research performed in these areas will answer many of the questions regarding the feasibility and profitability of such combination, especially for U.S. producers. 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.), and economic aspects (gains in energy vs. 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.

2.3.3. Direct Firing and Co-Firing

With a wide variety of conversion technologies for bioenergy in existence, all of them with different requirements for research and development, it becomes difficult to select an appropriate technology or group of technologies for study. However, the analysis of conversion technologies depends heavily in the end-use of the biofuel, such as domestic heating, district heating, industrial power generation, or transport applications (Bauen, 2005). Following these principles, processes such as fermentation, anaerobic digestion, and esterification are either on early demonstration stages, or requires very specific types of biomass resources (Table 2.2).

Table 2.2. Biomass technologies, end users, and status. (Modified from Bauen, 2005)

Conversion Technology	Resource Type	Example of fuels	Product	End-Use	Technology Status
Combustion	Solid Biomass	Wood logs, chips, pellets, torrefied wood, solid waste	Heat	Heat, Electricity	Commercial
Gasification	Solid Biomass	Wood chips, pellets, torrefied wood	Syngas	Heat, Electricity	Demonstration/ early commercial
Pyrolisis	Solid Biomass	Wood chips, pellets, torrefied wood	Pyrolisis oil and by-products	Heat, Electricity (engine)	Demonstration/ early commercial
Pressing/ Sterification	Oleaginous crops	Oilseed rape	Biodiesel	Heat (Boiler), Electricity (engine), Transport fuel	Commercial
fermentation/ Hydrolysis	Sugar/starch/ lignocellulose	Sugarbeet, corn, fibrous and woody biomass	Ethanol	Transport fuel	Early demonstration
Anaerobic Digestion	Wet biomass	manure, sewage sludge	Biogas and by-products	Heat (boiler), Electricity	Commercial

Processes such as combustion, gasification, and pyrolisis are in a more commercial stage at this moment, and require only a solid biomass input, being more versatile than other processes in the type of biomass used, and the end-uses. Combustion of biomass includes direct firing and co-firing of biomass with coal, from which currently, there are more than 40 combined heat and power plants utilizing co-fired woody biomass in the U.S. alone. The U.S. Department of Energy, through the New Technology Demonstration Activities program, has developed and evaluated the benefits and potential of biomass firing and co-firing, including cost-savings mechanisms, and factors influencing performance. Preliminary results of this evaluation indicated that biomass co-firing reduces operating and landfill costs, reduces the fuel price risk, allows facilities to make use of local biomass supplies, and only (if any) requires minimum modifications to existing equipment and operations (DOE, 2004). Since firing and co-firing biomass with coal is expected to become more widespread in the U.S. in the near future, technical and economic aspects of the biomass and biofuel types utilized for this process must be further and thoughtfully evaluated, in order to provide with accurate delivered costs and energy content of the biomass received, which may determine the profitability ad suitability of the biomass and biofuel used for co-firing.

3. METHODOLOGY

3.1. Overview of the Methodological Approach

In this dissertation the types of potential biomasses and variables that affect the technical and economic aspects of producing solid biofuels intended for burning and/or co-firing are analyzed. A flow chart is presented in Figure 3.1 illustrating an overview of the methodology followed for developing the project.

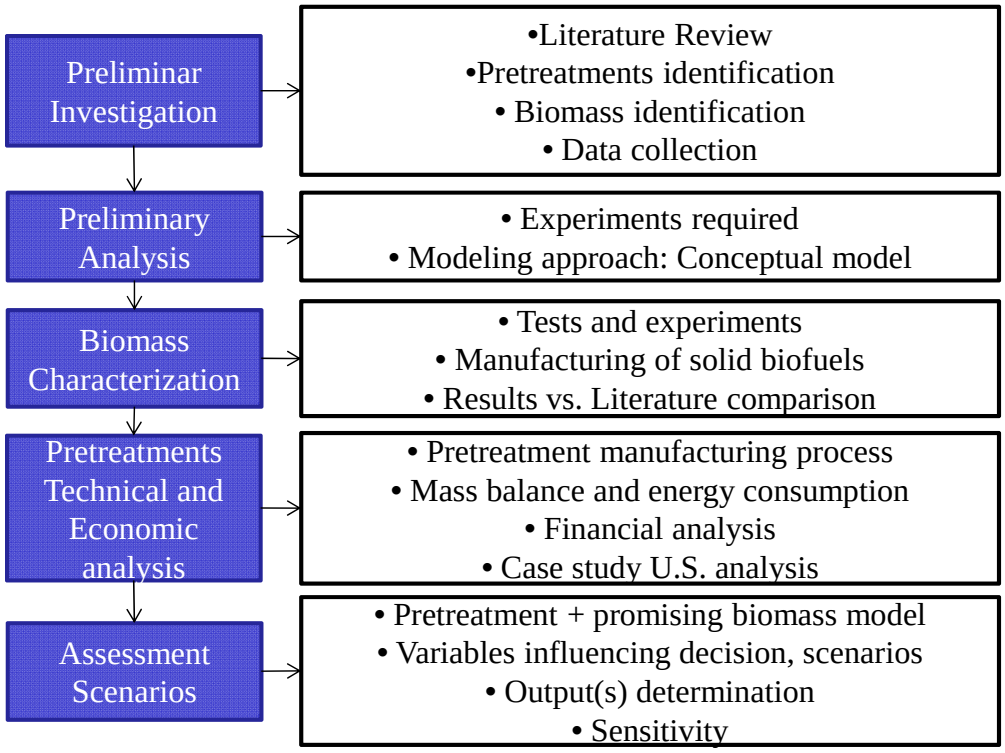


Figure 3.1. Methodological diagram developed and followed by the research team

Detailed methodologies are presented in each peer reviewed article that is included in this dissertation. A general overview of the methodology is discussed below.

3.2. Variables: Identifying potential sources of biomass and promising pre-treatments

The first step taken was identifying potential sources of biomass and promising pre-treatments to serve as fuel sources for burning and/or co-firing.

Species of biomass influences the cost and availability of feedstock. Wood availability, raw material cost, and other factors also influence the selection of biomass. Southern yellow pine was selected due to its large availability, wide range of growth in the U.S., industry experience in its harvesting and characteristics, and its expanding utilization in the solid biofuels industry. Eucalyptus species were selected for its potential to become a sustainable source of biomass for the U.S. in the near future, due to recent advances in cold tolerance, growth rates, properties, and the interest of many programs and companies in its

utilization for biofuels. In addition, mixed sources of residues are also important for evaluation, since they represent considerable amounts of biomass that are currently underutilized, with many standing in the forests, increasing the risk of wildfires, and many being removed from forests and disposed later.

In the United States, over the past several years, there has been a tremendous amount of investment in building pellet mills to supply European coal fired electrical generation plants with a bio-fuel to be mixed in with coal as a mitigation for reducing carbon emissions. In addition, countries such as Sweden heavily rely on wood pellets for domestic heating, importing much of its consumption from Canada (Hansen, 2009). Due to this high interest in wood pellets production for direct firing and co-firing, and the market expansion experienced in the U.S., this process is ideal for further study in technical and economic aspects.

Additionally, there has been a great deal of interest by researchers and policy makers in torrefaction, but so far there has been little adoption of the technology by energy producers. Mainly, torrefaction is still in early trials and commercialization stage, and the preliminary results that many institutions and companies are obtaining give indication of promising applications for this technology (Melin, and2011; Kiel, 2007; Bergman and Kiel, 2005; Bergman et al. 2005), reason why its study (technical and economic) is important at this point.

With preliminary tests developed in the production of torrefied wood, and an extensive body of literature and experience in the manufacturing of wood pellets, companies, institutions and researchers have pondered the possibility of combining both technologies in a single dedicated process for the production of torrefied wood pellets, stating that such product will further enhance the properties of the torrefied wood by increasing the energy density (energy contained in the biomass per unit of volume), and facilitating its used in coal burners and boilers (Zwart et al. 2006). The challenges of manufacturing such product, as well as the characteristics of the process, and the economics of its production are still to be developed, making this combined process an ideal third candidate for solid biofuel pre-treatment evaluation.

Thus, three types of pre-treatments were identified as suitable for the production of highly efficient solid biofuels for co-firing, along with three different types of woody biomass. In order to assess properties and characteristics, different data collection mechanisms were utilized for pre-treatments and for biomass sources (Figure 3.2).

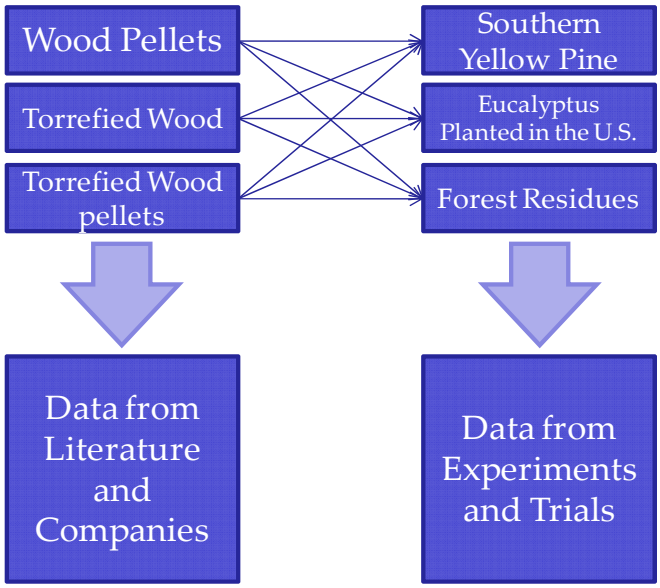


Figure 3.2. Data sources, biomass sources, and pre-treatments

Furthermore, to compare these pre-treatments, a base case has to be established as a point of reference and comparison. In the wood fuels industry, the ideal base-case scenario is the transportation of green wood chips to the burning/co-firing facility, or port (in the case of exports market). This base case is use to be compared with the proposed pre-treatment options (pellets, torrefied wood, and torrefied wood pellets).

3.3. Modeling Approach

A conceptual model (Figure 3.3.) identifies the relationship between the biomass sources, pre-treatments and firing method, allowing developing a sequence of intended publications in each area, in order to correlate the most adequate pre-treatment with a type of biomass, and end-users/applications scenarios.

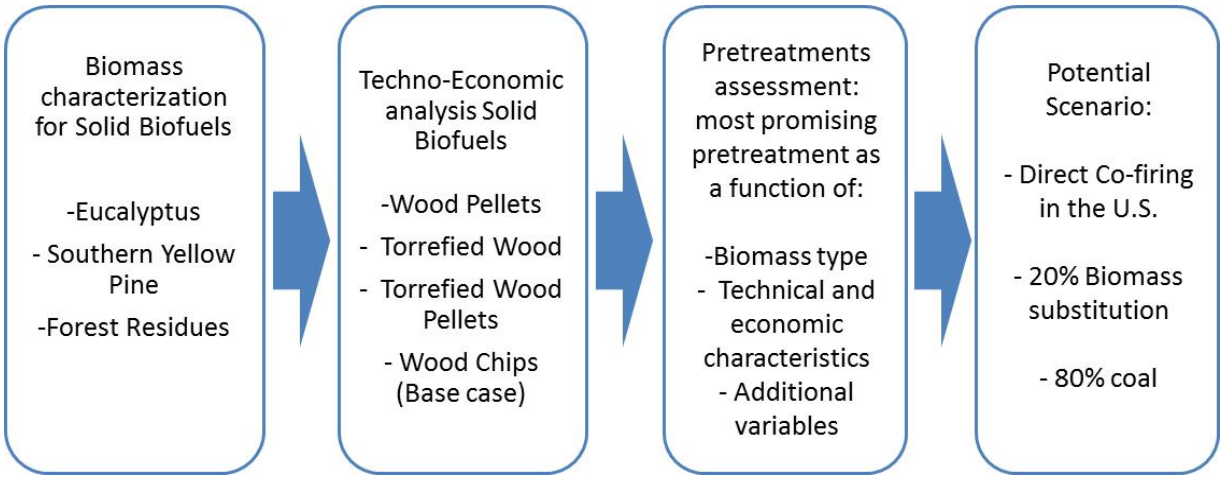


Figure 3.3. Conceptual Model considering biomass, pre-treatments, economic and technical variables, and end-users

Following the structure of the conceptual model, a set of peer-reviewed papers deal with the technical and economic analyses of pre-treatments for solid biofuels. A second set of published, peer-reviewed papers analyses the characteristics of the most promising sources of woody biomass for solid biofuels, through experimental results and comparisons with literature values. Below is a list of intended publications dealing with each pre-treatment, and biomass analyses:

- Freeze tolerant eucalyptus biomass: a study of characteristics and suitability for solid fuels production. Status: Under review, Biomass and Bioenergy Journal.
- Fuel Properties and Suitability of Eucalyptus Benthamii and Eucalyptus Macarthurii for Torrefied Wood and Pellets. Status: Published. Bioresources Journal.
- Techno-Economic Analysis of Wood Pellets for U.S. producers. Status: Published. Bioresources Journal.
- Techno-Economic Analysis of Torrefied Wood Production in the U.S. Status: Accepted with changes; changes already submitted for re-consideration and editing. Bioenergy Research.

- Techno-Economic Analysis of Torrefied Wood Pellets for U.S. Producers. Status: Accepted with changes; changes already submitted for re-consideration and editing. Energy Conversion and Management.
- Technical and Economic Assessment of current technologies for solid biofuels production with woody biomass intended for direct co-firing in U.S. markets. Status: Published. Bioresources Journal.

Data and analysis for southern yellow pine biomass, and the base-case scenario of green chips for burning is added as chapters of this document, but is not included as peer-reviewed publications.

It is important to note that the final publication mentioned (Technical and Economic Assessment) is a comprehensive analysis that comprises the findings developed through the pre-treatments' models with the characteristics found for the biomasses evaluated, including additional variables that influence a decision regarding the best pre-treatment choice. This publication considers additional variables and scenarios that influence not only production of a given type of solid biofuel, but also variables such as final energy outputs depending on biomass types, processes, and energy input, production volumes that may influence the economics of a given pre-treatment, energy conversion efficiency, and market scenarios.

Previous to perform experiments with biomass, and modeling the pre-treatments, the premises and limitations of the model process are listed and defined, in order to understand its implications and perform successful models. The following paragraphs depicted the assumptions, premises and limitations of the modeling process.

3.1.4 Biomass Characterization

As previously mentioned, biomass characterization for southern yellow pine, eucalyptus species, and forest residues are obtained through direct experimentation. Samples from southern yellow pine, several eucalyptus species, and forest residues are tested and processed to produce wood pellets, torrefied wood, and torrefied wood pellets, evaluating the characteristics of each raw material and of the final product. For this characterization, the

ASTM standards are used. Each standard used is described in detail in each chapter dealing with biomass characterization and solid biofuels production.
In addition, the results obtained from each characterization parameter are compared to results obtained in previous studies if available.

3.5. Technical and Economic Analyses

To appropriately evaluate the technical and economic variables for the different biomass sources and pre-treatments, a modeling approach must be utilized to gain information about mass balance and energy consumption in order to develop estimated production rates and production costs. To conduct this evaluation Microsoft Excel™ is utilized to develop a spreadsheet model. Each model created for each pre-treatment is detailed explained in each pre-treatment's chapter.

3.6. Verification and Validation

In each chapter developed for the pre-treatments technical and economic evaluations there is a section that deals with verification and validation for the models. Since the characteristics and market availability of the pre-treatments are different, the verification and validation section varies according to each pre-treatment.

A common element of verification and validation for every pre-treatment is a sensitivity analysis. Changes in the most important production variables are introduced in the model, and the economic outputs such as Net Present Value (NPV) and Internal Rate of Return (IRR) are measured. The percentage of change in these variables compared to the original case represents a measure of the sensitivity of the variables, and allows also verifying that the models tolerate changes in the variables, and adjusts the results as a function of the changes. Depending on the market status of the technology, the validation of the outputs varies. If the technology is commercially available, the verification and validation is performed based on real market data, such as current average prices and production costs, verifying that the model delivers similar information. In the case in which the technology is not commercially available, comparisons can be made with previous literature (if available), and with estimates of the scale-up of bioenergy facilities.

3.7. Assessment Scenarios

Once the pre-treatments have been detailed described, and a functional model has been proposed, an assessment of the pre-treatments, combined with the utilization of a given biomass (previously characterized) determines the potential energy content that can be obtained from the product. In this assessment, several other variables, most of them yet to be researched, will influence the selection of one pre-treatment over another. Proposed variables that may influence this decision include, but may not be limited to:

- Production volumes
- Biomass selected
- Energy density
- Energy balance (energy used to manufacture the product vs. energy obtained from the product)
- Transportation and additional handling processes and costs
- Energy conversion efficiency
- End-Use and/or End Users (e.g. U.S. market)

In order to test the assessment proposed, it is developed a set of scenarios. Such scenarios may consider changes in production parameters (volume), raw material characteristics (energy content, availability), or additional variables. The objective of such scenarios is to test changes in the variables of the assessment, and evaluate if those changes may also cause a change on the selection of the most promising pre-treatment. If this is the case, it can be said that the pre-treatment selection is sensitive to one or more of the variables modified, and can give as a result a “range” in which one pre-treatment will be preferred in detriment of another, under different conditions.

3.8. Assumptions and Premises

When handling the data for this project, several assumptions are made previous to the analysis of the collected sets of values in each variable:

- For the development of the pre-treatments models, it is assumed that the biomass has a fixed cost as received on the factory yard, and is denominated delivered costs of biomass. In most cases, these delivered costs are based on previous literature recently published, which analyses and deals with all the aspects of delivering biomass to a bioenergy factory. In this sense, it is of special importance the work performed by Gonzalez et al. (2010a, 2010b, 2010c); from the models developed by him, several delivered costs for biomass have been obtained, and adjusted to the present year's economic conditions.
- Biomass characterization is solely based on direct experimental results. Several authors describe methods that calculate certain parameters for biomass characterization, such as Boie (1952), who developed a method for calculating the energy content (heating value) of a given biomass based on its elemental composition. These formulations provide, in the majority of cases, a good approximation of the experimental values; however, to increase the accuracy of the study, only experimental values are utilized.

3.9. Limitations

- The boundaries of the models for technical and economic evaluation of the pre-treatments are considered as "factory gate", meaning that the models start with received material at factory gate, at a given price, and end with a final product in the warehouse, without considering delivery to distributors or final users.
- A basic evaluation of the conversion efficiency of the biomass to bioenergy through combustion processes is evaluated in the assessment. A detailed and throughout evaluation of the energy conversion efficiency would require a body of literature and development project on its own. In this project, approximations and assumptions that simplify the calculations are used, carefully evaluating the bias that such analysis could cause.

In the next chapters, a set of publications for biomass characterization are presented, with experimental data and findings for the biomasses selected for the study. Following, a complete development of the models for technical and economic evaluation of the pre-treatments is performed. Results from the models and case studies are also discussed in these

chapters. In addition, wood pellets, torrefied wood, and torrefied wood pellets are manufactured from the biomasses, and the results of its manufacturing are also discussed.

4. Literature Cited

Amidon, T. E. 2006. The biorefinery in New York: Woody biomass into commercial ethanol. Pulp Pap-Canada. 107: 47–50.

Anderl, H., and A. Mory. 1998. Operation Experiences in the CFB Gasification Project BioCoComb for Biomass with Co-combustion of the Gas in a PF Boiler at Zeltweg Power Plant, Austria. Proceedings of VTT Seminar: Power Production from Biomass III, Espoo, Finland. September 14-15.

Arcate, J.R. 2002. “Torrefied wood, an enhanced wood fuel”, Paper presented at Bioenergy 2002 conference, Idaho.

Auburn University. 2011. High Tonnage Forest Biomass Production Systems from Southern Pine Energy Plantations. Available at: http://www.nrmdi.auburn.edu/documents/HighTonnageProjectSummary.pdf. Consulted on: 07/29/2011.

Bakthavatsalam, V. 2000. Lending in the Biomass Energy Sector. Bioenergy: Vision for the New Millennium. Science Publishers, Inc. Plymouth, U.K.

Bauen, A. 2005. Chapter 2. Biomass in Europe. Bioenergy- Realizing the Potential. Swedish Energy Agency. Elsevier.

Balat M. 2008a. Hydrogen-rich gas production from biomass via pyrolysis and gasification processes and effects of catalyst on hydrogen yield. Energy Sources Part A. 30:552–64.

Balat M. 2008b. Progress in biogas production processes. Energy Educ Sci Technol. 22:15–36.

Balat M. 2009. Possible methods for hydrogen production. Energy Sources Part A. 31:39–50.

Balat, M., M. Balat, E. Kirtay, and H. Balat. 2009. Main Routes for the Thermo-Conversion of Biomass into Fuels and Chemicals. Energy Conversion and Management. 50: 3147-3157.

Baldridge, A., T. Dreaden, M. Kosa, K. Woody, C. Young, and A.J. Rakauskas. 2009. Wood Pellets for Biopower in the U.S. and in the E.U. Georgia Institute of Technology, Department of Chemistry and Biochemistry.

Basore, C.A. 1930. Fuel Briquettes from Southern Pine Sawdust. Engineering Experiment Station of the Alabama Polytechnic Institute. Bulletin 1.

Basore, C.A., and A.C. Moore. 1942. The production of lump charcoal from pine sawdust without a binder. Engineering Bulletin. 14.

Battacharya, S. C. 1990. Carbonized and Uncarbonized Briquettes from Residues. Procedures of workshop on biomass Thermal processing, London, Shell.

Bauen, A. 2005. Biomass in Europe. Bioenergy- Realizing the Potential. Swedish Energy Agency. Elsevier.

Bergman, P. 2005. Combined Torrefaction and Pelletisation: The TOP Process; Report C--05-073; Energy Research Centre of The Netherlands (ECN): Petten, The Netherlands; p 29.

Bergman P., A.R. Boersma, J. Kiel, and R. Zwart. 2005. Development of torrefaction for biomass co-firing in existing coal-fired power stations. BIOCOAL concept version, ECN report.

Bergman, P., and J. Kiel. 2005. Torrefaction for Biomass Upgrading. 14th European Biomass Conference & Exhibition, Paris, France, 17-21 October 2005

Bezzon, G., and J. Dilcio Rocha. Pyrolisis. 2000. Pyrolisis. Industrial Uses of Biomass Energy, The Example of Brazil. Taylor & Francis, London.

Bioenergy. NCR-SARE Bioenergy Position Paper. Nov. 2007. http://www.sare.org/ncrsare/bioenergy.htm. Consulted on: 04/06/2011

Biomass Energy Centre. 2011. What is Biomass?. Available at: http://www.biomassenergycentre.org.uk/portal/page?_pageid=76,15049&_dad=portal&_schema=PORTAL. Consulted on: 04/06/2011.

Boerrigter, H., J. Kiel, and P. Bergman. 2006. Biomass Pre-treatment by Torrefaction. Third ThermalNET Meeting, 3-5 April 2006. Lille, France.

Boie, W. 1952. Wissenschaftliche Zeitschrift der Technischen Hochschule Dresden. 2:687.

Bowyer, J.L. 2008. The Green Movement and the Forest Products Industry. For.Prod. J. 58(7):6 –13.

Bridgeman,T.G., J.M. Jones, A. Williams, and D.J. Waldron. 2010. An investigation of the Grindability of Two Torrefied Energy Crops. Fuel. 89: 3911-3918.

Bringezu, S., H. Schutz, M. O´Brien, L. Kauppi, R. W. Howarth, and J. McNeely. 2009. Towards Sustainable Production and Use of Resources: Assessing Biofuels. The United

Nations Environment Programme. Available at: http://www.uneptie.org/scp/rpanel/pdf/Assessing_Biofuels_Full_Report.pdf. Consulted on: 05/22/2011.

Carolina Pacific, LLC. 2009. Clean Power from the Americas to Europe. Available at: http://carolina-pacific.com/1.html. Consulted on: 07/29/2011.

Chambost, V., B. Eamer, and P. Stuart. 2007a. Forest biorefinery: Getting on with the job. Pulp Pap-Canada 108, 19–22.

Chambost, V., R. Eamer, and P.R. Stuart. 2007b. Systematic methodology for identifying promising forest biorefinery products. Pulp Pap-Canada 108, 30–35.

Chynoweth, D. P., C. E. Turick, J.M. Owens, D. E. Jerger, and M. W. Peck. 1993. Biochemical Methane Potential of Biomass and Waste Feedstocks. Biomass. 5: 95-111.

Conrad, J.L.; M. Bolding, and M. Chad. 2011. Virginia's Woody Biomass Market: Opportunities and Implications. Southern Journal of Applied Forestry, 35(2): 67-72.

Coombs, J., 1996. Bioconversion Assessment Study. CPL Scientific Ltd., UK, Air-CT92-8007.

Demirbas, A. 2005. Biodiesel Production from Vegetable Oils by Supercritical Methanol. J Sci Ind Res. 64: 858-865.

Demirbas A. Biohydrogen generation from organic wastes. 2008a. Energy Sources Part A. 30:475–82.

Demirbas A. 2008b. Hydrogen production from carbonaceous solid wastes by steam reforming. Energy Sources Part A. 30:924–31.

Demirbas A. 2008c. Present and future transportation fuels. Energy Sources Part A. 30:1473–83.

Demirbas A. Bio-fuels from agricultural residues. 2008d. Energy Sources, Part A. 30:101–9.

Demirbas A. 2009. Political, economic and environmental impacts of biofuels: A review. Applied Energy. 86: S108-S117.

Demirbas, A., and I. Demirbas. 2007. Importance of Rural Bioenergy for Developing Countries. Energy Conversion and Management. 48: 2386-2398.

DOE. 2004. Biomass Cofiring in Coal-Fired Boilers. Available at: http://www.nrel.gov/docs/fy04osti/33811.pdf. Consulted on: 08/06/2011.

Domac, J., K. Richards, and S. Risovic. 2005. Socio-economic Drivers in implementing Bioenergy Projects. Biomass and Bioenergy. 28: 97-106.

Duijn, C. 2004. “Torrefied wood uit resthout en andere biomassastromen”. Presentation held at “Praktijkdag Grootschalige Bio-energie Projecten”, June 2004, SenterNovem.

EPRI. 1997. Renewable Energy technology Characterizations. Washington D.C., Electric Power Research Institute.

Evans, A. M., and R. T. Perschel. 2009. An Assesment of Biomass Harvesting Guidelines. Forest Guild, January 2009. Available at: http://www.csbp.org/files/Evans%20An%20Assessment%20of%20Biomass%20Harvesting%20Guidelines%2001%202009.pdf . Consulted on: 04/09/2011.

Exxon Mobil. 2004. A Report on Energy Trends, Greenhouse Gas Emissions, and Alternative Energy. Available at:

http://esd.lbl.gov/SECUREarth/presentations/Energy_Brochure.pdf. Consulted on: 05/20/2011.

FAO (Food and Agriculture Organization of the United Nations). 2004. Unified Bioenergy Terminology: UBET. Available at: ftp://ftp.fao.org/docrep/fao/ 007/j4504e/j4504e00.pdf. Consulted on 03/15/2011.

FAO (Food and Agriculture Organization of the United Nations). 2006a: Introducing the International Bioenergy Platform (IBEP); Rome - ftp://ftp.fao.org/docrep/fao/009/A0469E/A0469E00.pdf

Farrell, A.E., and A.R. Gopal. 2008. Bioenergy Research Needs for Heat, Electricity, and Liquid Fuels. MRS Bulletin. 33: 373-380.

Fox, T. R., E.J. Jokela, and H. Allen. 2004. The Evolution of Pine Plantation Silviculture in the Southern United States. General Technical Report SRS-75, U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, pp. 63–82.

Fox, T. R., E.J. Jokela, and H. Allen. 2007. The Development of Pine Plantation Silviculture in the Southern United States. J. For. 15, 337–347.

Frank, J. R., and W. H. Smith. 1993. Methane from Biomass. Science and Technology 1: Feedstock Development. Biomass. 5: 1-2.

Fritsche, U. W., K Hünecke, A. Hermann, F. Schulze, and M Adolphe. 2006. Sustainability Standards for Bioenergy. WWF Germany, Frankfurt am Main, November 2006. Available at: http://www.biofuelstp.eu/downloads/ WWF_Sustainable_Bioenergy_final_version.pdf. Consulted on: 04/08/2011.

Fung, P.H.Y., M.U.F. Kirschbaum, R.J. raison, and C Stucley. 2002. The potential for bioenergy production from Australian forests, its contribution to national greenhouse targets and recent developments in conversion processes. Biomass & Bioenergy. 22. 223-236.

Gigler, J., R. Sims, and J. A. Adams. 2002. Small Scale, Biomass-fired Electricity Production Systems – Present and Future. Massey University, Palmerton North, New Zealand. Pp. 47.

Gilbert, D. 2007. Eucalyptus, Foxtail Millet, Red Algae, and Novel Microbial Communities Added to Growing Bioenergy and Carbon Cycling Portfolio. Available at: http://www.jgi.doe.gov/News/news_6_8_07.html. Consulted on: 07/29/2011.

Grammelis, P. 2011. Solid Biofuels for Energy: A Lower Greenhouse Gas Alternative. Preface. Springer-Verlag London Limited.

Green, A. 1986. Proposal for a Gasification Studies Institute in Conjunction with U. Fla Cogeneration Plant.

Green, A., M. Zanardi, and S. Peres. 2000. Thermal Conversion of Biomass. Bioenergy: Vision for the New Millennium. Science Publishers, Inc. Plymouth, U.K.

Green Circle Bio Energy Inc. 2011. Pellet Specifications. Available at: http://www.greencirclebio.com/products.php. Consulted on: 04/15/2011.

Gonzalez, R., D. Saloni, R. Phillips, and J. Wright. 2010a. Loblolly Pine Biomass Delivered Cost. 2010 Biomass Conference, Minneapolis, MN.

Gonzalez, R., J, Wright, and D. Saloni. 2010b. The business of growing Eucalyptus for biomass. Biomass Magazine. April 2010.

Gonzalez, R., T. Treasure, R. Phillips, H. Jameel, D. Saloni, R. Abt, and J. Wright. 2010c. Converting Eucalyptus biomass into ethanol: Financial and sensitivity analysis in a co-current dilute acid process. Part II. Biomass and Bioenergy, 35(2), 767-772.

Hansen, M.T. 2009. Preliminary Pellet Market Country Report, Sweden. Available at: http://pelletsatlas.info/pelletsatlas_docs/showdoc.asp?id=090810135438&type=doc&pdf=true. Consulted on: 08/15/2011.

Hetman, F. 1973. Society and the Assessment of Technology. OECD, Paris.

Hinchee, M., W. Rottmann, L. Mullinax, C. Zhang, S. Chang, M. Cunningham, L. Pearson, N. Nehra. 2009. Short-rotation woody crops for bioenergy and biofuels applications. In Vitro Cell.Dev.Biol.—Plant. 45: 619–629.

Hoadley, R. B. 2000. Understanding Wood: A Craftsman's Guide to Wood Technology. The Taunton Press.

Hohenstein, W., and L. L. Wright. 1994 Biomass Energy Production in the United States: An Overview. Biomass and Bioenergy. 6(3): 161-173.

Hoque, M., S. Sokhansanj, T. Bi, S. Mani, L. Jafari, J. Lim, P. Zaini, S. Melin, T. Sowlati, and M. Afzal. 2006. Economics of Pellets Production for the Export Market. CSBE/SCGAB 2006 Annual Conference, Edmonton, Alberta, July 16-19 2006.

House of Commons, Environmental Audit Committee. 2008. Are Biofuels Sustainable? First Report of Session 2007-08. Available at: http://www.biomassenergycentre.org.uk/pls/portal/docs/PAGE/RESOURCES/REF_LIB_RES/PUBLICATIONS/BIOMASS%20SUSTAINABILITY%20STUDIES/76.PDF Consulted on: 04/10/2011.

Hunt, T., and D. Tennant. 2009. Co-Firing Biomass. Power Engineering. November 2009. 226-229.

IEA. 2009. Bioenergy – a Sustainable and Reliable Energy Source. IEA Bioenergy ExCo:2009:06. Available at: http://www.task39.org/LinkClick.aspx?fileticket=8IsypIOAwXs%3D&tabid=4426&language=en-US. Consulted on: 04/11/2011.

IEA Bioenergy. 2009a. Deliverable 4: Technical Status of Biomass Co-firing. Available at: http://www.ieabcc.nl/publications/091654%20D4%20Technical%20status%20paper%20bio mass%20co-firing.pdf. Consulted on: 07/28/2011.

IEA Bioenergy. 2009b. Global Co-firing Database. Available at: http://www.ieabcc.nl/database/cofiring.php. Consulted on: 08/02/2011.

IEA RETD. 2010. Better Use of Biomass for Energy. Position Paper. Available at: http://www.ieabioenergy.com/LibItem.aspx?id=6476 Consulted on: 04/11/2011.

IEA Bioenergy. 2011. Biomass Combustion and Co-firing: An Overview. Available at: http://www.ieabcc.nl/publications/t32.pdf. Consulted on : 08/02/2011.

Jerger, D. E., and D. P. Chynoweth. 1987. Anaerobic Digestion of Sorghum Biomass. Biomass. 14: 99-113.

Junginger, M., T. Bolkesjø, D. Bradley, P. Dolzan, A. Faaij, J. Heinimö, B. Hektor, Ø. Leistad, E. Ling, M. Perry, E. Piacente, F. Rosillo-Calle, Y. Ryckmans, P. Schouwenberg, B. Solberg, E. Trømborg, A. da Silva Walter, M. de Wit. 2008. Developments in International Bioenergy Trade. Biomass and Bioenergy. 32: 717-729.

Kaltschmitt, M., and M. Weber. 2006. Markets for solid Biofuelswithin the EU-15. Biomass and Bioenergy. 30: 897-907.

Kiel, J. 2007. Torrefaction for biomass upgrading into commodity fuels. Available at: http://www.ieabcc.nl/meetings/task32_Berlin_ws_system_perspectives/03_Kiel.pdf. Consulted on: 07/25/2011.

Kim, H., S. Kim, and B. E. Dale. 2009. Biofuels, Land Use Change, and Greenhouse Gas Emissions: Some Unexplored Variables. Environ. Sci. Technol., 2009, 43 (3), pp 961–967.

Klass, D. 1998. Biomass for Renewable Energy, Fuels, and Chemicals. Academic Press.

Kellet, P. 2004. Expansion of the Wood Pellets Market in Europe. Sustainable Energy Ireland, Renewable Energy Information Office.

Kong, L., G. Li, B. Zhang, W. He, and H. Wang. 2008. Hydrogen production from biomass wastes by hydrothermal gasification. Energy Sources Part A. 30: 1166–78.

Koopmans, A., and J. Koppejan. 1998. Agricultural and Forest Residues Generation, Utilization and Availability. Regional Consultation on Modern Applications of Biomass Energy, 6-10 January 1997, Kuala Lumpur, Malaysia.

Kotra, R. 2007. Closing the energy circle. Available at: http://biomassmagazine.com/article.jsp?article_id=1331. Consulted on: 02/25/2011.

Larson, E. D., S. Consonni, S. Katofsky, K. Iisa, and W.J. Frederick. 2006. Benefit Assessment of gasification-based biorefining in the kraft pulp and paper industry, 4 volumes, Department of Energy, Washington D.C., U.S.A.

Lev-Yadun, S. and R. Sederoff. 2000. Pines as Model Gymnosperms to Study Evolution, Wood Formation, and Perennial Growth. J. Plant Growth Reg. 19, 290–305.

Lipinsky, E.S., J.R. Arcate, and T.B. Reed. 2002. Enhanced Wood Fuels Via Torrefaction. Fuel Chemistry Division Preprints. 47(1): 408-410.

Lovins, A. B., et al. 2004. Winning the Oil Endgame: Innovation for Profits, Jobs, and Security, B. T. Aranow, Ed. Rocky Mountain Institute, Snowmass, CO. pp. 1–122.

Marinescu, M., and T. Bush. 2009. Wood to Energy: Use of the Forest Biomass for Wood Pellets. Available at: http://edis.ifas.ufl.edu/pdffiles/FR/FR26900.pdf. Consulted on 07/29/2011.

McKendry, P. 2002. Energy Production from Biomass (part 1): Overview of Biomass. Bioresource Technology. 83: 37-46.

Medford, D. 1973. Environmental Harassment or Technology Assessment?. Elsevier, London.

Melin, S. 2011. Torrefied Wood: A New Emerging Energy Carrier. Wood Pellets Association of Canada. Presented to: Clean Coal Power Coalition CCPC, March 9, 2011. Available at: http://www.pellet.org/linked/2011-03-09%20ccpc%20presentation%20(2).pdf. Consulted on: 08/06/2011.

Merkle, S., and M. Cunningham. 2011. Southern Hardwood Varietal Forestry: A New Approach to Short-Rotation Woody Crops for Biomass Energy. Journal of Forestry. January/February 2011.

Milbrandt, A. 2005. A Geographic Perspective on the Current Biomass Resource Availability in the United States. Technical Report. NREL/TP-560-39181.

Miles, Patrick D. 2004. Fuel Treatment Evaluator: Web-Application Version 1.0. U.S. Department of Agriculture, Forest Service, North Central Research Station, St. Paul,

Minn. Available at: http://ncrs2/4801/fiadb/fueltreatment/fueltreatmentwc.asp. Consulted on: 08/04/2011.

Moran, J.C., E. Granada, J. Porteiro, and J.L. Miguez. 2004. Experimental Modeling of a Pilot Lignocellulosic Pellets Stove Plant. Biomass and Bioenergy. 27: 577-583.

Nicholls, D., R. A. Monserud, and D. P. Dykstra. 2009. Biomass Utilization for Bioenergy in the Western United States. Forest Products Journal. 58 (1/2): 6-16.

Oak Ridge National Laboratory. 2011. The bioenergy Cycle: A Vision of the Future. Factsheet. Available at: http://bioenergy.ornl.gov/main.aspx. Consulted on: 04/09/2011.

Overend, R. P. 2004. Heat, Power and Combined Heat and Power. Bioenergy Options for a Cleaner Future. Elsevier, London. Pp.63-102.

Panoutsou, C. 2011. Solid Biofuels for Energy: A Lower Greenhouse Gas Alternative. Chapter 1, Supply of Solid Biofuels: Potential Feedstocks, Cost and Sustainability Issues in EU27. Springer-Verlag London Limited.

Parikka, M. 2004. Global Biomass Fuel Resources. Biomass Bioenergy 27, 613.

Parr Instruments. 2008. 1108 Oxygen Combustion Bomb, operating Instruction Manual. Available at: http://parrinst.com. Consulted on: 02/18/2011.

Patzek, T.W., and D. Pimentel. 2005. Thermodynamics of Energy Production from Biomass. Critical Reviews in Plant Sciences, 24: 5, 327 — 364

Penksa-Blanchard, M., P. Dolzan, A. Grassi, J. Heinimo, M. Junginger, T. Ranta, and A. Walter. 2007. Global wood pellets markets and industry: Policy drivers, market status and raw material potential. IEA Bioenergy Task 40. Available at:

www.bioenergytrade.org/downloads/ieatask40pelletandrawmaterialstudynov2007final.pdf. Consulted on: 07/12/2011

Perlack, R., L.L Wright, A.F. Turhollow, R. Graham, B.J. Stokes, and D. C. Erbach. 2005. Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply. Available at: http://www.osti.gov/bridge. Consulted on 08/05/2011.

Peter, G.F. 2008. Southern Pines: A Resource for Bioenergy. Genetic Improvements of Bioenergy Crops. Springer.

PFI (Pellets Fuel Institute). 2011. Benefits of Wood Pellets. Available at: http://pelletheat.org/pellets/benefits-of-pellets/. Consulted on: 07/22/2011.

Phanphanich, M., and S. Mani. 2011. Impact of Torrefaction on the Grindability and Fuel Characteristics of Forest Biomass. Bioresource Technology. 102: 1246-1253.

Phipps, K. E., K. Arha, K. G. Cassman, M. A. Delucchi, M. Z. Jacobson, J. R. Koseff, P. A. Matson, R. L. Naylor, B. H. Thompson. 2007. The Opportunities and Risks of Large-scale Production of Biofuels. Available at: http://woods.stanford.edu/docs/biofuels/BiofuelsCommentary.pdf. Consulted on: 04/08/2011.

PiR (The Swedish Association of Pellet Producers). 2006. Available at: http://www.pelletsindustrin.org. Consulted on: 04/30/2011.

Pirraglia, A., R. Gonzalez, D. Saloni, and J. Wright. 2010. Wood Pellets: An Expanding Market Opportunity. Biomass Magazine.

Ragauskas, Arthur., C. K. Williams, B. H. Davison, G. Britovsek, J. Cairney, et al. 2006. The Path Forward for Biofuels and Biomaterials. Science. 311. 484-489.

Ramamurthi, R., and G. Bali. 2000. Bioenergy. Bioenergy: Vision for the New Millennium. Science Publishers, Inc. Plymouth, U.K.

Raymond, D. and Closset, G. 2004. Forest products biorefinery: technology for a new future. Solutions September 2004: 49–53.

Reddy, K., and D. Rockwood. 1989. Breeding Strategies for Coppice Production in a Eucalyptus Grandis Base Population with Four Generations of Selection. Silvae Genetica. 38 (3-4).

REN21 (Renewable Energy Policy Network for the 21st Century) 2006: Renewables Global Status Report 2006 update; Paris www.ren21.net

REN21 (Renewable Energy Policy Network for the 21st Century) 2010: Renewables 2010, Global Status Report. Available at: http://www.ren21.net/Portals/97/documents/GSR/REN21_GSR_2010_full_revised%20Sept2010.pdf. Consulted on: 04/10/2011.

Resch, H. 1989. Fuel from wood residues; a profit center for mills. Forest industries.

Rice, T., and A. Burton. 2010. Meals per Gallons: The Impact of Industrial Biofuels on People and Global Hunger. Available at: http://www.actionaid.org.uk/doc_lib/meals_per_gallon_final.pdf. Consulted on: 04/11/2011.

Rockwood, D., C. Comer, D. Dippon, and J. Huffman. 1985. Woody Biomass Production Options for Florida. Fla. Agr. Exp. Sta. Tech. Bull. 856. 29 p.

Rockwood, D., and J. DeValerio. 1986. Promising Species for Woody Biomass Production in Warm-humid Environments. Biomass. 11: 1-17.

Rockwood, D., and G. Prine. 1988. Alternative Production Systems: Woody Crops (Chapter 17). Methane from Biomass-A systematic Approach. Elsevier Appl. Sci. 277-289.

Rockwood, D., and D.R. Dippon. 1989. Biological and economic potentials of Eucalyptus grandis and slash pine as biomass energy crops. Biomass 20, 155–165.

Rockwood, D., N. Pathak, and P. Sataphathy. 1993. Woody Biomass Production Systems for Florida. Biomass and Bioenergy. 5(1): 23-24.

Rockwood, D. 2000. Woody Biomass Production. Bioenergy: Vision for the New Millennium. Science Publishers, Inc. Plymouth, U.K.

Rosillo-Calle, F., S. V. Bajay, and H. Rothman. 2000. Industrial Uses of Biomass Energy, The Example of Brazil. Taylor & Francis, London.

Rosillo-Calle, F., P. de Groot, and S. L. Hemstock. 2007. The Biomass Assessment Handbook. Chapter 2: General Introduction to the Basis of Biomass Assessment Methodology. Earthscan, London.

Rothman, H., and A. Furtado. 2000. The Potential Contribution of Technology Assessment to Bioenergy Programmes. Industrial Uses of Biomass Energy, The Example of Brazil. Taylor & Francis, London.

Samson, R. 2006. The Potential for Biomass Energy Crop Production in Canada. Resource Efficient Agricultural Production (REAP)-Canada. Available at: http://www.fcpp.org/pdf/RogerSamsonMPEpresentationFeb0306.pdf. Consulted on: 05/22/2011.

Samson, R., C. H. Lem, S. B. Stamler, and J. Dooper. 2008. Chapter 16: Developing Energy Crops for Thermal Applications: Optimizing Fuel Quality, Energy Security and GHG Mitigation. D. Pimentel (ed.), Biofuels, Solar and Wind as Renewable Energy Systems, Springer Science+Business Media B.V.

Scientific American. 2009. Biomass: Can Renewable Power Grow on Trees?. Available at: http://www.scientificamerican.com/article.cfm?id=biomass-renewable-power-wood. Consulted on: 04/08/2011

Schmidt, A. 1992. Biomass Projects in Europe. Biomass for Energy and Industry, 7th E.C. Conference Oct. 1992, in Conference Proceedings, p. 95, Ponte Press, Germany.

Schroeder, R. 2000. Bioenergy. Bioenergy: Vision for the New Millennium. Science Publishers, Inc. Plymouth, U.K.

Seenayya, G., G. Reddy, M. Sai Ram, M. V. Swamy, and K. Sudha Rani. 2000. Production of Ethanol from Lignocellulosic Materials Using Clostridium thermocellum- A Critical Review. Bioenergy: Vision for the New Millennium. Science Publishers, Inc. Plymouth, U.K.

Senthilkjumar, V., and P. Gunasekaran. 2005. Bioethanol production from cellulosic substrates: engineered bacteria and process integration challenges. J Sci Ind Res. 64: 845–853.

Sheehan, J., V. Cambreco, J. Duffield, M. Garboski, and H. Shapouri. 1998. An overview of biodiesel and petroleum diesel life cycles, A report by US Department of Agriculture and Energy. P. 1–35.

Silveira, S. 2005. Bioenergy- Realizing the Potential. Swedish Energy Agency. Elsevier.

Sims, R. 2002. The Brilliance of Bioenergy in Business and in Practice. James & James, London.

Sims, R., and P. Venturi. 2003. All-year-round Harvesting of Short Rotation Coppice Eucalyptus Compared with the Delivered Costs of Biomass from More Conventional Short Season, Harvesting Systems. Biomass and Bioenergy. 26: 27-37.

Sims, R., and N. El Bassam. 2004. Biomass and Resources. Bioenergy Options for a Cleaner Future. Elsevier, London. Pp.1-28.

Silveira, S. 2005. How to Realize the Bioenergy Prospects?. Bioenergy - Realizing the Potential. Elsevier.

Siry, J. P., W.D. Greene, T.G. Harris, R.L. Izlar, A.K. Hamsley, K. Eason, T. Tye, S.S. Baldwin, and C. Hyldahl. 2006. Wood supply chain efficiency and fiber cost – What can we do better? For. Prod. J. 56, 4–10.

Smith, K.R., M. Kaltschmitt, and D. Thrän. 2001. Renewable Energy from Biomass. Contribution for the Encyclopedia of Physical Science

Smith, P H., F. M. Bordeaux, M. Goto, A. Shiralipour, and A. Wike. 1988. Methane from Biomass: A Systems Approach. Elsevier, London. Pp. 291-334.

Smith, P H., and J. R. Frank. 1988. Methane from Biomass. Elsevier, London. Pp. 79-82.

Sokhansanj, S. 2011. 2011 DOE Biomass Program Review Universal Project Abstract. Feedstock Treatments for Thermal Reactors. Oak Ridge National Laboratory.

Somerville C. 2006. The billion-ton biofuels vision. Science 312: 1277.

Southern Pine Council. 2011. Using Southern Pine. Available at: http://www.southernpine.com/using-southern-pine.asp. Consulted on: 07/29/2011.

Spelter, H., and D. Toth. 2009. North America's wood pellet sector. Research Paper FPLRP656. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 21 p.

Steinbeck, K., and T.M. Skinner. 1985. Growing Short-Rotation Forests in the Southeastern U.S. Bioenergy. 84 (2):63-69.

Stuart, P. 2006. The forest biorefinery: Survival strategy for Canada's pulp and paper sector?. Pulp Pap-Canada 107, 13–16.

Southern Environmental Law Center, 2011. Proposed and Existing Woody Biomass Facilities in the Southeastern U.S. Available at: http://www.southernenvironment.org/uploads/fck/file/biomass/woody_biomass_facilities_detailed_map_list_new.pdf. Consulted on 05/01/2011.

Syring, J., A. Willyard, R. Cronn, and A. Liston. 2005. Evolutionary Relationships Among Pinus (Pinaceae) Subsections Inferred from Multiple Low-copy Nuclear Loci. Am. J. Bot. 92, 2086–2100.

The Joint Genome Institute. 2011. Eucalyptus Grandis Genome. Available at: http://www.phytozome.net/eucalyptus.php. Consulted on 7/29/2011.

Tillman, D. 2000. Biomass co-firing: The Technology, The Experience, The Combustion Consequences. Biomass and Bioenergy. 19 (6): 365-384.

Towers, M., T. Browne, R. Kerekes, J. Paris, and H. Tran. 2007. Biorefinery opportunities for the Canadian pulp and paper industry. Pulp Pap-Canada 108, 26–29.

Tschaplinski, T.J., G.A. Tuskan, G.M. Gebre, and D.E. Todd. 1998. Drought Resistance of Two Hybrid Populus Clones Grown in Large-Scale Plantation. Tree Physiol. 18:653–658.

Turnbull, J. W. 1999. Eucalyptus Plantations. New Forests 17: 37–52.

Tuskan, G.A. 1998. Short-rotation woody crop supply systems in the United States: What do we know and what do we need to know? Biomass & Bioenergy. 14:307–315.

Tuskan, G.A., S. Difazio, S. Jansson, J. Bohlmann, et al. 2006. The genome of western black Cottonwood, Populus Trichocarpa (Torr. & Gray ex Brayshaw). Science. 313: 1596-1604.

Uhlenbrook, S. 2007. Biofuel and water cycle dynamics: what are the related challenges for hydrological processes research?. Hydrol. Process. 21: 3647–3650

University of Pretoria. 2011. Eucalyptus tree genome deciphered: Key to new possibilities for renewable bioproducts. ScienceDaily. Available at: http://www.sciencedaily.com/releases/2011/05/110512104214. Consulted on: 08/05/2011.

USDA-FS (U.S. Department of Agriculture - Forest Service). 2003. "A Strategic Assessment of Forest Biomass and Fuel Reduction Treatments in Western States," Available at: http://www.fs.fed.us/research/infocenter.htm. Consulted on: 08/04/2011.

Van Heiningen, A. 2006. Converting a kraft pulp mill into an integrated forest biorefinery. Pulp Pap-Canada 107, 38–43.

Van Loo, S., and J. Koppejan. 2008. The Handbook of Biomass Combustion and Co-Firing. Earthscan.

Walter, A., A. Faaij, and A Bauen. 2000. Electricity Production from Biomass. Industrial Uses of Biomass Energy, The Example of Brazil. Taylor & Francis, London.

Wear, D. and J. Greis, 2002. Southern forest resource assessment. U.S. For. Serv. Gen. Tech. Rep. Asheville, NC, p. 635.

Wijayatunga, P., U. Daranagama, and K. P. Ariyadasa. 2005. Techno-Economic Feasibility of Biomass-based Electricity Generation in Sri Lanka. Bioenergy- Realizing the Potential. Swedish Energy Agency. Elsevier.

Wise, D. L. 1981. Fuel Gas Production from Biomass, Vol. 1. CRC Press, Boca Raton, Florida. U.S.A.

Wood Institute for the Environment. 2007. The Environmental, Resource, and Trade Implications of Biofuels. Available at: http://woods.stanford.edu/docs/biofuels/Biofuels2a.pdf. Consulted on: 04/10/2011.

Wopienka, E., G. Friedl, and W. Haslinger. 2009. Reality Check for Agricultural Biofuels. World Sustainable Energy Days, 25-27 February, 2009. Available at: http://www.bioenergy2020.eu/files/publications/pdf/2011-03-23-153609WSED 2009 .pdf. Consulted on: 04/10/2011.

Wopienka., E. 2011. Agricultural Biomass for Small-scale Combustion Units. CEBC 2011. Available at: Consulted on 04/10/2011.

Worgetter, M., J. Rathbauer, L. Lasselsberger, H. Dissemond, H. Kopetz, J. PLANK, and C.H. Rakos. 2003. Bioenergy in Austria: Potential, Strategies, Success Stories. 3rd Research and Development Conference Central and Eastern Europe Institutes of Agricultural Engineering, 11-13 September 2003.

Worldwatch Institute. 2007. Biofuels for Transport, Global Potential and Implications for Sustainable Energy and Agriculture. Earthscan, London.

Wright, L. 2006. Worldwide Commercial Development of Bioenergy with a Focus on Energy Crop-based Projects. Biomass and Bioenergy 30 706–714

Wright, J.A. 2010. Wood-Based Biofuels, Biomass & Bioenergy: Opportunities and Challenges in Louisiana. Bioenergy Forest Plantations, April 23, 2010.

Zwart, R., H. Boerrigter, and A. Van der Drift. 2006. The Impact of Biomass Pretreatment on the Feasibility of Overseas Biomass Conversion to Fischer-Tropsch Products. Energy & Fuels. 20: 2192-2197.

5. FREEZE TOLERANT EUCALYTPUS BIOMASS: A STUDY OF CHARACTERISTICS AND SUITABILITY FOR SOLID FUELS PRODUCTION

5.1 Abstract

Two freeze-tolerant *Eucalyptus* species (*E. benthamii* and *E. macarthurii*) were studied for their potential use for biofuels production. Analyses for the determination of moisture content, bark thickness, basic density, ultimate analysis (elemental composition), proximate analysis (ash, fixed carbon, volatiles content), and heating values were performed. In addition, the properties of these species were evaluated as a solid biofuel, producing wood pellets with the addition of binders. Three combinations of binders and wood were produced for *E. macarthurii*, while five combinations were produced for *E. benthamii*. Published data for these two species is scarce, and comparisons of the characteristics were performed based on similar eucalyptus species, and values obtained for hardwoods and softwoods commonly used for bio-energy purposes. Results indicate that wood density and heating values found in these species are comparable to softwoods and hardwoods naturally occurring in the southern U.S. These eucalypts will make adequate their use as biomass source for bio-energy purposes due to their fast growth rate and freeze tolerance characteristics. Both species are adequate for biofuel utilization, since their heating values are only slightly lower when compared to other hardwoods. Results indicate that some binder-wood combinations can enhance the heating value of the product compared to the wood without binders, but binders will increase the ash content per unit of weight.

5.2 Introduction

Eucalyptus is the most planted forestry genus in the world, with more than 30 million acres planted in 90 countries (James and Del Lungo, 2005; Forrester et al 2006). Eucalyptus has attained worldwide attention, due to the benefits that it has brought to forestry suppliers, due to its fast growth rate, and its economic benefits for impoverished populations (Worldwatch Institute, 2007; Luzar, 2007), and for the paper industry due to established pulp markets, high pulp yield, and excellent technical properties (Patt et al. 2006). There are more than 700 species of Eucalyptus worldwide, being one of the most successful genus of trees

for successful use for plantations and fiber production in numerous countries such as Australia, USA (Hawaii), Ireland, South Africa, Brazil, Uruguay, Portugal, Spain and Venezuela (Gonzalez et al 2008, 2009; Hinchee et al. 2009; Keffer et al. 2009). Most eucalypt species are native of Australia with a few species native from Indonesia and Papua-New Guinea. Many species are fast-growing and have the potential to provide foresters and farmers with a substantial, affordable, and sustainable source of wood (NRI, 2010).

Several companies and research facilities have realized the potential of Eucalyptus as a woody biomass resource for biofuels, such as Embrapa Florestas in Brazil (Duarte et al. 2000), and the Australian Centre for International Agricultural Research (Hardwood, 2005; Larson, 2008). A key fact that demonstrates the importance of Eucalyptus as biomass source for different industries is the recent increase in exports, and the sustained increase in production. The market for Eucalyptus has experienced a 38% increase in exports of Australian Eucalyptus chips from 2009 to 2010 (Wood Resources International, 2010), while Brazil is one of the largest producers of pulpwood in the world, typically producing more than 45 m^3/ha/yr., with a 3-fold increase in exports between 1990 and 2005 (Brazilian Wood Pulp and Paper Association, 2008; Greenwood Management, 2008). In addition, an increased interest in Eucalyptus for pellets production has been developed in recent years, especially in Australia, were companies have already produced and exported nearly 20.000 tons of wood pellets to European countries during 2010 (Wood Resources International, 2010).

According to several authors, many drivers for the increase in woody biomass utilization include pulp, paper and wood products, pellets for heat and power, advanced biofuels, and direct and co-firing electricity generation (DeBell et al. 1985; Perlack et al. 1995; Dermibas, 2000, Van Bueren et al. 2003; Wright, 2009; Pirraglia et al. 2010). Gonzalez et al. (2010c) stated that rapid growth and freeze-tolerant Eucalyptus could be a source of low-cost delivered biomass for bio-energy that can be produced and delivered in the Southern U.S. at competitive costs. During the “Farm to Fuel Summit” in 2009, it was stated the importance that Eucalyptus could achieve as an energy crop, due to its logistical benefits (“year-round harvest, and existing infrastructure for sustainable biomass production, harvest and transportation”), high productivity, adaptability to marginal lands, high bulk density, and high carbon storage (Wright, 2009). Another important advantage of Eucalyptus

utilization for biofuels is the fast growth rate of many species, providing a short rotation, high yield source of biomass, with an energy yield ranging between 450 GJ/ha/yr. (Brazil average) and 1.000 GJ/ha/yr. (maximum commercial standard) achieved for Eucalyptus at Aracruz (Moreira, 2006). Moreover, the adequate selection of a cellulosic biomass source for biofuels production is a critical task, since cellulosic feedstock is the single major cost in biomass-to-bioenergy conversion (Pirraglia et al. 2010; Gonzalez et al. 2010a; Tao and Aden, 2009).

However, eucalyptus species present a challenge for their potential use in the biofuels industries. Eucalypts grow very well in tropical environments with weather patterns similar to those found in its native land (Australia), and are the "backbone" of tropical plantation forestry (NRI, 2010). However eucalypts present a challenge for its planting, care and harvesting in environments with low temperatures. Such weather conditions are present in many States in the U.S., reducing the possibilities of using eucalyptus for industrial purposes, especially for the northern U.S. Since the late 19th century, organizations such as the U.S. Department of Agriculture have expressed interest in planting and managing several Eucalyptus species, finding sixteen species growing in southern Florida in 1911 with different degrees of success, proving that Eucalyptus can be profitable for commercial plantations (Zon and Briscoe, 1911). Since these early attempts, several companies have noticed the potential of Eucalyptus as a biomass source, as well as its limitations regarding freeze-tolerant characteristics. Since the early 1970's many organizations have been planting and managing tree improvement programs (including clonal plantations) for several different Eucalyptus species, such as *E. Urophylla* and *E. Grandis* (Wright and Osorio, 1996), and recently, several companies have developed and conducted successful efforts in planting freeze-tolerant eucalyptus seedlings in order to address freeze-tolerant limitations. These species can be grown and harvested in southern states of the U.S., such as Louisiana, Mississippi, South Carolina, Florida, Alabama, Georgia and Texas, and be used for energy production and solid biofuels.

Among the characteristics of freeze tolerant Eucalyptus for the biomass market are: high ratio of wood to foliage, can be densely planted and managed on short rotations, can be coppiced, and is suitable for mechanized harvest systems (Pirraglia et al. 2010; Sims and

Venturi, 2004). Regions such as Louisiana, Florida, Georgia, Alabama, Texas and South Carolina have seen the successful establishment of plantations of freeze-tolerant seedlings. In 2010, the Forest Productivity Cooperative at North Carolina State University established freeze tolerant Eucalyptus trials in order to understand biomass productivity and survival for several regions in U.S., including North Carolina (Forest Nutrition Cooperative, 2011). Rotation length and yields for pulpwood can be 5-8 years with a mean annual increment (MAI) of 8-16 green tons $acre^{-1}$ $year^{-1}$ (10 to 20 dry ton ha^{-1} $year^{-1}$), while biomass for bioenergy can be 3 to 4 years with MAI of 10 to18 green tons per acre per year (12.3 to 22.4 dry ton ha^{-1} $year^{-1}$) (Gonzalez et al. 2009). According to several authors, Eucalyptus is currently being widely researched for pellets and ethanol production (Gonzalez et al. 2008, 2010a, 2010b; Ferrari et al. 2004), and is known that biotechnology improvements in its planting and managing can increment the biomass yield from 0.5 dry tons/acre/year, to around 17.5 to 22+ dry tons/acre/year, also incrementing the bio-power yield from 800 kWh/acre/year to around 27,600 to 35,500 kWh/acre/year (Wright, 2010).

Two particular Eucalyptus species *E. benthamii* and *E. macarthurii* (Butcher et al. 2005), grown in southern U.S. (South Carolina), are rendering promising results for their freeze-tolerance and their use as a sustainable source of biomass, with field test results that indicate a freezing tolerance to approximately 16°F (-8° to -9° C) (Arborgen, 2010). Figure 5.1 shows an aerial photograph of Eucalyptus trials in Alabama, demonstrating the effect of freezing temperatures on a control Eucalyptus group, and freeze tolerant Eucalyptus, the control group has lost all the leaves, while the surviving (green) trees are Freeze Tolerant Eucalyptus.

Figure 5.1. Eucalyptus trials in Alabama, results from the second winter season. Trees without the leaves are the control group, and green trees are freeze-tolerant Eucalyptus (Arborgen, 2010).

Eucalyptus benthamii and *Eucalyptus macarthurii* have been successfully planted, and many are full-grown trees after 8 years, averaging 10-12 inches of diameter (at breast height, DBH). These two Eucalyptus species present promising opportunities for its use on the biofuels industry. However, the characteristics and potential of Eucalyptus species coming from tree improvement programs, such as proximate and elementary (ultimate) analysis, High Heating Value (HHV), and Basic Density; as well as their manufacturing suitability for biofuels, such as easiness to densify and produce Eucalyptus pellets, or other types of solid biofuels, have not been assessed. Thus, this research proposes to achieve two objectives: to obtain a characterization of *E. benthamii* and *E. macarthurii* from conventional tree improvement programs, for the woody biomass/biofuels industry, and to test the two species for its suitability to manufacture wood pellets with the addition of binders, characterizing its fuel properties, such as Gross heating value, elemental composition, and proximate analysis.

5.3 Materials and Methods

Two species of freeze-tolerant Eucalyptus (*E. benthamii* and *E. macarthurii*, Figure 5.2) were studied in order to determine the following wood properties: moisture content (assessed at the time of harvesting), basic density, bark thickness, proximate analysis (volatiles content, ash content, and fixed carbon content), ultimate analysis (C-H-O-N content), and high heating value (HHV). Samples of both species were collected during winter season from a plantation located in South Carolina. The methodology used for the determination of these properties is fully described in the following paragraphs.

Figure 5.2. *E. Benthamii* (4 years old) plantation in South Carolina (Wright, 2010).

ASTM tests and standards were used in the determination of different properties of wood samples from *Eucalyptus benthamii* and *Eucalyptus macarthurii*. Such standards are briefly described below for each test performed:

- Moisture Content Determination: Determination of Moisture content is based on the ASTM Standard D 4442 (ASTM International, 2002a), Test methods for Direct Moisture Content Measurement of Wood and Wood-Base materials. Samples were taken from adult specimens of each species, without the presence of bark, and measures of its weight before and after drying were taken to a precision of ±0.1 grams. Samples were dried in an oven at

103 ± 2 °C until there was no appreciable change in weight. Thirty two (32) samples taken for *E. benthamii*, 39 samples taken for *E. macarthurii*, based on availability of samples.

- Bark-Wood ratio: Bark-to-wood ratio was measured and calculated according to the methods described by Meyer (1946). Samples were taken from large specimens of both species, at the same height. Ten samples were taken, each one measured at 6 points, and calculating the average thickness of the 6 measurements.
- Basic Density: Determination of Density is based on the ASTM Standard D 2395-02 (ASTM International, 2002b), using the alternate method B described in the standard. This method utilizes the volume displaced by a sample when immersed in water. Samples were taken from adult specimens of each species (32 samples for *E. benthamii*, 39 samples for *E. macarthurii*).
- Volatile Matter: Determination of volatile matter was performed following the ASTM D 3175-07 (ASTM International. 2009a), Standard Test Method for Volatile Matter in the Analysis Sample of Coal and Coke. 3 replications with 7 samples each were performed for *E. benthamii*, and 3 replications with 5 samples each were performed for *E. macarthurii*. In this same sense, the bark for both species was also evaluated, with 2 replications with 7 samples each for *E. benthamii* bark, and 2 replications with 5 samples each for *E. macarthurii* bark.
- Ash Content: Ash Content determination was performed following ASTM D 3174-04 (ASTM International, 2009b), Standard Test Method for Ash in the Analysis Sample of Coal and Coke from Coal. The sampling size and number of replicas used for each experiment are identical to the ones for Volatile Matter.
- C-H-O-N Analysis: The analysis for Carbon, Hydrogen, Oxygen and Nitrogen was performed according to the standard ASTM D 3176 (ASTM International, 2009c), Standard Practice for Ultimate analysis of Coal and Coke. Oxygen is back-calculated, assuming that the entire composition of the samples is reduced to these 4 elements (sulfur content is negligible). Three samples were analyzed for each species, and its bark.
- High Heating Value (HHV): The High Heating Value of the two species studied and its bark were calculated following the ASTM Standard D 2015 (ASTM International, 2000), Standard Test Method for Gross Calorific Value of Coal and Coke by the Adiabatic Bomb

Calorimeter. 10 samples were analyzed for *E. benthamii*, while 6 samples were analyzed for *E macarthurii* and the bark of both species.

In order to achieve the second objective of the research, by manufacturing and characterizing wood pellets from *E. benthamii* and *E. macarthurii,* combinations of different binders and quantities were added to the wood particles of *E. benthamii* and *E. macarthurii*, creating 8 different pellet trials (3 for *E. macarthurii*, and 5 for *E. benthamii*). After manufacturing the pellets, these were subject to the same tests and procedures as the ones mentioned before for the evaluation of the Eucalyptus wood, in order to assess the differences that binders may produce in the composition and characteristics of the wood pellets. The treatments for each pellet trial are described in detail in Section 3.2, Table 5.3.

5.4 Results and Discussion

5.4.1 Physicochemical Tests for the Wood of *E. benthamii* and *E. macarthurii*

E. benthamii and *E. macarthurii* are species of Eucalyptus not frequently used in plantations. For this reason, few data are readily available regarding their main physicochemical characteristics. Some of these characteristics, such as moisture content and density are extremely important for both the wood and paper industry, in order to correctly evaluate the potential use of the wood. In the bio-energy and biofuels field, characteristics such as volatile matter, ash content, fixed carbon, composition, and heating value are critical in order to assess the potential of the wood for energy purposes. In this discussion, values found for several characteristics of *E. benthamii* and *E. macarthurii* were compared to previous research and data found in the literature. Useful comparisons with Poplar and Pine are presented, since these species are currently being used for bio-energy purposes. At this time, the largest wood pellet manufacturer in the world produces around 500 thousand tons/year of pellets made from pine (Green Circle, 2010), while poplar (*Populus Spp*.) is one of the fastest growing trees in North America and are a good source for bio-energy production and other biobased products, in addition to being produced throughout most

regions of the U.S. (Tuskan, 2010). These comparisons are useful, since Eucalyptus can be a potential substitute for these species in the bio-energy field.

5.4.1.1 Moisture Content:

The moisture content for both species at harvesting time was calculated. This moisture content represents the amount of water contained as a function of the weight of the wood "as received" (Table 5.1).

Table 5.1. Average moisture content, standard deviation, and sample size for each species evaluated

Description\Species	***E. benthamii***	***E.macarthurii***
n (# samples)	32	39
Moisture content	54.10%	53.90%
Standard deviation	2.80%	2.60%

5.4.1.2 Bark Proportion:

Table 5.2 summarizes results from the determination of bark proportion for *E. benthamii* and *E. macarthurii*. Every sample was taken at the mid-span section of 6 feet long, large diameter logs.

Table 5.2. Average bark proportion for each species evaluated

Description\Species	***E. benthamii***	***E.macarthurii***
n (# samples)	10	10
Bark-Wood Ratio	12.10%	11.70%
Standard deviation	1.80%	1.00%

No previous information was found regarding the bark-wood ratio of these Eucalyptus species. However, previous work from Meyer (1946) on oak (red, black and scarlet), white pine, and maple indicate a bark-wood ratio of 19%, 19%, and 14% respectively, being higher than the results found in the two Eucalyptus species.

5.4.1.3 Density:

The determination of basic density of the wood was performed on an oven-dry basis (oven-dry weight of the sample/air-dry volume) with 32 samples of *E. benthamii* and 39 samples of *E. macarthurii*, based on availability of material. Figure 5.3 shows the average basic density for both species evaluated.

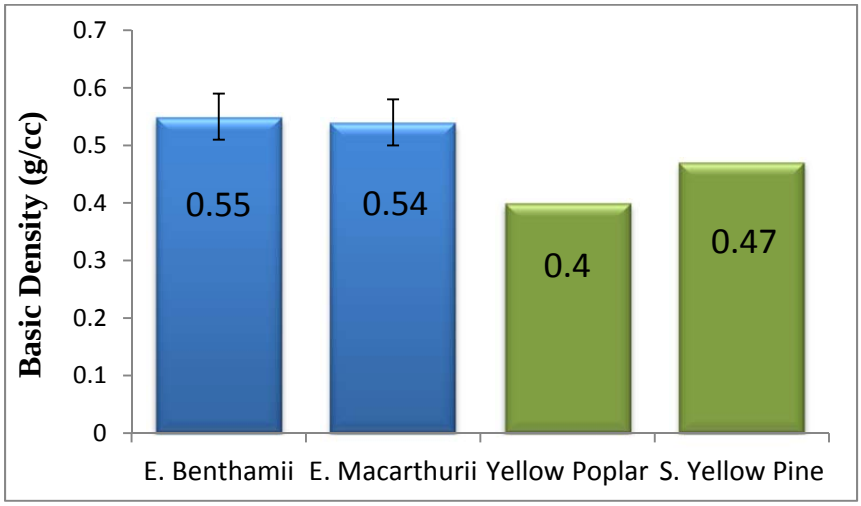


Figure 5.3. Comparison of Basic Density of *E. benthamii* and *E. macarthurii.* compared to Yellow Poplar and Southern Yellow Pine

Basic density of 0.55g/cc (± 0.04 g/cc) for *E. benthamii*, and 0.54g/cc (± 0.04 g/cc) for *E. macarthurii* were found to be similar to results from Clark and Hicks (2002), that reported a basic density of 0.52g/cc and 0.54g/cc for *E. benthamii* and *E. macarthurii*, respectively. When compared to southern yellow pine (0.47 g/cc,) and yellow poplar (0.40 g/cc,) (ASTM International. 2006), the density of the species evaluated is higher.

5.4.1.4 Volatile Matter, Ash content, and Fixed Carbon content:

Experiments for the determination of volatile matter, ash content, and fixed carbon content are part of an experimental procedure denominated proximate analysis. This procedure requires the experiments for each characteristic to be performed in sequence from the same sample. For that reason, the analysis of these characteristics is presented combined.

Volatile matter is determined in the first experimental step (in an oven-dry condition, to avoid water vapor being considered as part of volatiles content); ash content is determined in a second experiment, and fixed carbon content is back-calculated as 100 percent of the sample weight, minus the sum of volatile matter and ash content. The samples considered for bark characteristics include the loose bark typically found in these species, and the tight bark as well. Table 5.3 shows the number of samples and results for the proximate analysis of both species.

Table 5.3. Volatile Matter, Ash content, and Fixed Carbon content for *E. benthamii* and *E. macarthurii*

Species	# of Samples	Volatile Matter	Standard Deviation	Ash Content	Standard Deviation	Fixed Carbon	Standard Deviation
E. benthamii	21	83.20%	2.20%	0.40%	0.20%	16.30%	2.20%
E. macarthurii	20	85.20%	2.30%	0.60%	0.20%	14.10%	2.40%
***E. benthamii*, Bark**	14	77.50%	1.70%	4.60%	0.40%	17.80%	1.60%
***E. macarthurii*, Bark**	10	88.10%	1.50%	6.60%	0.40%	5.20%	1.60%

Results of the proximate analysis for *E. benthamii* were found to be similar to those described by Duarte et al. (2002) that reported values of 83.6%, 1.3%, and 15.1% for volatiles, ash, and fixed carbon content, respectively. No previous studies were available for proximate analysis of *E. macarthurii*. In the same sense, no previous literature was available that evaluates the proximate analysis of the bark for both species, however, values for proximate analysis are similar to those reported by Cordero et al. (2001) for lignocellulosic wastes and chars, and Jimenez and Gonzalez (1991). Another comparison can be made for lodgepole pine (Campbell et al. 1990), which reports similar values of volatiles, fixed carbon, and ash content (82.6%, 17.0%, and 0.3%, respectively), as compared to the eucalyptus species studied. Results obtained for both species are higher in volatiles and fixed carbon content, and lower in ash content, when compared to results obtained in poplar by Ghetti et

al. (1996), who found volatile, fixed carbon, and ash contents of 72.4%, 16.3%, and 1.2% respectively.

5.4.1.5 C-H-O-N Analysis:

The determination of **C**arbon, **H**ydrogen, **O**xygen and **N**itrogen composition for wood and wood based materials is known as Ultimate analysis. In this analysis, **C**, **H**, and **N** are directly determined, while **O** is back-calculated (the remaining balance), assuming that the composition of the wood is based only on these four elements, and the sulfur content and other elements are negligible. Figure 5.4 shows the results for these experiments, based on the average of three samples analyzed for each species and its bark.

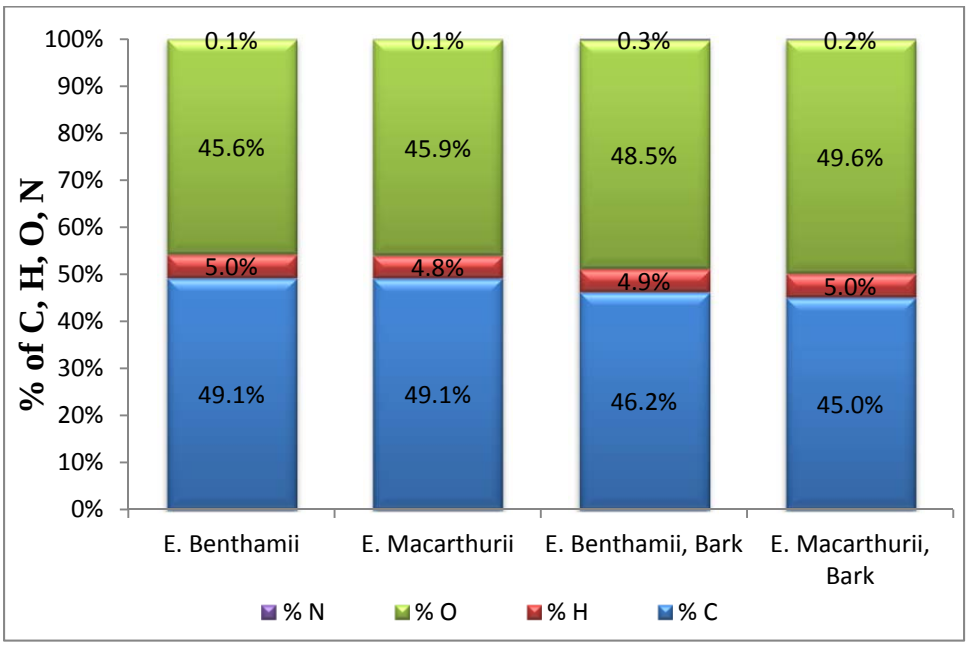


Figure 5.4. Ultimate Analysis for the bark and wood of *E. benthamii* and *E. macarthurii*.

Previous studies for the ultimate analysis of *E. benthamii* and *E. macarthurii* were found in the published literature. Comparisons with general values of carbon, hydrogen, oxygen and nitrogen percentage reported by Cordero et al. (2001) indicate that the values obtained in this experiment (Figure 5.4) are in the range of those typical for lignocellulosic and carbonaceous materials, and are similar to result obtained by Tancredi et al. (1996) on *Eucalyptus grandis*. In addition, results obtained in the experiments are very similar to values

reported by Ragland et al. (1991) in its study of the average ultimate analysis for 11 hardwood and 9 softwood species, with the exception of Hydrogen (reported as 6.2%) being lower in the experiments performed (5.0% and 4.9% respectively for *E. benthamii* and *E. macarthurii*). In addition, results differ from those obtained for poplar (Ghetti et al. 1996), having higher percentages of Carbon (49.2% and 49.1% vs. 43.4%) and Oxygen (45.6% and 45.9% vs. 48.4%), and lower percentage of Hydrogen (4.8% and 5.0% vs. 8.2%) in the samples of the eucalyptus species. An additional comparison may be established between pine (48.3% C, 43.2% O, 7.3% H, and 0.3% N) and the species analyzed, finding that values of Carbon and Nitrogen are close to those reported by Wang et al. (2005), while values of Hydrogen and Oxygen differ from those obtained in the experiments with Eucalyptus.

5.4.1.6 High Heating Value (HHV):

Analysis of the heating value of *E. benthamii* and *E. macarthurii* indicate that both species have similar energy content per unit mass. On the contrary, the bark for both species presents a more noticeable difference in its heating value (16.52 MJ/Kg for the bark of *E. benthamii*, and 15.81 MJ/Kg for the bark of *E. macarthurii*). Table 5.4 shows the heating values obtained for each experiment, in cal/gram, and MJ/Kg.

Table 5.4. Average HHV for *E. benthamii, E. macarthurii,* and its bark, in two measurement units.

	E. benthamii	***E. macarthurii***	***E. benthamii* Bark**	***E. macarthurii* Bark**
n (# samples)	10	6	6	6
HHV (cal/g)/(MJ/Kg)	4371.00 (18.29)	4380.31 (18.33)	3947.59 (16.52)	3778.48 (15.81)
Standard Deviation	3.37 (0.01)	3.13 (0.01)	15.91 (0.07)	27.06 (0.11)

Comparisons of the results for heating value (HHV) of both species studies indicate that the gross heating value of *E macarthurii* and *E. benthamii* is slightly lower than values reported in the literature (Figure 5.5). However, comparisons were made with other eucalyptus species, and hardwoods and softwoods in general, due to the lack of a

comprehensive specific body of literature for *E. benthamii* and *E. macarthurii*. Reviews of the literature indicates that average heating values for the wood of hardwoods varies from 18.6 to 19.8 MJ/Kg, and the bark varies from 17.2 to 22.8 MJ/Kg. For softwoods, heating values range from 20.0 to 22.1 MJ/Kg, and the bark varies from 20.4 to 25.1 MJ/Kg, having both a higher range of HHV than hardwoods (Resch, 1989); Figure 6 presents a graphical comparison between results from the experiments and those found for hardwoods/softwoods. More specific published literature regarding heating values for the species studied in this report were not readily available. However, the authors have found other eucalyptus species results published, finding values are 19.19 MJ/Kg (*E. camaldulensis*), 18.95 MJ/Kg (*E. globulus*), and 18.84 MJ/Kg (*E. grandis*) (Annamalai et al. 1987). For other hardwoods such a poplar, and softwoods such as pine, values of 18.82 MJ/Kg and 19.74MJ/Kg were found from the literature (Ghetti et al. 1996).

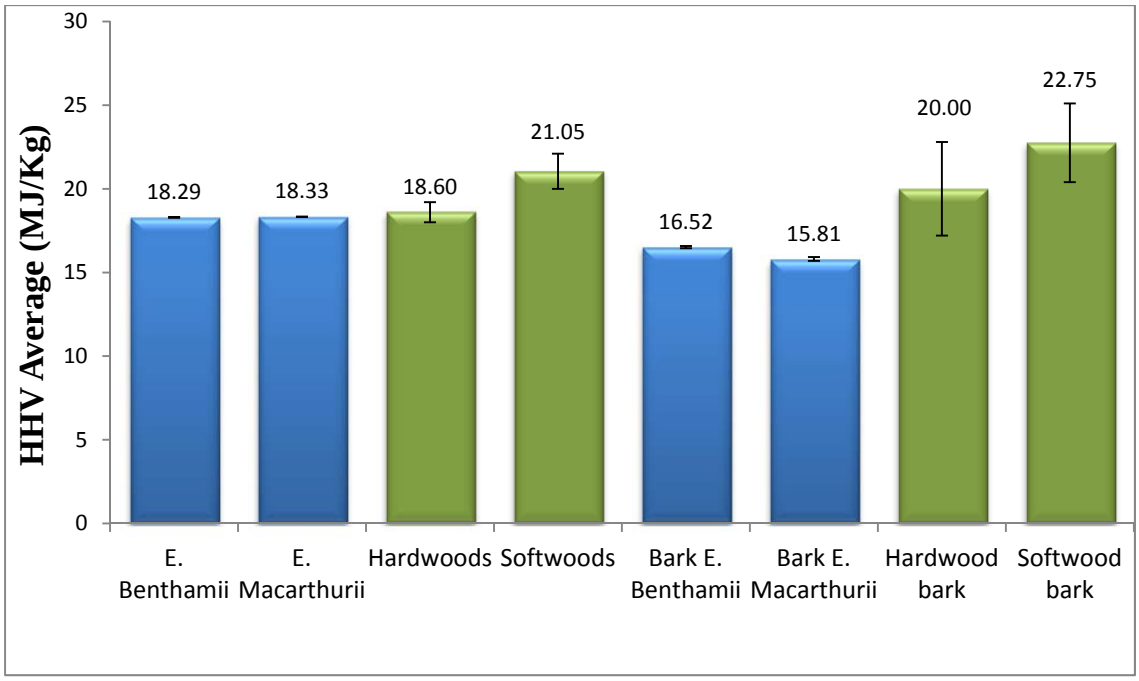


Figure 5.5. Comparison on the Heating values and its standard deviation for the experiments performed, and those typical for hardwoods/softwoods.

Summarizing, high heating value (HHV) results indicate that one BDT of *E. benthamii* and *E. macarthurii* will produce 18.290 MJ (17.335.575 BTU) and 18.330 MJ (17.373.488 BTU) of energy respectively, while its bark will deliver 16.520 MJ (15.657.939 BTU) and 15.810 (14.984.989 BTU) of energy respectively. In comparison, pine and poplar will deliver 19.740 MJ (18.709.910 BTU) and 18.820 MJ (17.837.918 BTU) of energy respectively.

5.4.2 Physicochemical tests for wood pellets trials from *E. benthamii* and *E. macarthurii*

Previous to the description of results for the evaluation of the compaction experiments, an identification of the pellet trials must be assessed in order to identify the binder and characteristics assigned to each pellet trial. Three wood pellet trials were performed using *E. macarthurii* and different binders' combinations, while five trials were performed using *E. benthamii* and other binders' combinations. No technical published data was available describing characteristics of pellets produced from any Eucalyptus species. The comparisons performed in this report are made between the original wood from *E benthamii* and *E. macarthurii*, and the pellet trials that were performed, evaluating the effect that the different binders can produce in the composition, moisture content, and heating value of the material. Table 5.5 summarizes the characteristics and formulation applied to each trial. The selection of different binders, and quantities in the formulation were determined based on previous experience in manufacturing pellets with laboratory-size mills. Characteristics of machinability and ease of material flow through the mill determined the use of the binders and the particle size of the grinded Eucalyptus wood. The abbreviation EM stands for *Eucalyptus macarthurii*, and EB stands for *Eucalyptus benthamii*, while the abbreviation DDG stands for distillers dried grain.

Table 5.5. Characteristics and binders of each pellet trial

Code	Binders and quantities added to Pellets					
EM1	5.700 cc *E. macarthurii*	30 cc corn starch	237 cc DDG	30 cc water	15 cc vegetable oil	
EM2	5.700 cc *E.macarthurii*	30 cc corn starch	237 cc DDG	30 cc water	15cc vegetable oil	60% MC
EM3	5.700 cc *E.macarthurii*	237 cc DDG				
EB1	5.700 cc *E.benthamii*	473 cc DDG				
EB2	5.700 cc *E. benthamii*	473 cc soybean				
EB3	5.700 cc *E. benthamii*	710 cc DDG	No drying	27% MC		
EB4	5.700 cc *E. benthamii*	473 cc DDG	11% MC			
EB5	5.700 cc *E. benthamii*	710 cc DDG				

5.4.2.1 Moisture Content:

The moisture content (MC) of the pellets was calculated for each pellet trial. This MC represents the amount of water contained as a function of the weight of the pellets "as received". The MC of the different trials differs appreciably, being EM3 the sample with the lowest MC (4.72%), and EB5 having the highest MC (12.85%). Figure 5.6 shows the differences in MC present on each trial.

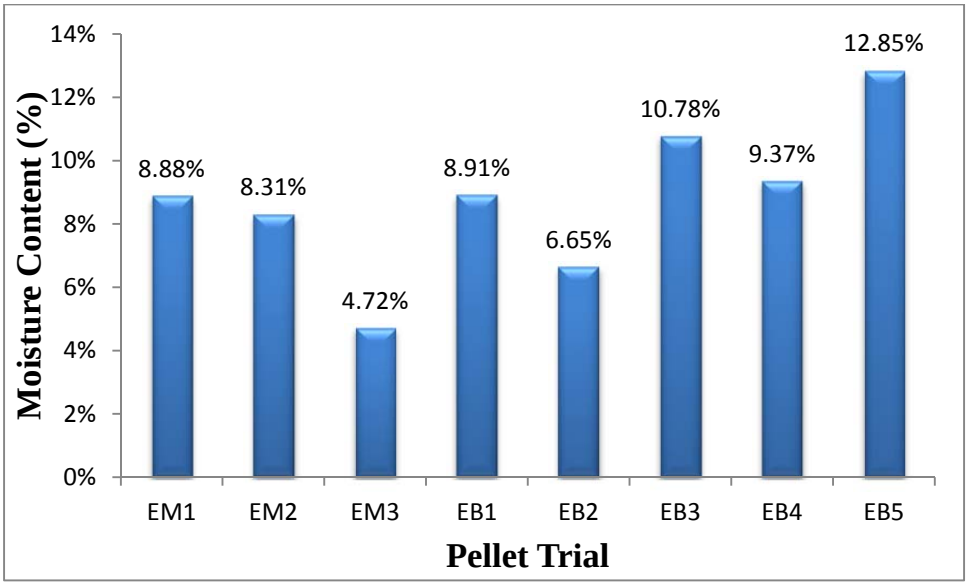


Figure 5.6. Moisture content in each pellet trial

5.4.2.2 Volatile Matter, Ash content, and Fixed Carbon content:

Experiments for the determination of volatile matter, ash content, and fixed carbon content were performed for each pellet trial. These experiments were performed using the same methodology employed previously for the analysis of the *E. benthamii* and *E. macarthurii* wood samples. Three replicates of each pellet trial were performed, and the results are presented in Table 5.6.

Table 5.6. Volatile matter, ash content, and fixed carbon content for *E. benthamii* and *E. macarthurii*

Pellet Code	Volatile Matter	Standard Deviation	Ash Content	Standard Deviation	Fixed Carbon	Standard Deviation
EM1	82.39%	1.01%	3.05%	0.06%	14.57%	0.96%
EM2	81.22%	1.56%	2.83%	0.15%	15.95%	1.58%
EM3	85.36%	1.15%	4.03%	0.08%	10.61%	1.12%
EB1	82.33%	2.75%	3.13%	0.34%	14.55%	2.71%
EB2	88.68%	1.32%	3.33%	0.07%	8.00%	1.38%
EB3	80.00%	2.60%	3.88%	0.04%	16.12%	2.57%
EB4	80.39%	4.50%	3.52%	0.37%	16.09%	4.14%
EB5	75.78%	3.85%	3.89%	0.08%	20.32%	3.77%

Results of the proximate analysis for the trials demonstrate that depending upon the binder and treatment used for pellet production, the composition in terms of volatiles, ash, and carbon content differs on each trial (Figure 5.7). The ash content on each pellets trial, as a percentage of the sample weight, is highly increased from that of the raw material (*E. benthamii*, 0.44% ash content versus 3.1% ash content in the lowest ash pellet sample, EB1, and *E. macarthurii*, 0.64% ash content versus 2.8% in the lowest ash pellet sample, EM2). Despite the increase in ash content, there is an appreciable loss of volatiles in the majority of the samples, being as low as 75.8% (EB5). The loss in volatiles may indicate a reason for the increase in ash content, since these values are determined as a function of the total weight of the sample.

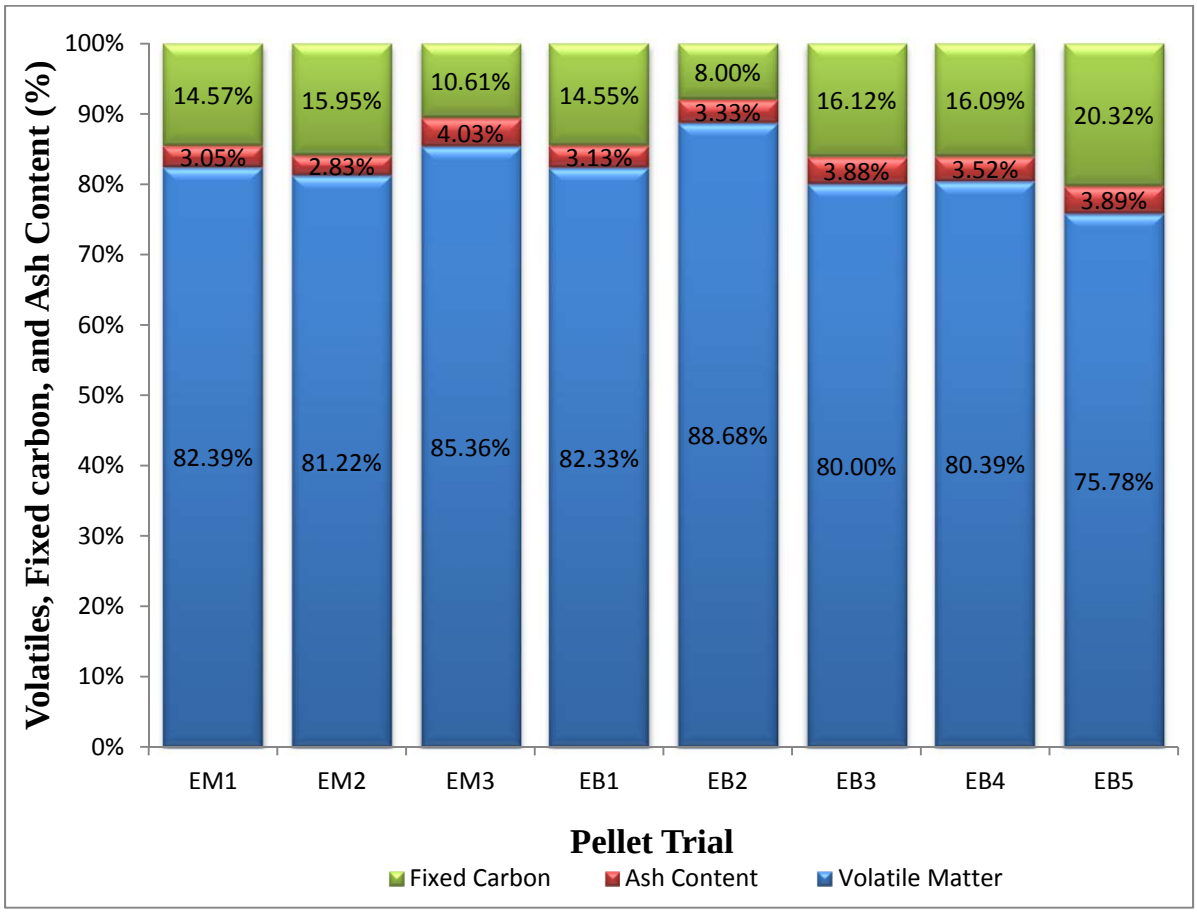


Figure 5.7. Proximate analysis from the pellet trials

In addition, an important increase in fixed carbon content is observed in two trials (EM2, 16.0%, and EB5, 20.3%) as compared to the original values of *E. macarthurii* (14.14%) and *E. benthamii* (16.30%), while there is an important decrease in fixed carbon content in EM3, EB1, and EB2. Based on these results, the recommended combination of binders and treatments for pellet production from *E. benthamii* and *E. macarthurii* are EM2 and EB5, since these combinations deliver a lower volatiles content, and higher fixed carbon percentage, despite the increase in ash content. In order to test and effectively produce pellets without the addition of binders, several dies and rollers combinations should be tested in a commercial scale pellet mill.

5.4.2.3 C-H-O-N Analysis:

The determination of Carbon, Hydrogen, Oxygen and Nitrogen composition for each pellet trial was determined assuming that the composition of the pellets is based only on these four elements, and the sulfur content and other elements are negligible. Figure 5.8 shows the results for these experiments, based on the average of three samples analyzed for each trial.

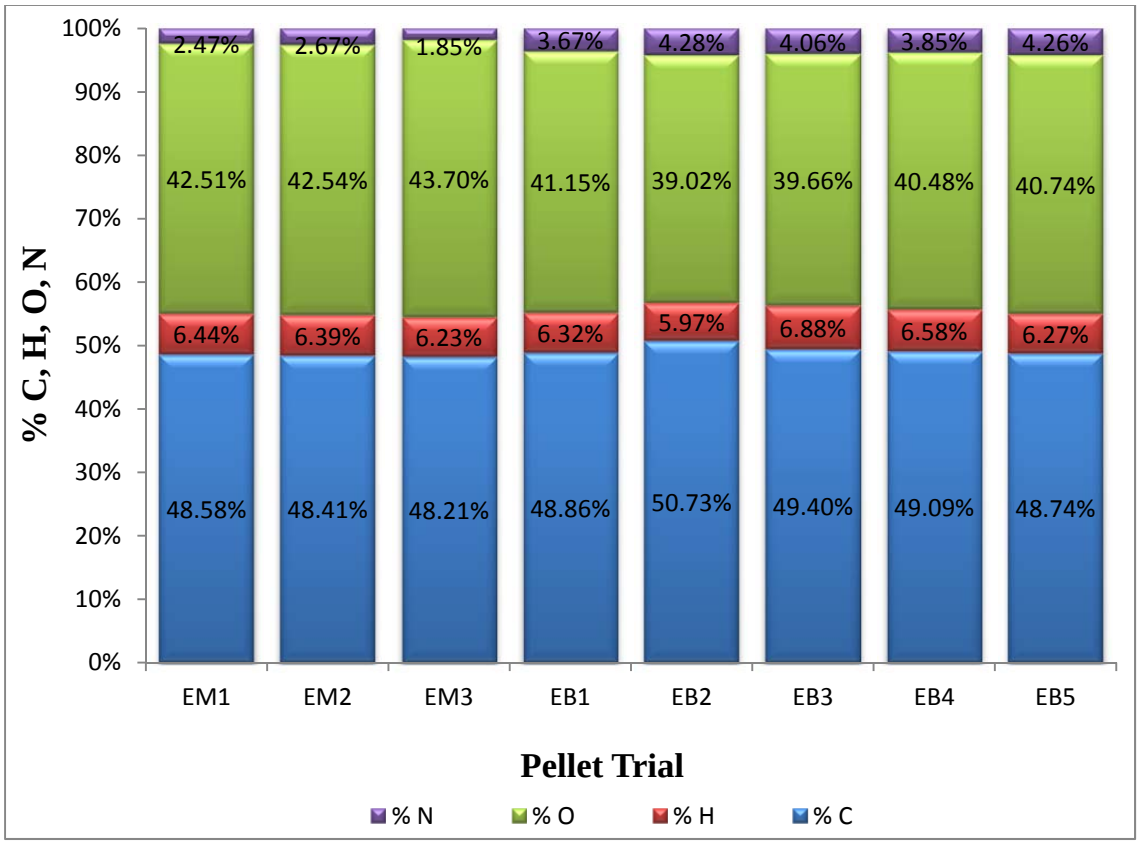


Figure 5.8. Ultimate analysis from the pellet trials

The ultimate analysis of the trials shows very similar results among the samples studied. However, when compared to previous results obtained for *E.benthamii* and *E. macarthurii* (not pelletized) there is a slight increase in Nitrogen levels (0.16% *E. benthamii*, and 0.11% *E. macarthurii*, versus values between 1.85% and 4.28%). In this sense, levels of Carbon remain similar to the original material (49.10%), levels of Hydrogen are slightly

higher (5.0% in the original material versus levels ranging from 5.97% to 6.88%), and levels of Oxygen are slightly lower than in the original material (45.91% versus levels between 39.02% and 43.70%). Figure 5.9 summarizes the information previously described.

5.4.2.4 High Heating Value (HHV):

Analysis of the heating value for the trials was performed in order to evaluate the effect of a binder in the heating value delivered by the product per unit of mass. Table 5.7 shows the heating values obtained for each experiment, in cal/gram, and MJ/Kg.

Table 5.7. HHV for pellet trials from *E. benthamii* and *E. macarthurii.*

	EM1	EM2	EM3	EB1	EB2	EB3	EB4	EB5
n (# samples)	3	3	3	3	3	3	3	3
HHV Average (cal/g)/(MJ/Kg)	4408.9 (18.45)	4466.4 (18.69)	4411.8 (18.46)	4530.6 (18.96)	4760.1 (19.92)	4832.8 (20.22)	4751.4 (19.88)	4857.6 (20.32)
Standard Deviation (cal/g)/(MJ/Kg)	4.12 (0.02)	3.71 (0.02)	3.53 (0.01)	4.14 (0.02)	4.23 (0.03)	3.92 (0.02)	3.54 (0.01)	3.24 (0.01)

Results from the Net Heating Value tests of the pellet trials (Figure 5.9) leads to several discussions. The tests performed with *E. macarthurii* have similar heating values to those of the original material (18.33 MJ/Kg versus 18.45; 18.69 and 18.45 MJ/Kg for pellets from EM1, EM2, and EM3), while tests from *E. benthamii* (which have a different binder combination) show higher heating values than the original material (18.29 MJ/Kg versus values from 19.88 to 20.32 MJ/Kg for the pellet tests). Since the tests with the two species differ in the binder and treatment (moisture content) added to the wood, the heating value obtained in the pellet tests indicate that the binder has a significant effect in its calorific value. The pellets produced with the combination of binders and *E. benthamii* enhanced the HHV of the product, while the tests performed with the combination of different binders and *E. macarthurii* did not enhance the HHV of the original material.

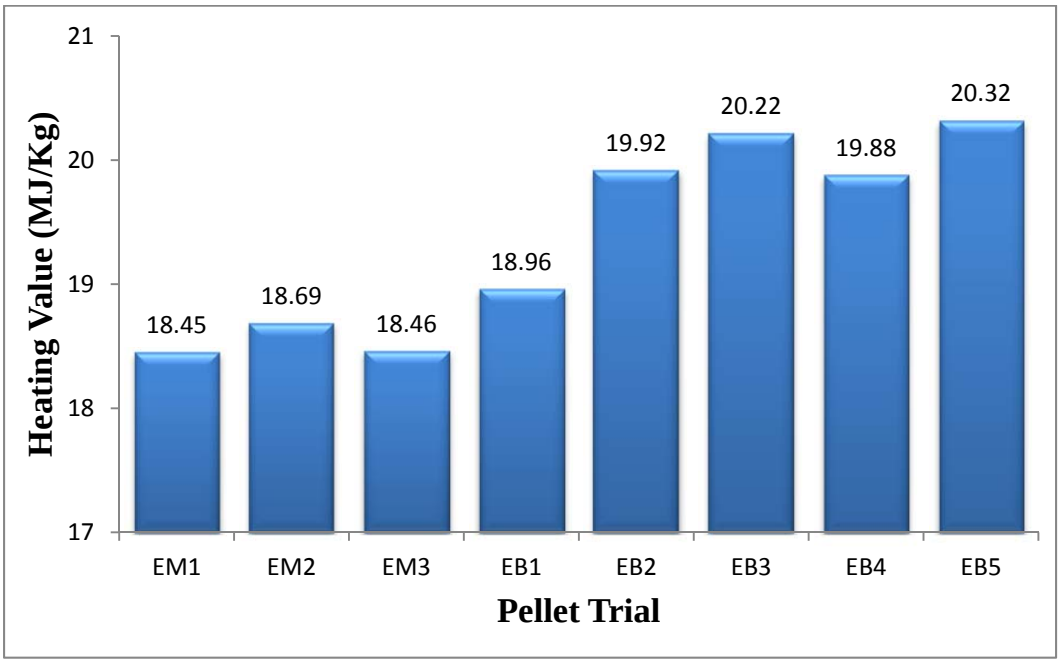


Figure 5.9. HHV analysis from the pellet tests

As a final thought, the tests that showed a higher fixed carbon content, EB3, EB4 and EB5, are the same ones that showed a higher heating value, but the increase in ash content makes the use of binders less desirable for high quality pellets, yet the pellets could be used for domestic commercial/industrial level pellets. Additional tests with a commercial-size pellet mill, with the adequate combination of dies is recommended in order to evaluate the feasibility of producing pellets from Eucalyptus on an industrial level, and without the addition of binders or pre-treatments. If binders were required, the selection of an adequate binder and its proportion in the pellet mix has to be carefully reviewed in order to enhance the HHV of the product, while keeping low ash content levels.

5.5 Conclusions

Fast-growing and freeze-tolerant Eucalyptus species show a potential use for energy production purposes, by being a sustainable and readily available source of wood; it also can become an important raw material for the production of wood pellets for co-firing, or direct burning in factories. Despite this potential, the scarcity of information regarding the fuel

characteristics of Eucalyptus makes it difficult for companies, investors and researchers to assess its true potential. In this sense, the present research determined that:

- Freeze-tolerant Eucalyptus can become an important biomass source for the production of solid biofuels, and advanced liquid biofuels.
- Basic Density of the species evaluated is higher than that present on commonly used species, allowing a higher yield in terms of amount of biomass available for energy per unit of volume.
- Results of Proximate and Ultimate (CHON) analyses are similar to those of some commercial species, making up for a good substitute for woody biomass for bioenergy, by being a fast-growing and freeze-tolerant biomass source.
- Softwoods (in average) will deliver a slightly higher Heating Value (HHV), deficiency that can be overcome by the fast-growth rate of Eucalyptus, and the higher density, incrementing the availability of biomass for bioenergy production.
- Experiments performed for the bark of these species indicate that they are suitable for its use in direct co-firing to power biofuels facilities, knowing that the bark will deliver a higher ash content, but also a suitable HHV for this process.

Moreover, the production of pellets from these species required the addition of a binder, or combination of binders for the analytical tests. However, in an industrial production level, the addition of binders may not be required, by having the right combination of dies, rollers, and torque necessary in the pellet mill for processing the studied species. In the laboratory-scale, results indicate that binders change the characteristics of the pellets as compared to the original raw material. The proportion of ash in the pellets is highly increased in every case, with a Fixed Carbon content that is increased in some tests. The increase in the amount of Fixed Carbon is beneficial for the production of bioenergy from the pellets manufactured. Additionally, the elemental composition of the pellets is affected, having a high increase in the amount of Nitrogen, and a reduction of Oxygen as compared to the original wood. An additional characteristic that is modified by the addition of a binder in the pellet production is the Heating Value (HHV) of the pellets, being enhanced in some

combinations of binder and *E. Benthamii* (specifically in trials EB3, EB4 and EB5). In this sense, the best combination, which delivers a higher heating value (producing more energy per unit of mass), with lower proportion of volatiles content is given in EB5, and also represents the sample with higher fixed carbon content proportion.

5.6 Literature Cited

Annamalai, K., J. M. Sweeten, and S. C. Ramalingam. 1987. Estimation of Gross Heating Values of Biomass Fuels. Transactions, ASAE. 30(4): 1205-1208.

ASTM International. 2000. ASTM Standard D 2015 Standard Test Method for Gross Calorific Value of Coal and Coke by the Adiabatic Bomb Calorimeter.

ASTM International. 2002a. ASTM Standard D 4442 Test Method for Direct Moisture Content Measurement of Wood and Wood-Based Materials.

ASTM International. 2002b. ASTM Standard D 2395-02 Standard Test Methods for Specific Gravity of Wood and Wood-Based Materials.

ASTM International. 2006. Standard Practice for Establishing Clear Wood Strength Values.

ASTM International. 2009a. ASTM Standard D 3175-07 Standard Practice for volatile matter in the analysis sample of Coal and Coke.

ASTM International. 2009b. ASTM Standard D 3174-04 Standard Practice for ash in the analysis sample of Coal and Coke.

ASTM International. 2009c. ASTM Standard D 3176 Standard Practice for Ultimate analysis of Coal and Coke.

Arborgen. 2010. Freeze Tolerant Eucalyptus. Available at: http://www.arborgen.us/index.php/products/product-pipeline/freeze-tolerant-eucalyptus. Consulted on 11/15/2010.

Brazilian Wood Pulp and Paper Association-BRACELPA. 2008. Sector Numbers. Sao Paulo. Available at: http://www.bracelpa.org.br. Consulted on: 12/02/2010.

Butcher, P. A., A. K. Skinner, and C. A. Gardiner. 2005. Increased inbreeding and inter-species gene flow in remnant populations of the rare Eucalyptus Benthamii. Conservation Genetics. 6(2): 213-226.

Campbell, A. G., W. J. Kim, and P. Koch. 1990. Chemical variation in lodgepole pine with sapwood/heartwood, stem height, and variety. Wood and Fiber Science. 22(1): 22-30.

Clarks, N. B, and C. C. Hicks. 2002. Evaluation of the pulpwood quality of 13 lesser-known Eucalyptus species. Proceedings from the 56th APPITA Annual Conference.

Cordero, T., F. Marquez, J Rodriguez-Mirasol, J. J. Rodriguez. 2001. Predicting heating values of lignocellulosic and carbonaceous materials from proximate analysis. Fuel. 80: 1567-1571.

DeBell, D., C. D. Whitesell, and T. H. Schubert. 1985. Mixed Plantations of *Eucalyptus* and leguminous Trees Enhance Biomass Production. USDA Research Paper. PSW-175. Available at: http://www.fs.fed.us/psw/publications/documents/psw_rp175/psw_rp175.pdf. Consulted on: 01/10/2011.

Dermibas, A. 2000. Biomass resource facilities and biomass conversion processing for fuels and chemicals. 42(11): 1357-1378.

Duarte Pereira, J. C., J. A. Sturion, A. Royei, R. C. Victoria, and J. Yukio. 2000. Caracteristicas da Madeira de Algumas Especies de Eucalipto Plantadas no Brasil. Embrapa Florestas. Documentos 38.

Duarte Pereira, J.C., E.G. Schaitza, and J. Shimizu. 2002. fisicas, quimicas e rendimentos da destilacao seca da Madeira de Eucalyptus Benthamii. Embrapa. 35: 1-2.

Ferrari, M., Neirotti, E., Albornoz, C., Saucedo, E. 2004. Ethanol production from eucalyptus wood hemicellulose hydrolysate by Pichia stipitis. *Biotechnology and bioengineering*, 40(7), 753-759.

Forest Nutrition Cooperative. 2011. Eucalyptus in the southeastern United States. Available at: http://www.forestnutrition.org/2011Eucmeeting.htm Consulted on: 01/15/2011

Forrester, D., J. Bauhus, A. L. Cowie, and J. K. Vanclay. 2006. Mixed-species plantations of Eucalyptus with nitrogen-fixing trees: A review. Forest Ecology and Management. 233: 211–230.

Ghetti, P., L. Ricca, and Luciana Angelini. 1996. Thermal analysis of biomass and corresponding pyrolisis products. Fuel. 75(5): 565-573.

Greenwood Management Ltd. 2008. Eucalyptus: The Financial Picture for Brazilian Grown Eucalyptus. Available at: http://www.greenwood-management.com/ eucalyptus.html. Consulted on 12/05/2010.

Gonzalez, R., Saloni, D., Dasmohapatra, S., Cubbage, F. 2008. South America: industrial roundwood supply potential. *BioResources*, **3**(1), 255-269.

Gonzalez, R., Wright, J., Saloni, D. 2009. Filling a need: Forest Plantation for Bioenergy in the Southern US Biomass Magazine 2009 (8) 44-47

Gonzalez, R., Treasure, T., Phillips, R., Jameel, H., Saloni, D., Abt, R., Wright, J. 2010a. Converting Eucalyptus biomass into ethanol: Financial and sensitivity analysis in a co-current dilute acid process. Part II. *Biomass and Bioenergy*, 35(2), 767-772.

Gonzalez, R., Treasure, T., Wright, J., Saloni, D., Phillips, R., Abt, R., Jameel, H. 2010b. Exploring the potential of Eucalyptus for energy production in the Southern United States: Financial analysis of delivered biomass. Part I. *Biomass and Bioenergy*, 35(2), 755-766.

Gonzalez, R., J, Wright, and D. Saloni. 2010c. The business of growing Eucalyptus for biomass. Biomass Magazine. April 2010.

Green Circle. 2010. Available at: http://www.greencirclebio.com/products.php Consulted on: 01/20/2011.

Hardwood, C. 2005. Eucalyptus and Acacia breeding programs in some Asian countries. Available at: http://iufro.uncronopio.org/node/6. Consulted on: 12/01/2010

Hinchee, M., Rottmann, W., Mullinax, L., Zhang, C., Chang, S., Cunningham, M., Pearson, L., Nehra, N. 2009. Short-rotation woody crops for bioenergy and biofuels applications. *In Vitro Cellular & Developmental Biology-Plant*, 1-11.

James, R., Del Lungo, A., 2005. The potential for fast-growing commercial forest plantations to supply high-value roundwood. Planted Forests and Trees Working Papers, Working Paper 33. Forest Resources Development Service, Forest Resources Division. FAO, Rome, Italy.

Jimenez, L., and F. Gonzalez. 1991. Study of the physical and chemical properties of lignocellulosic residues with a view to the production of fuels. Fuel. 70(8):947-950.

Keffer, V., Turn, S., Kinoshita, C., Evans, D. 2009. Ethanol technical potential in Hawaii based on sugarcane, banagrass, Eucalyptus, and Leucaena. *Biomass and Bioenergy*, **33**(2), 247-254.

Larson, E. D. 2008. Biofuel Production Technologies: Status, Prospects and Implications for Trade and Development. United Nations Conference on Trade and Development. New York and Geneva.

Luzar J. (2007). The Political Ecology of a "Forest Transition": Eucalyptus forestry in the Southern Peruvian. *Ethnobotany Research & Applications*.

Meyer, H. 1946. Bark Volume Determination in Trees. Journal of Forestry. 44(12): 1067-1070.

Moreira, J. R. 2006. Global Biomass Energy Potential. Mitigation and Adaptation Strategies for Global Change. 11: 313-342.

NRI. 2010. Notes on Eucalyptus. Conference Proceedings on the Issues for Sustainable use of Biomass Resources for Energy. Available at: http://www.nri.org/projects/biomass/conference_papers/notes_on_eucalypts.pdf. Consulted on: 12/05/2010

Patt, R., O. Kordsachia, and J. Fehr. 2006. European hardwoods versus Eucalyptus globulus as a raw material for pulping. Wood Science and Technology.40: 39-48.

Perlack, R., L. L. Wright, M. A. Huston, and W. E. Schramm. 1995. Biomass Fuel from Woody Crops for Electric Power Generation. Oak Ridge National Laboratory. Available at: http://bioenergy.ornl.gov/reports/fuelwood/toc.html. Consulted on: 01/12/2011

Pirraglia, A., Gonzalez, R., Saloni, D. 2010. Techno-economical analysis of wood pellets production for U.S. manufacturers. *BioResources*, 5(4), 2374-2390.

Ragland, K. W., D. J. Aerts, and A. J. Baker. 1991. Properties of wood for combustion analysis. Bioresource Technology. 37: 161-168.

Resch, H. 1989. Fuel from wood residues; a profit center for mills. Forest industries.

Sims, R., and P. Venturi. 2004. All-year-round harvesting of short rotation coppice eucalyptus compared with the delivered costs of biomass from more conventional short season, harvesting systems. Biomass and Bioenergy 26: 27 – 37.

Tancredi, N., T. Cordero, J. Rodriguez-Mirasol, and J. Rodriguez. 1996. CO_2 Gasification of Eucalyptus Wood Chars. Fuel. 75(13): 1505-1508.

Tao, L., Aden, A. 2009. The economics of current and future biofuels. *In Vitro Cellular & Developmental Biology-Plant*, 45(3), 199-217.

Tuskan, G. 2010. Popular Poplars, Trees for many purposes. Oak Ridge National Laboratory. Available at: http://bioenergy.ornl.gov/misc/poplars.html Consulted on: 01/20/2011.

Van Bueren, M., and D. Vincent. 2003. Eucalyptus biomass fuels: Price competitive or way off the money?. 47th Annual Conference of the Australian Agricultural and Resource Economics Society, Perth, 12th-14th February, 2003. Available at: http://www.iadb.org/intal/intalcdi/PE/2009/02274.pdf. Consulted on: 01/05/2011.

Wang, T., J. Chang, and P. Lv. 2005. Synthesis gas production via biomass catalytic gasification with addition of biogas. Energy & Fuels. 19: 637-644.

Wood Resources International LLC. 2010. Australia Increased Chip Exports of both, Eucalyptus and Pine in 2010, Reports The Wood Resource Quarterly. Available at: http://newsblaze.com/story/20100812094502181 51.ew/topstory.html. Consulted on: 12/01/2010

WorldWatch Institute. (2007) State of the World: Our Urban Future. Available at: http://en.wikipedia.org/wiki/State_of_the_World_(book_series). Consulted on: 01/05/2011

Wright, J.A., and L.F. Osorio. 1996. Comparison of *Eucalyptus urophylla* provenance performance at half rotation in Colombia and hybrid strategies with *Eucalyptus Grandis*. Forest Ecology and Management. 83: 117-122.

Wright, J. 2009. Improvements through Biotechnology Maximize Potential of Purpose Grown Trees for Biomass. Farm to Fuel Summit, July 30, 2009. Available at: http://www.arborgen.com/uploads/presentations/farm-to-fuel-presentation%20final.pdf?phpMyAdmin=iPU8Ia6jISo93dPyYdigjfeIV%2C3. Consulted on: 11/29/2010

Wright, J.A. 2010. Wood-Based Biofuels, Biomass & Bioenergy: Opportunities and Challenges in Louisiana. Bioenergy Forest Plantations, April 23, 2010.

Zon, R., and J. M. Briscoe. 1911. Eucalyptus in Florida. U.S. Department of Agriculture. Forest Service, Bulletin 87.

6. FUEL PROPERTIES AND SUITABILITY OF EUCALYTUS BENTHAMII AND EUCALYTUS MACARTHURII FOR TORREFIED WOOD AND PELLETS

6.1 Abstract

Torrefaction is the process of heating a material in the absence of oxygen, a pre-treatment that represents a promising option for biofuels. Two eucalyptus species harvested in South Carolina, *E. benthamii* and *E. macarthurii*, were processed in a torrefier, and wood pellets were manufactured. Eucalyptus represents a promising biomass source in southern U.S. due to fast growth rates and the availability of cold-tolerant plantations. Analyses of moisture content, proximate and elemental composition, and net heating value of "light roasted" wood were assessed. The heating value of the eucalypts and pellets was enhanced by 19% (average), compared to the original material, while the moisture and volatiles content were drastically reduced. This reduction leads to an increase in the amount (w/w) of carbon, enhancing the energy content in the material. Thus, torrefaction is useful for improving the heating value of woody biomass, while consuming little process energy. The pellets showed increased energy density, providing improved properties for transportation and handling.

6.2 Introduction

Torrefaction of wood is one of the most readily available bio-technologies (Sklar 2009), being an attractive pre-treatment option for biomass intended for conversion and combustion processes (Zwart et al. 2006), with results more financially attractive than traditional pelletization of biomass, when comparing their economic feasibilities (Bergman and Kiel 2005). Torrefaction is defined as a "mild pyrolysis" that separates water, volatile organic compounds (VOCs), and hemicellulose from the cellulose and lignin contained in woody biomass (Sklar 2009). Fonseca et al. (1998) described torrefaction as a slow heating of biomass in an oxygen-free atmosphere with a maximum temperature of 300 °C. The VOCs and hemicellulose fractions are combusted to generate heat, leaving cellulose and lignin to constitute the torrefied wood, which has a charcoal appearance. Depending on the residence time of the wood in the torrefier, the torrefied wood yield can be high, varying between 66% and 75% (Sklar 2009).

The process of torrefaction applied to woody biomass is not a new concept, being evaluated as early as 1930, when Basore (1930) proposed a method for profitable disposal of large amounts of southern pine sawdust generated from sawmills in southern U.S. The method proposed is very similar in concept to the actual parameters utilized in a typical modern torrefaction process, and the inventor even proposed the "densification" as briquettes, of the charcoal-like material obtained, in order to optimize handling, transportation, and utilization of the biomass. Furthermore, Basore and Moore (1942) proposed an additional refined method for the production of lump charcoal from pine sawdust. Despite these early efforts, torrefaction was not widely implemented as a process for biomass conversion or properties optimization. Instead, the torrefaction of biomass was overlooked and is still at an early stage in industrial applications, with limited commercial availability (Uslu et al. 2008).

In the last two decades, more research has been performed regarding the characteristics of the material produced in the torrefaction process (Bourgeois and Guyonnet 1988; Gevers et al. 2002), as well as the gases obtained in the heating chamber (Pach et al. 2002; Uslu et al. 2008); however, very little literature can be found regarding large-scale (industrial) manufacturing of torrefied wood. Few species have been tested, with most of the attention being focused on birch and southern pine (Bourgeois and Guyonnet 1988, Pach et al. 2002). In addition, the development of pre-treatment options such as torrefied pellets has deemed necessary by several large-scale biomass users, scientists, and members of the IEA Task 40 on sustainable international bioenergy trade (Junginger and Sikkema, 2008). Among the types of biomass with promising properties for bioenergy production in the U.S. are some Eucalyptus species (Gonzalez et al. 2008; Gonzalez et al. 2011a,b) and its utilization in pre-treatments such as torrefaction should be evaluated in detail (Gonzalez et al. 2011c,d). Countries such as Brazil have already shown the potential that such short-rotation crops may have for the bioenergy industry (Couto et al. 2004; Rosillo-Calle, 2004; Wright, 2006; Gonzalez et al. 2008). Recent advances in characteristics such as coppicing, cold tolerance, and growing rates make eucalypts an ideal biomass source for energy production in southern U.S. (Gonzalez et al. 2008; Wright, J. 2009, Gonzalez et al. 2011a,b). Typical plantations of eucalyptus can yield around 450 GJ ha^{-1} $year^{-1}$ of energy, while traditional wood sources

from commercial forests in the U.S. yield around 100 GJ ha^{-1} $year^{-1}$ (Moreira, 2006). Eucalypts have a rotation period (for bioenergy purposes) of less than 7 years (Carvalho et al. 2009). Despite these characteristics, very few species have been assessed for their properties for the bioenergy industry, especially in combination with pre-treatments such as pelletization and torrefaction, and only Brazil has been consistently converting eucalyptus to charcoal for the pig iron and steel industry (Wright, L. 2006). With many Eucalyptus plantations established in the last 10 years in southern U.S. states such as South Carolina, Florida, Georgia, Alabama, and Louisiana (Wright, J. 2010; Gonzalez et al. 2011c,d; Pirraglia et al. 2011), and an increasing need to produce bioenergy from sustainable sources, it is necessary to perform further research in a timely manner evaluating the properties and suitability of eucalyptus species for bioenergy production. In this sense, two eucalyptus species, *E. benthamii* and *E. macarthurii* from a plantation in South Carolina were assessed for its basic properties for biofuels production (Pirraglia et al. 2011), obtaining promising results for its suitability as a solid biofuel for power and heat generation; thus additional research needs to be performed in order to fully assess its properties when subject to torrefaction and further pelletization pre-treatments.

The main objective of this research was to assess the characteristics of torrefaction as biomass pre-treatment in two cold-resistant eucalyptus species (*E. benthamii*, and *E. macarthurii*), measuring and comparing physico-chemical characteristics of the torrefied wood material. An additional objective of the research was to manufacture and evaluate the characteristics of torrefied wood pellets from the eucalyptus samples, torrefied in a large-scale torrefaction unit, and pelletized in a laboratory-scale pellet mill with the addition of binders, assessing the main fuel characteristics of these pellets.

6.3 Materials and Methods

In previous work performed by the authors (Pirraglia et al. 2011), *E. benthamii* and *E. macarthurii* were evaluated for its raw material properties, and pellets were manufactured with the addition of binders. In the present work, it is of particular interest to further evaluate properties of the species when subjected to a torrefaction process, and pelletization with

binders. In order to compare the original raw material and the processes applied to them, the same properties of the samples must be evaluated, utilizing the same procedures and standards. The following properties were evaluated for both the torrefied material, and the torrefied pellets with the addition of binders for the two species: moisture content of the torrefied material after cooling, proximate analysis (volatiles content, ash content, and fixed carbon content), ultimate analysis (C-H-O-N content), and high heating value (HHV). The procedures and standards used for the determination of these properties are fully described below. In order to achieve the proposed objectives, several ASTM standards were used to determine several properties of torrefied wood from *E. benthamii* and *E. macarthurii*, and for the determination of properties of wood pellets produced with the torrefied wood of *E. benthamii*. Such standards are briefly described below for each test performed:

- **Moisture Content Determination:** Determination of Moisture content is based on the ASTM Standard D 4442, Test Methods for Direct Moisture Content Measurement of Wood and Wood-based Materials. Samples were taken from torrefied wood produced with each species; and measures of its weight before and after drying were taken to a precision of ±0.1 grams. Samples were dried in an oven at 103 ± 2 °C until there was no appreciable change in weight. Three replicates were completed for each species of torrefied *E. benthamii* and *E. macarthurii*.
- **Volatile Matter:** Determination of volatiles was performed following the ASTM D 3175-07, Standard Test Method for Volatile Matter in the Analysis Sample of Coal and Coke. Three replicates were performed for each torrefied wood produced from *E. benthamii* and *E. macarthurii*.
- **Ash Content:** Ash Content determination was performed following ASTM D 3174-04, Standard Test Method for Ash in the Analysis Sample of Coal and Coke from Coal. Three replicates were used for each experiment in each species.
- **C-H-O-N Analysis:** The analysis for Carbon, Hydrogen, Oxygen and Nitrogen of the torrefied wood produced was performed according to the standard ASTM D 3176, Standard Practice for Ultimate analysis of Coal and Coke. Oxygen is back-calculated, assuming that

the entire composition of the samples is reduced to these four elements (sulfur content is assumed negligible). Three replicates were analyzed for the torrefied wood of each species.

- **High Heating Value (HHV):** The High Heating Value of the torrefied wood produced was calculated following the ASTM Standard D 2015, Standard Test Method for Gross Calorific Value of Coal and Coke by the Adiabatic Bomb Calorimeter.

In order to achieve the additional objective of pelletizing the torrefied biomass, two different binders were added to the torrefied wood of *E. benthamii*, resulting in two pellet trials. Due to the characteristics of the torrefied material, in terms of being abrasive and difficult to pelletize in a laboratory scale unit, this trial was only performed with *E. benthamii*. These pellets were studied using the same tests and procedures as the ones previously described for the evaluation of the raw material, gaining understanding of the differences produced when pelletizing torrefied wood with the addition of binders.

The binders utilized for the pellets were Dried Distiller Grain (DDG), and soybeans, with the addition of water to increase the moisture content of the wood prior to pelletizing. Dried Distillers Grains present good properties for gluing the wood particles together in pellets, due to its content of condensed distiller's solubles, including fats and starch (Weiss et al. 2007; Kingsly et al. 2010). Soybeans have also been successfully used as binder in the wood industry, especially wood composites (United Soybean Board, 2006), and present good characteristics for pelletizing wood (PelletPros, 2007). These binders were hammermilled and mixed with the torrefied wood particles and water. Details on the formulations for the pellets are provided below.

Previous work has been performed by the authors regarding pellets manufacturing from *E. benthamii* and *E. macarthurii* with the addition of binders, and pelletized in a flat-die mill from Pelletpros Inc., model PP220 (PelletPros, 2010; Pirraglia et al. 2011). Based on this previous experience, two different formulations of materials and binders were selected in order to produce pellets trials with the torrefied material. Table 6.1 describes these formulations.

Table 6.1. Formulations with Binders for Each Pellet Trial

Code	Binders and quantities added to Pellets		
EB6	3000 cc *E. benthamii*	750 cc soybeans	83.33 cc Water
EB7	3000 cc *E. benthamii*	750 cc DDG	83.33 cc Water

The formulations provided and tested have a ratio of 36:9:1 of *E benthamii*, Binder, and Water. This ratio provides a good approach for a scale-up production with the formula, and provides the right amount of moisture and binder to allow for better densification and flow of the material through the rollers and dies, improving production rate and durability of the pellets.

6.4 Results

Biomass properties for energy in Eucalyptus species has not been widely studied, especially properties of the biomass after being pretreated for solid biofuels, such as pelletizing and torrefaction. This characteristic, along with the fact that few data pertaining to the properties of *E. benthamii* and *E. macarthurii* are readily available, makes comparisons with previous literature difficult. To address this limitation, the authors compare the results obtained after the pre-treatment and after the pelletization process, with results previously obtained for the original wood material of both species (Pirraglia et al. 2011). Below, a brief description of the torrefied process applied to the eucalyptus wood is given in order to adequately interpret the results of the experiments performed for determining the properties of torrefied eucalyptus. The torrefier unit utilized for the experiments was designed and developed at NC State University. The unit operates by heating the wood in a low-oxygen environment in order to remove water, volatile organic compounds (VOCs) and hemicellulose (HC) from the cellulose and the lignin. The VOC's and HC are combusted to generate 80% of the torrefaction process heat. Figure 6.1 demonstrates a schematic view of the torrefaction process for the unit designed at NC State University (James 2009).

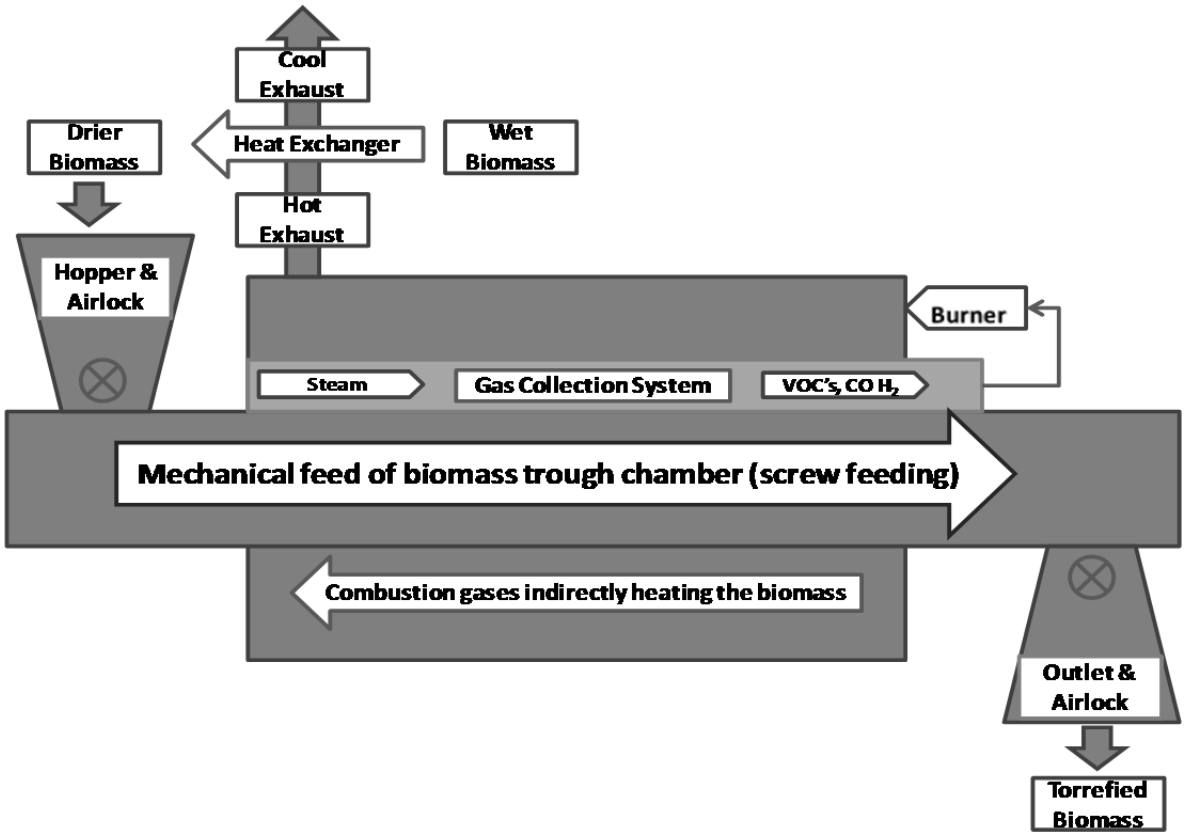


Figure 6.1. Schematic process for the production of torrefied eucalyptus

One of the most important variables affecting the torrefied wood that can be produced with this unit, along with the temperature of the chamber, is the residence time. This residence time determines the degree to which the wood is "roasted", and its properties modified. The longer the residence time, the more coal-like the material is going to be obtained at the exit of the machine. This residence time also determines the yield. If the residence time is long (between 5 and 6 minutes) most of the VOCs from the wood are removed, leaving a charcoal material with highly increased heating value, and extremely low moisture content, which is regained at the exit and posterior cooling of the torrefied wood, even when the material becomes hydrophobic (Bergman et al. 2005). It is advisable that the torrefaction process must be further studied; variables such as residence time, temperature, and characteristics of the torrefied product are of extreme importance to obtain a uniform product, and may provide improved results and more consistent comparisons between both species. In order to establish the most similar conditions for an industrial-level process with

continuous and high-volume flow, the machine was set up for low residence times, established around three minutes from the instant in which the material enters the unit through the hopper, to the moment in which it exits the machine. These three minutes are the lowest residence time utilized in the machine in order to obtain a torrefied material. The result of a material with this residence time is described as “light roast” or “slightly torrefied”; this “roast” degree was mostly established by observing the change of color on the wood at the exit of the unit, changing from brown to black in different scales and depending on the particle size of the wood (James 2009). Most small particles (1-5 mm) exit the unit with a charcoal color, while bigger particles still have some brown color left in them. Some other properties that can be measured are applied to the torrefied wood in order to define the “roast” degree; a “lightly roast” is usually defined as torrefied wood that contains around 60 to 70% of the original VOCs content of the wood, and a carbon content 20 to 30% higher than the original carbon content, thus enhancing the heating value of the wood. Also, when considering a mass balance, or mass yield, the light torrefaction process has a yield of 80 to 85% compared to the original mass (W/W). In order to facilitate the understanding and discussion of the results, a code is used to define the species of torrefied wood. Table 6.2 describes the codes used and their meanings.

Table 6.2. Codes used for Identification of each Torrefied Wood According to the Species

Code	Torrefied wood description
EMT1	1st replica of *E. macarthurii* tests, 3 samples per replica
EMT2	2nd replica of *E. macarthurii* tests, 3 samples per replica
EMT3	3rd replica of *E. macarthurii* tests, 3 samples per replica
EBT1	1st replica of *E. benthamiii* tests, 3 samples per replica
EBT2	2nd replica of *E. benthamiii* tests, 3 samples per replica
EBT3	3rd replica of *E. benthamiii* tests, 3 samples per replica

6.4.1 Physicochemical Tests of Torrefied Wood of *E. benthamii* and *E. macarthurii*

Moisture content

The moisture content for the torrefied wood of both eucalyptus species was calculated, representing the amount of water contained as a function of the weight of the wood after being processed in the torrefier, and cooled; this was calculated for each of the treated species. The calculation of this moisture content was performed by comparing the weight of the wood after torrefaction and cooling vs. the weight after drying the samples in an oven at 103°±2°.

Three replicates for moisture content were performed using *E. macarthurii* (EMT) and *E. benthamii* (EBT), obtaining 5.55% and 5.05% of moisture (average) respectively. No technical published data was available describing moisture content of torrefied wood from the eucalyptus species evaluated in this research. The average moisture content of the samples is significantly lower than that of the received material for both species, both of them around 5% compared to the original moisture content around 54 to 57%. This represents a reduction in weight of around 50%.

Volatile matter, ash content, and fixed carbon content

Experiments for the determination of volatile matter, ash content, and fixed carbon content were performed for each torrefied wood species. These experiments were performed using the same methodology previously used by the authors in the analysis of wood samples from *E. benthamii* and *E. macarthurii* (Standards ASTM D 3174-04 and ASTM D 3175-07). Three replicates of each torrefied wood species were performed, and the results (average of the three replications) are presented in Table 6.3.

Table 6.3. Volatile Matter, Ash content, and Fixed Carbon Content for Torrefied wood of *E. benthamii* and *E. macarthurii*

Torrefied wood Code	Volatile Matter	Ash Content	Fixed Carbon
EMT1	67.80%	3.61%	28.54%
EMT2	76.70%	4.22%	19.09%
EMT3	77.00%	4.22%	18.81%
EBT1	61.60%	1.83%	41.69%
EBT2	55.71%	1.85%	36.61%
EBT3	57.85%	1.88%	40.27%

Results of the proximate analysis (Figure. 6.2) for the torrefied material indicate a higher content of ash and fixed carbon as compared to the original material. This characteristic is due to the displacement of volatiles from the samples, caused by torrefaction process that the wood has been exposed to. Figure 6.2 demonstrates the change in Volatiles, Fixed Carbon, and Ash content from the original material to the torrefied one. In this sense, the ash content obtained from *E. macarthurii* torrefied (4.0%) is notably higher than the one obtained from *E. benthamii* (1.8%).

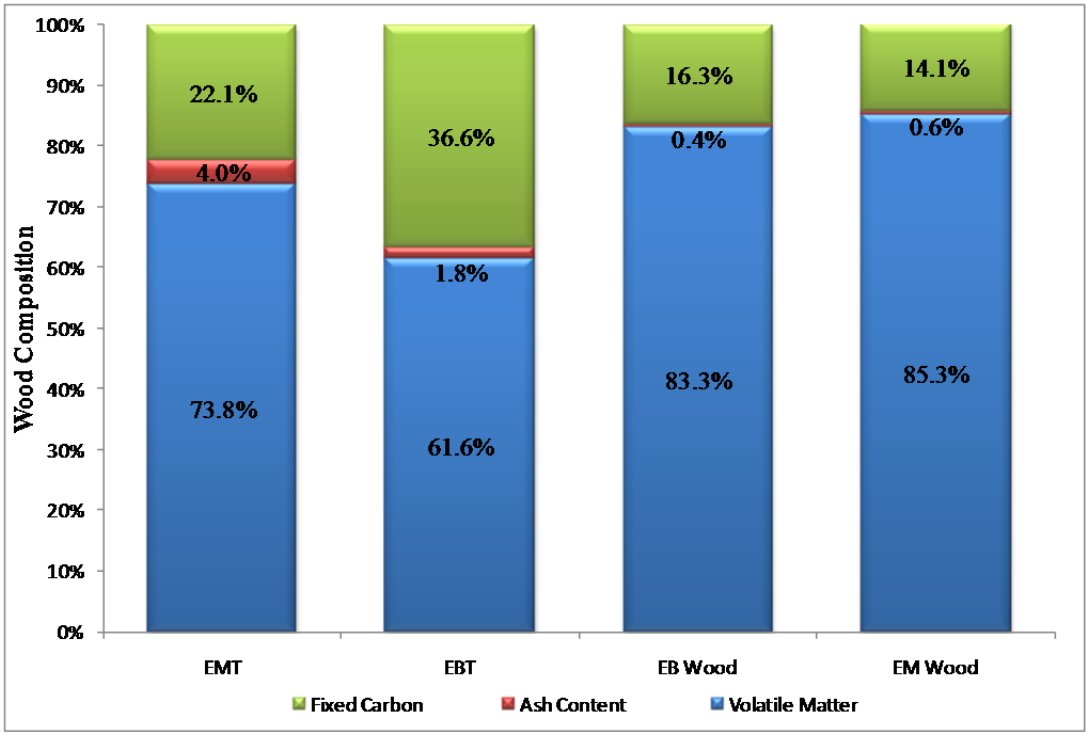


Figure 6.2. Proximate analysis for the torrefied wood compared to non-treated eucalyptus

Furthermore, the fixed carbon content of *E. benthamii* torrefied (36.6%) was considerably higher than that obtained with *E. macarthurii* torrefied (22.1%). These results indicate that *E. benthamii* provided better fixed carbon content with lower ash content as compared to *E. macarthurii*, when exposed to the torrefaction process. However, both species showed an increase in their fixed carbon content in weight percentage. The results demonstrated the suitability of both the torrefaction process and the utilization of its product as a biofuel, either as raw material for further processing, or for direct burning and co-firing, since the fixed carbon content is directly related to the heating value of a given biomass (Demirbas 1997; Parikh et al. 2005).

C-H-O-N analysis

The determination of carbon, hydrogen, oxygen, and nitrogen composition for each torrefied wood sample was determined assuming the composition of the torrefied wood is based only on these four elements, and the sulfur content is negligible. Table 6.4 shows the average of C, H, O, and N, based on the average of three samples analyzed in each replication.

Table 6.4. C, H, O, and N % for each Torrefied Wood Sample

Torrefied Sample ID	Elemental composition average			
	% C	% H	% O	% N
EMT1	62.21%	4.27%	33.30%	0.22%
EMT2	61.60%	4.41%	33.77%	0.22%
EMT3	61.93%	4.41%	33.44%	0.22%
EBT1	64.92%	4.29%	30.64%	0.15%
EBT2	66.67%	3.98%	29.18%	0.17%
EBT3	67.49%	4.00%	28.35%	0.16%

The ultimate analysis of the torrefied material showed lower oxygen content in the samples, when compared to the original material (Figure 6.3). The nitrogen content did not show a difference as substantial as the one found for oxygen, while the samples also displayed a high increase in the elemental carbon content, due to the displacement of oxygen out of the samples. The increase in elemental carbon content is an indication of an enhanced

heating value of the material being torrefied (Uslu et al. 2008), as it is demonstrated later for the HHV tests of the samples.

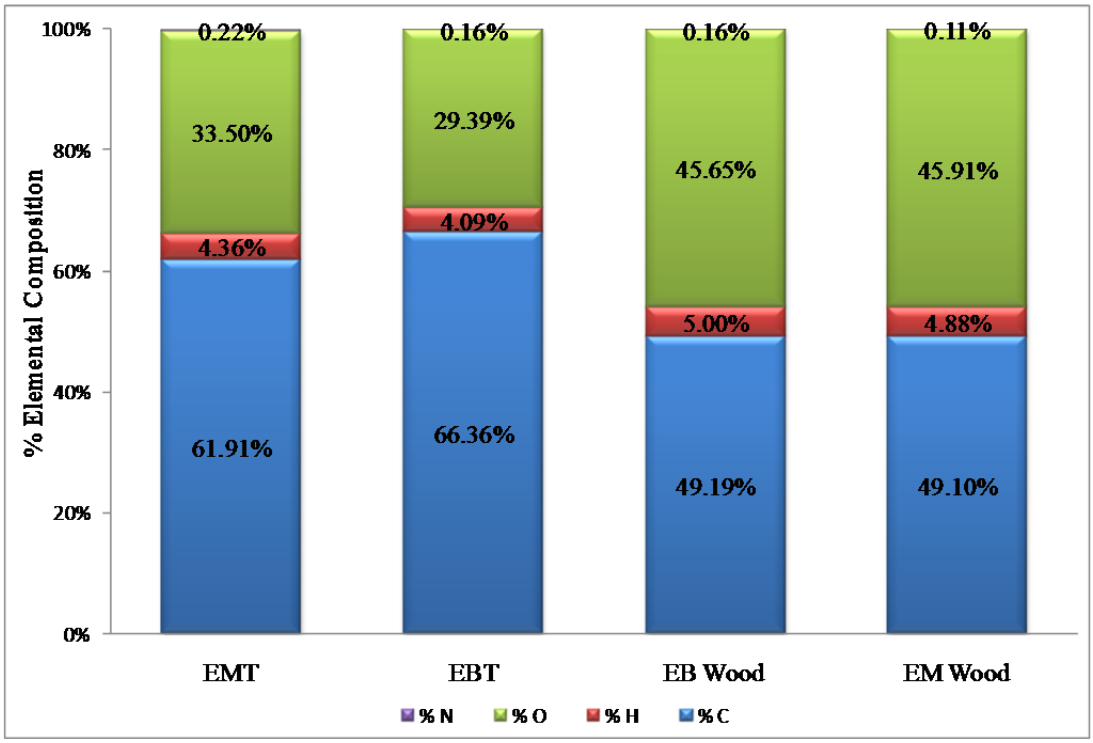


Figure 6.3. Ultimate analysis for torrefied vs. non-treated wood

High Heating Value (HHV)

Analysis of the heating value for the torrefied wood was performed in order to evaluate the effect of this treatment in the heating value delivered per unit of mass. Table 6.5 shows the heating values obtained for each experiment, in cal/gram, and MJ/Kg.

Table 6.5. HHV for Torrefied Wood from *E. benthamii* and *E. macarthurii*

	EMT1	EMT2	EMT3	EBT1	EBT2	EBT3
n (# samples)	3	3	3	3	3	3
HHV Average	5481.01	5571.51	5483.30	5875.33	5838.14	5843.41
cal/g/(MJ/KG)	(22.95)	(23.33)	(22.96)	(24.60)	(24.41)	(24.52)

Results from the net heating value tests of the torrefied wood (Figure 6.4) indicate a high increase in the energy that can be obtained from the samples. An average increase of 19.7% could be obtained with the "light roast" torrefaction process for *E.macarthurii*, while an average of 19.6% increase in heating value could be obtained from "light roast" torrefaction of *E. benthamii*.

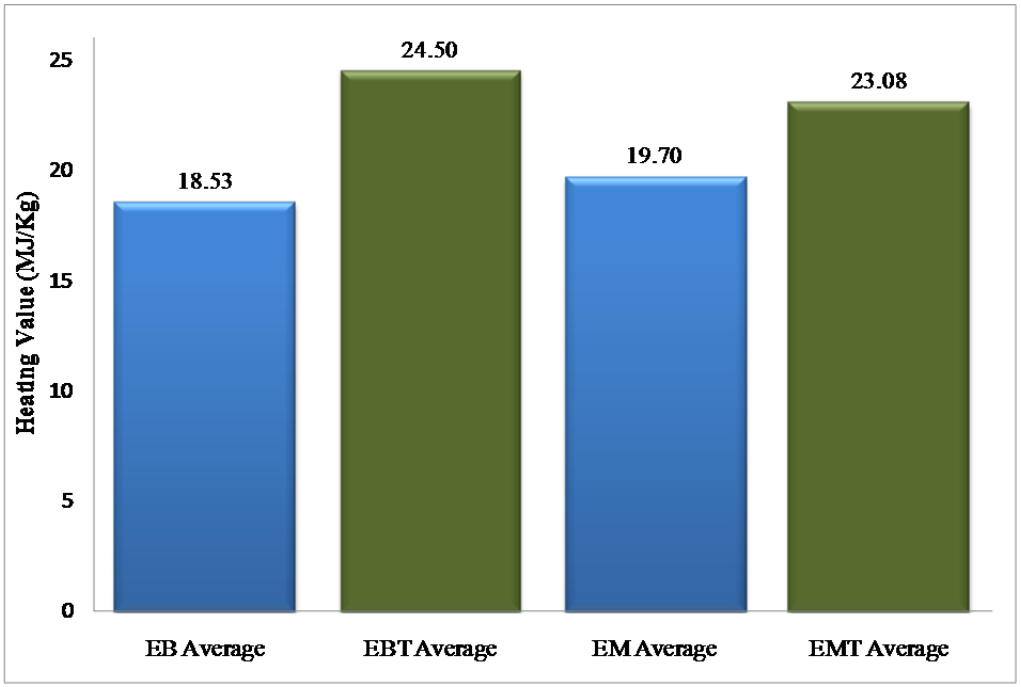


Figure 6.4. HHV analysis from the torrefied wood tests, with comparison of the average of 3 replicates in each category

This enhanced heating value is related to the low moisture content of the product, and the partial elimination of volatiles content from the wood, leaving more carbon (as a percentage weight) for use as burning fuel. It is important to consider that the process of torrefaction requires little energy input, since the process is 80% self-sustained by the recirculation (heat source) of gases, while the remaining 20% is obtained from a methane flame stream. A detailed analysis of energy (energy balance) for the torrefactor and the product is highly recommended, since this process is noticeably increasing the HHV of the material, while using very little external energy. Such analysis would demonstrate the

advantages and economic feasibility of this process with a biomass source such as eucalyptus. At the present time, authors report an estimated torrefied wood production cost of around 58 € ton^{-1} (Uslu et al. 2008), without considering feedstock costs, and in a small-scale factory. Further analysis is also needed to assess production costs of torrefied wood considering economy of scale, and U.S. market conditions.

6.4.2 Physic-chemical Tests of Torrefied Wood Pellets Made from *E. benthamii*

As Zwart et al. (2006) concluded a combination of torrefaction and pelletization may be one of the more feasible pre-treatments of biomass in terms of transportation and suitability for bulk handing. In addition, the denominated "TOP Pellets" carry the advantages of an increased energy and material density (Bergman 2005), a hydrophobic property of the material, and a lower electrical demand required for further grinding/pulverization (Zwart et al. 2006). In this chapter, comparisons are made between previous pellets trials of *E. benthamii* and *E. macarthurii* performed by the authors (Pirraglia et al. 2011).

Moisture content

Moisture Content (MC) levels of the pellets trials were assessed, showing a MC of 7.54%, and 8.29% for EB6 and EB7, respectively. The pellets manufactured from torrefied wood showed lower moisture content when compared to levels in conventional standard (10%) and utility quality pellets (10%), and a similar moisture content as compared to premium quality pellets (8%) (Pellets Fuel Institute 2010). These results are in concordance with observations obtained by Cremers (2009) regarding the lower MC in torrefied wood pellets as compared to regular wood pellets. MC levels are important for transportation costs of pellets; a lower MC allows transporting and delivering more energy per unit of weight and volume. In this sense, if pellets can be produced from torrefied wood without the addition of binders, the moisture content levels will be lower than 5% (since the moisture content of the torrefied material in section 3.1.1 is 5%), allowing to deliver a higher energy content per bulk of pellets.

Volatile matter, ash content, and fixed carbon content

The determination of volatile matter, ash content, and fixed carbon content in the pellets produced from *E. benthamii* wood were assessed utilizing 7 samples in 3 replicates. These experiments were performed using the same methodology employed previously for the analysis of *E. benthamii* and *E. macarthurii* wood samples (Pirraglia et al. 2011). Comparisons of the torrefied wood pellets were performed with the characteristics of the original wood as described in previous research by (Pirraglia et al. 2011). The original wood of *E. benthamii* contains around 16% of fixed carbon, 0.44% of ash content, and 83% of volatile matter. In comparison, the torrefied and pelletized material (Figure 6.5) contains 11% more fixed carbon (27% fixed carbon content in the torrefied pellets), and 14% less volatile matter (69% volatile matter in the torrefied pellets).

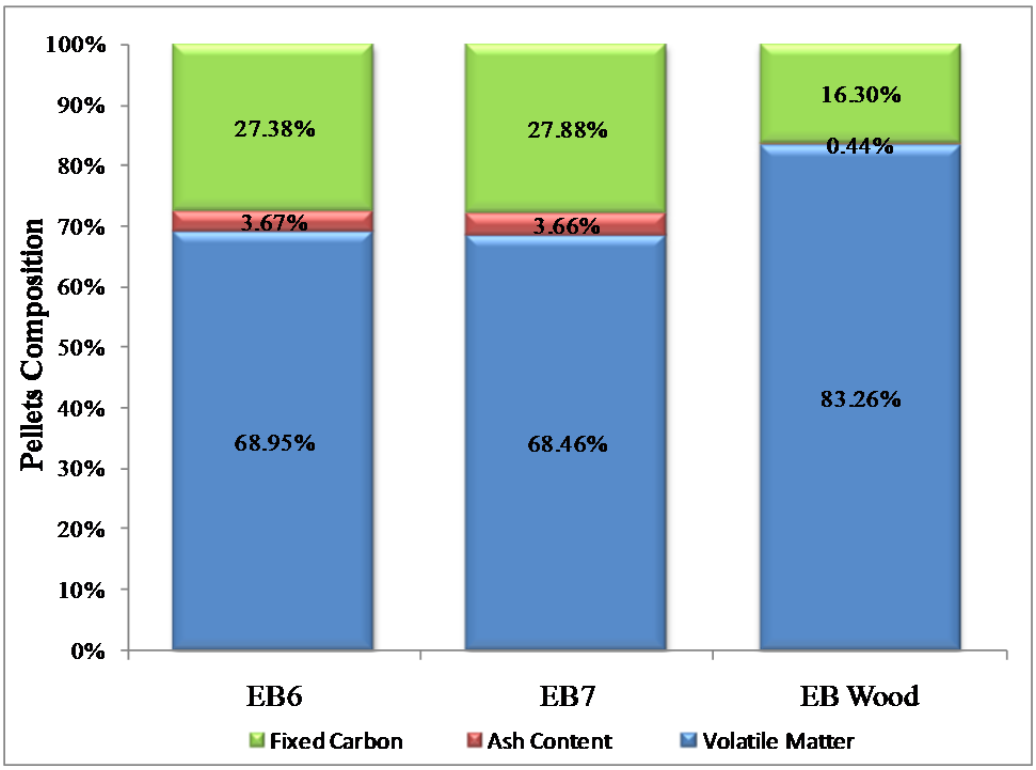


Figure 6.5. Volatile matter, ash content, and fixed carbon content for pellets of *E. Benthamii*

These results are similar to those presented by several authors when comparing average results on torrefied wood samples (69.24% volatile matter, 29.74% fixed carbon, and 1.04% ash content, Pentananunt et al. 1990), and better than values obtained for beechwood by Couhert et al. (2009) in a recent study, with 75.7% of volatile matter, 0.4% of ash content, and 24.2% of fixed carbon. It is well known that fixed carbon content and volatile matter are directly related to the heating value (energy content) of a wood sample (Jimenez and Gonzalez 1991; Kucukbayrak et al. 1991; Raveendran and Ganesh, 1996; Demirbas, 1997; Cordero et al. 2001). A combination of higher fixed carbon and lower volatile matter content enhances the heating value of the wood, characteristic that is achieved through the torrefaction process, thus improving the properties of the wood for biofuels purposes. The results from Figure 6.5 are also comparable to those obtained by Almeida et al. (2010) on the wood of *E. grandis* and *E. saligna*, for both, the untreated wood and the torrefied material, in which they obtained very similar values in fixed carbon, volatile matter, and ash content.

C-H-O-N analysis

The elemental composition (carbon, hydrogen, nitrogen, and oxygen content) was determined for the torrefied pellets trials, and the results were compared to the original wood material of *E. benthamii*. Figure 6.6 shows the average results obtained for each element in the torrefied pellets (EB6 and EB7) versus *E. benthamii* wood.

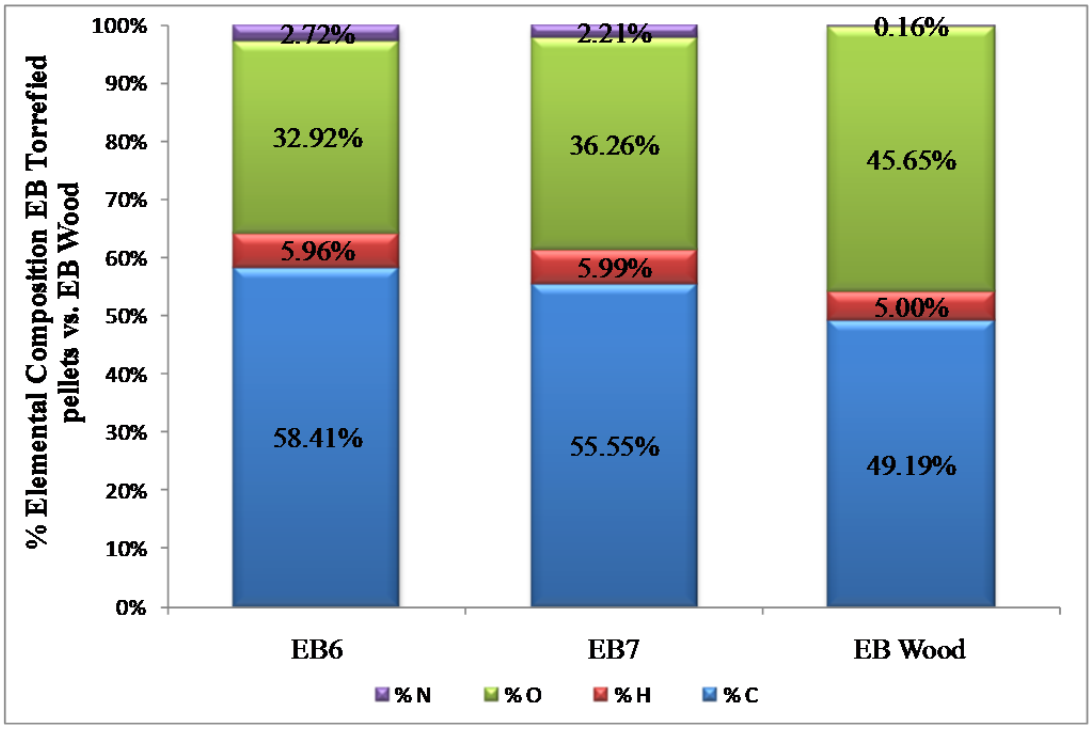


Figure 6.6. C, H, O, and N % for each torrefied pellets trial vs. EB wood

Is important to note that the composition of the pellets is based on these four elements, by assuming the sulfur content of the material negligible (it is typically lower than 0.1% for wood materials). As compared to the original material (EB wood), the torrefied pellets showed a considerable increase in the carbon and nitrogen content, a slight increase in hydrogen content, and presented a noticeable decrease in the oxygen content. According to a formula for estimating the gross heating value developed by Boie (1952), which utilized 16 biomass-based fuels, 66 coal, char and coke fuels, and 67 oil fuels (including alcohols), determined that an increase in carbon, nitrogen, and hydrogen content positively influences the gross heating value of a given biomass, while a decrease in the oxygen content also carries an increased heating value. As mentioned by Annamalai et al. (1987), this characteristic is due to the fact that if the amount of oxygen is greater, there will be less available percentages of carbon and hydrogen for combustion (due to combinations of CO, H_2O, OH groups, etc.). In the pellet trials developed (EB6 and EB7), there was less oxygen

present, thus, having more carbon and hydrogen available which contributes to achieve a highly energy-dense fuel.

High Heating Value (HHV)

Previous results from the proximate and ultimate (CHON) analyses indicate an increase in the heating value of the torrefied and pelletized wood tested. Direct measurements of the heating value by an adiabatic bomb were performed in this section in order to verify the previous indications. Table 6.6 shows the heating values obtained for the trials, in cal/gram and MJ/Kg.

Table 6.6. HHV for Torrefied Pellet Trials from *E. benthamii*

	EBT Average	**EB6**	**EB7**
n (# samples)	**3**	3	3
HHV Average cal/g/(MJ/KG)	24.50	24.28	24.30

The tests performed to determine the HHV of the torrefied pellet trials indicate similar heating values when compared to the original torrefied material of *E. benthamii* (24.28 MJ/Kg for EB6 and 24.30 MJ/Kg for EB7, versus an average of 24.5 MJ/Kg for torrefied EB). These results indicate that the binders have little effect in changing the energy properties of the torrefied material, while they allow for a better packing and densification of the torrefied wood, providing a more energy-dense product, and making it more suitable for transportation. This characteristic further enhances the desirable properties for handling and transportation in a solid biofuel produced from biomass sources. Further analysis of the cost/benefit of the binder is under development in order to determine the economic feasibility of using the binders.

As a final thought, pelletization of torrefied woody biomass is on early stages of development and industrial application. In laboratory-scale mills, pelletization is difficult to achieve, due to low horsepower transmitted to the rollers and dies, and being a flat-die mill. Some authors report that successful production of torrefied pellets in industrial scale has been already achieved (Boerrigter et al. 2006; Mitchell et al. 2007) by means of a TOP process,

and ring-die pellet mills (Bergman, 2005). This indicates that many technical difficulties of pelletizing torrefied biomass may be produced on laboratory scale units only. In addition, it is stated that at torrefaction temperatures, the lignin in wood becomes plastic, and serves as a natural binder for the individual wood particles (James, 2010), improving the flowability of the material through the dies, which may be further improved with the addition of other binders. These properties will help overcome the abrasive nature of the torrefied material, allowing producing quality pellets with durability about 2 times more than regular wood pellets, and significantly lowering moisture uptake (James, 2010).

Other benefits that favor the torrefaction and pelletization process is the fact that , torrefaction reduces the fibrous nature of the wood, making it easily grindable, significantly reducing power consumption in the grinding operation prior to pelletization (Bridgeman et al. 2010). A major problem present in co-firing coal with biomass is the differences in energy density, burning range, and poor flowability, reducing the thermal efficiency and capacity of boilers (Hughes and Tillman, 1998; Tillman, 2000; Phanphanich and Mani, 2011). Many of these problems can be addressed by utilizing torrefied wood pellets, which are easily grindable, improve combustion characteristics in co-firing, and are suitable for storage.

6.5 Conclusions

- Torrefaction pre-treatment shows great potential for eucalyptus, eliminating water and volatiles, significantly enhancing its heating value an average of 19% compared to the original material. More aggressive torrefaction temperatures and residence times may increase the heating value of the biomass significantly more.
- Further enhancement can be achieved by changing residence time and operation temperature, being these critical variables for the product’s uniformity.
- Torrefied pellets have lower moisture and volatile matter, and higher fixed carbon content compared to traditional premium quality pellets, delivering higher energy content per bulk, with improved handling, and transportation.
- In addition, binders do not affect the energy content on the pellets. However, further economic analysis on binders is necessary to assess the pre-treatment’s profitability.

6.6 Literature Cited

Almeida, G., Brito, J. O., and Perre, P. (2010). "Alterations in energy properties of eucalyptus wood and bark subjected to torrefaction: The potential of mass loss as a synthetic indicator," *Bioresource Technology* 101, 9778-9784.

Annamalai, K., Sweeten, J. M., and Ramalingam, S. C. (1987). "Estimation of gross heating values of biomass fuels," *Transactions, ASAE* 30(4), 1205-1208.

Basore, C. A. (1930). "Fuel briquettes from southern pine sawdust," Engineering Experiment Station of the Alabama Polytechnic Institute. Bulletin 1.

Basore, C. A., and Moore, A. C. (1942). "The production of lump charcoal from pine sawdust without a binder," Engineering Bulletin. 14.

Bergman, P. C. A. (2005). "Combined torrefaction and pelletisation: The TOP process," Report C--05-073; Energy Research Centre of The Netherlands (ECN): Petten, The Netherlands; p 29.

Bergman, P. C. A., Boersma, A. R., Kiel, J. H. A., and Zwart, R. W. H. (2005). "Development of torrefaction for biomass co-firing in existing coal-fired power stations, BIOCOAL concept version," ECN report.

Bergman, P. C. A., and Kiel, J. H. A. (2005). "Torrefaction for biomass upgrading," Published at 14th European Biomass Conference & Exhibition,Paris, France, 17-21 October 2005. Available at: http://www.ecn.nl/docs/library/report/2005/rx05180.pdf. Consulted on: 04/03/2005.

Boerrigter, H., J. Kiel, and P Bergman. (2006). Biomass Pre-treatment by Torrefaction. Third ThermalNET Meeting, 3-5 April 2006, Lille, France.

Boie, W. (1952). *Wissenschaftliche Zeitschrift der Technischen Hochschule Dresden*. 2, 687.

Bourgeois, J. P., and Guyonnet, R. (1988). "Characterization and analysis of torrefied wood," *Wood Sci. Tech*. 22.

Bridgeman, T.G., J.M. Jones, A. Williams, and D.J. Waldron. 2010. An investigation of the grindability of two torrefied energy crops. *Fuel* 89, 3911-3918.

Carvalho, A., Henrique, K., Da Silva, M. L., and Silva Soares, N. (2009). "Competitiveness of Brazilian wood pulp in the international market," *Cerne, Universidade Federal de Lavras, Brasil*. 15(4), 383-390.

Cordero, T., Marquez, F., Rodriguez-Mirasol, J., and Rodriguez, J. J. (2001). "Predicting heating values of lignocellulosic and carbonaceous materials from proximate analysis," *Fuel* 80, 1567-1571.

Couhert, C., Salvador, S., and Commandré, J.-M. (2009). "Impact of torrefaction on syngas production from wood," *Fuel* 88, 2286-2290.

Couto, L., Muller, M. C., Barcellos, D. C., and Couto, M. M. F. (2004). "Eucalypt based agroforestry systems as an alternative to produce biomass for energy in Brazil (extended abstract)," Proceedings of conference on biomass and bioenergy production for economic and environmental benefits, Charleston, S.C. November 2004. Available at: www.woodycrops.org/publications.html. Consulted on 03/22/2011.

Cremers, M. F. G. (2009). "Technical status of biomass co-firing," IEA Bioenergy Task 32. Deliverable 4.

Demirbas, A. (1997). "Calculation of higher heating values of biomass fuels," *Fuel* 76, 431-434.

Fonseca, F., Luengo, C. A., Bezzon, G., and Beaton, P. (1998). "Bench unit for biomass residue torrefaction," Proceeding of Int. Conf. Biomass for Energy and Industry. Würzburg, Germany.

Gevers, P., Ramaekers, G., Frehen, A., Sijbinga, M., van Steen, E., Sturms, J., and Taks, B. (2002). "Green energy, from wood or torrefied wood?" Final Report, University of Technology Eindhoven, Netherlands. Available at: http://students.chem.tue.nl/ifp02/downloads/Final_Report.pdf. Consulted on: 01/25/2011

Gonzalez, R., Saloni, D., Dasmohapatra, S., and Cubbage, F. (2008). "South America: Industrial roundwood supply potential," *BioResources* 3(1), 255-269.

Gonzalez, R., Phillips, R., Saloni, D., Jameel, H., Abt, R., Pirraglia, A., and Wright, J. (2011a). "Biomass to energy in the southern United States: Supply chain and delivered cost," *BioResources* 6(3), 2954-2976.

Gonzalez, R., Treasure, T., Wright, J., Saloni, D., Phillips, R., Abt, R., and Jameel, H. (2011b). "Exploring the potential of eucalyptus for energy production in the southern United States: Financial analysis of delivered biomass, Part I.," *Biomass and Bioenergy* 35(2), 755-766.

Gonzalez, R., Treasure, T., Phillips, R., Jameel, H., and Saloni, D. (2011c). "Economics of cellulosic ethanol production: Green liquor pretreatment for softwood and hardwood, greenfield and repurpose scenarios," *BioResources* 6(3), 2551-2567.

Gonzalez, R., Treasure, T., Phillips, R., Jameel, H., Saloni, D., Abt, R., and Wright, J. (2011d). "Converting Eucalyptus biomass into ethanol: Financial and sensitivity analysis in a co-current dilute acid process, Part II," *Biomass and Bioenergy* 35(2), 767-772.

Hughes, E.A., and D.A. Tillman. (1998). Biomass Cofiring: Status, Prospects. *Fuel*

Processing Technology 54 (1–3), 127–142.

James, J. (2009). "Using torrefied Wood as a Coal Replacement for Superior Pellets and Cellulosic Ethanol Production," Available at: http://www.agri-techproducers.com/. Consulted on: 11/01/2010.

James, J. (2010). "Using Torrefied wood for electricity, Briquettes, and Pellets Production" Available at: http://pelletheat.org/pdfs/JoeJames.pdf. Consulted on: 07/21/2011.

Jimenez, L., and Gonzalez, F. (1991). "Study of the physical and chemical properties of lignocellulosic residues with a view to the production of fuels," *Fuel* 70(8), 947-950.

Junginger, M., and Sikkema, R. (2008). "The global wood pellet trade – markets, barriers and opportunities: Workshop summary," Copernicus Institute, Utrecht University. Available at: http://www.pelletsatlas.info/pelletsatlas_docs/showdoc.asp?id=090420111608&type=doc&pdf=true. Consulted on: 01/15/2011.

Kingsly, A.R.P., K.E. Ileleji, C.L. Clementson, A. Garcia, D.E. Maier, R.L. Stroshine, and S. Radcliff. (2010). The effect of process variables during drying on the physical and chemical characteristics of corn dried distillers grains with solubles (DDGS) – Plant scale experiments. *Bioresource Technology* 101, 193-199.

Kucukbayrak, S., Durus, B., Mericboyu, A. E., and Kadioglu, E. (1991). "Estimation of calorific values of Turkish lignites," *Fuel* 70, 979-981.

Mitchell, P., J. Kiel, B. Livingston, and G. Dupont-Roc. (2007). A Foresighting Study into the Business Case for Pellets from Torrefied Biomass as a New Solid Fuel. A Presentation to All Energy '07. May 24th 2007. Available at: http://www.all-energy.co.uk/UserFiles/File/2007PaulMitchell.pdf. Consulted on: 07/21/2011.

Moreira, J. R. (2006). “Global biomass energy potential,” *Mitigation and Adaptation Strategies for Global Change* 11, 313-342.

Pach, M., Zanzi, R., and Björborn, E. (2002). Torrefied biomass a substitute for wood and charcoal,” 6th Asia-Pacific International Symposium on Combustion and Energy Utilization, Kuala Lumpur.

Parikh, J., Channiwalab, S. A., and Ghosalc, G. K. (2005). “A correlation for calculating HHV from proximate analysis of solid fuels,” *Fuel* 84, 487-494.

Pellets Fuel Institute (2010). “Pellet fuels institute standard specification for residential/commercial densified fuel,” Available at: http://pelletheat.org/wp-content/uploads/2010/01/PFI-Standard-Specification-for-Residential-Commercial-Densified-Fuel-10-25-10.pdf . Consulted on: 03/10/2011.

PelletPros. (2007). Testing Log. Available at: http://www.pelletpros.com/id81.html. Consulted on 07/21/2011.

PelletPros. (2010). Small Pellet Mills. Available at: http://www.pelletpros.com/id68.html. Consulted on 07/21/2011.

Pentananunt, A., Mizanurt Rahman, A. N. M., and Bhattacharya, S. C. (1990). “Upgrading of biomass by means of torrefaction,” *Energy* 15(12), 1175-1179.

Phanphanich, M., and S. Mani. (2011). Impact of torrefaction on the grindability and fuel characteristics of forest biomass. *Bioresource Technology* 102, 1246-1253.

Pirraglia, A., Gonzalez, R., Saloni, D., and Wright, J. (2011). “Freeze tolerant eucalyptus biomass: A study of characteristics and suitability for solid fuels production,” *Biomass and Bioenergy*, under review.

Raveendran, K., and Ganesh, A. (1996). "Heating value of biomass and biomass pyrolysis products," *Fuel* 75, 1715-1720.

Rosillo-Calle, F. (2004). "A brief account of Brazil's biomass energy potential," *Biomassa & Energia* 1(3), 225-236.

Sklar, T. (2009). "Torrefied wood, a bio-energy option that is ready to go," Available at: http://biomassdigest.net/blog/2009/12/31/torrefied-wood-a-bio-energy-option-that-is-ready-to-go-a-biomass-digest-special-report/. Consulted on: 10/25/2010.

Tillman, D.A. (2000). Biomass Cofiring: the Technology, the Experience, the Combustion Consequences. *Biomass and Bioenergy* 19 (6), 365–384.

United Soybean Board. (2006). Soy-Based Composites, Technical Research. Available at: http://www.soynewuses.org/downloads/Tech_Composites.pdf. Consulted on: 07/22/2011.

Uslu, A., Faiij, A. P. C., and Bergman, P. C. A. (2008). "Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation," *Energy* 33, 1206-1223.

Weiss, B., M. Eastridge, D. Shoemaker, and N Saint-Pierre. (2007). Distillers Grains. Ohio State University Extension. Available at: http://ohioline.osu.edu/as-fact/pdf/ distillers.pdf. Consulted on: 07/23/2011.

Wright, J. (2009). "Improvements through biotechnology maximize potential of purpose grown trees for biomass," Farm to Fuel Summit, July 30, 2009. Available at: http://www.arborgen.com/uploads/presentations/farm-to-fuel-presentation%20_final.pdf?phpMy Admin=iPU8Ia6jISo93dPyYdigjfeIV%2C3. Consulted on: 11/29/2010.

Wright, J. A. (2010). "Wood-based biofuels, biomass & bioenergy: Opportunities and challenges in Louisiana," *Bioenergy Forest Plantations*, April 23, 2010.

Wright, L. (2006). "Worldwide commercial development of bioenergy with a focus on energy crop-based projects," *Biomass and Bioenergy* 30, 706-714.

Zwart, R., Boerrigter, H., and Van der Drift, A. (2006). "The impact of biomass pre-treatment on the feasibility of overseas biomass conversion to Fischer-Tropsch products," *Energy Fuels* 20, 2192-2197.

7. TECHNO-ECONOMIC ANALYSIS OF WOOD PELLETS PRODUCTION FOR U.S. MANUFACTURERS

7.1 Abstract

Many companies in the U.S. are entering the wood pellets market due to the increasing importance of woody biomass utilization for energy purposes. Despite a 200% increase in U.S. production, it is difficult to obtain reliable information from the research community about production costs, requirements, and market trends for wood pellets. Based on comprehensive investigations, a techno-economic model for the determination of production costs for U.S. manufacturers (internal market, with sell strategy based on bagged product) was developed, considering the most important technical and financial factors that affect pellet production. Outcomes from a case-study show that pellet production is profitable for U.S. manufacturers and distributors/retailers, with more revenue margin for retailers. Sensitivity analyses were performed, showing that a pellet plant is especially sensitive to changes to the cost of biomass and labor. In addition, changes in energy and CAPEX also affect the NPV and IRR of the project, but not as significantly as biomass and labor costs. Additional findings indicate that increasing the plant size especially increases CAPEX, with labor being the least increased cost factor; in addition, production factors have to be closely monitored for small-scale producers, due to increases in operational costs.

7.2 Introduction

Wood pellets have become a successful internationally traded biomass (Junginger et al. 2008) with a market size that was projected to double from 2007 to 2010 (Savolainien 2007). Hess and Jacobson (2009) indicated that from 2002 through 2006, the internal demand of wood pellets in the United States increased by 200 percent. Moreover, production forecasts for 2012 were set at 6.0 million metric tons (10% moisture content) per year in the U.S.; however, by the year 2009 the market capacity increased faster than forecasted, with an approximate production of 6.2 million metric tons (Spelter and Toth 2009; Mani, 2006).

Ryu et al. (2006) stated that a critical element for biomass fuels to successfully compete with other energy sources is densification; in this sense, wood pellets provides an

enhanced heating value of wood per unit of volume, low moisture content, a more complete and efficient burning, with low ash and particulate emissions content, optimized transportation over long distances, and a variety of applications, from small-scale residential heating to large-scale co-firing in coal power plants (Wahlund et al. 2004; Junginger et al. 2008; Spelter and Toth, 2009). Additionally, pellets can be easily produced from wood waste, forest-thinning, other biomass ingredients, and wood production by-products (PFI, 2009, Bergman and Zerbe, 2008).

Production and characteristics of wood pellets in the U.S. are subject to wood supply availability, and are based on a "per bag" selling strategy, instead of the common bulk delivery used in the European Union. In Western U.S., most pellets are made from softwoods sawdust, being a residue from sawmills, while in the Mountain region mills are using Lodgepole Pine (*Pinus Contorta*) trees killed by the pine beetle. In the South and Midwest, mills are using waste stream from the wood flooring and furniture business, while in the East, mills are using hardwood unsuitable for lumber (PelletSales 2009). The Southern US is drastically increasing its production capacity, with recently opened large size factories, and a reliable supply of southern yellow pine (Green Circle 2010). Based on the wide variety of biomass that can be used for its manufacturing, wood pellets have become attractive as an alternative fuel; however, in the U.S., the wood pellets market is still behind in demand and internal utilization as compared to mature markets such as Canada and Europe, which have applications for residential heating as well as industrial and commercial energy production (Hoque et al. 2006). By 2006, there were 600.000 homes in the U.S. using wood pellets for heat (PFI, 2006), increasing to 800.000 in 2007 (Biomass Energy Resource Center, 2008), and with an estimated of 1.000.000 residences/business by 2010 (PFI, 2010), but data is scarce on industrial and commercial applications and its future development.

In the U.S, around 90 plants are producing wood pellets, with many more to come into full production in the near future, having a 33 percent forecast increase in manufacturers from 2006 to 2010 (Hess and Jacobson 2009; Peksa-Blanchard et al. 2007). Despite this increase, it is difficult to obtain reliable information from the research community about production costs, requirements, and market trends for wood pellets in the U.S. Several efforts have been performed to identify, compare, model and calculate production costs of wood

pellets in Europe (Thek and Obernberger, 2004; Di Giacomo and Taglieri, 2008; Stahl and Wikström, 2009; Mahapatra et al. 2007) and in Canada (Mani, 2006; Chau et al. 2009); but more information is needed for the U.S. wood pellets market, regarding production and financial characteristics, logistic barriers (market pricing habits, transportation, storage, and operating costs, Swaan and Melin 2008), and specific parameters for the determination of competitive wood pellets prices (biomass delivered cost, equipment, energy consumption, and labor costs, Thek and Obernberger 2004).

7.2.1 Objective

The main objective of this project was to develop and validate a techno-economic model that estimates the production costs of pellets, as well as performing financial and sensitivity analyses for pellets production in the U.S. internal market (bagged pellets market).

7.3 Methods

The techno-economic model for pellets production was developed in Microsoft Excel 2007®; detailed information on the characteristics of the model is provided in the following paragraphs.

7.3.1 General Aspects of the Model

The first step for the development of the techno-economic model for pellet production costs is the identification of all the individual processes necessary for pellet manufacturing (Figure 7.1).

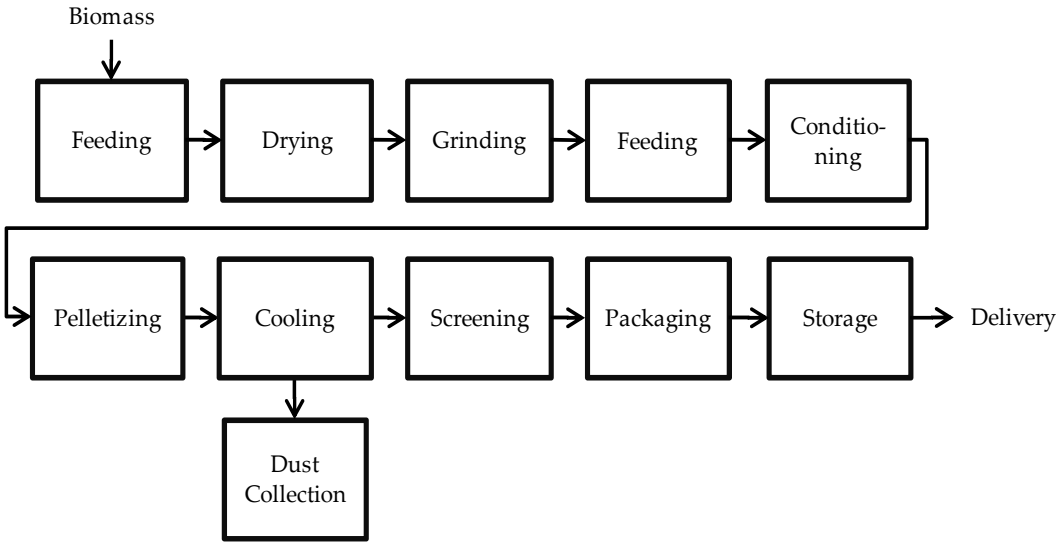


Figure. 7.1. Typical manufacturing process for wood pellets

The processes in Figure 7.1 are typical for a pellet production facility. Processes such as grinding or drying depend on the raw material characteristics; if the raw material comes already dried and/or in the adequate particle size, then these processes are not required. It is assumed that collection, storage, and transportation of the biomass to the facility are outside the boundaries of the model (that can be performed by another company, or another division of the same company), and the biomass cost is "as-delivered" to the factory gate. A model developed at NC State University that deals with delivered costs of biomass (Gonzalez et al. 2010), according to hauling distances and biomass type, was used for the as-received cost of raw material (in this case, utilizing debarked roundwood, loblolly pine, hauled an average distance of 50 miles) into the factory, totaling $63/metric ton (estimations for other biomass types may be included in the wood pellets model, once the delivered biomass cost has been calculated from Gonzalez et al. 2010). Storage and delivery after production of wood pellets are also considered to be outside the boundaries of the model.

In order to facilitate the development of the techno-economic model, three main areas were identified in a conceptual scheme (Figure. 7.2).

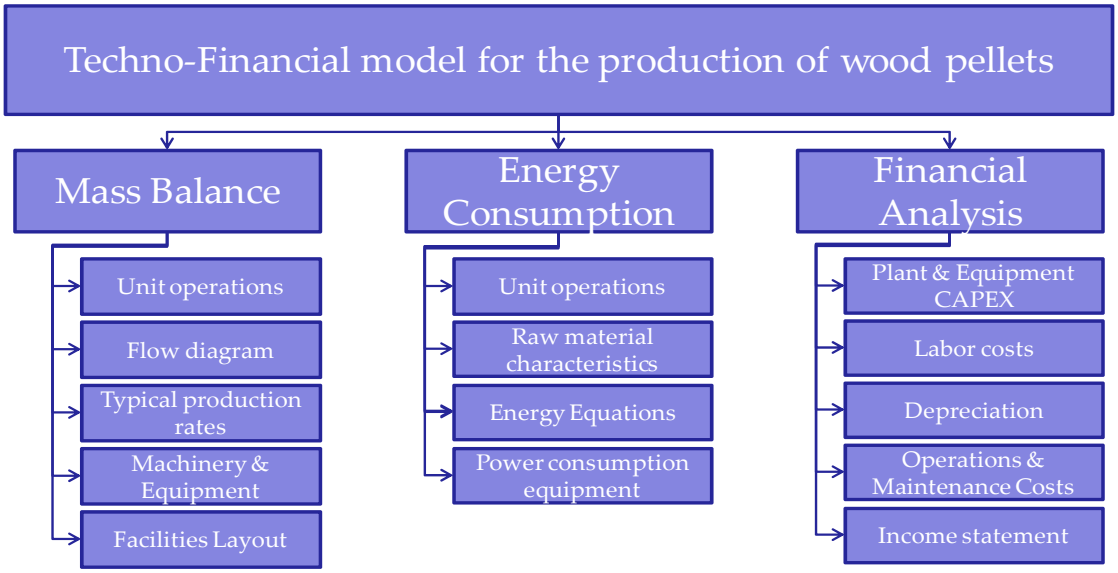


Figure. 7.2. Conceptual model for the production of wood pellets under U.S. conditions

The first area (Figure 7.2) considered for the model was a detailed mass balance, facilitating the understanding and calculation of production rates, amount of biomass entering and leaving each unit operation, losses, capacity, and efficiency of machinery and equipment. The energy consumption, section in Figure 7.2, indicates the amount of energy required for pellets production, depending on the raw material and energy consumption of the equipment. The final area is a comprehensive financial analysis, considering a fixed delivered cost of raw material and containing information of plant and equipment costs (CAPEX), labor costs and structure, depreciation, operation and maintenance costs, and an income statement, summarizing the financial information for a given year (Figure 7.2).

Additionally, the main inputs for the model were identified as: annual production (metric tons), number of working hours per year (considering number of shifts per day), factory location, type and characteristics of biomass used, moisture content as delivered, and pellet quality standard. When these inputs are entered in the model, the mass, energy balance, and financial spreadsheets are automatically updated.

7.3.2 Mass Balance

The mass balance section is based on the unit operations defined for the pellet production process, being automatically updated whenever any input of the model changes, or if any of the processes become optional, such as drying or grinding as discussed previously. Mass losses are considered for each process, and can be defined by the user; however, it is typical for a pellet factory to re-circulate any crumbles, fines, or defective pellets into the particle reduction operation, thus the mass losses in the system are reduced. The moisture content of raw material changes throughout the process, being decreased to 6±1% in the drying, increased to 10±1% in the conditioner, and decreased to a final moisture content of 7±1% during the pellet mill, screening, and cooling processes. The machinery efficiency was set at a default value of 100%, except for the screening operation, in which 10% of the mass not converted to durable pellets is re-circulated. Machinery efficiencies can be modified by the user, automatically updating mass losses. It is also considered that steam addition is necessary in the conditioning unit of the pellet mill, for softening the fibers (Leaver 2008); this steam was produced by an 800 kWh boiler; no heat recovery was considered in the factory.

7.3.3 Energy Consumption

The data for energy consumption of each unit operation was obtained from the literature and verified by interviewing several pellets' manufacturers. Data for the drying, grinding/hammermilling, and miscellaneous units (such as packing and bagging) were obtained from Digiacomo and Taglieri (2009); data regarding pellet milling and cooling were obtained from manufacturers specifications (Lange 2009), and data for the screening operation was obtained from Mani (2006). Figure 7.3 summarizes the combined energy consumption of each unit operation (% of the total energy consumed).

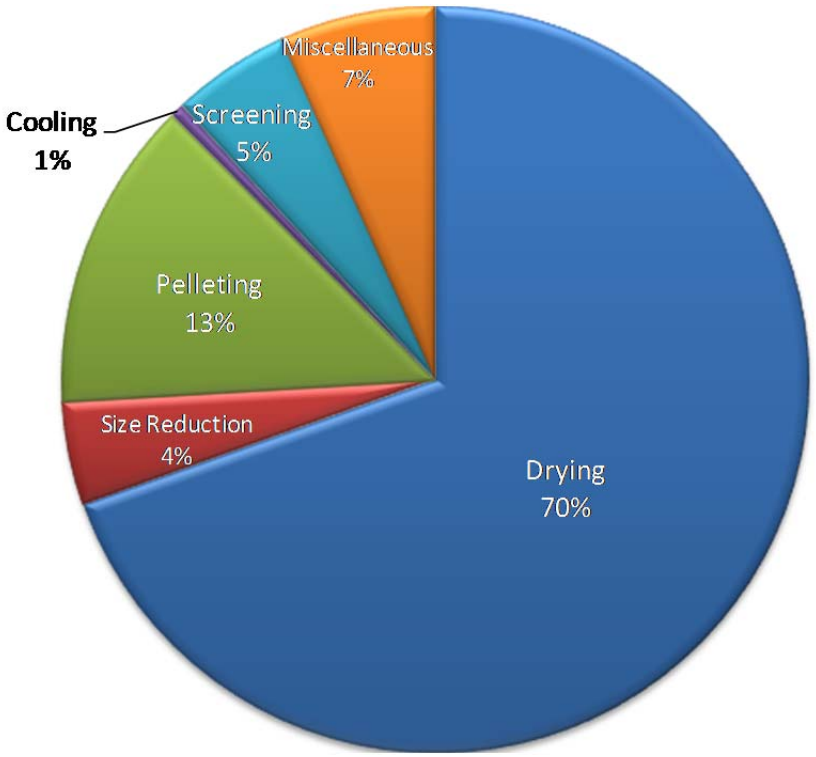


Figure. 7.3. Energy consumption of each operation performed in the factory

An energy summary spreadsheet shows the total energy consumption per year, the cost of electricity according to the location of the facility, cost of steam produced from natural gas boiler, and the current cost of electricity for industrial applications (updated every month by the Energy Information Administration EIA 2009), according to the required annual production. In the model, it is not included the addition of wood-waste boilers, which can highly improve the costs of energy for the facility if availability and supply can be reliably ensured in a long term basis.

7.3.4 Financial Analysis

Facilities and machinery capital expenditure is a core element in the model. Since the received raw material is debarked roundwood, it is assumed that a debarking process is not required. Prices for industrial equipment were obtained directly from manufacturers and distributors (dryer, chipper, hammermill, pellet mill, cooler, screener/shaker, and bagging system), while peripheral and miscellaneous equipment such as feeders, conveyors and front-

end loaders, as well as building and office spaces were calculated from recent literature (Samson et al. 2000; Campbell 2007) and adapted to the year 2009 using the CWCCIS (Civil Works Construction Cost Index System) conversion index. Equipment prices (capital investment per unit) obtained from Samson et al. (2000) were based on a one metric ton per hour production rate (and equipment capacity). In order to calculate the capital investment of a different capacity equipment, a scale-up of the capital investment, from the original size equipment, is performed automatically in the model. Perry's Chemical Engineering Handbook (1997) recommends the power law rule for this purpose; this rule estates that: $Inv=Inv_L x(P/P_L)^{0.7}$, in which *Inv* represents the capital investment according to the plant size requirements, Inv_L represents the capital investment of the original equipment, and P and P_L represent the capacity required on the equipment, and the capacity of the original equipment respectively, and it is presented in the cost per each equipment column. This method provides a way of calculating the capital investment of bigger capacity equipment, based on the size and capital cost of the original machine. A scaling factor of 0.7 is used in the equation based on Andersson et al. (2006), since some process equipment involve several parallel units instead of one single large unit. The CAPEX section of the model incorporates this formula to calculate machinery capacities when bigger sizes are required. Indirect costs and contingency costs were 24% and 10% of the total calculated facilities and machinery total, based on Woodworth et al. (1997). Storage capacity was added to the CAPEX, representing 7.6% of the total plant building space (Thek and Obernberger 2004). Plant and equipment depreciation was calculated using a MACRS-7 method, and was automatically updated if any values contributing to the CAPEX were modified.

The labor requirements of the model (structure, number of shifts, wages, benefits, and fringes) were obtained and modified from Campbell (2007), and the Bureau of Labor Statistics (2009). Labor structure is automatically increased depending on the plant capacity, since the number of workers required for operations depends on production rates. For instance, the model utilizes 3 production workers per shift for capacities below 4 metric tons/hour, and 1 supervisor, forklift operator, and maintenance technician; for capacities higher than 4 metric tons/hour, the model adds one more worker on each category per shift, for every 4 metric tons/hour production increase. Administrative personnel are not dependent

on production rate, thus, its number changes with the addition of a controller and accounting assistants for capacities higher than 100,000 metric tons/year. This information is summarized as a total annual cost of direct and indirect labor.

Consumables costs for a pellet production facility are an important factor to be considered, and these were assumed to be directly linked to the production (no consumables were assumed for office and administrative labor). It is assumed that the majority of pellets for the U.S. market are sold to retailers and distributors in 40 lb. bags, which may cost $0.12 to $0.25/bag; it is assumed that a durable plastic bag (0.0035 to 0.005 mils) with one-color printing would cost $0.2 (Campbell, 2007), and 50 bags are needed per each metric ton of product. In addition, a pallet of product holds 50 bags (1 metric ton) of pellets, and the cost of each EU approved 40x48, 2-way entry pallet (pallets that can be entered by a forklift and pallet jack from only the two ends) is $14.35 (Far packaging Company 2009). The model considers that these pallets are for a one-time use once delivered to the distributor/retailer. Additional improvements of costs can be achieved if pallets are considered for multiple uses. Additional packing material is required for support and fixing of the bags to the pallets. Slip sheets and stretch wrapping is required, and its cost is estimated at $4.00 per metric ton ($4.00 per pallet). Additional costs include parts and replacements (dies and rollers for pellet mills, and spare parts for hammermills) ($3.00/metric ton), marketing and sales fees, and incentives (assumed to be $6.00/metric ton), which accounts for marketing and sales costs for promotions, discounts, rebates, broker fees, placement fees, and other forms of compensation and incentives (Campbell 2007). A final spreadsheet contains pricing information for the type of biomass selected to be pelletized. This information was based on a model provided by Gonzalez et al. (2010), which calculates biomass delivered cost to factory gate (debarked roundwood).

An income statement spreadsheet summarized the financial information of the company for the current and upcoming years (projected), based on every cost incurred in the production of wood pellets. The income statement incorporates an add-in calculation of the price of pellets for a desired Internal Rate of Return (pre-determined IRR of 6%, 8%, 10%, 12% and 14%, with no inflation rate assumed).

7.4 Results and Discussion

In order to analyze the outputs results that can be obtained from the techno-economic model, a case study is described next. Since the majority of factories producing pellets for the internal U.S. market are in the range of 30 to 100 thousand metric tons/year; the case study described considers a pellet plant producing 75.000 metric tons/year (7±1% Moisture Content of final product, MC, in order to reach a premium grade product according to Pellet Fuel Institute Standards, PFI) of pellets. The plant is assumed to operate 50 weeks/year, seven days/week, with three shifts of 8-hours/day, totaling 8,400 production hours, from which 112 hours/year are dedicated to maintenance and unexpected shutdowns. It was assumed that the pellets were to be produced from southern yellow pine (55% MC). Debarking was assumed not to be required in the factory; drying and grinding of the raw material, however, were assumed to be required, and the pellets were to be sold to retailers in 40 lbs. bags.

7.4.1 Case Study Results

Mass balance calculations indicated a production rate of 8.93 metric tons/hour of pellets in order to meet 75,000 metric tons/year rate (75,000 metric tons/8400 hours = 8.93 metric tons/hour), with an energy consumption of 4,932.15 (41,430,066.24 kW/year) kWh (Table 7.1).

Table 7.1. Annual Electrical Consumption and Cost (for U.S. average location)

Annual electrical energy consumption	41,430,066.24	kW/year
Average Electricity cost	0.0689	$/kWh
Total energy cost per year	2,854,531.56	$/year

Capacities, number of machines, building size, and capital and installation costs (CAPEX) were calculated by the model assuming two separate lines operating in the facility. Table 7.2 shows CAPEX calculations adapted for the case study, and validated by several pellet manufactures.

Table 7.2. CAPEX for a 75,000 metric tons/year Plant, Expressed in Thousands of Dollars

Item	Capacity (t/h)	Number required	Cost per equipment	Installation cost	Total Equipment costs	Total Installation costs	**Total Equipment + Installation costs**
Conveyors & misc. equipment	-	8	29	10	228	78	**307**
Front-end loader	-	2	113	-	226	-	**226**
Feed hopper	-	13	10	4	132	54	**186**
Dryer, burner & air system	5	5	140	204	700	1,020	**1,720**
Hammer mill	8	2	55	78	110	157	**267**
Live bottom bin	-	13	175	14	2,275	181	**2,456**
Pellet mills(s)	5	2	535	168	1,070	336	**1,406**
Pellet cooler	5	2	150	37	300	73	**373**
Pellet shaker	8	2	15	40	29	79	**109**
Boiler (800 Kwh)	-	4	110	1	440	4	**444**
Bagging bin	-	2	4	9	9	19	**27**
Bagging system	10	2	36	14	73	28	**101**
Fork lift	-	2	22	-	44	-	**44**
Site and site preparation	-	1	156	-	156	-	**156**
Paving, receiving station, load area	-	1	60	-	60	-	**60**
Building & office space	-	1	1,020	-	1,020	-	**1,020**
Total equipment costs					**$ 6,872**	**$ 2,030**	**$ 8,902**
Storage warehouse							$ 78
Indirect costs (24%)							$ 2,155
Contingency (10%)							$ 1,114
Total installed costs							**$ 12,249**

In addition, the model includes an additional 24% of the CAPEX for indirect costs, 10% for contingency, and 7.6% of the total building cost for short- term storage warehouse (Woodworth et al 1996), bringing the total installed costs of the factory to $12,249,000. This short-term storage is considered necessary at the exit of the bagging process, for further palletizing and wrapping of the bags prior to be loaded in distribution trucks, for this instance, the warehouse area is considered as open-wall facility, with no requirements for temperature/gas sensing devices, or forced ventilation systems, which may be required for long term storage, or bulk delivery of pellets.

The direct and indirect labor force required for a 75,000 metric tons/year plant totals 30 people over 3 shifts per day, with total labor costs of $3,762,150 per year ($3,235,650 direct labor, $526,500 indirect labor). Costs of consumables, as described in the methods

section, were calculated according to the production rate, accounting for $2,321,600 per year. Additional costs (as described in methods) accounted for $500,250 per year. These operating costs are summarized in Table 7.3.

Table 7.3. Summary of operating costs for a 75,000 metric tons/year Plant

Operating Cost	$/year
Direct Labor	3,235,650
Indirect Labor	526,500
Consumables	2,321,600
Additional Costs	500,250
Total Operating costs ($/year)	6,584,000

7.4.2 Case Study Analysis

Segmentation of the production costs is useful to understand their influence on the total costs of producing wood pellets (Figure. 7.4). The most important cost driver was represented by biomass (27%), closely followed by labor costs (24%). Energy and consumables represented 17% and 15%, respectively. Depreciation represented 11% of the non-cash costs per metric ton, and taxes and others (marketing fees, incentives, and maintenance costs) represented the smallest cost in pellets production, being 3% each.

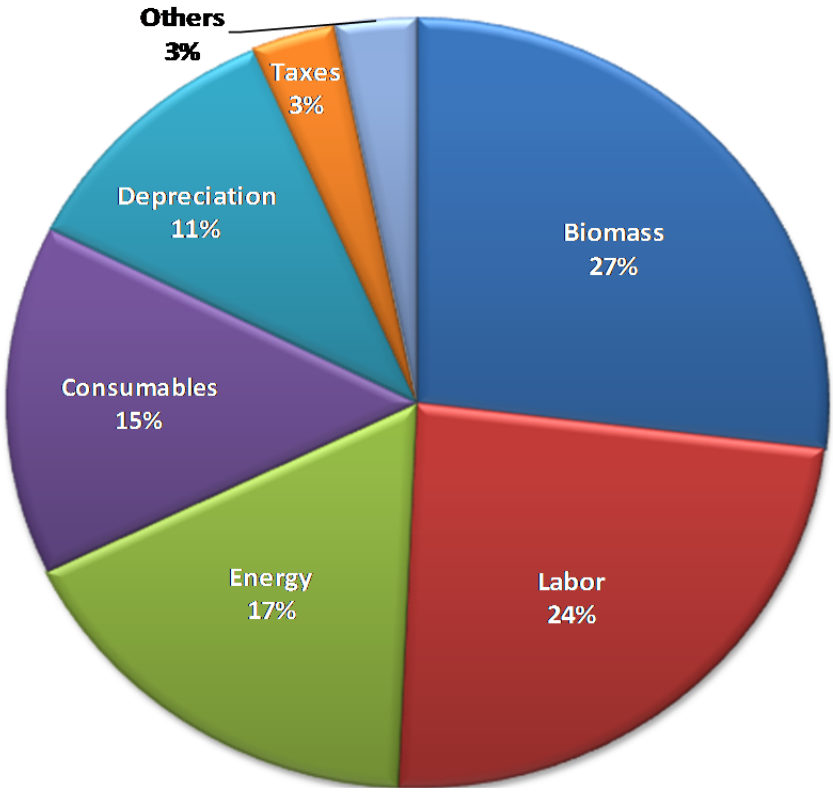


Figure. 7.4. Share costs of wood pellets per metric ton

The model indicates a total production cost of $203.7/metric ton, which is obtained in the income statement by assuming no inflation, depreciating according to MACRS-7, and with a CAPEX spending schedule of 20%, 40%, and 40% from the year 2009 through 2011. In addition, an add-in function in the income statement made it possible to back-calculate the corresponding price per metric ton of pellets, to achieve a specific expected internal rate of return (IRR), with a discount rate set at 12% by default. Figure 7.5 shows the net present values (NPV) of the plant, and selling price of pellets when the model is adjusted to 6%, 8%, 10%, 12%, and 14% IRR using this add-in function.

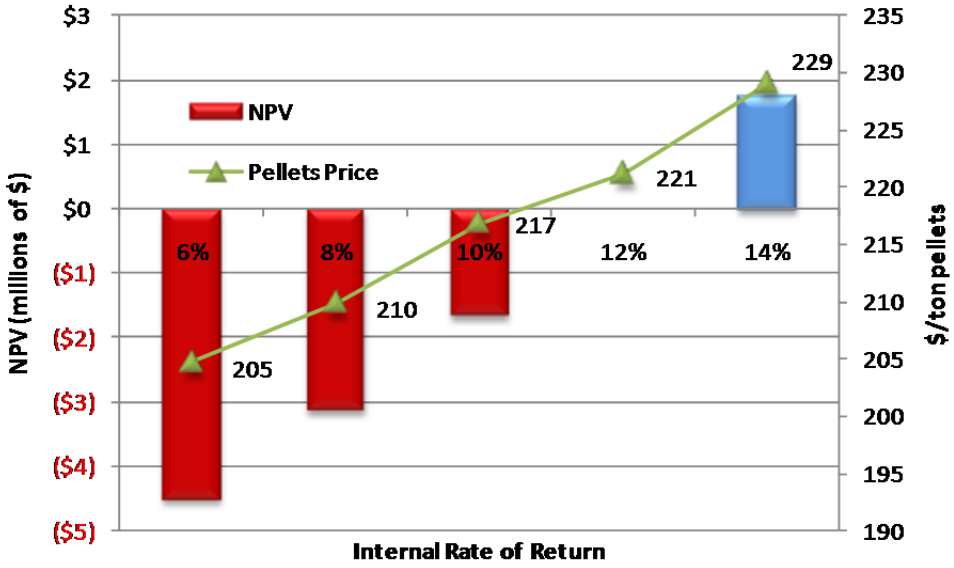


Figure. 7.5. Net present value (NPV) and price of pellets for the case study, adjusted to different IRRs

Figure 7.5 indicates that in order to obtain a positive NPV, the back-calculated price of pellets at the factory gate has to be higher than $221/metric ton. Assuming that a price of $229/metric ton (for a 14% IRR) is more desirable, and having production costs of $203.7/metric ton, this adjusted price indicates an achievable revenue margin of $25.3/metric ton for producers.

An additional transportation cost is added to this price, assuming that pellets have to be loaded, hauled, and unloaded from the factory to retailers and distributors, with trucks loading 20 metric tons/truck (Rhode 1999), and a travelling average distance of 50 miles. This transportation cost is assumed to be similar to that reported by Brechbill and Tyner (2008), having a fixed element of $15/metric ton, and a variable element of $0.12/mile, giving a total of $15.3/metric ton in the case study. This transportation element, added to the pellet price determined for a 14% IRR ($229/metric ton), totaled $244.3/metric ton at the retailers/distributors gate. When comparing this price to an average retailer selling price of $276/metric ton for the U.S. internal market (Pirraglia et al. 2010), a revenue margin of approximately $31.7/metric ton can be obtained by retailers. Based on the fact that the majority of factories in the U.S. are in the range of 70,000 metric tons/year (Spelter and Toth,

2009), similar to the 75,000 metric tons/year assumed for the case study, it demonstrates that the wood pellets industry is profitable for both, the majority of producers and distributors/retailers in the internal U.S. market.

7.4.3 Case Study Sensitivity

Sensitivity analyses were performed for the case study by modifying the most critical variables of the model, while observing the behavior of the NPV and IRR for a fixed selling price ($229/metric ton). This fixed selling price is similar to the one obtained when a 14% IRR is desired, and ensures profitability and positive NPV of the factory. Changes of ±25% in biomass cost, labor costs, energy costs, and CAPEX were studied for this fixed selling price, and are described below.

7.4.3.1 Biomass Cost Sensitivity

When increasing the cost of biomass by 25% (Figure 7.6), the project can be adversely affected in its IRR, having a negative NPV of -$1.68 million (10% IRR). Reductions by 25% in the biomass cost resulted in a high increase in the NPV ($6.3 million) and IRR (19%), demonstrating the sensitivity of a pellet plant to changes in the raw material cost. In order to offset the impact of an increased biomass cost, pellets plants might negotiate long-term agreements with suppliers located close to wood baskets, in order to minimize changes in cost for the raw material. In addition, it must be taken into consideration that the raw material availability and hauling distance is an element that heavily influences the cost of biomass, making this element more likely to have costs fluctuations, further enhancing its sensitivity.

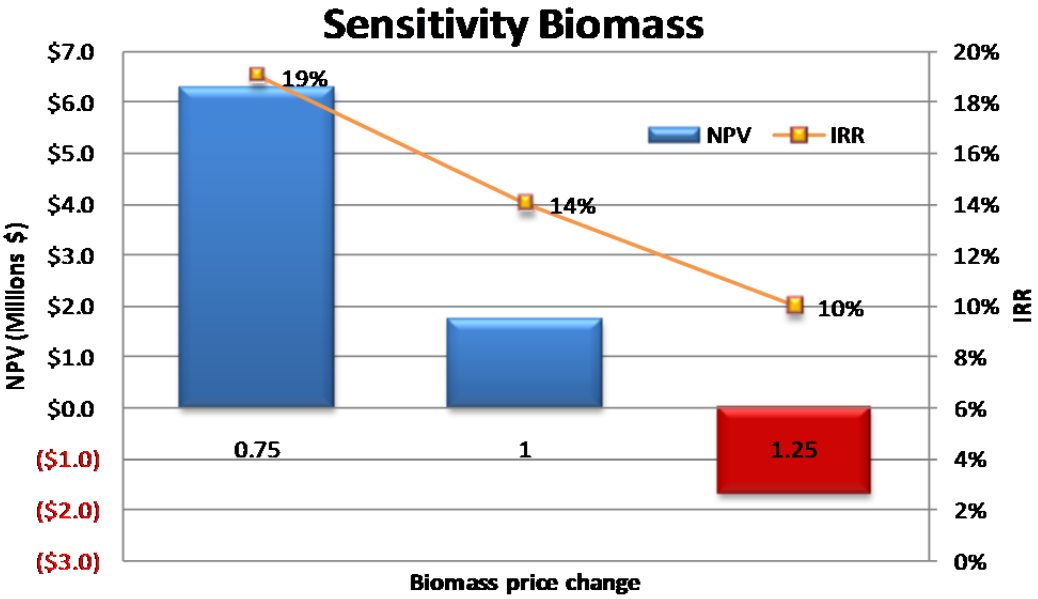


Figure. 7.6. Sensitivity of NPV and IRR of the pellet plant with changes on biomass cost

7.4.3.2 Labor Costs Sensitivity

The second most important sensitivity factor of the project was determined when analyzing changes in labor costs (Figure. 7.7). These changes caused a variation from $5.8 million to -$1.9 million in the NPV of the project for decreases/increases in labor costs. The IRR of the project also showed a variation from 19% to 10%.

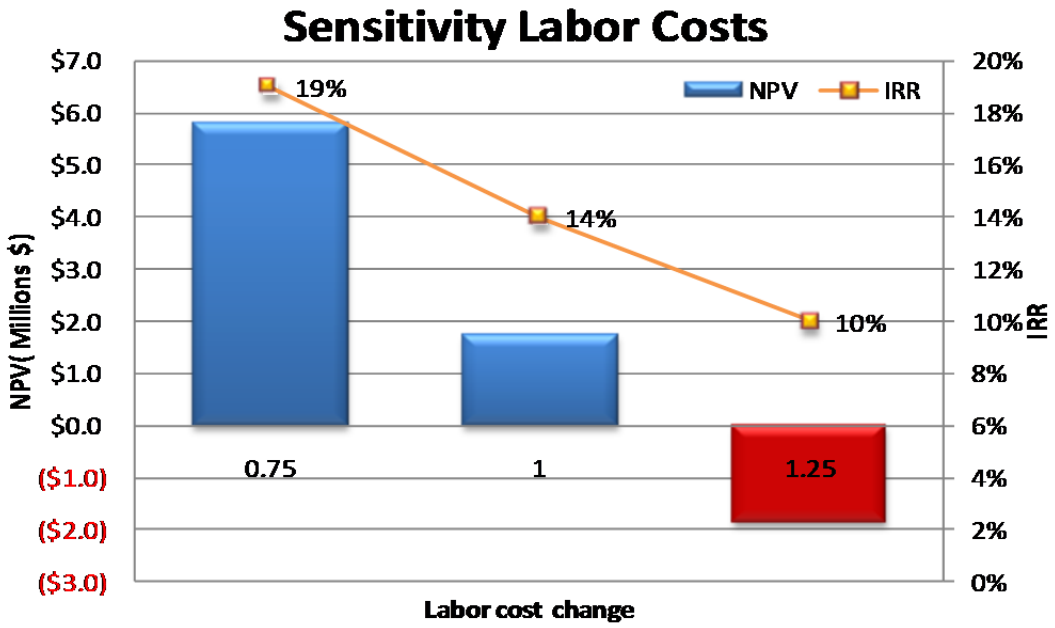


Figure. 7.7. Sensitivity of the pellet plant project to changes in Labor costs

Considering that a pellet factory operates with few personnel, and that it was previously demonstrated that labor costs have a high impact on costs per metric ton of pellets produced (Figure. 4), it becomes extremely important to adequately dimension, plan, and monitor the personnel needs of a pellet plant.

7.4.3.3 CAPEX Sensitivity

CAPEX represents the third most sensitive cost element when compared to biomass and labor costs; the NPV of the project was notably increased when the CAPEX is reduced (Figure. 7.8), becoming almost 3 folders bigger than the original NPV ($4.64 million vs. $1.73 million). In addition, the IRR of the project was more sensitive to decreases in CAPEX (increase from 14% to 19%), while an increase in CAPEX only reduced the IRR by 2% (14% to 12%).

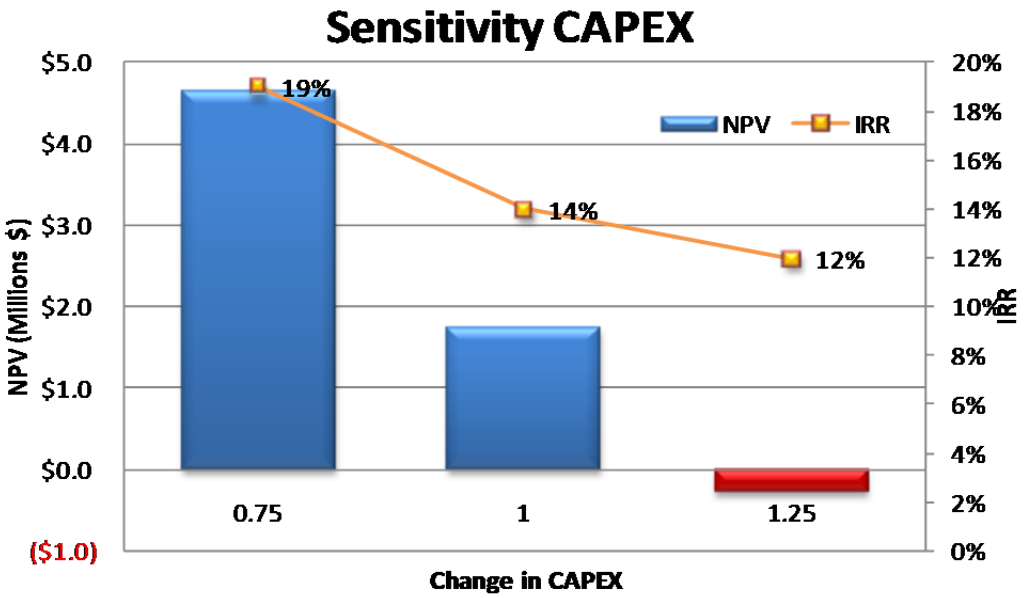


Figure. 7.8. Sensitivity of the pellet plant to CAPEX variations

7.4.3.4. Energy Cost Sensitivity

Changes in energy (Figure. 7.9) did not tend to affect the project as much as biomass or labor costs were projected to. However, a 25% increase in energy could still produce a low NPV ($243,443), while the IRR was not significantly affected between actual energy costs and the increased costs (14% IRR vs. 12% IRR). A different case occurred for the decrease of energy costs, which can highly increase the NPV of the factory. In this sense, the sensitivity to energy costs increase can be offset with the self-generation of energy, either to be utilized in the factory, or to be sold to the power grid. Additionally, energy sensitiveness can be reduced for the case in which drying and other operations are not required, since the drying process represents 70% of the total energy consumption of the factory, but it must be taken into consideration that dried raw material costs are higher.

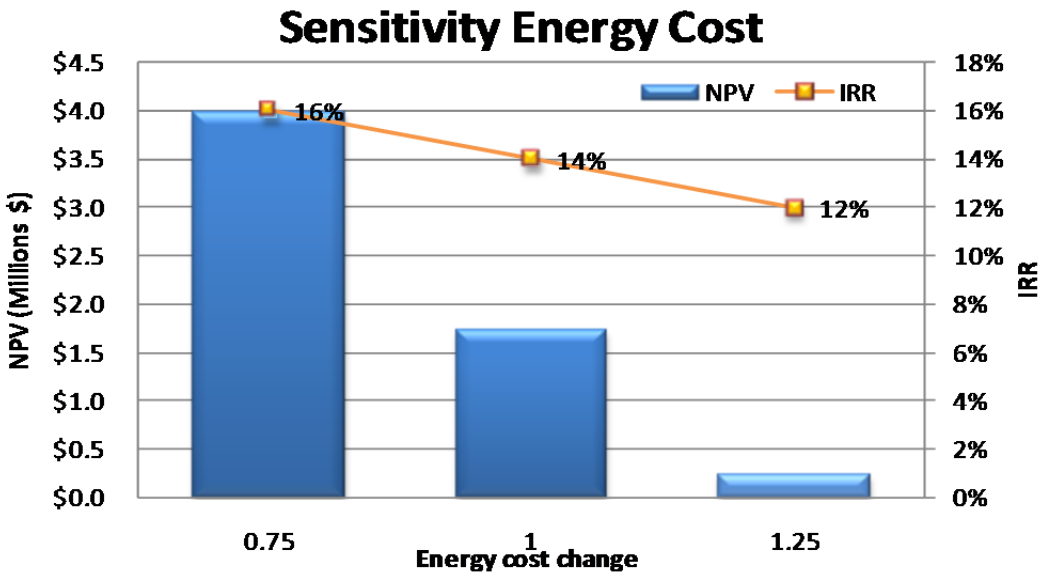


Figure. 7.9. Sensitivity of the project to Energy costs

7.4.4 Additional Remarks

Since new plants in the U.S. are significantly increasing in size, and many well established factories are in the production range of 75 thousand metric tons per year, a comparison of the costs between large and medium sized factories for the internal market is important. Table 7.4 shows the detailed costs of pellets production, and the values obtained for two different plant sizes (75 thousand metric tons/year vs. 125 thousand metric tons/year).

Table 7.4. Costs Comparison, 75 vs. 125 thousand metric tons/year (thousands of dollars)

Description	75.000 metric tons/year plant	125.000 metric tons/year plant
Labor	$ 3,763	$ 3,763
Consumables	$ 2,322	$ 3,816
CAPEX(with indirect costs & fees)	$ 12,249	$ 19,259
Energy	$ 2,695	$ 4,758
Taxes	$ 520	$ 2,668
Other costs	$ 501	$ 834
Biomass	$ 4,050	$ 6,750
Total	**$ 26,861**	**$ 41,848**
% Increase from factory size	**-**	**36%**
Selling price for a 12% IRR	**$ 219**	**$ 187**
Price difference	**-**	**17%**

The change in size of a factory of 75,000 metric tons/year to 125,000 metric tons/year represents a total cost increase of 36%. This change in costs is mainly due to changes in CAPEX and energy, to adapt for the requirements of a large factory. However, advice should be taken when making direct comparisons for the CAPEX of two different size factories, since the model utilizes the power law (Perry et al. 1997) to scale-up the CAPEX, and it represents only an approximation of the capital investment for the new factory size. Labor costs are the least influencing factor for this comparison, since indirect labor was not changed for this plant capacity (being lower than 100,000 metric tons/year), and direct labor did not considerably increase when increasing the plant size. In addition, a factory producing 125,000 metric tons/year has a selling price that is 17% lower than the one required for a 75,000 metric tons/year factory (considering a selling price of $219/metric ton, which determines a zero NPV, at 12% IRR). This difference in prices allows a bigger factory to have a wider revenue margin, and capture market share by having lower prices than smaller competitors; however, large factories require larger wood sources, making it difficult for them to rely on a single wood source or waste wood stream to supply the factory. Thus, costs and production conditions have to be closely monitored for small scale manufacturers, in order to be able to effectively compete with larger producers on a price only basis, while supply conditions have to be accurately determined for large factories in order to remain competitive on a long term basis.

As a final remark, the model and case study was validated with the assistance of several wood pellets producers in the Southern U.S., with production rates higher than 75,000 metric tons/year, who reviewed the model and case study, considering their own production conditions as well as all the relevant details and variables for pellet production, validating that results obtained from the model were accurate, since similar costs and prices were obtained by them, and up-to-date according to market conditions.

7.5 Conclusions

This research focused on the development of a techno-economic model for evaluating the feasibility of pellet production for the internal market in the U.S. The main conclusions from this project are:

- Previous research and technical information from producers indicated that the most important variables for wood pellets production are: biomass type (species, MC, and form of delivered biomass), plant and equipment prices, energy costs, and labor structure.
- Pellet production for the U.S. internal market is profitable for both producers and distributors/retailers, for selling prices higher than $241.3/metric ton, considering actual price trends and transportation costs. The pellets business proves to be more profitable for retailers/distributors ($31.7/metric ton vs. $25.3/metric ton revenue margin for producers). However, specific production costs should be closely monitored for small-scale producers in order to effectively compete with larger producers.
- Sensitivity analyses determined that biomass and labor costs were the most important cost drivers for wood pellets. In this sense, pellet production was especially sensitive to biomass cost. Thus, long term agreements for the supply of biomass located near the factory may minimize raw material costs.
- Additionally, labor represented a very sensitive cost factor, and needs to be accurately dimensioned in order to reduce its potential negative impact on the NPV.
- Energy costs represents an important price-reduction factor if drying is not considered in the operations, since it accounts for 70% of the total energy consumption; however, the impact of using previously dried raw material must be evaluated in detail. In addition, a strategy of energy co-generation from the factory may positively reduce the sensitiveness of this factor in the overall production costs.
- CAPEX was the third sensitive cost factor of the pellet plant. A CAPEX reduction strategy may be achieved by better machinery effectiveness, higher unit capacities, or reduction of unit operations such as drying, grinding or hammermilling, but further analyses must be conducted regarding increases in the raw material costs, since activities such as drying must be performed by suppliers, increasing the delivered cost of biomass.

7.6 Literature Cited

Andersson, E., Harvey, S., and Berntsson, T. (2006). “Energy efficient upgrading of biofuel integrated with a pulp mill,” *Energy* 31, 1384-1394.

Bergman, R., and Zerbe, J. (2008). “Primer on Wood Biomass for Energy,” USDA Forest Service, State and Private Forestry Technology Marketing Unit, Forest Products Laboratory.

Biomass Energy Resource Center. (2008). “Wood Pellet Heating Guidebook”. (http://www.mass.gov/Eoca/docs/doer/pub_info/doer_pellet_guidebook.pdf)

Brechbill, S., and Tyner, W. (2008). “The economics of biomass collection, transportation, and supply to Indiana cellulosic and electric utility facilities,” Working paper #08-03. Department of Agricultural Economics, Purdue University, (http://ageconsearch.umn.edu/bitstream/6148/2/wp080003.pdf).

Bureau of Labor Statistics. (2009). Yearly Average Wages and Salaries.

Campbell, K. (2007). “A feasibility study guide for an agricultural biomass pellet company”. Agricultural Utilization Research institute.

Chau, J., Sowlati, T., Sokhansanj, S., Preto, F., Melin, S., and Bi, X. (2009). “Techno-economic analysis of wood biomass boilers for the greenhouse industry,” *Applied Energy* 86, 364-371.

Di Giacomo, G., and Taglieri, L. (2008). “Renewable energy benefits with conversion of woody residues to pellets,” *Energy* 34, 724-731.

Far Packaging Company, C.A. EU certified wood pallets catalog, (http://www.farpackaging.com/catalog.asp)

Gonzalez, R., Saloni, D., Phillips, R., and Wright, J. (2010). “Loblolly pine biomass delivered cost,” 2010 Biomass Conference. Minneapolis, MN.

Green Circle Bio Energy Inc. Pellet Specifications. (2010). (http://www.greencirclebio.com/products.php).

Hess, J. R., and Jacobson, J. J. (2009). *Sustainable International Bioenergy Trade: Securing Supply and Demand; Country Report-United States*, International Energy Agency (IEA).

Hoque, M., Sokhansanj, S., Bi, T., Mani, S., Jafari, L., and Lim, J. (2006). *Economics of Pellet Production for Export Market*. Presentation at the CSBE/SCGAB 2006 Annual Conference. Edmonton, Alberta.

Junginger, M., Bolkesjø, T., Bradley, D., Dolzan, P., Faaij, A., Heinimo, J. (2008). “Developments in international bioenergy trade,” *Biomass & Bioenergy* 32, 717-729.

Lange, P. (2009). “Biomass pelleting, Industrial production of wood pellets,” California Pellet Mill (CPM) Presentation.

Leaver, R. (2008). *The Pelleting Process*. Andritz Sprout.

Mahapatra, K., Gustavsson, L., and Madlener, R. (2007). “Bioenergy innovations: The case of wood pellet systems in Sweden,” *Technology Analysis & Strategic Management* 19(1), 99-125.

Mani, S. (2006). “Simulation of biomass pelleting operation,” Bioenergy Conference and Exhibition.

PelletSales. (2009). *Where Does Pellet Fuel Come From?* http://www.woodpellets.com/heating-fuels/pellet-sources.aspx

Peksa-Blanchard, M., Dolzan, P., Grassi, A., Heinimö. J., Junginger, M., and Ranta, T. (2007). *Global Wood Pellets Markets and Industry: Policy Drivers, Market Status and Raw Material Potential*. IEA Bioenergy Task 40.

Perry, R. H., Maloney, J. O., and Green, D. W. (eds.) (1997). *Perry's Chemical Engineers' Handbook*. (NY) USA: McGraw-Hill.

PFI (The Pellet Fuel Institute). (2006). (http://www.pelletheat.org)

PFI (The Pellet Fuel Institute). (2009). (http://www.pelletheat.org/3/residential/index.)

PFI (The Pellet Fuel Institute). (2010). (http://pelletheat.org/pellets/benefits-of-pellets/)

Pirraglia, A., Gonzalez, R., Saloni, D., and Wright, J. (2010). *Wood Pellets: An Expanding Market Opportunity*. Biomass Magazine.

Rhode, M. (1999). *Biomass Power for Rural Development. Department of Energy*. (www.nrel.gov/docs/fy00osti/28024.pdf)

Rakos, C. (2009). "The heat market – Key to the transformation of our energy system," ProPellets Austria. (http://propellets.at/cms/cms.php?pageName=50)

Ryu, C., Yang, Y. B., Khor, A., Yates, N. E., Sharifi, V. N., and Swithenbank, J. (2006). "Effect of fuel properties on biomass combustion: Part I. Experiments—fuel type, equivalence ratio and particle size," *Fuel* 85, 1039-1046.

Samson, R., Duxbury, P., Drisdelle, M., and Lapointe, C. (2000). "Assesment of pelletized biofuels," Resource Efficient Agricultural Production, Canada.

Savolainien, M. (2007). “Pellet production and use in Europe,” Presentation from VAPO Group.

Spelter, H., and Toth, D. (2009). “North America’s Wood Pellet Sector,” Research Paper, United States Department of Agriculture.

Stahl, M., and Wikström, F. (2009). “Swedish perspective on wood fuel pellets for household heating: A modified standard for pellets could reduce end-user problems,” *Biomass & Bioenergy* 33, 803-809.

Thek, G., and Obernberger, I. (2004). “Wood pellet production costs under Austrian and in comparison to Swedish framework conditions,” *Biomass & Bioenergy* 27, 671-693.

Wahlund, B., Yan, J., and Westermark, M. (2004). “Increasing biomass utilisation in energy systems: A comparative study of CO_2 reduction and cost for different bioenergy processing options,” *Biomass & Bioenergy*; 26, 531-544.

Woodworth, R., Kelly, J., Namazian, M., and Miller, G. (1997). *Biobinder Process for Reconstitution of Fine Coal*. Altex Technology Corporation. (http://domex.nps.edu/corp/files/govdocs1/064/064997.pdf).

8. TECHNICAL AND ECONOMIC MODELING FOR THE PRODUCTION OF TORREFIED LIGNO-CELLULOSIC BIOMASS FOR THE U.S. DENSIFIED FUEL INDUSTRY

8.1. Abstract

During recent years, a renovated interest in the pre-treatment of biomass through torrefaction has led to several proposals on industrial-scale application of the technology. Torrefaction holds promising characteristics for obtaining a high-energy yield biomass for further processing, including densified biofuels such as pellets and briquettes, at low overall costs, low energy input, and high capacity and availability for the near future, having the capability of displacing coal in power facilities. Despite many efforts in developing the technology at an industrial scale, very few manufacturers and companies are offering torrefied machinery and ligno-cellulosic torrefied biomass. Furthermore, information about the actual profitability of the business, sensitivity, and costs of torrefied biomass are very scarce, and are limited to very focused studies in some areas of the production, but not in the overall supply chain, and manufacturing processes. This study aimed to develop and validate a technical and economic model for the production of ligno-cellulosic torrefied biomass for its utilization in the solid biofuels industry, with a focus on production and delivered costs for U.S. potential manufacturers. This model also includes analysis of important variables affecting production, such as biomass delivered costs, CAPEX, and technology availability. Results indicate that the production of torrefied ligno-cellulosic biomass can be profitable for U.S. manufacturers, subject to a high sensitivity on biomass cost, CAPEX, and technology affordability for large-scale production. Other sensitive facts include carbon credits scenarios, which may influence profitability based on analyses of net present value and internal rate of return for the manufacturing facility.

8.2. Introduction

Material that has been torrefied from biomaterials such as wood, grasses, and agricultural waste are regarded as promising solid biofuels and as feed stock for further

advanced biofuels (Bergman, 2005; Bergman and Kiel, 2005; Bergman et al. 2005; Chiaramonti et al. 2010; Pach et al. 2002). Torrefaction is a thermochemical process, or "mild pyrolysis" of biomass in an oxygen-free atmosphere (Sklar, 2009). In this process there is a degradation of the hydrophilic polysaccharides (complex carbohydrates in wood that interact with water molecules, such as hemicellulose and cellulose) and hydroxyl radicals, resulting in an increase in the percent of lignin content, causing a reduction in the hydroscopicity of the material and an increase in the energy per unit-mass, and a carbon-like appearance (Fonseca et al. 1998; Hakkou et al. 2006; Mburu et al. 2007; Pirraglia et al. 2012; Sklar, 2009). The potential attractiveness of using torrefied biomass for solid biofuels is the increase in energy density of the material even at the expense of losing 25%-33% (dry basis) of the original biomass, and 10 to 20% of the original energy content (Bergman, 2005; Pach et al. 2002) through volatilization of CO_2, acetic acid, phenolic compounds, etc. (Girard and Shah, 1991; Rowell, 2005; Sklar, 2009), producing a fuel with a high energy yield output. Additional benefits of torrefied biomass include reductions in CO_2 emissions when compared to coal (Childs, 2012), and better grindability properties for co-firing (reducing energy required for grinding of wood particles, Arias et al. 2008).

Torrefaction is not a newly developed concept, and its technical principles were first reported in 1930. During the 1980's it was reexamined in France as a method of producing a biomass-based reducing agent for metallurgic facilities (Pechiney Process, Bergman et al. 2005; Bourgeois and Doat, 1985; Bourgeois and Guyonnet, 1988). This resulted in a demonstration plant operating until the early 1990's. The concept of torrefaction was revived with recent attention given to biomass as a fuel source and is still in either the early development stages (pilot phase) or as a proof-of-concept (Pirraglia et al. 2012; Uslu et al. 2008).

One of the main reasons for the lack of large-scale implementation of torrefaction is the scarcity of information on the technical and economic principles that would drive the operation of a commercial facility, including capital investments, production levels, etc. (Bergman, 2005, Bergman et al. 2005; Uslu et al. 2008). Jacobs (2008) indicated that due to the small number of existing units and their limited scale, the economics of a commercial facility could only be estimated. Previous research work by Bergman et al. (2005) was

heavily focused on process design and process simulation with Aspen™, and provides background for further economic analyses. There is still a need for further research in the detailed economic aspect of torrefaction including the variables such as the biomass delivered costs, required capital investments, process energy costs and transportation costs. Previous attempts to describe and assess the feasibility of torrefaction as a pre-treatment have been limited by the lack of data (Bridgwater, 2009), with existent information regarding costs of torrefaction units currently dependent on potential suppliers and start-up companies' estimates. Previous work in evaluating the technical and economic feasibility of factories in Europe producing woody biomass fuels was performed by Pirraglia et al. (2010), Mani (2006), and Samson et al. (2000) on wood pellets, while Bergman et al. (2005), and Bridgwater (2009), report technical and economic feasibility for the production of torrefied wood in large scale. However, these previous efforts in assessing torrefied wood as a biofuel were performed for European countries scenarios, and further research is needed in describing its possible implementation in the United States, and the characteristics of such project.

The objective of this research is to develop and verify a technical/economic model developed in a dynamic spreadsheet-based program that provides detailed information on the feasibility of woody biomass torrefaction based on defined assumptions. The model is intended to provide information on the manufacturing cost structure based on the plant and biomass requirements, capital investments, labor, and the characteristics of the torrefied material. A sensitivity analysis is also conducted on the most significant variables that affect the profitability of the operation.

8.3. Methods

The technical/economic model was developed in dynamic macro-enabled spreadsheets utilizing Microsoft Excel 2010®. A conceptual model similar to that proposed by Pirraglia et al. (2010) helped identifying three key areas of development for the model: mass balance, in order to understand and quantify the biomass required by the facility; energy consumption, in order to correctly account for energy consumption and costs utilizing different process configurations and production capacities; and a financial analysis, which

integrates all the information from the mass balance and energy consumption and calculates financial indicators such as Internal Rates of Return (IRR), Net Present Value (NPV), minimum revenue, and production costs.

8.3.1. Torrefaction Process

The process of torrefaction is regarded as an accessible technology that is capable to produce a biomass based energy source with very uniform characteristics (Zwart et al. 2006). In order to correctly assess the requirements in biomass, CAPEX (Capital Expenditure), and energy balance for a torrefaction facility, the process must be completely understood. Figure 8.1 shows the general process for producing torrefied biomass, assuming that the biomass is received as debarked roundwood (debarking included in the biomass delivered cost).

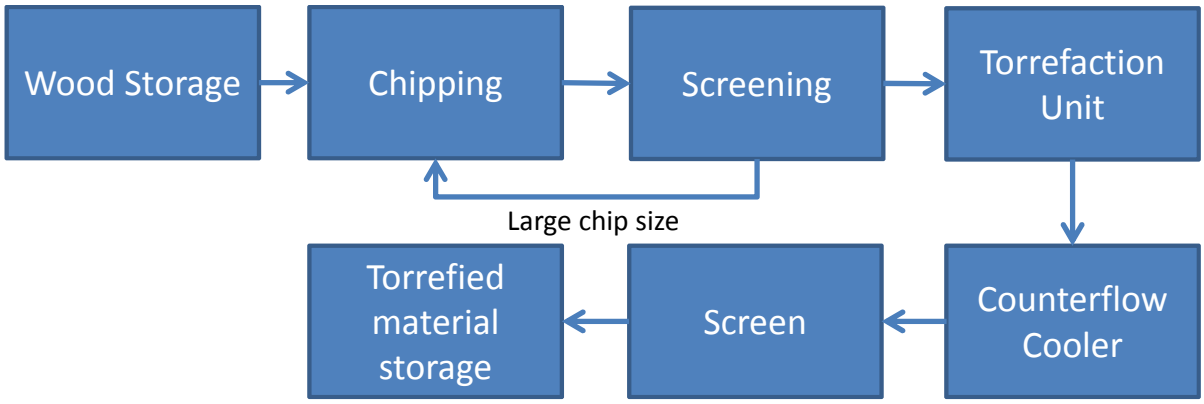


Figure 8.1. Torrefaction process for a commercial-scale factory producing torrefied wood.

Since biomass contains a great deal of water (moisture), one of the first steps in its conversion is removing water by drying; a process which typically requires high energy inputs (Evergreen Renewable, 2009). A key element for the successful application of torrefaction is to pre-dry the biomass prior to enter the reactor with the VOC's and off gases from the biomass being treated. Pirraglia et al. (2012) and James (2009) described a commercial-scale torrefaction unit built and demonstrated at North Carolina State University, with a nominal capacity between 1/2 to 1 metric ton/hour depending on the biomass type, and which is able to generate more than 80% of the required process's heat by combusting the

VOC's from the biomass, using this heat to pre-dry and remove moisture from the biomass before entering the reactor, and removing VOC's and Hemicellulose inside the reactor. Companies such as Biomass Technology Group (BTG, 2011) have proposed processes and machinery for torrefaction with similar principles, using the gases released in the reactor as a heat source, by burning them in a combustion chamber, and producing heat for drying. Bergman et al. (2005) also proposed that torrefaction is capable of utilize the energy content of torrefaction gases to completely produce the heat required for the process and for biomass drying, operating in a point denominated "autothermal operation". A torrefaction factory operating at the autothermal point, with "green" or "wet" biomass received, would not require a separate drying process. Figure 8.2 shows the biomass and off gases flow in the torrefaction unit. Notice the lack of a separate drying unit, which in the autothermal condition, is assumed as a pre-drying sub-process, and consequently, an element inside the torrefaction unit. In the model developed, a detailed assessment of this unit allows to correctly calculate the mass and energy balance necessary for accurate costs calculations.

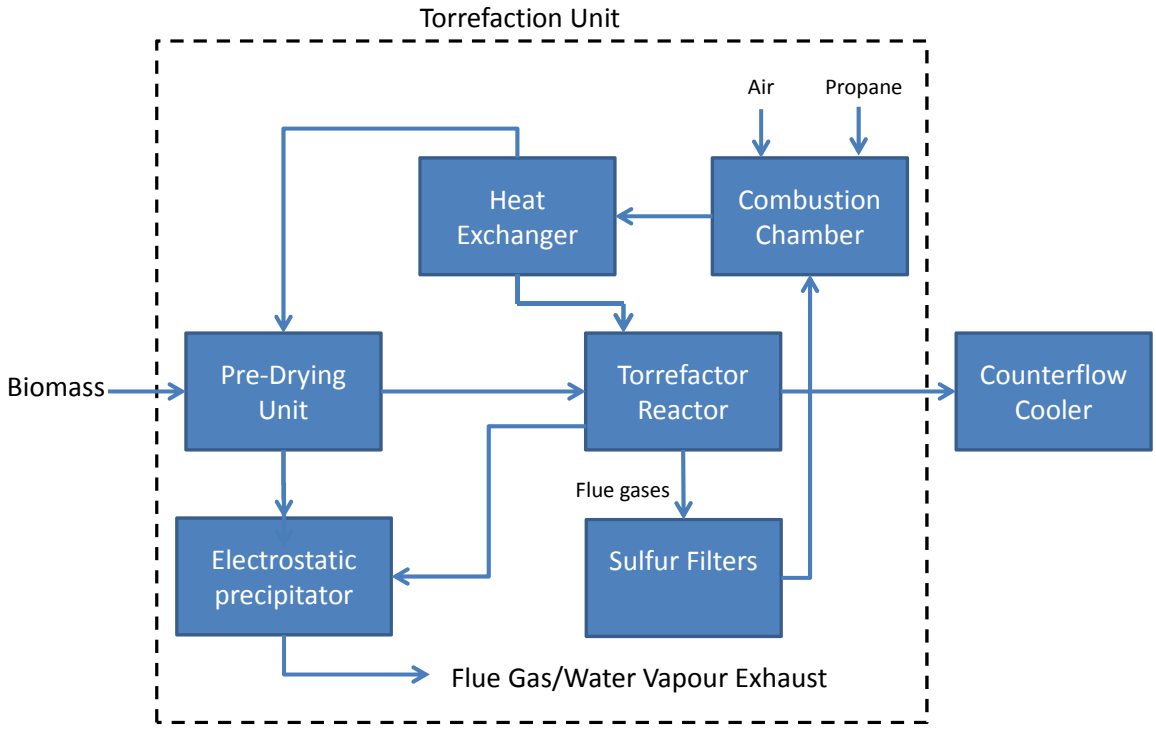


Figure 8.2. Schematic detail of the proposed Torrefaction unit, including pre-drying.

The structure and process utilized by the torrefaction unit in the model is similar to that proposed by Lipinsky et al. (2002), and Topell Energy (2011a, b) in which torrefaction off-gases are combusted to generate heat for the torrefaction process, as well as residual heat for pre-drying of the biomass before entering the reactor. Three different types of reactors (screw reactor, rotating drum, and moving-bed) can be specified based on the production schemes proposed by Bergman (2005). The type of reactor determines mainly the capital investment and maintenance costs of the unit. Once the proper equipment and flow of biomass through the torrefaction unit is identified, a mass balance can be calculated, and automatically adjusted depending on key production variables. The boundaries of the model consider debarked roundwood (cost of debarking included in biomass delivered costs) received in an open-air storage area and a vented load area for trucks after processing the biomass. Hence, the prices and production costs of the biomass reported hereby are considered at the factory gate, ready to ship. The process for torrefaction is linear, and is assumed as a best practice, four parallel lines of product being produced at the same conditions (Bergman, 2005).

Previous literature (Bergman and Kiel, 2005; Bergman et al. 2005; Brechbill and Tyner, 2008; Brigwater, 2009; Gonzalez et al. 2011a, b, c, and d) and previous experience in economic models for biomass facilities (Pirraglia et al. 2010) aided in the identification of the main production variables required to calculate accurate financial indicators of a torrefaction facility. These are variables that are user-modified inputs of the model including annual production, biomass type and form, biomass moisture content, plant location, and annual production hours per year. In addition to these, torrefaction-specific variables also identified were torrefaction level, and carbon credits scenario. These variables are further defined and explained below.

Previous investigations indicate that two critical variables for achieving a specific level of torrefaction and uniform product are the residence time and operating temperature (Pirraglia et al. 2012). Researchers report a wide variety of temperatures and residence times (James, 2009; Pach et al. 2002), varying from 1 minute to 35-40 minutes, and from 200° to 400°, although such high temperatures re rarely reached. For this model experimental data from the NC State torrefaction machine was utilized to define the operating temperatures and

residence times. These two parameters define the “degree” by which irreversible changes are produced in the wood, and the amount (% wt.) of VOC’s that are released. These parameters define the type of material that will be obtained as a product, and the total output versus the total amount of “green” biomass (mass/mass) that the facility will need. In this work, these two parameters are summarized in a single measure that can be adjusted by the user, denominated “Torrefaction Level”. This variable considers three levels of torrefaction, based on experimental information that has been obtained in the North Carolina State University’s commercial torrefaction unit: light torrefaction, defined by a short residence time (3 minutes), and a temperature of 280°C; medium torrefaction, characterized by a residence time of 4 minutes, and a temperature of 320°C; and dark torrefaction, with a long residence time (5 minutes), and high temperature (around 350°C); these high temperatures. In addition, average heating values for woody biomasses (energy density) that can be obtained from each treatment level are displayed in the model (8,458 Btu/lb. for light torrefaction, 9,060 Btu/lb. for medium torrefaction, and 9,502 Btu/lb. for dark torrefaction, James, 2009); actual torrefaction heating values will depend on the biomass used in the unit, and can be modified in the model, which will automatically adjust moisture content (MC) and theoretical energy values (HHV) for the biomass processed. Is important to highlight that testing results from the North Carolina State University torrefaction unit indicate that in order to obtain higher heating values than the average HHV reported in this model, longer residence times at the same temperature ranges should be utilized, with the downside of a reduction in the hourly nominal capacity of the unit (currently between ½-1 metric ton/hour). Additionally, changes in HHV, MC, and torrefaction level automatically adjust the mass and energy balance of the model. Data from James (2008) was utilized in this section.

8.3.2 Mass Balance

Detailed mass and energy balances for torrefaction of lignocellulosic biomass have been extensively researched, with various technologies and species evaluated (Bergman and Kiel, 2005; Topell Energy, 2011a; Yan et al. 2010). These investigations have been primarily focused on identifying the chemical composition of the gases released, and its relative amount. Part of the information obtained from these previous works (outputs of torrefaction

processes as a weight percentage of the biomass being fed) is used to model the mass balance presented in this research.

The mass balance in the model includes user-modified losses (mass %) throughout the production process, with each mass loss initially set at a default value of zero percent, except for the second screening before storage, in which a 10% mass loss is assumed due to fines and dust particles. Moisture content and VOC's losses are automatically re-calculated according to the inputs: annual production, torrefaction level, and working hours per year. The pre-drying process inside the torrefaction unit has the capability of eliminating all moisture from the biomass, being automatically adjusted when moisture content of the biomass as received is changed in the model. The dry biomass enters the torrefaction reactor, and depending on the torrefaction level selected, the mass balance calculates a VOC's elimination from the biomass of 30% (light torrefaction), 40% (medium torrefaction), or 50% (dark torrefaction) of the biomass oven-dry weight.

With this information, flue gases (VOC's) circulating to the combustion chamber and heat exchanger are calculated, as well as the additional energy required (propane utilization in this case, being this a requirement in order to keep a pilot flame that ensures a proper combustion of the gases in the chamber). Based on experimental information from the torrefaction unit being used at North Carolina State University (James, 2009), liquid propane utilization in the combustion chamber accounts for approximately 2% of the flue gases (VOC's) entering the chamber (% weight), and considers the propane/air mixture with 120% excess air under normal (autothermal) operation conditions (information necessary for energy costs calculations). In addition, the heat exchanger considered for separation of the necessary heat utilized for pre-drying, and for the torrefaction reactor is separated as 20% (pre-drying) and 80% (torrefaction reactor) of the mass entering the exchanger, being adjustable if the moisture content of the biomass in pre-drying is increased from the pre-set value of 45%, requiring more heat in the pre-drying process.

8.3.3 Energy balance

The most important element of the energy balance for this model is given by the torrefaction unit, since this unit requires the necessary heat for pre-drying the biomass, and

for the torrefaction reaction itself. Under autothermal conditions (and depending on the biomass source) the most important torrefaction product gasses, and the ones that contribute to most of the heat generated in the combustion chamber are usually formaldehyde/acetaldehyde, methanol, pyruvaldehyde/propanal-2-one, furfural, furfuralalcohol, and coniferyl alcohol, among other product gases (Pomer et al. 2010), contributing to the aforementioned 80% of the heat process (torrefaction and pre-drying).

Although it is stated by several authors that torrefaction in autothermal conditions does not require external energy sources, the authors included a propane pilot flame in order to keep uniformity of the product and reduce the possibility of pressure and heat losses; following guidelines of operation in the commercial scale unit operating at North Carolina State University, this pilot flame contributes to approximately 20% of the required heat for pre-drying and torrefaction, and for its utilization every time the torrefaction unit requires start-up until reaching autothermal point. Energy (electrical) consumption of the machinery (%) per each ton of torrefied material produced is presented below (Figure 8.3), considering that the torrefaction unit utilizes only propane, and that screw systems, fans, and blowers, are part of miscellaneous equipment.

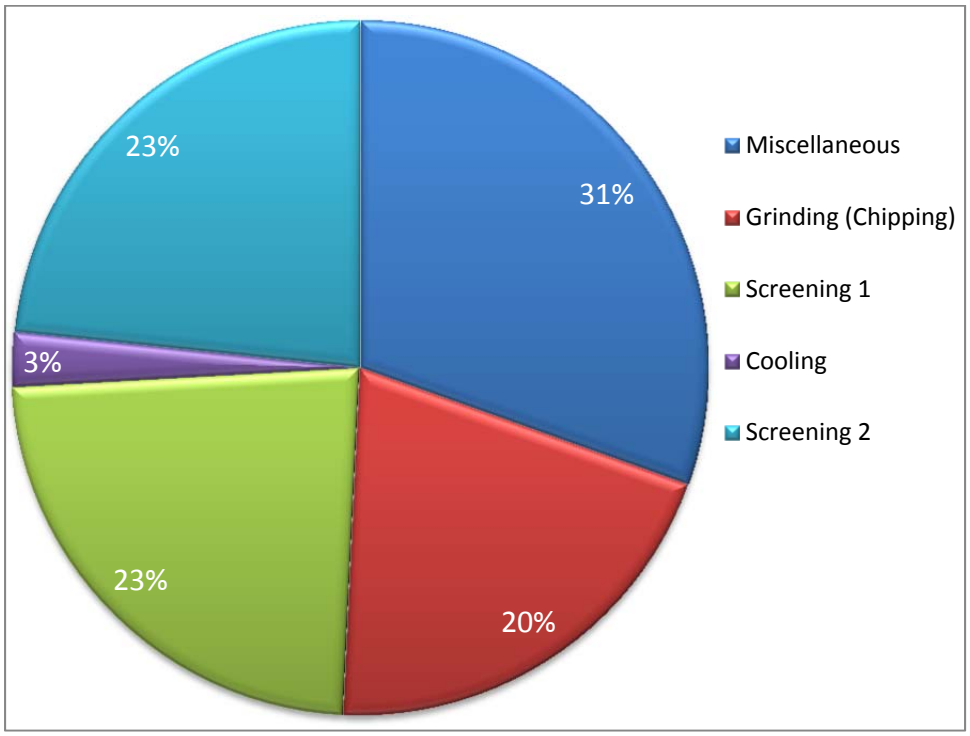


Figure 8.3. Distribution of electricity use in the factory by machine. Considering the torrefactor mechanical systems as part of miscellaneous equipment.

Power consumption for the machines (kWh/Year) was estimated based on the work of Digiacomo and Taglieri (2009), Pirraglia et al. (2010), and Bergman and Kiel (2005). Considering the mechanically-driven equipment from the torrefaction unit (blowers, fans, screws, etc.) as miscellaneous, it represents the major electrical energy component of the torrefaction facility. With the information of energy consumption for each machine, including potential losses and efficiencies, and the working hours per year, the model calculates the annual electrical and propane consumption, and its associated costs, depending on the plant location, which influences the local unit costs of energy.

8.3.4 Economic Information

Capital expenditure for buildings and machinery, labor, energy, and biomass costs, represent the backbone of the model for the accurate calculation of financial indicators. Capital expenditures for machines and equipment were obtained (when possible) directly

from manufacturers information (grinder, screeners, and counter flow coolers), with miscellaneous equipment and installation costs being calculated from literature values (Campbell, 2007; Pirraglia et al. 2010; Samson et al. 2000; Thek and Obernberger, 2004), and adapted to 2011 values using the CWCCIS (Civil Works Construction Cost Index System) conversion index.

Special attention is given to the costs of a torrefaction unit. Capital costs for a torrefaction facility seem to be highly dominated by the cost of the reactor unit. Previous work on this field indicates that this is a common feature of newly developed torrefaction technologies (Bergman et al. 2005; Bridgwater, 2009). Due to the scarcity of potential suppliers of torrefaction units, and the lack of fully operational facilities in existence, it is difficult to obtain accurate market information for torrefaction unit costs and commercial capacities. Instead, some authors have estimated the costs of a torrefaction unit per ton of biomass produced. In this particular aspect, the work of Bergman et al. (2005), evaluating a plant producing 200,000 tons/year of torrefied material under European conditions is extensive and provides one of the few complete costs estimates for the unit, including pre-dryer, reactor, and other equipment, and adding engineering and supervision, installation, and construction expense costs. In addition, three types of technology are considered in their study, with different specific investment costs[1]: screw reactor, with $32.72/ton (€22/ton) costs, rotating drum with $23.80/ton (€16/ton) costs, and moving bed, with $16.36/ton (€11/ton); these estimates are used for the model developed in the present project. The selection of the technology is included as a modifiable feature in the model, adjusting the CAPEX values when modified.

Estimates of the capacity of equipment are adjusted by the model depending on the required annual production, and follows the power law rule proposed by Perry et al. (1997) which estates that: $Inv = Inv_L x(P/P_L)^{0.7}$; were Inv represents the capital investment depending on plant size requirements, Inv_L represents capital investment of the original equipment, and P and P_L represent the capacity required on the equipment, and the capacity of the original equipment respectively. A scaling factor of 0.7 is used, based on Andersson et

[1] 2005 average €/$ conversion rate, and adjusted to 2011 dollar values with CWCCIS Index

al. (2006), and on the utilization of 4 parallel production lines, considered to be running at 80% capacity. This scaling factor, as well as the estimates on the power rule obtained for capital costs of machinery and equipment is consistent with class 3 project estimates, following the classification system of AACE[2], which typically fall within an accuracy range of ±20% of the costs estimates. Further work and evaluations of torrefaction facilities, especially when new and existent technologies have been scaled-up to large commercial sizes, and parallel lines can be reduced, will involve and require refined estimates, for which the scaling factor would be closer to unity, and its application reduced to less significant equipment and machinery of the project. In addition, such refinement of estimates, and elimination of parallel lines in the future will possibly reduce the capital costs significantly increasing the likelihood of a torrefaction project.

Indirect and contingency costs are calculated as 24% and 10% respectively of the facilities and machinery total installed costs, as proposed by Woodworth et al. (1997). Storage capacity is necessary for the biomass entering the facility, and after production, torrefied biomass is directly dumped in delivery trucks/railroad, assuming a bulk-delivery selling strategy. Warehouse costs represent 7.6% of the total plant building space (Thek and Obernberger, 2004). Plant and equipment depreciation is calculated using a MACRS-7 method (Modified Accelerated Cost Recovery System, in 7-year class, which depreciates 14.29%, 24.49%, 17.49%, 12.49%, 8.93%, 8.92%, 8.93%, and 4.46% each year from the total assets value in seven years).

Labor costs per occupation, and headcount are calculated based on data for annual mean wages and salaries from the Bureau of Labour Statistics (2011). In addition, a labor structure similar to that proposed by Campbell (2007) is used. According to Bridgwater (2009), a torrefaction facility has very few labor requirements. Based on this information, the model calculates an estimate of direct labor and indirect labor adjusted to the size of the facility (annual production), and working hours per year, following the guidelines used by Pirraglia et al. (2010).

[2] Association of the Advancement of Cost Engineering, Cost Estimate Classification System as applied in Engineering, Procurement, and Construction Industries

Biomass costs (user-modifiable variable) at plant gate were established at $45 per bone dry ton (BDT, as an average delivered cost for softwoods and hardwoods), with an annual cost increase of 1%, with lower values than previously reported by Gonzalez et al. (2010), and Pirraglia et al. (2010), following a slight price decline that has been common during most of the year 2011, and more consistent with values from Forest2Market analyses (North American Wood Fiber Review, 2011;Stuber, 2011), and with values recently reported by Nielsen-Pincus et al. (2011). Initial assumptions of the model include a bulk delivery strategy of the finished product, reducing the consumables needed at the facility, having only plant and office tools, lubricant and spare parts for the torrefaction unit and other equipment, estimated at $3.00/ton. Additional costs include marketing/sales fees and incentives, maintenance and repairs, and forklift operating costs, estimated at $6.00/ton, $8.85/ton, and $0.17/ton respectively (Bergman et al. 2005; Campbell, 2007).

8.4 Results and Discussion

In order to further analyze the characteristics of a U.S. torrefied wood manufacturer, a case study is presented. In this case study, a factory producing 100,000 tons/year of torrefied biomass is considered. Table 8.1 summarizes the main parameters considered for the case study.

Table 8.1. Parameters utilized in the case study factory.

Parameter	Value
Annual Production	100,000 tons/year
Required Raw material (green)	238,096 tons/year
Initial Moisture Content	45%
Final Moisture Content	5%
Heating Value of Product	8,458 Btu/Lb.

In addition, the facility considers a scenario with no carbon credits placed (although alternate scenarios are considered, according to estimates by Childs, 2012). The size of the facility was selected to match similar proposed studies, in order to present results that may be comparable with similar research projects. Characteristics and estimates are similar to those

reported by Topell Energy (2011b), in their analysis of a 100.000 tons/year plant, especially in terms of capital investment, sales price, and labor estimates.

At this point, it is relevant to discuss some previous models developed for biomass torrefaction plants; Björklund (2011) indicated that a pre-feasibility study was performed in 2010 for a Metso factory producing 200,000 tons/year, utilizing a similar screw reactor directly heated, concluding that prices for a torrefactor units were still out of reach from an economic standpoint, and it required more technical demonstration. Mitchell et al. (2007) also performed a simulation of processes and costs for a factory producing 80,000 tons/year of torrefied wood. Other smaller sized factories have been proposed and analyzed, such as Topell Energy (2009), started production tests in a torrefied wood factory in Duiven, Netherlands, with a capacity of 60,000 tons/year; Metso proposed a 30,000 tons/year plant to be commissioned during 2012 (Björklund, 2011), and Radian Bioenergy has completed preliminary engineering on a torrefaction system (Phillips, 2011), however, few details are provided in the analysis of technical and economics of each proposal.

8.4.1 Energy Usage

The plant site (for electrical and propane costs effect) is considered as the average of U.S. electrical costs for plant locations, although the model is capable of selecting specific state locations with its associated local energy costs. Additionally, a screw reactor technology was selected for the torrefaction unit. For further analyses (sensitivity to type of unit), other options are considered. Table 8.2 shows the results for energy consumption and costs in the case study.

Table 8.2. Electrical and Propane usage and costs for the case-study factory, electricity and propane costs are obtained from the U.S. Energy Information Administration (2011, 2012).

Propane Usage (gallons/year)	222,837.00
Propane Cost ($/gallon)	3.00
Total Propane Costs	**299,939.00**
Electricity Usage (kWh/year)	9,380.95
Electricity cost ($/ton)	6.71
Total Electrical Costs	**670,785.00**

Energy usage in the facility represents a drastic reduction in costs as compared to other biomass pre-treatment options such as wood pellets. Pirraglia et al. (2010) reported energy costs of $2,854,532/year for a similarly sized factory, representing an energy cost reduction of approximately 69%, mainly due to the elimination of a separate drying process.

The facility is assumed to run with four parallel lines producing the material, as recommended by Bergman et al. (2005). Current capacities and availability of commercial torrefaction equipment is low, rarely exceeding 3-5 tons/hour and the scalability and product consistency for larger sized machines is still unclear, thus, requiring more than a single large-scale torrefaction unit in place for full capacity production. These reasons justify the use of four parallel product lines with smaller torrefaction units in order to reach full capacity, instead of utilizing a single line with a large capacity torrefaction unit. This imply (for CAPEX calculation effects), that there is a fixed number of machines (4 of each type, and its respective feeding system, conveyors, and miscellaneous equipment), and the capacity required from each machine will vary depending on the annual production. Once torrefaction units have reached higher capacities, and the different technologies have been field-tested in large scale, single large-scale production lines could become a better option instead of separate lines, reducing CAPEX needs, and floor space in the facility. Based on the case study and its mass balance, each torrefaction unit must be able to process 44 tons/hour (output) in order to meet production requirements. In this sense, the costs for a torrefaction unit were estimated by Bergman et al. (2005) as $32.72/ton (€22/ton), which is converted to $/ton considering the average euro-dollar exchange rate of 2005, and using the CWCCIS Index for extrapolating the unit costs to 2011 values. CAPEX calculations are presented below (Table 8.3).

Table 8.3. CAPEX for the case-study facility (in thousands of dollars).

Item	Number required	Cost per each equipment	Installation cost	Total Equipment costs	Total Installation costs	Total Equipment + Installation costs
Misc. Conveyors	8	15.2	7.6	121.5	60.8	182.3
Front-end Loaders	2	22.8	0.0	45.6	0.0	45.6
Feed Hopper	20	7.6	4.6	151.9	91.1	243.0
Grinder	4	766.1	113.9	766.1	455.7	1,221.8
Torrefaction Unit*	4	7,297.6	0.0	29,190.5	0.0	29,190.5
Live Bottom Bin	20	18.2	15.2	364.5	303.8	668.3
Counter flow Cooler	4	150.0	18.2	600.0	72.9	672.9
Screener 1	4	15.2	12.2	60.8	48.6	109.4
Screener 2	4	15.2	12.2	60.8	48.6	109.4
Fork Lift	2	22.8		45.6		45.6
Site and Site preparation	1	156.0		156.0		156.0
Paving/Receiving station/load area	1	60.0		60.0		60.0
Building & Office space	1	1,020.0		1,020.0		1,020.0
Total				32,643.1	1,081.4	33,724.6
Storage warehouse						77.6
Indirect costs (24%)						8,112.5
Contingency (10%)						4,191.5
Total installed costs						46,106.2

CAPEX of the facility are represented in its majority by the costs of the torrefaction unit, representing approximately 60% of the total installed costs. Such high percentage is considered as a first-plant cost, in which as subsequent plants are built, capital costs of the new technology can follow the rule that capital costs may be reduced by 20% for every doubling of the number of plants built (Bridgwater, 2009).

Operating costs of the facility include direct and indirect labor, totaling 33 operational and administrative personnel, with three shifts per day, and also includes consumables and additional costs. A summary of Operating costs is presented in Table 8.4.

Table 8.4. Operating costs for the case-study facility.

Operating Cost	$/year
Direct Labor	1,274,765
Indirect Labor	697,829
Consumables	794,285
Additional Costs	1,502,043
Total Operating costs ($/year)	**4,268,922**

Additional costs include, as mentioned in the methods section, marketing/sales fees and incentives, maintenance and repairs, and forklift operating costs. Labor structure, as calculated by the model, includes one supervisor, four production employees, one forklift operator, one maintenance technician, and one raw material employee for direct labor. While administrative personnel is composed of two accountants, two sales/marketing representatives, one executive/administrative assistant, one finance manager, and one general/production manager. Total production costs are in its majority dependent on the biomass delivered cost. Figure 8.4 summarizes the main elements that compose production costs of torrefied wood.

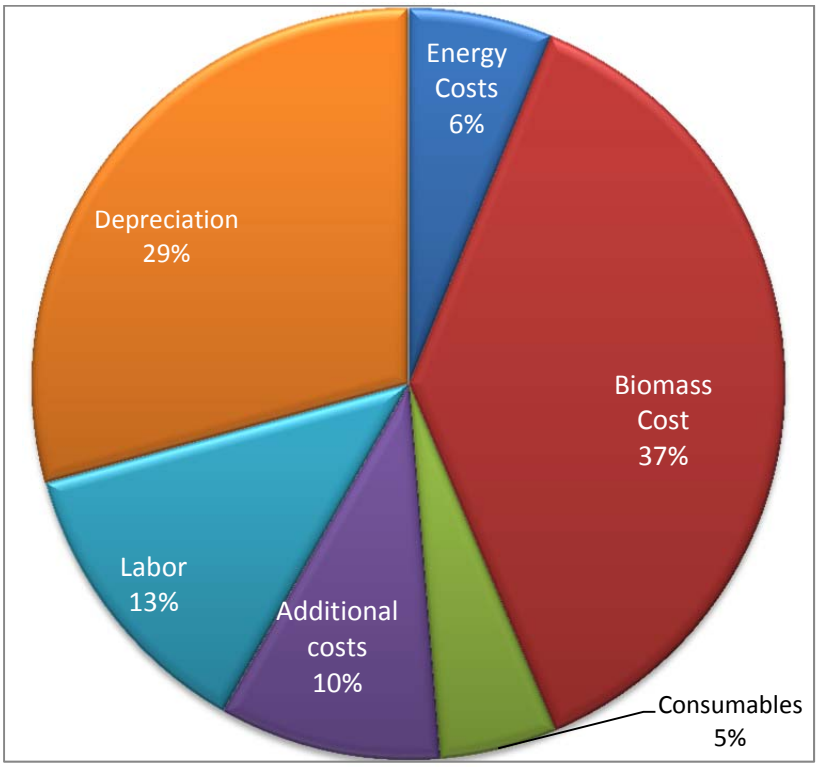


Figure 8.4. Production costs distribution according to results from the model.

Production costs for a 100,000 tons/year case are $193.53/ton, and are slightly higher than values reported from other independent studies. Mitchell et al. (2007) found costs of 199, 149, and 120 $/ton[3], depending on the biomass source (Sawmill co-products, Forest Residues, and wood processing co-products respectively). Cerezo (2011) reports a cost of $134.83/ton for torrefied wood under a minimum cost scenario, while Topell reported $169/tons for torrefied wood pellets (2011b).

Biomass costs (at $45/BDT) represent 37% of the total production costs, followed, in decreasing order, by depreciation (29%), Labor (13%), additional costs (10%), energy (6%), and consumables (5%). Contrary to other studies in biomass fuels (Pirraglia et al. 2010), energy costs represent a smaller fraction of the total production costs (6% vs. 17% for wood pellets), mainly due to the elimination of a separate drying process, and the autothermal

[3] Values reported were converted from 2007 €/$ (Euro to Dollar) average conversion rate, and transformed to 2011 dollar values with CWCCIS Index.

operation of the torrefaction unit; however, this variable requires further detailed study, since drying activities are mostly based on biomass burning to generate the required heat for drying, thus affecting or influencing the biomass costs and requirements, while torrefaction makes use of flue gases recirculation and a pilot propane flame. Thus, a detailed analysis of torrefaction and drying technologies with tis respective energy balances will allow for a direct comparison of energy consumption and more accurate estimates.

Production costs are calculated in the income statement, with MACRS-7 depreciation, and a CAPEX spending schedule of 20%, 40% and 40% in three years (2011-2013). Add-ins and macro-enabled functions in the income statement allow to adjust the production costs to obtain specific Internal Rate of Return (IRR), at a discount rate set at 12% (also modifiable). In Figure 8.5, the minimum revenue, and Net Present Value of the facility are presented, adjusted to IRR's ranging from 6% to 14%.

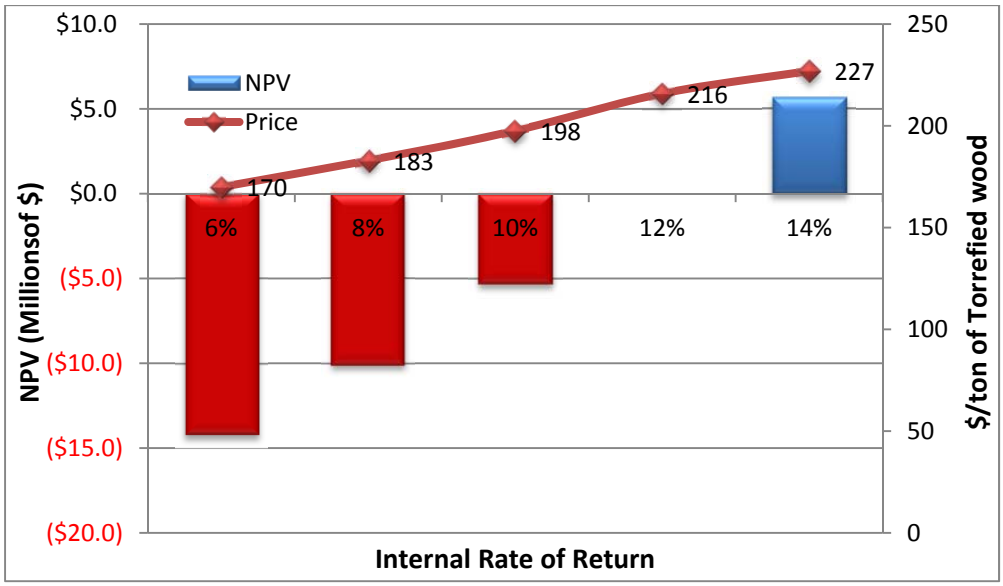


Figure 8.5. Torrefied biomass price and NPV changes at different IRR.

Back-calculated prices of torrefied wood with current conditions indicate that selling prices at factory gate (bulk delivery) must be higher than $216/ton, in order to obtain positive NPV's (12% IRR). With this adjusted minimum revenue as a baseline, potential revenue margins of $22.37/ton can be obtained for producers (at $193.53/ton production costs). This

minimum revenue is assumed to be at the facility exit (distribution docking); assuming that the torrefied material is loaded in trucks for its distribution (20 tons/truck capacity, Rhode, 1999), and that the biomass travels a maximum distance of 50 miles, a simple transportation cost may be added for calculating the delivered cost of torrefied material to power and co-firing facilities. Following the transportation model of Brechbill and Tyner (2008), with a fixed cost of $15/ton of biomass, and a variable cost of $0.12/ton, a delivered ton of torrefied wood reaches $237/ton at power plant gate ($216/ton price at factory gate, plus $21/ton for transportation within 50 miles distance). This delivered price is similar to other biomass pre-treatment options such as wood pellets (at $244.3/ton, Pirraglia et al. 2010), representing a potential alternative option for biomass power plants, in terms of delivered costs. The potential of combining these technologies, hence eliminating the drying process in pelletization, and combining other processes, represents a promising combination of pre-treatments that needs to be further evaluated. In addition, further work is required in order to evaluate the profitability of shipping torrefied biomass to European markets, considering that it will require port warehousing and fees, maritime transportation, and additional variables that may influence profitability, such as bonuses for high delivered heating values and low moisture content of the biomass.

An additional aspect that requires in-depth evaluation is the economy of scale for torrefaction facilities, and how the increase in size of these will influence the delivered price of torrefied woody biomass, as well as other critical economic variables. Such analyses should consider transportation costs for bulk delivery, and also a comparison between torrefaction and alternative pre-treatments such as wood pellets, torrefied wood pellets, chipping and drying, to determine in which scale torrefaction is economically attractive. Such analyses are currently being developed by the authors.

8.4.2 Sensitivity Analysis

In order to evaluate the economic feasibility of a torrefied wood facility, the sensitivity of the project to several critical variables must be assessed. In the case study presented (100.000 tons/year), the NPV and IRR are monitored while changing (increasing and decreasing) variables such as Capital Investment (CAPEX), Energy consumption, Labor,

and Biomass costs. A fixed minimum revenue of $216/ton was selected, being this the adjusted price for obtaining a 12% IRR (12% discount rate), and the variables were modified by ±25% of its current value. Figure 8.6 demonstrates the most sensitive variables of the model, in which CAPEX produces the largest changes in minimum revenue, being biomass the second most sensitive variable. More detail on the changes produced in the IRRs and NPVs of the facility for each one of the sensitive variables is presented in the next paragraphs and figures.

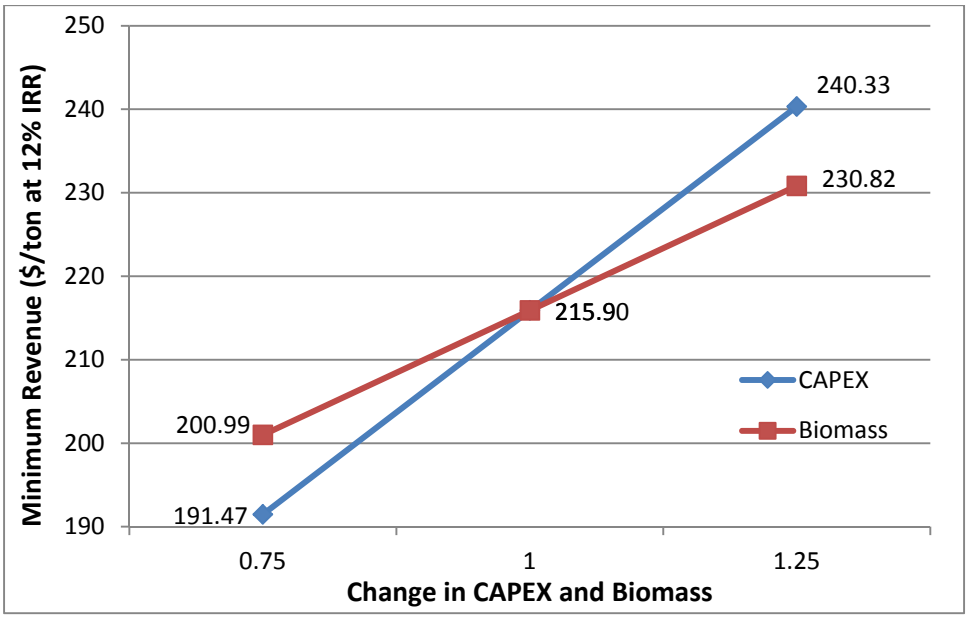


Figure 8.6. Sensitivity of minimum revenue to changes in CAPEX and Biomass delivered cost.

The current case study is particularly sensitive to changes in CAPEX, in which the IRR fluctuates from 19% to 10% and the NPV from $11,072,595 to -$7,513,473. This variable presents larger differences in IRR, and a steep decrease in NPV as the CAPEX are increased (Figure 8.7).

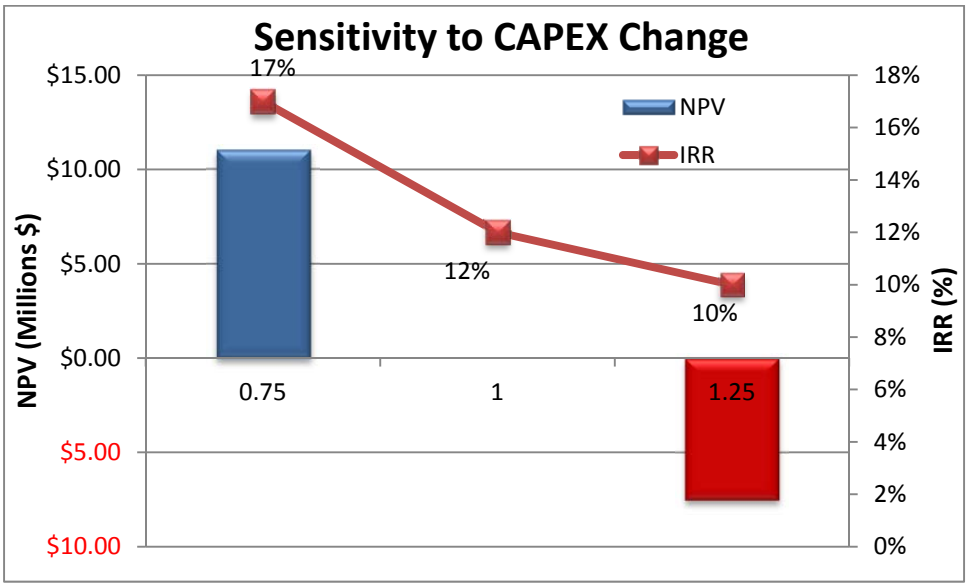


Figure 8.7. Sensitivity of the model to changes in CAPEX.

Although CAPEX changes seem to have large effects in IRRs and NPVs, the torrefaction technology, a major technological component of the investment, may produce the majority of these effects. The torrefaction unit represents approximately 60% of the total capital investment, and changes in the type of technology used greatly affect the overall Capital Investment of the facility. Figure 8.8 presents the sensitivity of the project to changes in the torrefaction technology used, having as base-case, the screw reactor (assumed as the standard unit in the case study, since it represents a well-studied technology concept for torrefaction, Bergman, 2005), and without any other variable changes.

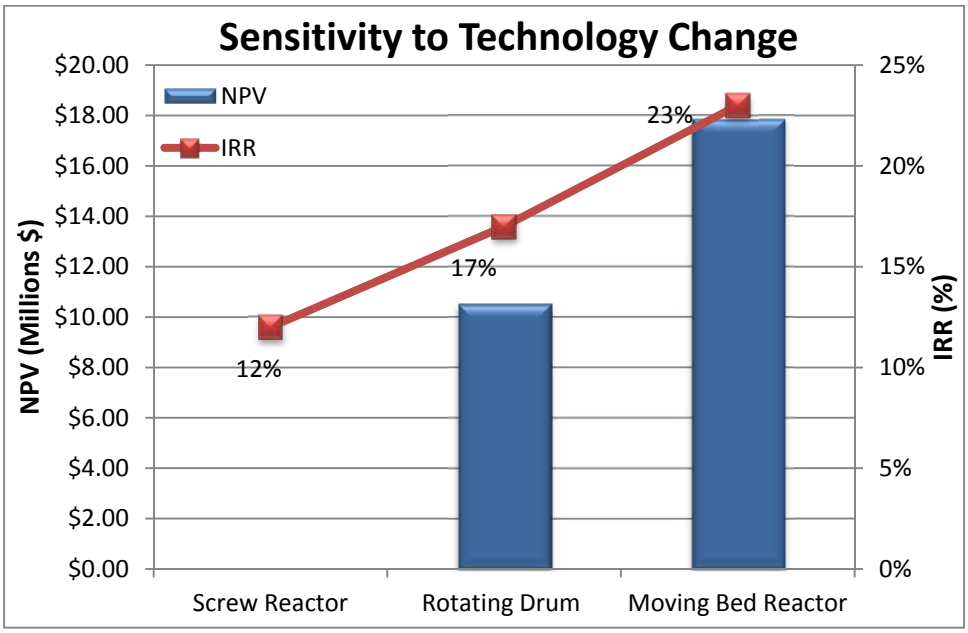


Figure 8.8. Sensitivity of the model to changes in the torrefaction technology used.

Screw reactor is a indirectly-heated technology in which hot gases and/or other heat transfer media (such as an oil jacket) circulate heat outside the screw system, heating the biomass that is moving inside the screw; Rotary drum technology is a directly heated method based on flue gas recirculation in a rotary drum, which heats the biomass by establishing a direct contact between its surface and the gases. Moving bed reactor is another directly heated method in which a blower supplies hot gas to the reactor and the biomass is heated in a moving conveying system, which optimizes heat transfer rates and provides for a compact design (Bergman, 2005).

The selection of a screw reactor, rotating drum, or moving bed reactor technology have a large effect in the IRR and NPV of the facility. Since rotating drum and moving bed reactor have lower investment and installation costs, these options greatly enhance the profitability of the facility. However, these technologies have only been tested in laboratory scale, while screw reactors have been tested in pilot facilities and ramp-up production runs, and its upgradability and associated costs are uncertain, in which case, a screw reactor represents the most proven technology for a large scale application at this moment. Further detailed analysis of scalability, risk assessment, maintenance costs, production rates, product

quality, and availability of suppliers for these technological options must be evaluated in order to accurately calculate the influence of the type of reactor in the total capital expenditure of a factory.

Biomass delivered cost is the second most sensitive variable of the model, drastically affecting the NPV of the project (-$3,438,522) if biomass costs are increased 25% and greatly increasing the suitability of the facility if biomass costs are lower than current evaluated costs ($33.75/ton; NPV: $7,061,525). Figure 8.9 shows the changes produced and its effect in IRR and NPV.

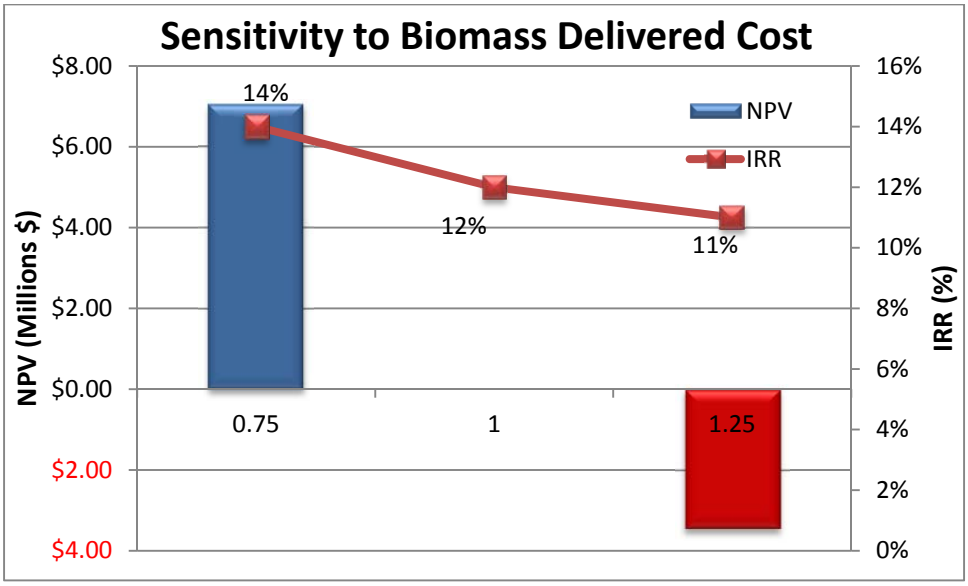


Figure 8.9. Sensitivity of the model to changes in delivered cost of biomass.

These results are in concordance to the breakdown of the production costs of torrefied wood (Presented in Figure 8.4), in which biomass cost represents 37 percent of the total production costs. Since biomass represents such a major component of the production cost (37%), minor changes in raw material delivered costs have major effects in the profitability of the business.

The rest of variables evaluated (energy costs and labor costs) present a less noticeable fluctuation in the IRRs and NPVs obtained, and might not represent a large sensitive factor. Mainly, energy costs remain low due to the elimination of separate drying process, and the

autothermal operation of the torrefaction units. Labor costs have a small effect in the overall financial indicators, due to the small direct labor requirements of such facility. In both cases, the IRR is not significantly affected (14% in all cases), and the NPVs are only slightly modified by ±$100,000. This represents a significant difference compared to similar analyses of biomass pre-treatments, in which Labor and energy costs are sensitive variables affecting profitability (Gonzalez et al. 2011b, and d; Pirraglia et al. 2010).

8.4.3 Additional Analyses

The possibility of benefiting from a carbon credits market is an important factor that needs further development and analysis in the profitability of a torrefied wood facility in the U.S. Integro Earthfuels (Childs, 2012) estimated that torrefaction companies in the U.S. could benefit from carbon credits in a range between $36/ton to $72/ton of torrefied wood produced, depending on the final characteristics of the product. Different scenarios were developed in order to make a preliminary comparison of how an increase or decrease in the carbon credits market may influence the financial indicators of the facility. Figure 8.10 shows the different scenarios evaluated at $0/ton (base case), $36/ton, $54/ton, and $72/ton of carbon credits, and its respective NPV and IRRs.

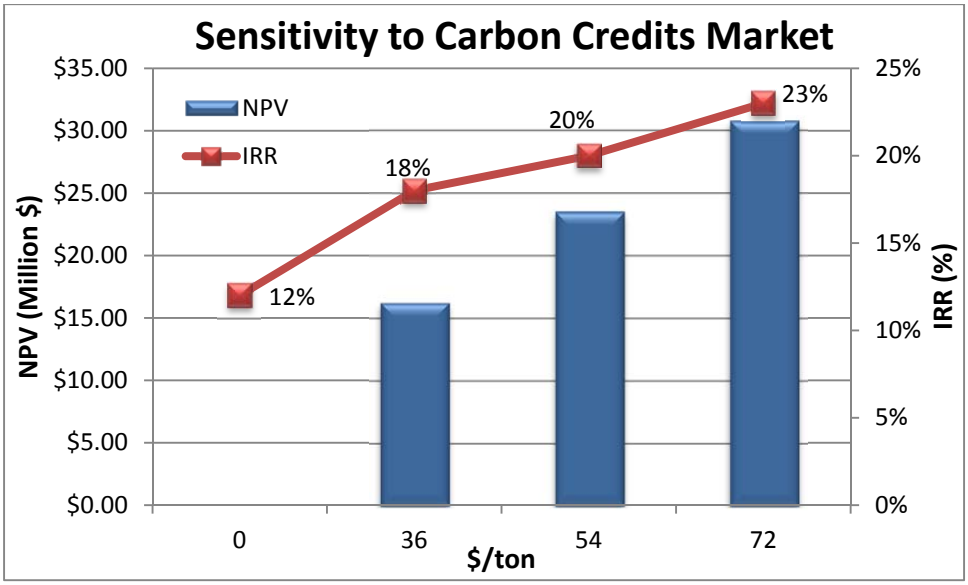


Figure 8.10. Sensitivity of the project to different carbon credits scenarios.

The increase or establishment of a carbon credits market produces a largely positive NPV, and a considerable increase in the IRR of the project. In this sense, price increases in the carbon credit market ($54/ton and $72/ton) highly enhances the profitability of the business, by increasing its net present value and internal rate of return. This exploratory analysis indicates that carbon credits may become a key variable for investors in new torrefaction facilities, and leaves ground for further research in this area, in which risk assessment has to be considered, as well as uncertainty, market fluctuations, and new regulations that may apply for U.S. producers.

8.5 Conclusions

A dynamic, spreadsheet-based model was created in order to evaluate and integrate the technical and economic variables and parameters of a biomass torrefaction facility, with the specific aim of U.S. based facilities with bulk delivery strategy, and intended for co-firing in power facilities. The information provided by the model (price in $/ton of torrefied material) is similar to other studies proposed, and indicates its accuracy in predicting financial and technical conditions for a facility. In addition, a sensitivity analysis for changes in the key variables of the model was performed. Results from the model and its sensitivity analysis indicate that:

- Minimum revenue (back calculated) for torrefied wood in order to obtain at least a zero NPV (break even, with 12% IRR) must be higher than $216/ton, providing a potential revenue margin of $22.37/ton for producers, although higher expected IRRs are recommended, such as 14% (producing an NPV of $5,702,000). Torrefied material delivered cost to power plants (co-firing) may reach $237/ton with a maximum hauling distance of 50 miles. This technology may be competitive (cost-wise) with other biomass pre-treatment options (pellets, briquettes), and a combined-facility analysis is recommended, in order to evaluate the potential profitability of combining these two biomass pre-treatments for further biomass enhancing. Further analysis is required for the profitability of delivered cost of

torrefied biomass for European markets, which should include maritime transportation, port warehouse space and fees, and bonuses for delivered heating value.

- Energy usage (electricity and propane) in a torrefaction facility operating under autothermal conditions is greatly reduced (nearly 60% costs reductions), as compared to other options for biomass pre-processing into solid fuels, such as wood pellets and briquettes; minimizing the impact of drastic changes in energy costs in the production costs, NPV, and IRR of the business. Further analyses of torrefaction technologies vs. drying technologies with its respective mass and energy balances with associated costs will allow for more accurate estimates for energy consumption and are highly recommended for future work.
- CAPEX represent a highly sensitive variable for a torrefaction factory. Changes in CAPEX can largely affect the NPV of torrefaction. One of the most important factors contributing to a high sensitivity of CAPEX is the torrefaction technology used. The selection of new technologies may highly increase the profitability of torrefaction, however, more technical information about scalability, product throughput and output quality, capacities, and maintenance must be evaluated before deciding the implementation of these technologies.
- Biomass cost represents the second most sensitive variable of the model for a torrefied wood facility, and will likely influence location near the biomass basket, since it represents the major component of the production costs (37%).
- The addition of carbon credits to the financial indicators of a torrefaction facility may become a key element if the market finds the right set of conditions and regulations in the U.S. Preliminary analysis indicates that an increase in carbon credit prices may drastically benefit the torrefied biomass business.

8.6 Literature Cited

Andersson, E., Harvey, S., and Berntsson, T. (2006). Energy efficient upgrading of biofuel integrated with a pulp mill. *Energy* 31: 1384-1394.

Arias B, Pevida C, Fermoso J, Plaza M.G, Rubiera F, and Pis J.J. (2008). Influence of torrefaction on the grindability and reactivity of woody biomass. Fuel Process Technology 89(2): 169-175.

Bergman P.C.A. (2005). Combined Torrefaction and Pelletization. The TOP Process. ECN Biomass. http://www.ecn.nl/docs/library/report/2005/c05073.pdf. Accessed 06 January 2012

Bergman P.C.A., and Kiel J. H. A. (2005). Torrefaction for Biomass Upgrading. 14th European Biomass Conference & Exhibition. Paris, France, 17-21 October 2005. http://www.energy.ca.gov/2009_energypolicy/documents/2009-04-21_workshop/comments/Torrefaction_for_Biomass_Upgrading_TN-51257.PDF. Accessed 06 January 2012

Bergman P.C.A., Boersma A.R, Zwart R.W.R, and Kiel J.H.A. (2005). Torrefaction for Biomass Co-firing in existing coal-fired power stations. ECN Biomass. http://www.ecn.nl/docs/library/report/2005/c05013.pdf. Accessed 05 January 2012.

Björklund P. (2011). Metso Torrefaction Concept. EUBIONET 3 Seminar. April 15th. Espoo, Finland.

Bourgeois J.P. and Doat J. (1985). Torrefied wood from temperate and tropical species: Advantages and prospects. Bioenergy 84, Proceedings of an Int. Conf. on bioenergy in Göteborg. 3: 153-159. Elsevier Applied Science Publishers.

Bourgeois J. P., and Guyonnet R. (1988). Characterization and analysis of torrefied wood. *Wood Sci. Tech*. 22.

Brechbill S., and Tyner W. (2008). The economics of biomass collection, transportation, and supply to Indiana cellulosic and electric utility facilities. Working paper #08-03. Department of Agricultural Economics, Purdue University. http://ageconsearch.umn.edu/bitstream/6148/2/wp080003.pdf. Accessed 06 January 2012

Bridgwater A.V. (2009). Technical and Economic Assessment of Thermal Processes for Biofuels. Life Cycle and Techno-Economic Assessment of the Northeast Biomass to Liquids Project. NNFCC project 08/018.

BTG. (2011). Torrefaction. http://www.btgworld.com/index.php?id=109&rid=8&r=rd. Accessed 05 January 2012.

Bureau of Labour Statistics. (2011). May 2010 Occupational Employment and Wages Estimates. http://www.bls.gov/oes/oes_dl.htm. Accessed 06 January 2012.

Campbell K. (2007). A Feasibility Study Guide for an Agricultural Biomass Pellet Company. Campbell Consulting LLC. An affiliated consultant of Cooperative Development Services, St. Paul, Minnesota. Agricultural Utilization Research institute.

Cerezo L.M. (2011). Biomass Torrefaction Workshop. EPRI's Biomass R&D. Pre-Treatment Technologies Update. Electric Power Research Institute.

Chiaramonti D, Rizzo A.M, Prussi M, Tedeschi S, Zimbardi F, Braccio G, Viola E, Pardelli P.T. (2010). 2nd Generation Lignocellulosic Bioethanol: is Torrefaction a Possible Approach to Biomass Pretreatment?. Biomass Conv. Bioref. 1: 9–15

Childs W. 2012. Torrefied Biomass: An Ideal Co-firing Solution. Presentation, Integro Earthfuels.

Digiacomo G., and Taglieri L. (2009). Renewable Energy Benefits with Conversion of Wood Residues to Pellets. Energy. 34: 724-731.

Evergreen Renewable LLC. (2009). Biomass Torrefaction as a Preprocessing Step for Thermal Conversion. http://evergreenrenewable.com/welcome_files/Biomass%20torrefaction.pdf. Accessed 14 January 2012.

Fonseca F, Luengo C. A, Bezzon G, and Beaton P. (1998). Bench unit for biomass residue torrefaction. Proceeding of Int. Conf. Biomass for Energy and Industry. Würzburg, Germany.

Girard P, and Shah N. (1991). Recent Developments on Torrefied Wood, an Alternative to Charcoal for Reducing Deforestation. REUR Technics Series. 20: 101-114.

Gonzalez R, Saloni D, Phillips R, and Wright J. (2010). Loblolly Pine Biomass Delivered Cost. 2010 Biomass Conference. Minneapolis, MN.

Gonzalez R, Phillips R, Saloni D, Jameel H, Abt R, Pirraglia A, and Wright J. (2011a). Biomass to energy in the southern United States: Supply chain and delivered cost. *BioResources* 6(3): 2954-2976.

Gonzalez R, Treasure T, Wright J, Saloni D, Phillips R, Abt R, and Jameel H. (2011b). Exploring the potential of eucalyptus for energy production in the southern United States: Financial analysis of delivered biomass, Part I. *Biomass and Bioenergy* 35(2): 755-766.

Gonzalez R, Treasure T, Phillips R, Jameel H, and Saloni D. (2011c). Economics of cellulosic ethanol production: Green liquor pretreatment for softwood and hardwood, greenfield and repurpose scenarios. *BioResources* 6(3): 2551-2567.

Gonzalez R, Treasure T, Phillips R, Jameel H, Saloni D, Abt R, and Wright J. (2011d). Converting Eucalyptus biomass into ethanol: Financial and sensitivity analysis in a co-current dilute acid process, Part II. *Biomass and Bioenergy* 35(2): 767-772.

Hakkou E.M, Patterson H.P, Williams M.C, and Gladney E.S. (2006). Investigations of the Reasons for Fungal Durability of Heat-Treated Beech Wood. Polymer Degradation and Stability 91: 393-397.

Jacobs J. (2008). Bioenergy: The Role of Short Manufacturing Processes. http://www.feast.org/roundtable2008/presentations/1.5_Jacobs.pdf. Accessed 07 January 2012.

James J. (2009). Using Torrefied Wood for Electricity, Briquettes and Pellets Production. Agri-Tech Producers, LLC.

Lipinsky E.S, Arcate J.R, and Reed T.B. (2002). Enhanced Wood Fuels Via Torrefaction. Fuel Chemistry Division Preprints 47(1): 408-410.

Mani S. (2006). Simulation of Biomass Pelleting Operation. Bioenergy Conference and Exhibition.

Mburu F, Dumarcay S, Petrissans M, and Gerardin P. (2007). Evaluation of Thermally Modified Grevillea Robusta Heartwood as an Alternative to Shortage of Wood Resource in Kenya: Characterization of physicochemical Properties and Improvement of Bio-Resistance. Bioresources Technology 98(18): 3478-3486.

Mitchell P, Kiel J, Livingston B, Dupont-Roc G. (2007). Torrefied Biomass. A Foresighting Study into the Business Case for Pellets from Torrefied Biomass as a New Solid Fuel. A Presentation to All Energy ’07. May 24th 2007.

Nielsen-Pincus M, Krumenauer M, MacFarland K, and Moseley C. (2011). Impacts of the Biomass Producer or Collector Tax Credit on Oregon’s Wood Fuels Market and Economy. Ecosystem Workforce Program. Working Paper Number 32, Fall 2011. http://ewp.uoregon.edu/sites/ewp.uoregon.edu/files/WP_32.pdf. Accessed 07 January 2012.

North American Wood Fiber Review. (2011). Study: Woody Biomass Prices Drop. http://www.woodworkingnetwork.com/news/woodworking-industry-trends-press-releases/Study-Woody-Biomass-Prices-Drop-137286098.html. Accessed 06 January 2011.

Pach M, Zanzi R, and Bjornbom E. (2002). Torrefied Biomass as a Substitute for Wood and Charcoal. 6th Asia-Pacific International Symposium on Combustion and Energy Utilization. 20-22 May, 2002, Kuala Lumpur.

Perry, R. H., Maloney, J. O., and Green, D. W. (eds.) (1997). *Perry’s Chemical Engineers’ Handbook*. (NY) USA: McGraw-Hill.

Phillips B.D. (2011). Radian Bioenergy Torrefaction Technology. http://www.radianbioenergy.com/documents/RadianBioEnergyTorrefactionPressRelease-1.17.11_000.pdf. Accessed 12 January 2012.

Pirraglia A, Gonzalez R, and Saloni D. (2010). Techno-Economical Analysis of Wood Pellets Production for U.S. Manufacturers. Bioresources 5(4): 2374-2390.

Pirraglia A, Gonzalez R, Saloni D, Wright J, and Denig J. (2012). Fuel properties and Suitability of Eucalyptus Benthamii and Eucalyptus Macarthurii for Torrefied Wood and Pellets. Bioresources 7(1): 217-235.

Pomer L, Gerber L, Olofsson I, Wiklund Lindstrom S, and Nordin A. (2010). Gas Composition from Biomass Torrefaction-Preliminary Results. 18th European Biomass Conference and Exhibition. http://www.tfe.umu.se/digitalAssets/61/61393_vp2_8_1-gas-composition-from-biomass-torrefaction_preliminary-results-submitted.pdf. Accessed 10 July 2012.

Rhode M. (1999). *Biomass Power for Rural Development. Department of Energy*. www.nrel.gov/docs/fy00osti/28024.pdf. Accessed 12 January 2011.

Rowell R.M. (2005). Chemical Modification of Wood. Handbook of Engineering Biopolymers. Hanser Publisher, Munich. 674-691.

Samson R, Duxbury P, Drisdelle M, and Lapointe C. (2000). Assessment of pelletized biofuels. Resource Efficient Agricultural Production, Canada.

Sklar T. (2009). Torrefied Wood, a Bio-Energy Option that is Ready to go. http://biomassdigest.net/blog/2009/12/31/torrefied-wood-a-bio-energy-option-that-is-ready-to-go-a-biomass-digest-special-report/. Accessed 12 January 2012.

Stuber D. (2011). Roundwood Price Update: 3Q2011 Results. Forest2Market. http://blog.forest2market.com/2011/10/28/3q2011-results/. Accessed 16 January 2012.

Thek G, and Obernberger I. (2004). Wood pellet production costs under Austrian and in comparison to Swedish framework conditions. *Biomass & Bioenergy* 27: 671-693.

Topell Energy. (2009). Topell on Torrefaction. Workshop IEA Bioenergy Task 32 – New Biomass Co-firing Concepts. Hamburg, June 30th.

Topell Energy. (2011a). Topell Energy. World Economic Forum. Technology Pioneers. Graz, January 28th, 2011. http://www.bioenergytrade.org/downloads/grazpostvanderburg2011.pdf. Accessed 07 January 2012.

Topell Energy. (2011b). Topell on Torrefaction. World Economic Forum. Technology Pioneers. http://www.bioenergytrade.org/downloads/topell.pdf. Accessed 07 January 2012.

U.S. Energy Information Administration. (2011). Form EIA-826, Monthly Electric Sales and Revenue Report with State Distributions Report. http://www.eia.gov/electricity/monthly/index.cfm. Accessed 12 January 2012.

U.S. Energy Information Administration. (2012). Heating Oil and Propane Update. http://www.eia.gov/petroleum/heatingoilpropane/. Accessed 12 January 2012.

Uslu A, Faiij A.P, and Bergman P.C.A. (2008). Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletization. Energy 33: 1206-1223.

Woodworth R, Kelly J, Namazian M, and Miller G. (1997). Biobinder Process for Reconstitution of Fine Coal. Altex Technology Corporation. http://domex.nps.edu/corp/files/govdocs1/064/064997.pdf. Accessed 12 January 2012.

Yan W, Hastings J.T, Acharjee T.C, Coronella C.J, and Vasquez V. (2010). Mass and Energy Balances of Wet Torrefaction of Lignocellulosic Biomass. Energy Fuels 24: 4738-4742.

Zwart R, Boerrigter H, and Van der Drift A. (2006). The Impact of Biomass Pre-Treatment on the Feasibility of Overseas Biomass Conversion to Fischer-Tropsch Products. *Energy Fuels* 20: 2192-2197.

9. TECHNICAL AND ECONOMIC ASSESMENT FOR THE PRODUCTION OF TORREFIED LIGNO-CELLULOSIC BIOMASS PELLETS IN THE U.S.

9.1 Abstract

Manufacturing and trade of wood pellets in the United States (U.S.) has seen an exponential growth in the last few years, triggered by its potential utilization in applications typically dominated by fossil fuels, such as heat, power, and combined cycle generation. The combination of biomass torrefaction with pelletization holds the promise of delivering a high density, high heating value fuel, being a better substitute for coal and other fossil fuels. However, this combined process exists only at pilot-plant levels. Scale-up of the technology and feasibility of such project remain largely unexplored. This research developed a techno-economic model for the production of torrefied wood pellets, considering critical production parameters, and evaluating sensitivity to changes in CAPEX (Capital Expenditure), biomass delivered costs, labor, and energy consumption of a facility, evaluated through a case-study. Results indicate that biomass delivered costs and depreciation are the most significant factors influencing production costs, with CAPEX being the most sensitive variable due to high investments in torrefaction reactors. The selection of different torrefaction technologies, and adequate binders, may represent a major improvement in the feasibility of a project by reducing capital costs drastically. Back-calculated price for torrefied wood pellets is $261/metric ton (100,000 metric tons/year facility), and delivered price may reach $282/ metric ton, being a similar cost compared to regular pellets. Preliminary analysis of carbon credits as additional income may considerably increase the likeability of the business, and further enhance profitability.

9.2 Introduction

The resurging interest in biofuels has produced a large amount of research and development in new technologies and reevaluation of old technologies. Among these technologies, torrefaction has been identified as one of the most promising pre-treatments (Van der Stelt et al. 2011) to improve the performance of biomass based fuels.

Traditional biofuels industries such as wood pellets have seen a renewed interest and an exponential market growth (Pirraglia et al. 2010a, and b) in recent years. Most of this market growth is due to government mandates policies. Even with moderate projections (10% demand increase annually), 10-12% of all harvested wood in the world would be destined to end up as wood pellets by 2025 (Wihersaari et al. 2009), and global markets are expected to double in 2014 (11.3 million metric tons in 2008 vs. 22 million metric tons by 2014, Wood Markets, 2010). Part of the industry's success relies on using proven technology (Bergman, 2005), making its expansion relatively easy, with only occasional problems typical of growing industries such as periodic shortages, hoarding, price volatility, etc. (Spelter and Toth, 2009).

Torrefaction of ligno-cellulosic biomass has been extensively investigated in the literature (Prins et al. 2006a, and b; Zwart et al. 2006; Hakkou et al. 2006; Mburu et al. 2007; Pirraglia et al. 2012a). It is described as a thermochemical process that degrades hydrophilic polysaccharides and hydroxyl radicals, producing an increase in the percentage of lignin on a dry weight basis. Thus reducing the hydroscopicity of the material and increasing energy density.

Wood pellets have also been broadly documented in previous literature. During pelletization the biomass is milled, dried and mechanically densified, enhancing its heating value and burning characteristics, improved transportation properties for a wide range of residential and large-scale applications (Pirraglia et al. 2010b; Spelter and Toth, 2009; Ryu et al. 2006; Junginger et al.2008).

Previous research proved the feasibility of producing torrefied pellets from ligno-cellulosic biomass (Bergamn, 2005; Lipinsky et al. 2002; Boyd et al. 2011), demonstrating improved properties such as heating value, bulk density, and grindability versus wood chips, pelletization, or torrefaction on its own.

A large part of the market growth of pelletized woody material has been intended to supplement or replace coal for power generation. Studies indicate that torrefied wood's energy content per kilogram could be similar to that of coal, and 12% to 41% greater than that of wood pellets depending on the degree of torrefaction (New Biomass Energy, 2011). The disadvantage of wood versus coal is its lower bulk density (641-721 Kg/m^3 vs. 897-993

Kg/m^3 for coal). The addition of densification (pelletization) to torrefaction would potentially create a bio based fuel with similar energy density to coal, prompting the adoption of this product for replacing coal in heat and power facilities.

Recent studies aim in the direction of making a combined torrefaction-pelletization process possible in a commercial scale (Wihersaari et al. 2009; Bergman, 2005).The Energy Research Centre Netherlands (ECN, Bergman et al. 2004) developed a production process for torrefied pellets, while Andritz developed a brand-named process with similar unit operations and principles as the ECN process (Trattner, 2011). Both processes are said to provide pellets with better hydrophobic properties, higher density, and similar strength characteristics as non-torrefied pellets.

Mitchell et al. (2007) evaluated the business case for torrefied wood pellets, describing that torrefied pellets may have twice the energy bulk density as wood pellets, with the potential of being highly competitive with heavy fuel, heating oil, and in co-firing with coal. Uslu et al. (Uslu et al. 2008) confirmed that merging torrefaction and pelletization reduced transportation and handling costs.

Van der Stelt et al. (2011) found three potential applications for torrefied wood pellets; entrained flow gasification, small scale combustion using pellets, and co-firing in pulverized coal fired power stations. Gasification is still a technology under development for commercial applications, while co-firing in power plants is a concept that has been evaluated by the authors in a previous publication (Pirraglia et al. 2012b).

Despite the vast research efforts of integrating torrefaction and pelletization to produce a pelletized fuel, only one aspect has been considered in a limited scope up to date: its technical and economic evaluation for full scale production in the U.S. In addition, uncertainty still exists in the determination of large scale production, and the properties of the pellets regarding durability, and the necessity of external binding agent addition for better properties, with its associated cost in large scale production.

The objective of this research is to develop a technical and economic assessment that allows evaluating the feasibility of torrefied wood pellets production in the United States; a case study for a 100,000 metric tons/year facility is utilized to describe and evaluate the results of such model. A second objective of the research is the identification of potential

binders for torrefied pellets production, and the determination of its influence on the economics and technical characteristics in a torrefaction-pelletization project.

9.3 Methods

The present model was developed with a similar concept as previous work performed by the authors (3, Pirraglia et al. 2012b; Gonzalez et al. 2010, 2011a, b, c, and d). The analysis of a completely integrated torrefaction-pelletization process involves the identification and assessment of variables in three areas: 1.) Mass balance which accounts for biomass weight and energy consumption. 2.) The type of fuel used in the production process and the associated energy costs. 3.) A financial section, integrating the main variables such as biomass delivered costs, capital expenditure, depreciation, labor, operating, and miscellaneous costs, into financial indicators that allow evaluating profitability of torrefied wood pellets production, such as Internal Rates of Return (IRR), Net Present Value (NPV), and sensitivity analysis.

The model allows user-friendly inputs of costs and production related variables to evaluate scenarios and different production conditions. Table 9.1 summarizes the user-modified variables in the model.

Table 9.1. User-modified variables utilized in the model

Type	Variable
Production Variables	Torrefaction Level
	Moisture Content of Biomass
	Working Hours/year
	Biomass Type/Form
	Binder Selection
	Mass Losses (per unit operation)
	Efficiency (per machine)
	Production Level (annual)
	Binder Requirements (%w/w)
Cost Variables	Biomass Delivered Costs
	Torrefaction Technology
	Binder Costs
	Plant Location
	Energy Costs
	Carbon Credits
	Capital Costs
	Discount Rate
	Internal Rate of Return
	Labor Costs
	Cost of Consumables

Torrefaction level represents a critical variable for determining the product properties and quality, and is defined by the residence time and temperature of operation inside the reactor (Pirraglia et al. 2012a; Pierre et al. 2011). These two parameters determine the changes in the levels of cellulose, hemicellulose, and lignin, as well as the amount of VOC's (Volatile Organic Compounds) available for combustion. A wide range of torrefaction temperatures and residence times have been reported in the literature, varying between 1-40 minutes, and from 200°-400°C. Experimental information from a torrefaction machine (screw-type reactor) in operation at North Carolina State University, and previously described by the authors (Pirraglia et al. 2012a), allowed to establish three torrefaction levels in the model. These levels influence the final moisture content, binder requirements, and High Heating Value (HHV) of the product. Light torrefaction was established at three minutes residence time, and 280°C with a resultant HHV of 19.7 MJ/Kg (8,458 Btus/lb.);

Medium torrefaction is defined as four minutes residence time at 320°C with a resultant HHV of 21.1 MJ/Kg (9,060 Btus/lb.), and dark torrefaction is defined as five minutes residence time at 350°C with a resultant HHV of 22.1 MJ/Kg (9,502 Btus/lb.).

In order to estimate the profitability of torrefied wood pellets production, the process design and unit operations have to be properly identified. Figure 9.1 presents the schematics of a proposed process for torrefied pellets production, from delivered biomass to final storage of torrefied pellets at the facility's gate, and assuming that biomass is debarked by wheeled forestry debarkers (cost of debarking included in biomass delivered costs), and delivered as debarked roundwood.

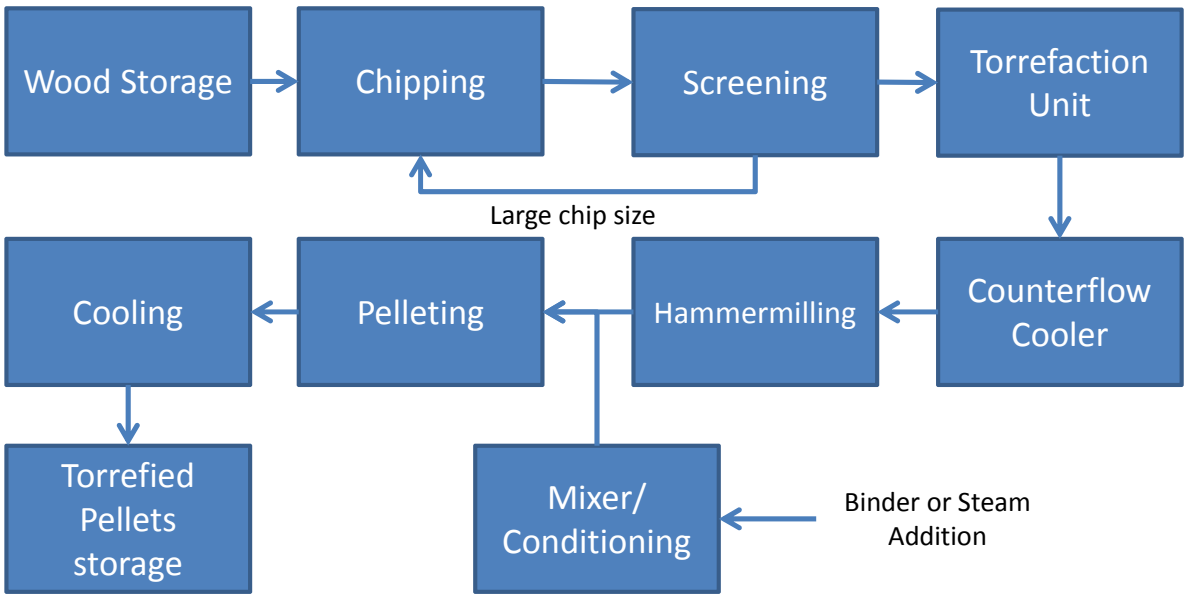


Figure 9.1. Torrefaction-Pelletization process for an industrial-scale factory.

9.3.1 Process Description

The process flow in Figure 9.1 is modified from previous investigations on torrefaction-pelletization as pre-treatment, with the addition of a mixing or conditioning process, for the inclusion of a binding agent to aid in pellets formation and durability, and a hammermilling process for further particle size reduction, allocated after particle cooling in the torrefaction unit. The model considers biomass received in an open-space storage area, and product is considered to be stored in a naturally ventilated warehouse area.

A torrefaction unit is capable of producing 80-100% of the necessary heat to pre-dry the biomass entering the reactor and during torrefaction (Pirraglia et al. 2012a; James, 2009), by combusting the VOC's released, removing the majority of moisture present in the biomass at the time of processing. In this model torrefaction is assumed to be an autothermal operation; a process that takes place without the addition of external heat except for initial ignition. The model proposed accounts for a thorough analysis of the torrefaction unit, calculating a detailed mass and energy balance of the process. One of the most important energy balance factors is represented in the torrefaction unit, in which water is evaporated from the biomass, a pilot flame of propane is kept, and the energy density of the biomass is increased, although 10% of the original energy is lost in the process. Figure 9.2 shows a schematic of the energy balance.

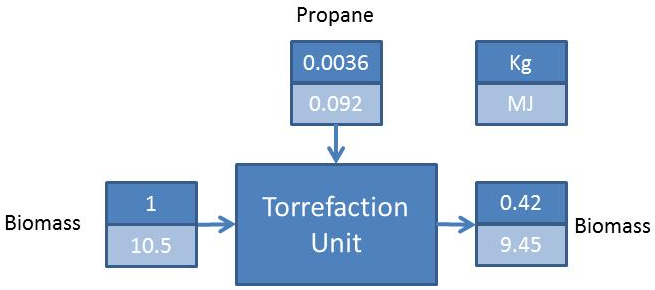


Figure 9.2. Mass and Energy balance for the Torrefaction unit, including pre-drying.

Biomass entering the unit is considered at 45% moisture content; an average 10.5 MJ/Kg heating value for wood is considered (wet weight basis), and VOC's extracted from the biomass are recirculated and burned in a combustion chamber along with propane. This type of mass balance is the minimum required for the autothermal operation of the unit. Figure 9.3 shows the detail (mass circulation) of the torrefaction unit.

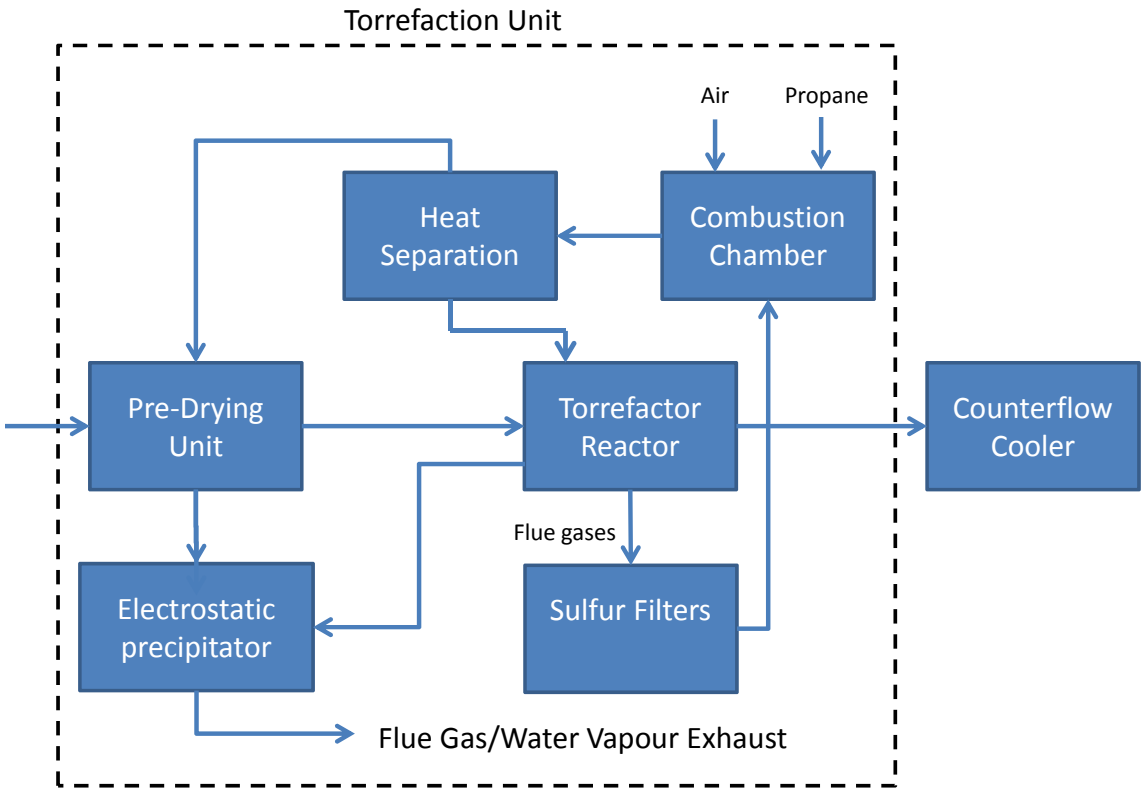


Figure 9.3. Schematics of the proposed Torrefaction unit, including pre-drying.

Previous studies indicate that torrefaction is performed in five main stages: initial heating, pre-drying, post-drying, torrefaction, and solids cooling (Van der Stelt et al. 2011). The stage of pre-drying is performed between 100°C and 200°C, eliminating the need for a separate drying unit in the process. In addition, due to high operation temperatures, biomass exiting the reactor requires cooling of the material prior to pelletization. This task is accomplished by utilizing a counterflow cooler after torrefaction, unit that operates by circulating fresh air through a bed of product circulating in opposite directions, discharging the product only when the required temperature has been reached, by adjusting either the speed of discharge, the flow of air, of a combination of both.

Three different types of feed mechanisms for the torrefier can be selected in the model; screw reactor, rotating drum, and moving-bed. Based on the recommendations of Bergman (2005) four separate production lines with same conditions are utilized in the model. The hammermilling process is allocated after torrefaction in order to minimize power

consumption (Phanphanich and Mani, 2011). Conditioning or binder addition to the biomass is performed due to the non-fibrous properties of the torrefied material in order to improve the quality of the pelletization process (Pirraglia et al. 2012a).

9.3.2 Binders

Binders in pellets are used to improve binding, lubrication, combustion properties, and abrasion characteristics (Oberngberger and Thek; 2004), by forming a bridge, film, matrix, or chemical reaction that strengthens inter-particle bonding (Kallio, 2011). In the manufacturing of regular wood pellets (without any pre-treatment), the lignin present in the wood acts as glue for the cellulose fibers (Tumuluru et al. 2010) allowing pelletization without the addition of binders, and depending on fibers characteristics (Rumpf, 1962; Hill and Pulkinen, 1988). Lignin thermosetting properties are activated at temperatures higher than 140°C, acting as a resin (Angles et al. 2011). Under normal pellet plant operating conditions, with 8-15% moisture content of the feedstock this temperature is reduced to 100-135°C. When strength, durability or heating value properties are not properly reached, the addition of binders become necessary to increase pellets quality (Kaliyan and Morey; 2010). During torrefaction, lignin undergoes loss of properties with temperatures above 270°C (Bergman, 2005; Bergman et al. 2004) reducing the possibility of its utilization as binding agent, making large-scale production of torrefied pellets difficult without adding external binders. Thus, several different option of binders were investigated and considered for this research, since binders will affect mass balance, energy balance, capital costs (addition of a mixer and/or conditioning unit), and production cost per metric ton of torrefied pellets.

Boyd et al. (2011) and Mani (2008) proposed the addition of steam to increase moisture content before pelletization, thus softening the lignin and aiding in the binding of the pellets. According to Kallio (2011), steam conditioning is essential to provide heat and moisture to activate inherent binders of the biomass. This type of binder may result adequate if lignin has not undertaken heavy denaturation, being ideal for “light” or mild torrefaction temperatures.

Tumuluru et al. (2010) reported the suitability of different types of binders and its influence in pellets quality. In this work starch and proteins binders have better properties for

pellets quality, as compared to lipids and fats. Starch acts as a binding and lubricant agent, easing the material flow through the die, while protein based binders improve binding capacity (Thomas et al. 1998; Nyanzi and Maga, 1992), increasing pellets durability (Briggs et al. 1999; Wood, 1987). Binders with combined proteins and starch content may have a more significant influence on densification and quality of pelletized biomass, producing denser and more stable pellets (Shankar et al. 2005, 2010). Mani (2008) proposed the addition of starch-based binders, bio-oil, black liquor and/or lignin to torrefied material in order to form durable pellets, if these binders can be procured at low costs. However, for large production volumes, availability of bio-oil, black liquor, or lignin may be limited. Thus, a binder that can be procured in large quantities and with well-established supplies must be selected.

Several binders have been detailed evaluated in previous literature (Kaliyan and Morey, 2009, 2010; Tabil et al. 1997). Kallio (2011) reports that small amounts of starch (2% weight/weight) increases pellets durability; Nikolaisen et al. (2002) reported the use of 2-5% (weight/weight) molasses as binding agent, while Wilen et al. (1986) used kaolin (3% weight/weight). Rapeoil (Nikolaisen et al. 2002) and pineoil (Kallio and Kallio, 2005) has also been evaluated, but results indicate that addition of fats/oils reduce pellets durability. Additionally, researchers and companies must keep in mind that certain markets may limit the utilization of some binders. Austria allows only 2% (weight/weight) binders addition rich in starch content (e.g., maize Obernberger and Thek, 2004), while Germany allows only molasses, natural paraffin or starch (Viak, 2000).

Soybeans represent a great candidate, providing considerable amounts of protein, starch and oil that may act as binder and lubricant, with a composition of 38% protein, 30% soluble and insoluble carbohydrates, 18% oil, and 14% moisture, ash and others (WiSHH, 2011). In addition, its procurement in the United States is relatively easy, since the U.S. represents the largest soybean producer (Soy Stats, 2011) with 35% of world production.

Corn is also another excellent binder, composed of 72% starch, 10% cellulose and hemicellulose, 9% protein, and 8% oil and other components (Baez, 2006), and is the most widely produced grain in the country, with 37% of the planted crop land being corn; since corn is currently being heavily utilized in the production of ethanol, and as a food crop, it is

recommended the utilization of feed corn (or cracked corn, byproduct of the corn harvesting and processing). Thus, corn for feed represents an optimal binder, which does not suggestively affect the food production industry.

DDG's (Distillers Dried Grains) composition makes it also an adequate candidate for binding agent. DDG's are typically by-products of the distillery industries (such as enzymatic hydrolysis processes for the production of ethanol). DDG's typical composition is 31% proteins, with 10% fat and 4% starch, and 55% cellulose and hemicellulose (Baez, 2006). The United States has a median estimated production of 39.7 million metric tons/year of DDG for 2012 (AgMRC, 2012), making it a readily available binder for the densified fuels industry.

In the present study, the authors include the previous mentioned options of binders for the model, steam (for conditioning of lightly torrefied biomass), feed corn, DDG, and soybeans. The evaluation of each binder influences the selection of further machinery (mixer or conditioner), capital costs, production costs, and mass balance of the process. Detailed information about binder ratios, costs, and addition in the model is provided in further paragraphs.

9.3.3 Mass Balance

The model developed back-calculates biomass requirements of the factory based on annual production (product output), biomass moisture content, torrefaction conditions (level), and biomass losses throughout each unit operation, giving a biomass throughput for each separate process. Information from previous literature was used to estimate flue gases, water vapor release, and fuel requirements for the torrefaction unit (Bergman and Kiel, 2005; Yan et al. 2010; Topell Energy, 2011). No mass losses are considered in subsequent unit operations, although these can be user-modified. Based on experimental information from the torrefaction unit at North Carolina State University, a propane pilot flame is used in the combustion chamber, at a 2% weight rate of the total gases entering the chamber. Although the torrefaction process can run without the addition of external heat sources in autothermal operation, the addition of the pilot flame ensures proper combustion, uniform heat flux and flow of gases, and helps maintain torrefaction temperatures, product quality, and uniformity.

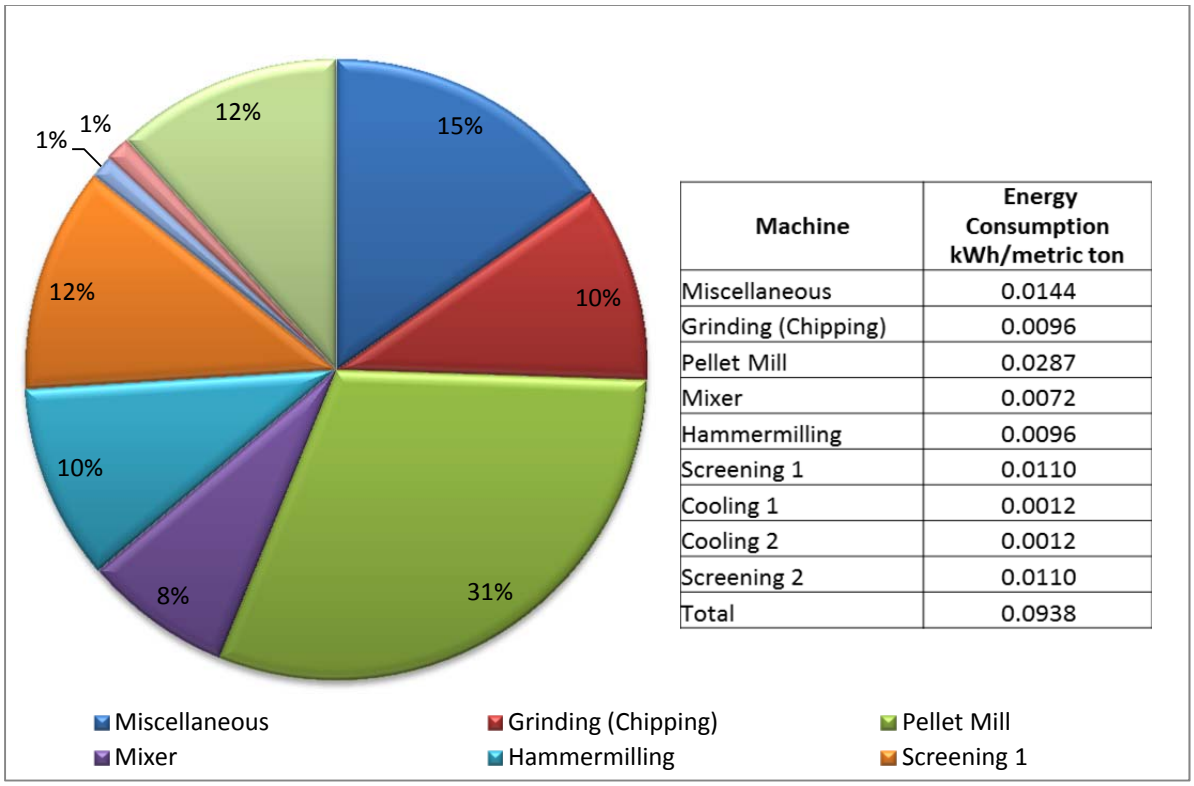
Calculations of the propane requirements are also included in the mass balance, and influence the annual costs of energy for the factory. Future work may consider the utilization of natural gas, which may deliver lower costs per unit of heat transferred.

The addition of a binder to the feedstock prior to pelletization has many different formulations. Adapa et al. (2010) studied biomass steam conditioning prior to pelletizing, suggesting a 25% weight-basis steam addition to the biomass (conditioning value utilized as a baseline in the model), while Tijmensen et al. (2002) suggested ratios of 19%, 34% and 60% steam addition in various gasification processes, being 34% the ratio most commonly used (in Kg steam/Kg biomass input). Suggested ratios of DDG's and other grains to pellets production are 85% wood with 15% grains (Kallio, 2011), and 12:1 ratio of wood to soybeans (approximately 8% weight, dry basis, Pellet Pros, 2011). This information is included in the model, and results and binder addition ratio in the mass balance are automatically modified when selecting a particular type of binder. In the topic of binder utilization for torrefied wood pellets, it is necessary to highlight the lack of information and available tests results regarding percentages, types, and use of binders for torrefaction, and the influence in product characteristics, economics, and storage properties (degradation, durability, etc.). Hence, there is still a need for detailed studies in the addition of binders in torrefied and densified biomasses, which will complement and enhance the results on binder addition presented in this research.

9.3.4 Energy Utilization

The electrical energy consumption of the machinery (kWh/year) in the facility is calculated based on the work of Digiacomo and Taglieri (2009), Pirraglia et al. (2010b), and Bergman and Kiel (2005). In this evaluation, the average power consumption of each process, operating at a 100% capacity based on the production requirements of the facility, is considered. The mechanical systems of the torrefaction reactor, such as fans, blowers, and valves, are considered part of the miscellaneous equipment in the electrical energy calculations. Additional propane burned in the combustion chamber is provided in case that conditioning of the biomass is required (for steam generation in the boiler, only required in conditioning). Considering the average energy consumption of the machines, the plant

location of the facility (for energy costs effect), and the working hours per year, the model calculates total yearly energy consumption of the factory, and average energy consumption per metric ton of torrefied pellets produced. Below (Figure 9.4) is presented the percentage of energy (electrical) consumption of each unit operation in the torrefied-pellets process, as well as the kWh of energy consumption per metric ton of torrefied pellets produced for each process.



Machine	Energy Consumption kWh/metric ton
Miscellaneous	0.0144
Grinding (Chipping)	0.0096
Pellet Mill	0.0287
Mixer	0.0072
Hammermilling	0.0096
Screening 1	0.0110
Cooling 1	0.0012
Cooling 2	0.0012
Screening 2	0.0110
Total	0.0938

Figure 9.4. Energy consumption in the factory by process, estimated for a 100,000 metric tons/year facility, with an approximate energy consumption of 0.094 Kwh/metric ton of torrefied pellets. Torrefactor mechanical systems are considered part of miscellaneous equipment.

The most significant energy consumption process is represented by pelletization, with the miscellaneous equipment of the facility being second in importance. If conditioning is required, significant steam generation costs (with propane) may be reached. Steam addition

costs widely vary depending on production rates, annual operating hours per year, boiler efficiencies, and type of fuel utilized to produce the steam. Considering propane and heat exchanging from the off-gases in the torrefaction process as fuel for steam generation, steam costs are calculated according to the following parameters (Table 9.2).

Table 9.2. Characteristics considered for steam costs calculations.

Feedwater Temperature	24^{o}C
Type of fuel	propane
Fuel Costs	$0.36/Liter ($1.346/gallon)
Efficiency	85.70%
Annual hours operating*	8,400
Operating Pressure	1,135.54 kPa. (150 psig)
Boiler Horsepower	255 BHP

Considering the parameters previously mentioned, and utilizing a Clever Brooks Boiler Steam Costs Calculator (Clever Brooks, 2011), along with propane technical tables from Alternate Energy Systems, Inc. (Alternate Energy Systems, 2011), average steam costs account for $78.64/metric ton of steam produced. More detail in the calculation of other binders is provided in the next section.

The evaluation of boiler, and combustion chamber requirements and costs to switch from a traditional burning fuel such as propane, to biomass burning from the same delivered biomass for pellets production, or from rejects and biomass waste, is a topic that needs further evaluation for its potential to reduce energy costs of the facility.

A critical energy element in the process is presented in the torrefaction unit. In order for the process to be efficient, the energy for pre-drying the biomass, and perform the torrefaction reaction in the unit must be self-generated. In the unit operating at North Carolina State University, it is estimated that 80% of the necessary heat for pre-drying and torrefaction is generated by combusting the off-gases of the biomass entering the process, and the remaining 20% of the required heat is generated through a propane flame that ensures not only that the required heat needs are met, but also ensures proper combustion of the gases in the chamber, uniformity of the product, and aids during start-up of the machine.

Under autothermal conditions (previously described in the Methods section), and depending on the biomass source, the torrefaction off-gases that contributes to most of the heat generated in the combustion chamber are formaldehyde/acetaldehyde, methanol, pyruvaldehyde/propanal-2-one, furfural, furfuralalcohol, and coniferyl alcohol, among other product gases (Pomer et al. 2010), generating the aforementioned 80% of the heat process (torrefaction and pre-drying).

9.3.5 Economic Parameters

This section contains detailed information on the capital expenditure of buildings and machinery, engineering, labor, energy, consumables, and biomass costs. The equipment costs, capacities, and engineering costs were obtained directly from manufacturers (in the case of boiler, grinders, screeners, counterflow coolers, hammermills, pellets mills, conditioners, and mixers). Costs of installation, siting, engineering, maintenance, and miscellaneous equipment, along with miscellaneous costs related to the boiler (costs of accessories: feedwater pumps, fans, fuel heaters, steam for fuel atomizers and soot blowing, treatment chemicals, and environmental and maintenance costs) are retrieved from recent literature (Pirraglia et al. 2010b; Thek and Obernberger, 2004; Campbell, 2007). The values obtained from previous literature were adapted to 2011 values using the CWCCIS (Civil Works Construction Cost Index System) conversion index.

The costs for a torrefaction unit, including combustion chamber, heat exchangers, feeding systems, reactor, and miscellaneous equipment, are difficult to estimate. Since torrefaction of biomass in large scale is a recent concept, there is still a lack of reliable sources for costs estimates. Suppliers of this type of equipment is scarce, and the majority are still in the pilot test stage for their technologies; however, some authors indicate that capital costs of torrefaction are mainly dominated by the cost of the reactor, being this a common trend of this process (Bergman et al. 2005; Bridgwater, 2009). Some authors have estimated the capital costs of torrefaction units per metric ton of biomass required per hour (capacity of the equipment), and depending on the type of technology implemented. In this sense, the work performed by Bergman et al. (2004, 2005), is of great importance. Although this work is performed under European market conditions, it provides with one of the few complete

and detailed estimates for torrefaction costs, including engineering & supervision, installation and construction costs. In their studies, three types of technologies, with their associated capital cost, are described (and therefore, utilized in this project): screw reactor, with $32.72/metric ton (€22/metric ton) costs, rotating drum with $23.80/metric ton (€16/metric ton) costs, and moving bed, with $11/metric ton (€11/metric ton); these estimates were developed under the assumption of a 200,000 metric tons/year factory. In the present project, these cost estimates are utilized, and are adjusted to $/metric ton using the average conversion rate of €/$ of 2005, and the CWCCIS index to convert it to 2011 dollar values. In the model, the three types of technologies are included, and can be modified by the user, automatically adjusting production parameters and capital costs.

For equipment other than the torrefaction unit, capital costs depend on the equipment capacity, and are adjusted (depending on annual production as input) utilizing the power law rule (Perry et al. 1997) which estates that: $Inv=Inv_L x(P/P_L)^{0.7}$; were Inv represents capital investment depending on plant size(metric tons/h), Inv_L represents capital investment of original equipment, and P and P_L represent the capacity required on the equipment, and the capacity of the original equipment respectively. 0.7 represents the scaling factor, following recommended values by Andersson et al. (2006).

In addition to basic capital costs, the model adds indirect and contingency costs, calculated as 24% and 10% of the total capital cost of equipment respectively, following the values proposed by Woodworth et al. (1997). Biomass storage after pelletization, with warehousing costs and space represent 7.6% of total plant building (Thek and Obernberger, 2004). This warehouse space is considered assuming that torrefied pellets are directly dumped into trucks/railroad, with a bulk-delivery logistics strategy. With all capital costs information, plant and equipment depreciation is calculated in the model using a MACRS-7 method (Modified Accelerated Cost Recovery System, in 7-year class, which depreciates 14.29%, 24.49%, 17.49%, 12.49%, 8.93%, 8.92%, 8.93%, and 4.46% each year from the total assets value in seven years), with a capital expenditure schedule of 20%, 40% and 40% in three years.

Labor costs, headcount, and structure are calculated based on the average wages provided by the Bureau of Labor Statistics (2011), and by previous literature (Pirraglia et al.

2010b; Campbell, 2007; Bridgwater, 2009). The model calculates, based on this information, the annual direct and indirect labor costs, adjusted depending on the annual facility production, number of shifts per day, and number of working hours per year.

Biomass delivered costs are fixed at $45/bone dry (metric) ton (BDT), considering an annual cost increase of 1%. This value is lower than previously reported delivered costs (Pirraglia et al. 2010b; Gonzalez et al. 2010); in order to be consistent with more recent delivered costs reported (Nielsen-Pincus et al. 2011). However, changes in biomass delivered costs can be performed in the model, and allow for sensitivity analyses. In addition, final product is intended for bulk delivery, reducing the handling, packaging, and consumables utilization in the facility, differing to previous reports on wood pellets facilities (Pirraglia et al. 2010b). Consumables are considered as plant and office tools ($80,000/year), and lubricants, rollers and dies for pelletizers ($3/metric ton), and spare parts for the torrefactor and other equipment ($3/metric ton). Additional costs are segmented in marketing/sales fees ($6/metric ton), maintenance and repairs ($8.85/metric ton), forklift and front-end loaders costs ($0.17/metric ton). Values for each estimate are taken from Campbell (2007), and Bergman et al. (2005).

In addition to the traditional consumables costs of a wood pellets factory and/or torrefaction facility, it has been previously discussed the need for a binding agent and process. The addition of a binder represents an additional cost that must be taken into consideration. The model can adjust the type of binder used, with four different choices: feed corn, DDG's, soybeans, and steam. Conditioning by Steam addition to the biomass seems more adequate for mild torrefaction treatments, being the default option when light torrefaction is selected in the model. As previously mentioned, the cost of steam for the facility, considering a 34% weight-weight addition of steam to biomass, is $78.64/metric ton of steam.

For every other torrefaction treatment selected in the model (medium and/or dark torrefaction), binding agents processed by mixing seem more adequate. In the model automatically adjust the percentage weight-weight of binder to biomass suggested in previous paragraphs, depending on the binder selection by the user, and also adjusts current costs per metric ton of binder added. Latest information on binders costs reports the

following: soybean prices have fluctuated between $420.05/metric ton and $509.93/metric ton during 2011 (commodity price, Index Mundi, 2012), with an average of $480.98/metric ton, DDG's prices are currently at $201.7/metric ton (national average, USDA, 2012a), and feed corn average 2011 prices (commodity) was $156.02/metric ton (USDA, 2012b). These costs are calculated in the model and added to the financial section (income statement). In the results and discussion section, a case study for the model is presented, assuming a factory producing 100,000 metric tons/year of torrefied wood pellets.

For the proposed case study, and in a similar structure as previously described by Pirraglia et al. (2010b), the parameters considered are summarized in Table 9.3; this case study considers no carbon credits.

Table 9.3. Parameters utilized in the case study factory

Parameter	**Value**
Annual Production	100,000 metric tons/year
Required Raw material (green)	230,956 metric tons/year
Initial Moisture Content	45%
Final Moisture Content	7%±1%
Heating Value of Product	19.673 KJ/Kg (8,458 Btu/Lb.)
Torrefaction Level	Light Torrefaction
Type of binding treatment	Steam conditioning
Binder Added (%w/w)	25%
Carbon Credits	$0/ metric ton

9.4 Results and Discussion

Other studies have analyzed size factories similar to the one proposed in this case study, such as Topell Energy (2011), a 200,000 metric tons/year plant described by Björklund (2011) utilizing a screw reactor technology, Mitchell et al. (2007) which described an 80,000 metric tons/year facility. While some of these studies concluded that prices for torrefied biomass are still not viable, they also state the need for more technical demonstration and accurate estimates (Björklund, 2011), especially since many of these studies provide scarce information about the economics, dimensions, calculations, and

assumptions of the ventures; In this section of the study, the authors intend to cover many of these aspects.

9.4.1 Energy Usage

The case-study factory considers the average electricity and propane costs ($/kWh and $/Liter) for the U.S., updated to January 2012. In the model, however, plant location can be modified to any State, and local and regional electricity and propane costs will be automatically adjusted, following the information collected from the U.S. Energy Information Administration on electricity and propane costs (U.S. Energy Information Administration, 2012a, and b). For energy calculations, it is assumed a screw reactor technology for the torrefaction unit, operating in the autothermal range, with miscellaneous mechanical equipment of the torrefier running on electrical power, and a steam boiler also running on propane. For sensitivity analyses, other torrefaction technologies, and different binder that do not require boilers running on propane, are considered. Table 9.4 shows the results for energy consumption and costs in the case study.

Table 9.4. Electrical and Propane usage and costs for the case-study factory

Propane Usage (Liters/year)	818,220.15
Propane Cost ($/Liter wholesale)	0.36
Total Propane Costs	**290,940**
Electricity Usage (kWh/year)	2,334
Electricity cost ($/metric ton)	13.35
Total Electrical Costs ($/year)	**1,334,760**

Energy costs present a reduction if compared with other alternatives of biomass pre-treatment such as wood pellets. Compared to the work by Pirraglia et al. (2010b) on a 75,000 metric tons/year wood pellets facility, reductions in total energy consumption are close to 43%, even considering that the size of the facility in the present study is 25% larger in metric tons per year manufactured. This indicates that energy consumption of this combined pre-processing might present a competitive advantage over the highest energy consuming pre-treatment (wood pellets). This characteristic is due to the absence of a separate drying

process; although other equipment increases the energy consumption of the facility, most of this energy is typically used in drying biomass, process that is eliminated by the autothermal operation and excess heat generated by the torrefaction unit.

9.4.2 Cost Structure

In the present study, four parallel lines of torrefied material are assumed before pelletization, as recommended by Bergman et al. (2005). For CAPEX (Capital Expenditure, expenditures that will benefit the business in the future, such as equipment) effects, this influences the selection and number of feeding systems, conveyors, and miscellaneous equipment, having a fixed value, with a difference in capacities if production levels are changed (increase and/or decrease). Based on the automatic calculations of the model (mass balance section), and the annual production set as 100,000 metric tons/year, the factory must process 11.9 metric tons/hour of torrefied wood pellets, with different levels of biomass being processed at each stage. Based on these requirements, and using the estimates by Bergman et al. (2005) on torrefaction costs per metric ton produced for a screw reactor (€22/metric ton), CAPEX of the torrefaction unit and the rest of the equipment was developed, considering the average euro-dollar exchange rate of 2005, and a CWCCIS index to extrapolate costs to 2011 values. Detailed CAPEX calculations are provided in Table 9.5.

Table 9.5. CAPEX for the case-study factory (in thousands of dollars)

Item	Number required	Cost per each equipment	Installation cost	Total Equipment costs	Total Installation costs	Total Equipment + Installation costs
Misc. Conveyors	8	15.2	7.6	121.5	60.8	182.3
Front-end Loaders	2	22.8	-	45.6	-	45.6
Feed Hopper	20	7.6	4.6	151.9	91.1	243.0
Grinder	4	174.9	113.9	174.9	455.7	630.6
Torrefaction Unit	4	7,078.7	-	28,314.7	-	28,314.7
Live Bottom Bin	20	18.2	15.2	364.5	303.8	668.3
Continuous dual-shaft biomass mixer	2	480.0	216.0	960.0	432.0	1,392.0
Hammer mill	2	83.5	38.0	167.1	75.9	243.0
Pellet mills(s) (including conditioning)	2	265.8	83.5	531.6	167.1	698.7
Boiler/Water Heater (255 BHP)	1	167.1	1.7	167.1	1.7	168.7
Counterflow Cooler 1	4	227.8	18.2	911.3	72.9	984.2
Counterflow Cooler 2	4	227.8	18.2	911.3	72.9	984.2
Screener 1	4	15.2	12.2	60.8	48.6	109.4
Screener 2	4	15.2	12.2	60.8	48.6	109.4
Fork Lift	2	22.8	-	45.6	-	45.6
Site and Site preparation	1	156.0	-	156.0	-	156.0
Paving/Receiving station/load area	1	60.0	-	60.0	-	60.0
Building & Office space	1	1,020.0	-	1,020.0	-	1,020.0
Misc. Conveyors	8	15.2	7.6	121.5	60.8	182.3
Total				34,346.1	1,891.8	36,237.9
Storage warehouse						77.6
Indirect costs (24%)						8,672.0
Contingency (10%)						4,480.5
Total installed costs						49,468.0

The cost of the torrefaction unit represents the major CAPEX element (43% of the total installed costs). Notice that according to the estimates provided by Bergman et al. (2005), engineering and installation costs are included in the reported value of €22/metric ton

for the torrefaction unit. The high percentage that torrefaction represents in the capital costs is said to be typical of a new technology, or a first-plant cost, and subsequent facilities can see capital costs reduced by as much as 20% for every doubling in the number of facilities (Bridgwater, 2009).

Direct and indirect labor total 33 employees and administrative personnel. The factory considers three eight-hour shifts per day. This information is part of the operating costs of the factory, along with consumables, binders, and additional costs. Since the binding agent considered for the case study is steam, the annual estimated cost of steam is reported. A summary of operating costs is presented in Table 9.6.

Table 9.6. Operating costs for the case-study factory

Operating Cost	$/year
Direct Labor	1,274,765
Indirect Labor	697,829
Consumables	1,465,714
Additional Costs	1,502,043
Binding Agent (Steam Conditioning)	2,673,760
Total Operating costs ($/year)	**7,614,111**

The labor structure proposed in the model considers one supervisor, four production employees, one forklift operator, one maintenance technician, and one raw material employee as direct labor. Administrative (indirect) personnel is structured with two accountants, two sales/marketing representatives, one executive/administrative assistant, one finance manager, and one general manager. With all the costs included in the model and dependent on the inputs, total production costs for the facility can be calculated, considering also depreciation as part of the production costs. Figure 9.5 shows the main production costs categories and its influence in the total production cost of torrefied wood pellets.

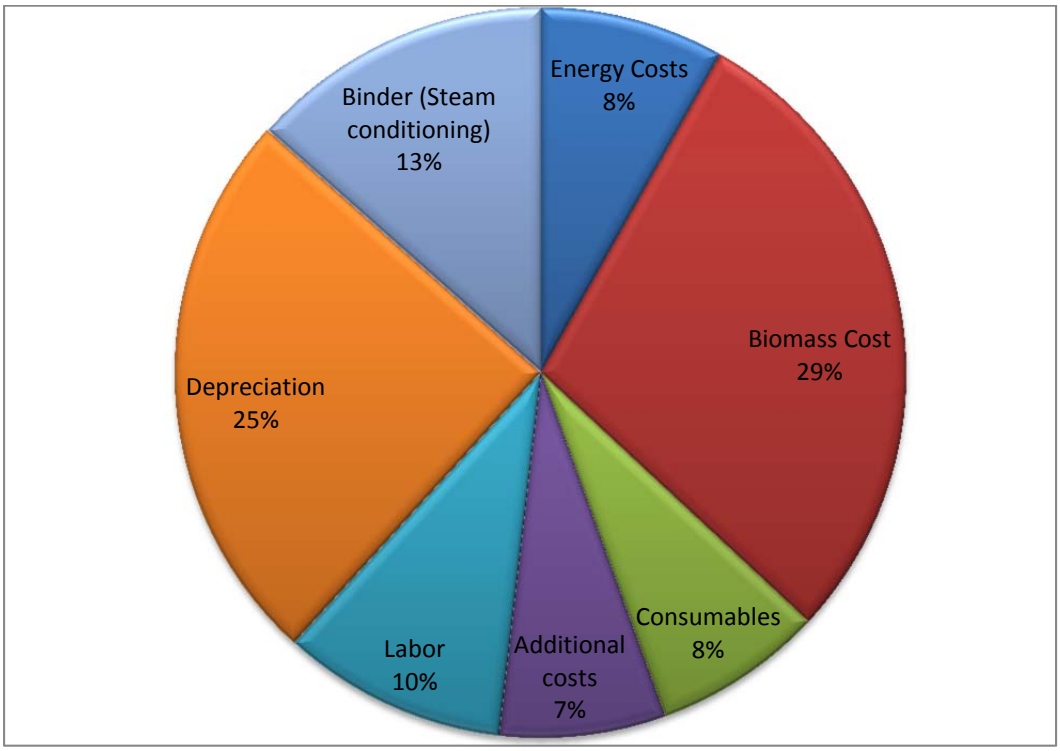


Figure 9.5. Production costs distribution according to results from the model ($199/metric ton production costs).

Biomass delivered cost (established at $45/metric ton) represents the largest production cost, accounting for 29%. Depreciation is also an important factor (25%), being close to biomass delivered cost, and greatly influenced by the torrefaction unit. However, it is substantial the percentage that binders (in this case steam) represent in the overall production costs (13%), being more significant than labor costs (10%) and energy costs (8%), and implying that selection and procurement of the adequate binder have an important effect in the overall production costs.

9.4.3 Production Costs and Potential Revenue

Production costs for a 100,000 metric tons/year facility sum $199/metric ton, being a slightly higher value than that reported by Topell Energy (2011). Mitchell et al. (2007) found very similar production costs for torrefied wood pellets, assuming a 80,000 metric tons/year

factory, with 199 $/metric ton[4], being sawmill co-products the biomass processed. Cerezo (2011) reported values of $135/metric ton for torrefied wood only, which, considering the addition of pelletization processes, binders, etc., may represent a close value to the one reported here. This production cost is comparable to that reported by Pirraglia et al. (2010b) on regular wood pellets ($203.7/metric ton), indicating that torrefied wood pellets may be a competitor as profitable as regular wood pellets for co-firing applications. Current delivered price of coal for 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, 2012b); at this cost of coal, torrefied wood pellets is still not competitive on a pure cost basis. However, regulations and mandates may influence the decision to utilize it in power plants beyond a cost analysis only.

The calculated production costs can be modified with add-in functions programmed in the income statement of the model, in order to adjust this cost to specific Internal Rates of Return (IRR), at a discount rate of 12% (also user modifiable variable), being able to obtain minimum revenue prices and Net Present Value (NPV) depending on a targeted IRR. Figure 9.6 presents the adjustment of this price to different IRR's, and its effect in the NPV of the factory.

[4] Converted from 2007 €/$ average rate, and transformed to 2011 dollar values with CWCCIS Index

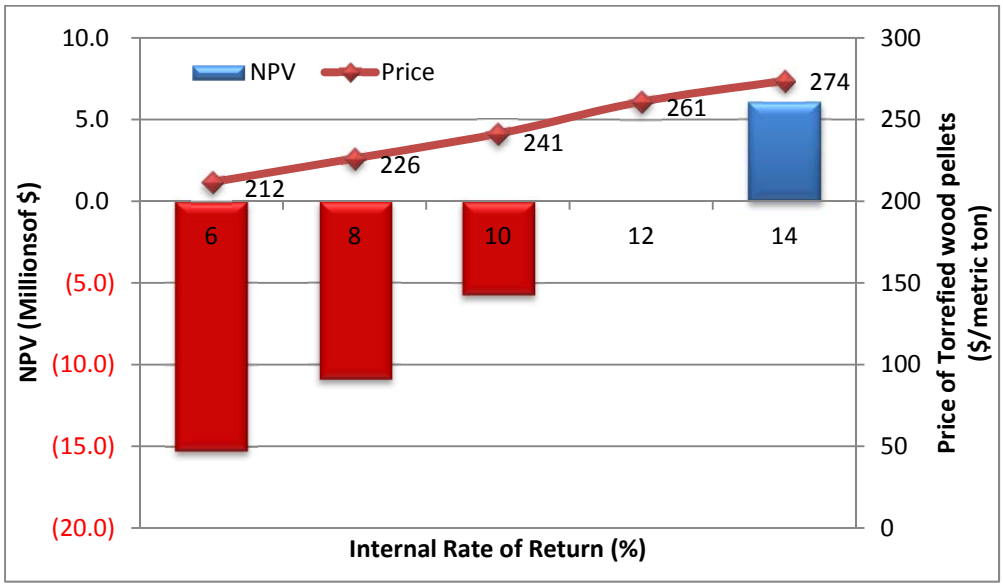


Figure 9.6. Torrefied pellets price and NPV changes at different IRR.

Current prices of regular "white" wood pellets vary depending on the producer, wood species, and region. In the current model, in order to obtain a break-even NPV (12% IRR, 12% discount rate), prices have to be greater than $261/metric ton. Compared to an average selling price of regular pellets of $280/metric ton (Pellets Direct, 2012), potential additional revenue of $19/metric ton can be achieved for producers considering this particular case. With additional transportation costs added following guidelines of Rhode (1999) and Brechbill and Tyner (2008), for maximum hauling distances of 50 miles (truck delivery), final delivered costs may reach $282/metric ton ($21/metric ton for transportation, being $15/metric ton fixed cost and $0.12/metric ton/mile, plus $261/metric ton selling price), being this a slightly higher price than the average wood pellets price per metric ton. However, since torrefied wood pellets are still not a commercial fuel, it is yet to be estimated how much of a premium cost is the potential market willing to pay for such an upgraded product, and should be the subject of further investigations in this field.

9.4.4 Sensitivity Analysis.

The previously presented case study allows for further investigation in the profitability of a potential torrefied wood pellets plant, by observing how changes in the

current values of the main variables for the model affect the NPV and minimum revenue of the facility. The changes tested and introduced in the values of CAPEX, Biomass, and other variables are ±25% of the current value evaluated in the model. Figure 9.7 shows how changes in CAPEX and biomass delivered cost, affect minimum revenue at a 12% IRR.

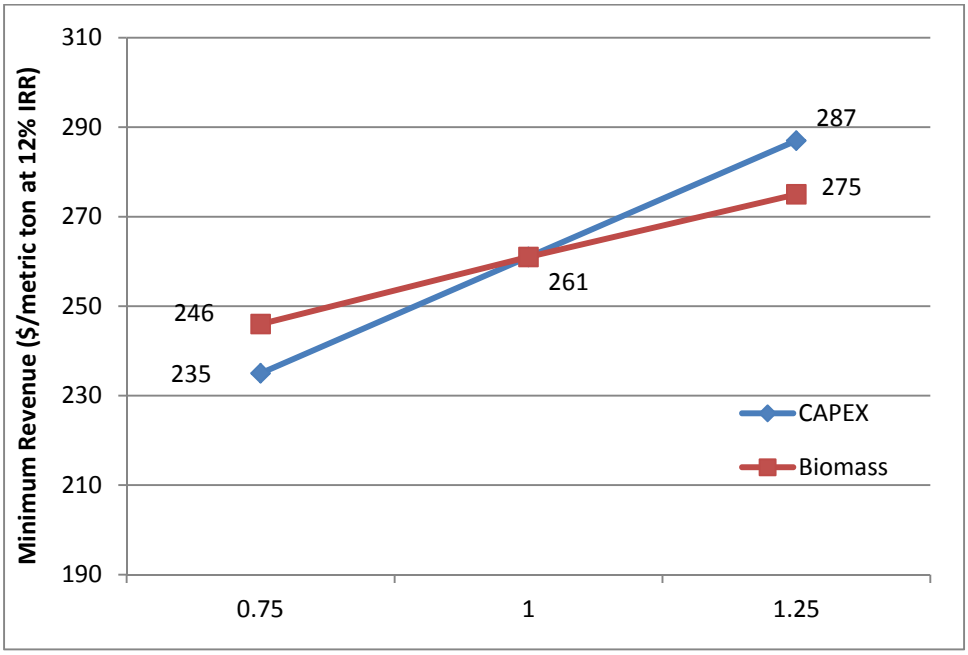


Figure 9.7. Sensitivity of minimum revenue to changes in CAPEX and Biomass delivered cost.

The case of a torrefied wood pellets facility seems to be more affected by changes in CAPEX, than those produced by biomass delivered costs. As seen in Figure 9.66, a change in ±25% in CAPEX has a deepened effect in the increase or decrease of the minimum revenue compared to that of biomass delivered cost. This case is opposite to that of regular wood pellets (as presented by Pirraglia et al. 2010a), in which biomass delivered cost is the most sensitive and influential variable in the profitability of a factory.

Changes in NPV and IRR when variables are modified can be seen in the next paragraphs. In the case of CAPEX, the NPV is affected reaching -$8,069,694 and 10% IRR if costs increase; while it will be positively influenced if capital costs are decreased

(NPV=$11,861,433; IRR=17%), which can be the case of further factories opening after the first successful ones are established, if the estimates of Bridgwater (2009) on 20% CAPEX reduction on each doubling in the number of facilities are assumed as correct. Figure 9.8 presents the information on IRR and NPV with changes in CAPEX.

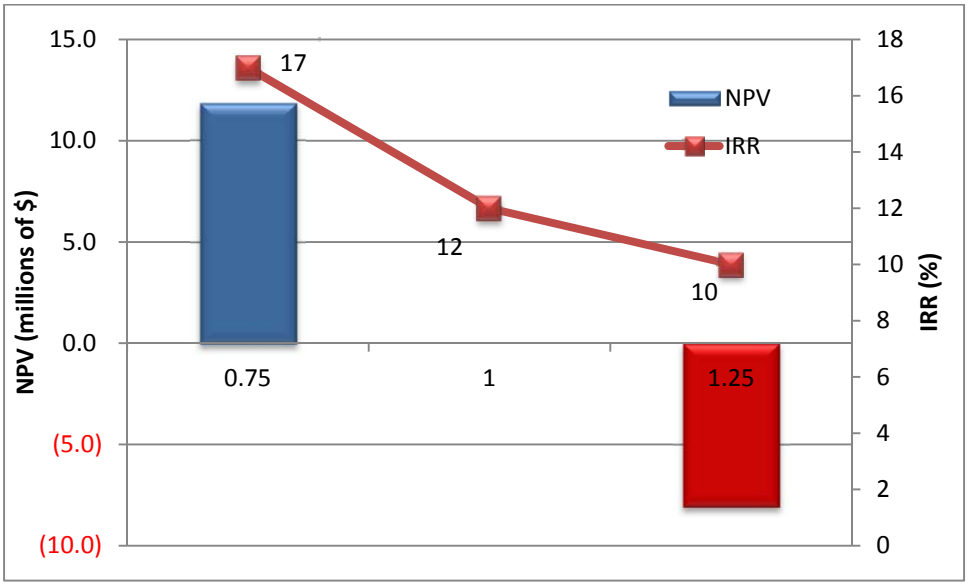


Figure 9.8. Sensitivity of the model to changes in CAPEX.

Changes in biomass delivered cost represent the second most sensitive factor of the facility, affecting the IRR (11%) and NPV to -$3,113,905, while a decrease in the biomass delivered cost generates an increase in IRR to 14% and $6,849,679 of NPV. Figure 9.9 demonstrates this effect.

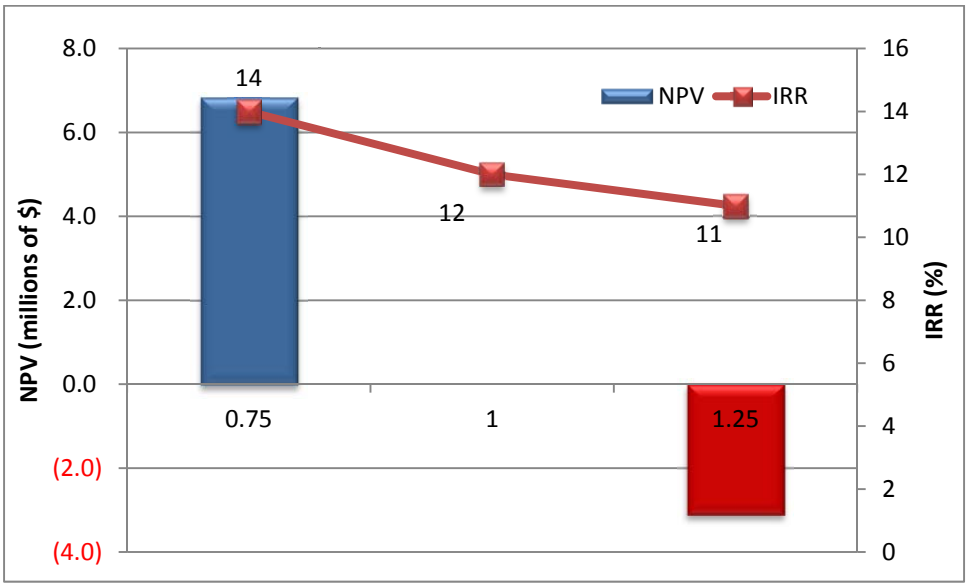


Figure 9.9. Sensitivity of the model to changes in biomass delivered cost.

Additional variables considered for this sensitivity analysis do not seem to have a substantial effect when compared to that of CAPEX and biomass delivered cost. However, the selection of an adequate binder, and a different technology in torrefaction, present some interesting results, due that these facts influence the CAPEX of the factory, by requiring either a conditioner and boiler unit (case of steam conditioning), or a set of biomass mixers (case of DDG, feed corn, and soybeans as binders), and due to the high capital cost of the current torrefaction technology selected (screw reactor). These analyses are presented next.

The selection of a different technology for the torrefaction process in the factory may have a considerable effect in the NPV and IRR, since this unit represents the majority of the capital costs of the facility. Figure 9.10 shows the changes produced in NPV and IRR when selecting a different torrefaction technology.

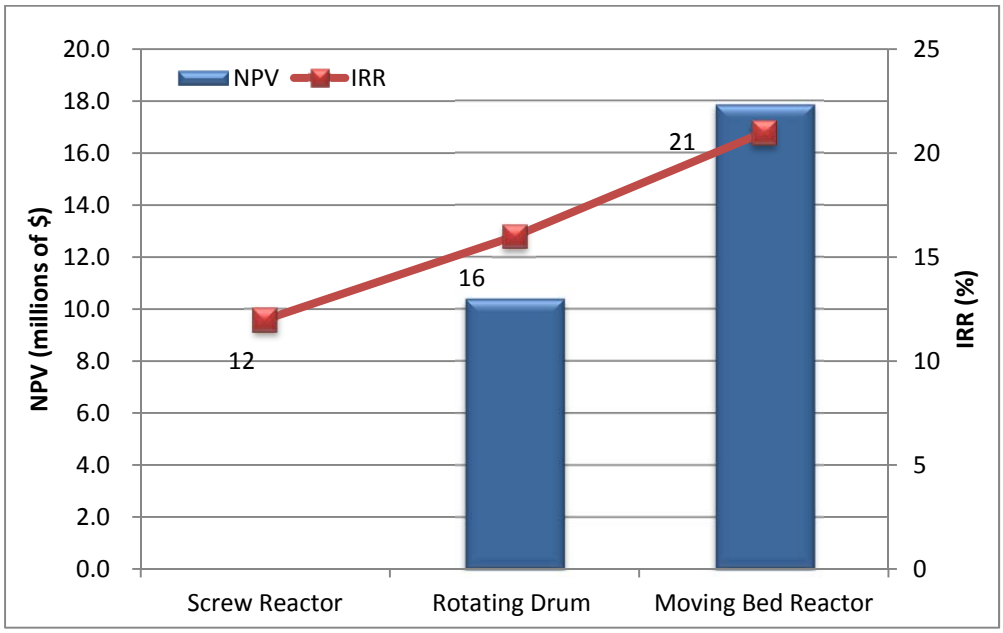


Figure 9.10. Sensitivity of the model to changes in the torrefaction technology used.

Analyses from Figure 9.10 indicate that if a technology such as rotating drum or moving bed reactor is implemented instead of the more traditional screw reactor, it might have a positive impact in the profitability of the business, subject to the condition that these alternative technologies become available and reliable at an affordable cost for the facilities. In addition, it is recommended to further explore other torrefaction technologies and its potential associated engineering, maintenance, and repairs costs, as well as secure information on when the potential technologies could become available in commercial scale, in order to obtain accurate estimates and compare more technological choices for the near future. Furthermore, a risk assessment of the technologies, suppliers, and potential for upgradability might complement this type of analysis and aid in decision making processes. Another important analysis for this type of facility is given by the binders utilized. In the case study, steam conditioning was assumed as the base case. However, changes in torrefaction parameters (medium and/or dark torrefaction) require the utilization of a different binder, thus producing changes in the amount of biomass required, amount of binder required, type of machines (mixers) utilized and capital costs associated. In Figure 9.11, the effect of binders in the overall profitability is presented.

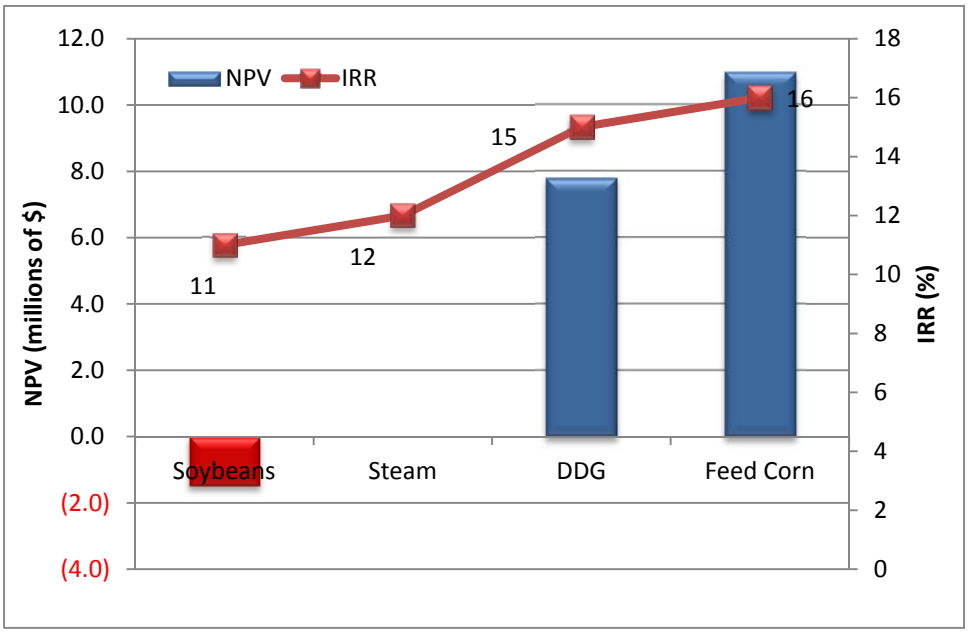


Figure 9.11. Sensitivity of the model to changes in type and proportion of binder utilized.

The selection of a different binder has varied effects in the profitability, when compared to the base case of steam conditioning. The selection of soybeans reduces the profitability of the business, due to its procurement cost and the proportion in which it must be used in the facility, this binder, with the current technology, is not recommended. The utilization of DDG and feed corn improves the IRR and NPV of the facility, being feed corn the best selection of binder for a torrefied wood pellets facility. Further analyses are needed in order to observe if the addition or change of a binder have a negative effect in the HHV of the torrefied pellets, although previous work demonstrated that the addition of binders from seeds and grains do not have a significant reduction effect in the HHV of torrefied pellets (Pirraglia et al. 2012a). It is important to highlight that depending on the technology utilized in the facility (torrefaction and pelletization in particular), it may become necessary to add steam conditioning even when utilizing soybeans or other binders, in order to enhance binding properties. Previous work performed by the authors have demonstrated that this step is not strictly required in order to form durable pellets (Pirraglia et al. 2012a), however, the increase in durability, better flow of material through dies, and other properties when adding

binder and steam conditioning requires further research in order to determine how necessary this step can be in large scale production.

An additional important variable introduced in the model is the utilization of carbon credits as an income source. In the base case scenario presented previously, all calculations were assumed with no carbon credits added. However, the addition of such income may significantly increase the likeability of a torrefied wood pellets facility. Childs (2012) estimated that torrefaction companies in the U.S. could benefit from carbon credits in a range between $36/metric ton to $72/metric ton of torrefied wood produced. Following these estimates, carbon credits income are considered in the model at a rate of $36/metric ton, and intermediate value of $52/metric ton, and a high value of $72/metric ton. Figure 9.12 presents the changes produced in IRR and NPV of the facility when such scenarios are evaluated.

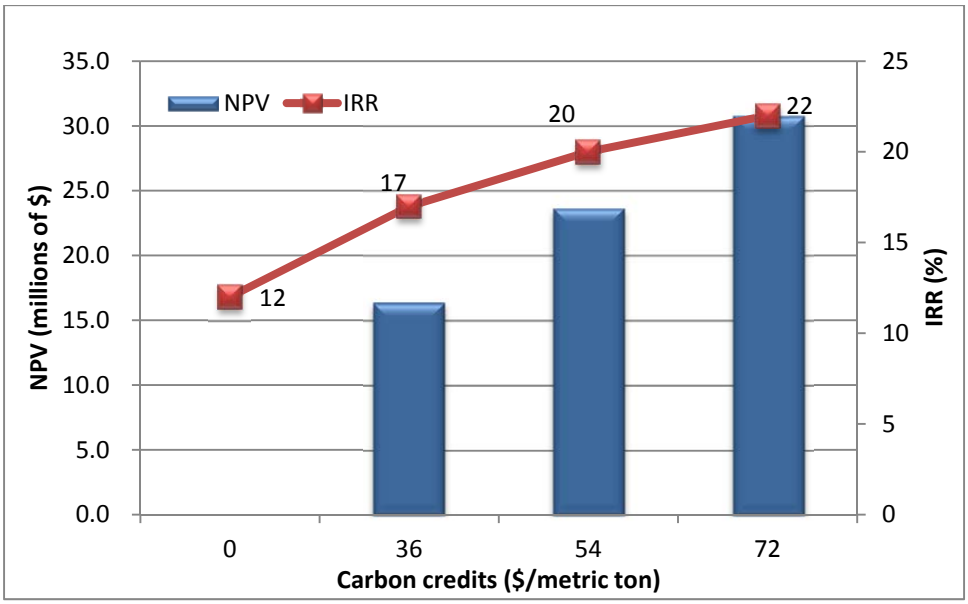


Figure 9.12. Sensitivity of the project to different carbon credits scenarios.

Figure 9.12 indicates how the implementation of a carbon credits market may make the torrefied pellets business much more attractive. Considering the base case of $0/metric ton carbon credits, the increase in income from carbon credits may report an IRR of 17%,

20% and 22% respectively, while NPV can increase from $0 in the base case, to more than $15 million on the lowest carbon credits estimate. Since the carbon credits market is still in its infancy in the U.S., caution is recommended when purely relying on these estimates. In the near future, however, it is possible that many companies would look to incorporate incomes from carbon credits, especially if the torrefied and pelletized material is intended for European markets, which has a more established regulation regarding carbon credits and bonuses for HHV delivered and carbon emissions reduction. These preliminary analyses indicate that carbon credits may be a key variable for this business in the short term, when analyzing its profitability.

As a final observation, further studies need to be developed in several areas to enhance and continue the work described in this research. Binder utilization and its effect on critical properties of torrefied and pelletized material, as well as types and quantities added needs to be developed. Another area that requires further attention is torrefaction technology. There are many different technologies being developed or near commercial stage, and the evaluation of these technologies in the model, as well as having updated cost estimates for these technologies, will greatly enhance the accuracy of the estimates, and provide with more information for an accurate evaluation of profitability.

9.5 Conclusions

A dynamic, spreadsheet-based model was created[5] which allows evaluating technical and economic variables of a torrefied wood pellets facility in the U.S. Results from the model and its sensitivity analysis indicate the following:

- The delivered costs of the biomass is the largest factor in the production costs of torrefied wood pellets, followed closely by the depreciation of the equipment, while energy consumption represents a small fraction on the production costs. The addition of a binder to this process also represents an important factor influencing production costs.

[5] For inquiries about the spreadsheet model, and further work, please contact the corresponding author to the provided e-mail and mailing address.

- When analyzing the sensitivity of the main variables that influence production costs, CAPEX represents the most sensitive variable, highly influencing the profitability of the facility (NPV and IRR); contrary to other options of biomass pre-treatment, such as wood pellets, in which biomass delivered cost represent the most sensitive variable. This is mainly due to the influence of the torrefaction unit in capital costs.
- The selection of a different torrefaction technology may have a significant influence in the CAPEX of the facility, thus further enhancing the profitability of the factory, subject to the capacity of the alternative technology to reduce overall capital costs, engineering, installation, and maintenance of the process, and subject to analysis of upgradability and risk.
- The selection of an adequate binder has a significant effect in the facility. The adequate selection of binder depending on torrefaction levels will allow improving and maintaining quality and consistency of the product. Additionally, selection of alternative types of binders may have an influence in the profitability of the business, since it modifies the equipment needs, capital costs, and proportion of binder to biomass utilized. In this sense, and with the current evaluated conditions, DDG's and feed corn are recommended over soybeans, in order to increase profitability.
- The back-calculated minimum revenue for a 100,000 metric tons/year facility for torrefied wood pellets is $261/metric ton, being this competitive revenue when compared to alternative pre-treatments such as regular "white" pellets, currently having an average cost of $280/metric ton. With the addition of transportation costs, delivered price of torrefied wood pellets may reach $282/metric ton on power plants, being a very similar cost compared to current biomass delivered options.
- A preliminary analysis of carbon credits as additional income in several different scenarios may considerably increase the likeability of the business, and further enhance profitability. However, more accurate scenarios must be described, in order to obtain up-to-date values of potential carbon credit income per metric ton of product depending on delivered heating value of the torrefied pellets. This will allow for more accurate estimates of the increase in profitability of the facility with carbon credits in the United States.

9.6 Literature Cited

P. Adapa. L. Tabil, G. Schoneau, A. Opoku, Pelleting Characteristics of Selected Biomass with and Without Steam Explosion Pretreatment, Int J Agric & Biol Eng. 3(3) (2010) 62-77.

AgMRC, Estimated U.S. Dried Distillers Grains with Solubles (DDGS) Production & Use, Agricultural Marketing and Resource Center. (2012) Available at: http://www.extension.iastate.edu/ agdm/crops/outlook/dgsbalancesheet.pdf. Consulted on: 02/12/2012.

Alternate Energy Systems, Inc., LPG Definitions and Technical Data. (2011) Available at: http://www.altenergy.com/technology/lpgproperties.htm. Consulted on: 02/14/2012.

E. Andersson, S. Harvey, T. Berntsson, Energy Efficient Upgrading of Biofuel Integrated with a Pulp Mill, Energy. 31 (2006) 1384-1394.

M. N. Anglès, F. Ferrando, X. Farriol, J. Salvadó, Suitability of Steam Exploded Residual Softwood for the Production of Binderless Panels. Effect of the Pre-treatment Severity and Lignin Addition, Biomass & Bioenergy. 21 (2001) 211–224.

M.A. Baez, Highly Efficient Hydrolytic Enzymes for the Development of Value-Added Products from DDGS, International Distillers Grains. Conference and Trade Show. September 12-14, 2006. Minneapolis, MN.

P.C.A. Bergman, Combined Torrefaction and Pelletisation: the TOP Process, Report ECN-C-05-073. Petten, The Netherlands: ECN. (2005).

P.C.A. Bergman, J.H.A. Kiel, Torrefaction for Biomass Upgrading. 14th European Biomass Conference & Exhibition. Paris, France, 17-21 October 2005. Available at: http://www.energy.ca.gov/2009_energypolicy/documents/2009-04-

21_workshop/comments/ Torrefaction_for_Biomass_Upgrading_TN-51257.PDF. Consulted on: 01/06/2012.

P.C.A. Bergman, A.R. Boersma, J.H.A. Kiel, M.J. Prins, K.J. Ptasinski, F.J.J.G. Janssen, Torrefaction for Entrained Flow Gasification of Biomass. Report ECN-RX-04-046. Petten, The Netherlands: ECN. (2004).

P.C.A. Bergman, A.R. Boersma, R.W.R. Zwart, J.H.A. Kiel, Torrefaction for Biomass Co-Firing in Existing Coal-Fired Power Stations “Biocoal”, Report ECN-C-05-013. Petten, The Netherlands: ECN. (2005).

P. Björklund, Metso Torrefaction Concept, EUBIONET 3 Seminar. (2011).

T. Boyd, D. de Vries, H. Kempthorne, J. Wearing, I. Wolff, Mass & Energy Balance for Torrefied Pellet Production, UBC Biomass Pelletization Workshop. (2011). Available at: http://www.biomass.ubc.ca/docs/NORAM%20UBC%20Biomass%20Presentation%20May%202011%20[Compatibility%20Mode].pdf. Consulted on: 02/14/2012.

S. Brechbill, W. Tyner, The Economics of Biomass Collection, Transportation, and Supply to Indiana Cellulosic and Electric Utility Facilities, Working paper #08-03, Department of Agricultural Economics, Purdue University. (2008). Available at: http://ageconsearch.umn.edu/bitstream/6148/2/wp080003.pdf. Consulted on: 04/05/2012.

A.V. Bridgwater, Technical and Economic Assessment of Thermal Processes for Biofuels, Life Cycle and Techno-Economic Assessment of the Northeast Biomass to Liquids Project, NNFCC project 08/018. (2009).

J.L. Briggs, D.E. Maier, B.A. Watkins, K.C. Behnke, Effects of Ingredients and Processing Parameters on Pellet Quality, Poultry Science. 78 (1999) 1464–1471.

Bureau of Labor Statistics, May 2011 Occupational Employment and Wages Estimates. (2011). Available at: http://www.bls.gov/oes/oes_dl.htm. Consulted on: 01/06/2012.

K. Campbell, A Feasibility Study Guide for an Agricultural Biomass Pellet Company, Campbell Consulting LLC, An affiliated consultant of Cooperative Development Services, St. Paul, Minnesota, Agricultural Utilization Research institute. (2007).

L.M. Cerezo, Biomass Torrefaction Workshop, EPRI's Biomass R&D. Pre-Treatment Technologies Update. Electric Power Research Institute. (2011).

W. Childs, Torrefied Biomass: An Ideal Co-firing Solution, Integro Earthfuels. (2012).

Clever Brooks, Boiler Steam Cost Calculator. (2011) Available at: http://www.cbboilers.com/scc/BoilerSteamCostCalculator.html. Consulted on: 02/14/2012.

G. Digiacomo, L. Taglieri, Renewable Energy Benefits with Conversion of Wood Residues to Pellets, Energy. 34 (2009) 724-731.

[24] R. Gonzalez, D. Saloni, R. Phillips, J. Wright, Loblolly Pine Biomass Delivered Cost, Biomass Conference. Minneapolis, MN. (2010).

R. Gonzalez, R. Phillips, D. Saloni, H. Jameel, R. Abt, A. Pirraglia, J. Wright, Biomass to Energy in the Southern United States: Supply Chain and Delivered Cost, BioResources. 6(3) (2011a) 2954-2976.

R. Gonzalez, T. Treasure, J. Wright, D. Saloni, R. Phillips, R. Abt, H. Jameel, Exploring the Potential of Eucalyptus for Energy Production in the Southern United States: Financial Analysis of Delivered Biomass, Part I, Biomass & Bioenergy. 35(2) (2011b) 755-766.

R. Gonzalez, T. Treasure, R. Phillips, H. Jameel, D. Saloni, Economics of Cellulosic Ethanol Production: Green Liquor Pretreatment for Softwood and Hardwood, Greenfield and Repurpose Scenarios, BioResources. 6(3) (2011c) 2551-2567.

R. Gonzalez, T. Treasure, R. Phillips, H. Jameel, D. Saloni, R. Abt, J. Wright, Converting Eucalyptus Biomass into Ethanol: Financial and Sensitivity Analysis in a Co-current Dilute Acid Process, Part II, Biomass and Bioenergy. 35(2) (2011d) 767-772.

E.M. Hakkou, H.P. Patterson, M.C. Williams, E.S. Gladney, Investigations of the Reasons for Fungal Durability of Heat-Treated Beech Wood, Polymer Degradation and Stability. 91 (2006) 393-397.

B. Hill, D.A. Pulkinen, Study of Factors affecting Pellet Durability and Pelleting
Efficiency in the Production of Dehydrated Alfalfa Pellets, Saskatchewan Dehydrators Association. 1988.

Index Mundi, Soybeans Daily Price. (2012) Available at:http://www.indexmundi.com/commodities/?commodity=soybeans&months=12. Consulted on 02/12/2012.

J. James, Using Torrefied Wood for Electricity, Briquette and Pellet Production. Agri-Tech Producers, LLC. (2009).

M. Junginger, T. Bolkesjø, D. Bradley, P. Dolzan, A. Faaij, J. Heinimo, Developments in International Bioenergy Trade, Biomass & Bioenergy. 32 (2008) 717-729.

N. Kaliyan, R.V. Morey, Densification Characteristics of Corn Stover and Switchgrass, Trans. ASABE, 52 (3) (2009) 907–920.

N. Kaliyan, R.V. Morey, Natural Binders and Solid Bridge Type Binding Mechanisms in Briquettes and Pellets Made from Corn Stover and Switchgrass, Bioresource Technology. 101 (2010) 1082–1090.

M. Kallio, Critical Review on the Pelletizing Technology, Intelligent Energy Europe. (2011). Available at: http://www.mixbiopells.eu/fileadmin/user_upload/WP3/D3.1_Overwiev_Production_Final.pdf. Consulted on: 02/12/2012.

M. Kallio, E. Kallio, E. Pirttinen, Pelletointikokeita Mäntyöljyä Sisältävällä Puuraakaaineella, VTT. Research report PRO2/2019/05. (2005).

E.S. Lipinsky, J.R. Arcate, T. B. Reed, Enhanced Wood Fuels Via Torrefaction. Fuel Chemistry Division Preprints. 47(1) (2002) 408-410.

S. Mani, Recent Developments in Biomass Densification Technology, Biological and Agricultural Engineering Department University of Georgia. (2008). Available at: http://openwetware .org/ images/e/e0/2008-03-08_IBE_Presentation_Mani.pdf. Consulted on: 02/14/2012.

F. Mburu, S. Dumarcay, M. Petrissans, P. Gerardin, Evaluation of Thermally Modified Grevillea Robusta Heartwood as an Alternative to Shortage of Wood Resource in Kenya: Characterization of physicochemical Properties and Improvement of Bio-Resistance, Bioresource Technology. 98(18) (2007) 3478-3486.

P. Mitchell, J. Kiel, B. Livingston, G. Dupont-Roc, Torrefied Biomass. A Foresighting Study into the Business Case for Pellets from Torrefied Biomass as a New Solid Fuel. A Presentation to All Energy ’07 May 24th. (2007).

New Biomass Energy, Torrefied Wood vs. Wood pellets vs. Coal. (2011) Available at: http://new biomass.com/torrefied-wood/torrefied-wood-vs-wood-pellets-vs-coal. Consulted on: 02/04/2012.

M. Nielsen-Pincus, M. Krumenauer, K. MacFarland, C. Moseley, Impacts of the Biomass Producer or Collector Tax Credit on Oregon's Wood Fuels Market and Economy, Ecosystem Workforce Program. Working Paper Number 32. (2011) Available at: http://ewp.uoregon.edu/sites/ewp.uoregon.edu/files/WP_32.pdf. Consulted on 01/07/2012.

L. Nikolaisen, T. Nørgaard-Jensen, K. Hjuler, J. Busk, H. Junker, B. Sander, L. Baxter, L. Bloch, Quality Characteristics of Biofuel Pellets, Danish Technological Institute. (2002).

F.A. Nyanzi, J. A. Maga, Effect of Processing Temperature on Detergent Solubilized Protein in Extrusion-cooked Cornstarch/soy Protein Subunit Blends, Journal of Agricultural and Food Chemistry. 40 (1992) 131–133.

I. Obernberger, G. Thek, Physical Characterization and Chemical Composition of Densified Biomass Fuels with Regard to their Combustion Behaviour, Biomass & Bioenergy. 27 (2004) 653–669.

Pellets Direct, Pellets Price Update 2012. (2012) Available at: http://pelletsdirect.com/09-10%20Early%20Buy%20Pricing.htm. Consulted on: 02/15/2012.

Pellet Pros, Testing Log. (2011). Available at: http://www.pelletpros.com/id81.html. Consulted on: 02/12/2012.

H. R. Perry, J. O. Maloney, D. W. Green. Perry's Chemical Engineers' Handbook. NY, McGraw-Hill. 1997.

M. Phanphanich, S. Mani, Impact of Torrefaction on the Grindability and Fuel Characteristics of Forest Biomass, Bioresource Technology. 102(2) (2011) 1246–1253.

F. Pierre, G. Almeida, J. O. Brito, P. Perre, Influence of Torrefaction on Some Chemical and Energy Properties of Maritime Pine and Peduculate Oak, Bioresources. 6(2) (2011) 1204-1218.

A. Pirraglia, R. Gonzalez, D. Saloni, Wood Pellets: an Expanding Market Opportunity, Biomass Magazine. June (2010a).

A. Pirraglia, R. Gonzalez, D. Saloni, Techno-Economical Analysis of Wood Pellets Production for U.S. Manufacturers, Bioresources. 5(4) (2010b) 2374-2390.

A. Pirraglia, R. Gonzalez, D. Saloni, J. Wright, J. Denig, Fuel properties and Suitability of Eucalyptus Benthamii and Eucalyptus Macarthurii for Torrefied Wood and Pellets, Bioresources. 7(1) (2012a) 217-235.

A. Pirraglia, R. Gonzalez, J. Denig, D. Saloni, Technical and Economic Modeling for the Production of Torrefied Ligno-cellulosic Biomass for the U.S. Densified Fuel Industry, Bioenergy Research. (2012b) (Accepted for publication with minor changes).

Pomer L, Gerber L, Olofsson I, Wiklund Lindstrom S, and Nordin A. (2010). Gas Composition from Biomass Torrefaction-Preliminary Results. 18th European Biomass Conference and Exhibition. http://www.tfe.umu.se/digitalAssets/61/61393_vp2_8_1-gas-composition-from-biomass-torrefaction_preliminary-results-submitted.pdf. Accessed 10 July 2012.

M.J. Prins, K.J. Ptasinski, F.J.J.G. Janssen, Torrefaction of wood Part 1. Weight loss kinetics, J. Anal. Appl. Pyrolysis. 77 (2006a) 28–34.

M.J. Prins, K.J. Ptasinski, F.J.J.G. Janssen, Torrefaction of wood Part 2. Analysis of Products, J. Anal. Appl. Pyrolysis. 77 (2006b) 35–40.

M. Rhode, Biomass Power for Rural Development, Department of Energy. (1999) Available at: www.nrel.gov/docs/fy00osti/28024.pdf. Consulted on:02/16/2012.

H. Rumpf, The strength of granules and agglomeration, in: W.A. Knepper (Ed.), Agglomeration, John Wiley, New York, 1962, pp. 379–418.

C. Ryu, Y.B. Yang, A. Khor, N.E. Yates, V.N. Sharifi, J. Swithenbank, Effect of fuel properties on biomass combustion: Part I. Experiments-fuel type, equivalence ratio and particle size, Fuel. 85 (2006) 1039-1046.

T.J. Shankar, S. Bandyopadhyay, Process Variables During Single Screw Extrusion of Fish and Rice Flour Blends, Journal of Food Processing and Preservation. 29 (2005) 151–164.

T.J. Shankar, S. Sokhansanj, S. Bandyopadhyay, A.S. Bawa, A Case Study on Optimization of Biomass Flow During Single Screw Extrusion Cooking Using Genetic Algorithm and Response Surface Method, Food and Bioprocess Technology. 3(4) (2010) 498-510.

Soy Stats, World Soy Statistics. (2011). Available at: http://www.soystats.com/2011/page_30.htm. Consulted on: 02/14/2012.

H. Spelter, D. Toth, North America's Wood Pellet Sector, United States Department of Agriculture. Forest Service. Forest Products Laboratory. Research Paper FPL-RP-656. (2009).

M.C.J. van der Stelt, H. Gerhauser, J.H.A. Kiel, K.J. Ptanski, Biomass Upgrading by Torrefaction for the Production of Biofuels: A Review, Biomass & Bioenergy. 35 (2011) 3748-3762.

L.G. Tabil, S. Sokhansanj, R.T. Tyler, Performance of Different Binders During Alfalfa Pelleting, Can. Agric. Eng. 39(1) (1997) 17-23.

G. Thek, I. Obernberger, Wood Pellet Production Costs under Austrian and in Comparison to Swedish Framework Conditions, Biomass & Bioenergy. 27 (2004) 671-693.

M. Thomas, T. van Vliet, A. F. B. van der Poel, Physical Quality of Pelleted Animal Feed 3. Contribution of Feedstuff Components, Animal Feed Science Technology. 70 (1998) 59–78.

M.J.A. Tijmensen, A.P.C. Faaij, C.N. Hamelinck, M.R.M. van Hardeveld, Exploration of the Possibilities for Production of Fischer Tropsch Liquids and Power via Biomass gasification, Biomass & Bioenergy. 23 (2002) 129–152.

Topell Energy, Topell on Torrefaction, World Economic Forum. Technology Pioneers. (2011) Available at: http://www.bioenergytrade.org/downloads/topell.pdf. Consulted on: 02/05/2012.

K. Trattner, The ACB Process-A Brief Introduction. (2011) Available at: http://www.bioenergytrade.org/downloads/graztrattner2011.pdf. Consulted on: 02/12/2-12.

J.S. Tumuluru, C.T. Wright, K.L. Kenney, J.R. Hess, A Technical Review on Biomass Processing: Densification, Preprocessing, Modeling, and Optimization, ASABE Annual International Meeting. Idaho National Laboratory. (2010). Available at:

http://www.inl.gov/technicalpublications/documents/4559449.pdf. Consulted on: 02/14/2012.

USDA, National Weekly Feedstuff Wholesale Prices, United States Department of Agriculture. (2012a) Available at: http://www.ams.usda.gov/mnreports/ms_gr852.txt. Consulted on: 02/12/2012.

USDA, New Feed Grain Data: Yearbook Tables Byproduct Feeds: Average Wholesale price, Bulk, Specified Markets. (2012b) Available at: http://www.ers.usda.gov/Data/FeedGrains/Table.asp?t=16. Consulted on: 02/12/2012.

U.S. Energy Information Administration (EIA), Electric Power Monthly. (2012a) Available at: http://www.eia.gov/electricity/monthly/index.cfm. Consulted on: 02/12/2012.

U.S. Energy Information Administration (EIA), Heating Oil and Propane Update. (2012b) Available at: http://www.eia.gov/petroleum/heatingoilpropane/. Consulted on: 02/12/2012.

A. Uslu, A.P. Faiij, P.C.A. Bergman, Pre-treatment Technologies, and their Effect on International Bioenergy Supply Chain Logistics. Techno-economic Evaluation of Torrefaction, Fast Pyrolysis and Pelletisation, Energy. 33 (2008) 1206-1223.

A. Viak, Wood pellets in Europe – State of the Art, Technologies, Activities, Markets.

AEBIOM, FastBränslePannor, Lambelet Heizungssysteme, Technische Universität München, Umdasch AG, Whitfield Gmbh, UMBERA. Part of the Thermie B project. (2000).

M. Wihersaari, D. Agar, M. Kallio, Scenario Analysis of Fuel-Pellet Production–the Influence of Torrefaction on Material Flows and Energy Balances. Shape your Sustainability Tools- and let your tools shape you, Uppsala, Sweden, September 23-24.

(2009). Available at: http://87.192.2.62/Eforwood/Portals/0/documents/Margareta %20Wihersaari.pdf. Consulted on: 02/05/2012.

C. Wilen, P. Ståhlberg, K. Sipilä, J. Ahokas, Pelletization and Combustion of Straw, Energy from Biomass and Wastes, IGT. April 7-10, 1986.

WiSHH, Composition of Soy, World Initiative for Soy in Human Health. (2011) Available at: http://www.wishh.org/aboutsoy/composition.html. Consulted on: 02/14/2012.

J.F. Wood, The Functional Properties of Feed Raw Materials and the Effect on the Production and Quality of Feed Pellets, Animal Feed Science and Technology. 18 (1987) 1–17.

Wood Markets, Wood Pellet Markets/Trends: Growth of the Global Wood Pellet Industry, (2010) Available at: http://www.unece.lsu.edu/marketing/documents/2010/gme10_03.pdf. Consulted on: 02/12/2012.

R. Woodworth, J. Kelly, M. Namazian, G. Miller, Biobinder Process for Reconstitution of Fine Coal, Altex Technology Corporation. (1997) Available at: http://domex.nps.edu/corp/files/govdocs1/064/064997.pdf. Consulted on: 02/10/2012.

W. Yan, J.T. Hastings, T.C. Acharjee, C.J. Coronella, V. Vasquez, Mass and Energy Balances of Wet Torrefaction of Lignocellulosic Biomass, Energy Fuels. 24 (2010) 4738-4742.

R. Zwart, H. Boerrigter, A. van der Drift, The Impact of Biomass Pre-treatment on the Feasibility of Overseas Biomass Conversion to Fischer-Tropsch Products, Energy Fuels. 20 (2006) 2192-2197.

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

10.1 Abstract

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.

10.2 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, thirty 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.

10.3 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 Figure. 10.1.

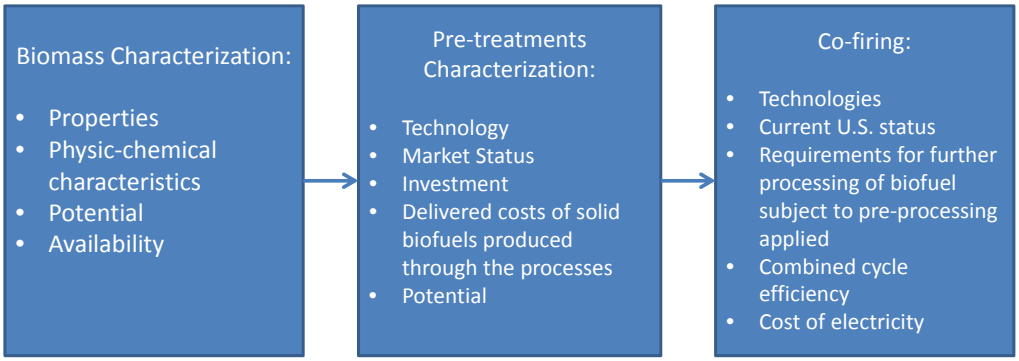


Figure. 10.1. Methodology for assessing biomass and pre-treatments options for co-firing in U.S. power plants

10.3.1 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).

Over the next twenty 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).

10.3.2 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 hard-wood 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. towards 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).

10.3.3 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 in 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 *et al.* 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.

10.3.4 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 the 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 Figure. 10.2 (Modified from U.S. Department of Energy, USDOE 2011).

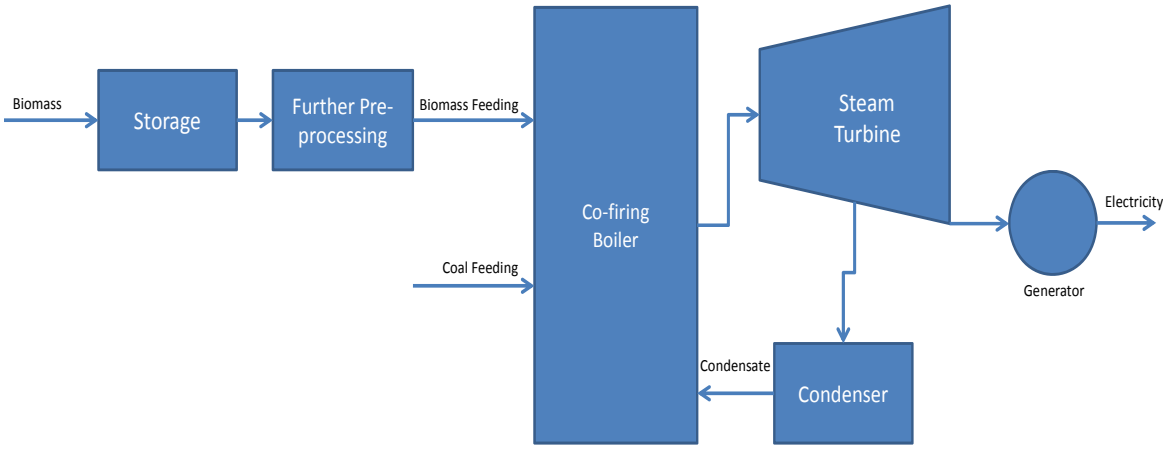


Figure. 10.2. Schematic of the analyzed co-firing process

In this process configuration for direct co-firing, all the different combinations of biomass and pre-treatments 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.

10.4 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 ($/MJ Delivered). Table 10.1 summarizes the properties (MC, HHV, LHV, UHV, and Energy Density) and delivered costs ($/ton and $/MJ delivered) of the biomass depending on the type of biomass and pre-treatment applied.

Table 10.1. 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 Deliv-ered
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 10.1. Continued *All acronyms are defined together in a table in the appendix.

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 Deliv.
(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

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 Department of Forest Biomaterials, North Carolina State University experimentation 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:

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

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

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

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 (2011) 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 condition-ing 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 10.2 shows the unit costs for each pre-treatment and summarizes these previously described costs and energy consumption.

Table 10.2. Transportation Costs, Grinding and Hammermilling Costs, and Energy Consumption of Different Pre-treatments

Type of pre-treatment	Total Trans-portation Costs ($/ton)	Energy for Grinding (Kwh/ton)	Cost of Grinding ($/ton)	Energy for Hammer-milling (Kwh/ton)	Cost of Hammer-milling ($/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/m3 (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; 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 10.3 summarizes the combined cycle efficiency and reports the cost of electricity generated ($/KWh) with each biomass option.

Table 10.3. 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.

10.4.1 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 100MWe 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 100MWh 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 10.3 and 10.4 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 100MWh 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, Figure. 10.4), however, may hinder its potential utilization. This may be the same case of softwood residues, requiring 9.08 tons/hour (Figure 10.4). 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.

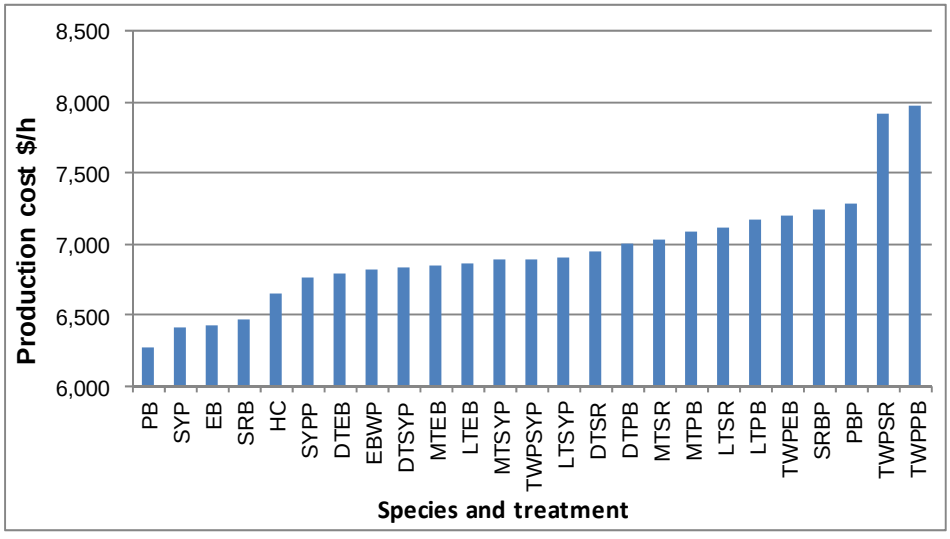


Figure. 10.3. Hourly production costs of electrical power from each different biomass source and pre-treatment in a 100 MWh power plant

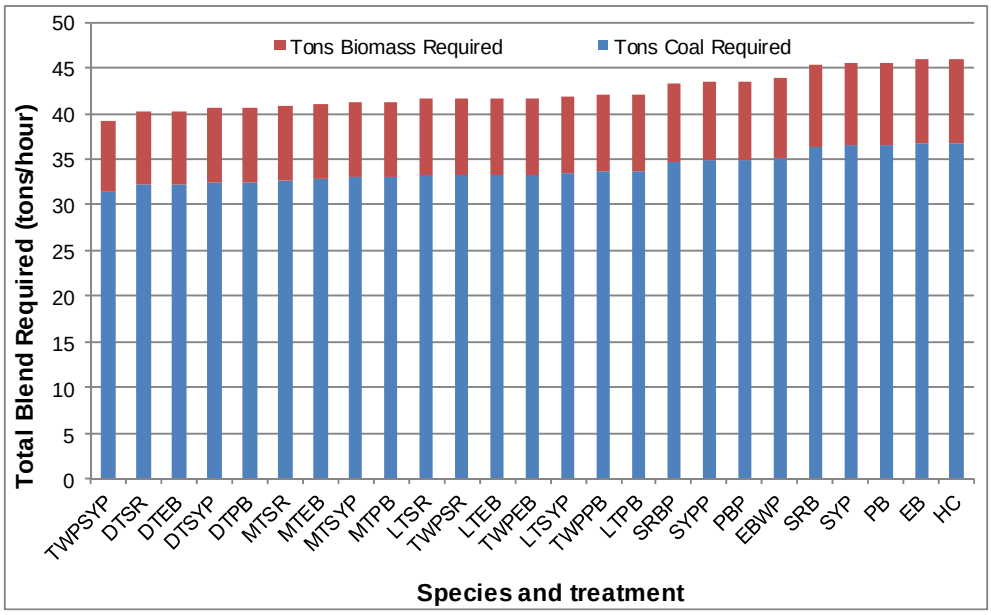


Figure. 10.4. Biomass and coal (blend) utilization for each different biomass source and pre-treatment in order to produce 100 MWh in a power plant

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 Figure. 10.4) 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, Figure. 10.4). 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 Figure. 10.5) and storage degradation of the biomass, reducing the overall efficiency of the cycle and creating potential operational problems in the boiler.

Figure. 10.5. 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.

10.5 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:

- 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.
- 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.
- 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 100MWh).
- 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.
- 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.

- 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.
- 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.

10.6 Literature Cited

Al-Mansour, F., and Zuwala, J. (2010). "An evaluation of biomass co-firing in Europe," *Biomass and Bioenergy* 34, 620-629.

Arcate, J. R. (2002). "Torrefied wood, an enhanced wood fuel," Paper presented at Bioenergy 2002 conference, Idaho.

Arrieche. R., Saloni, D., van Dyk, H., and Lemaster, R. (2011). "Evaluation of the energy balance for the production of briquettes from biomass," *Forest Products Journal*, 61(4), 302-309.

Battacharya, S. C. (1990). "Carbonized and uncarbonized briquettes from residues," *Procedures of Workshop on Biomass Thermal Processing*, Shell, London.

Belosevic, S. (2010). "Modeling approaches to predict biomass co-firing with pulverized coal," *The Open Thermodynamics Journal* 4, 50-70.

Bergman, P. C. A. (2005). *Combined Torrefaction and Pelletization: The TOP Process.* (http://www.ecn.nl/docs/library/report/2005/c05073.pdf).

Bergman, P. C. A., and Kiel, J. (2005). “Torrefaction for Biomass Upgrading,” 14th European Biomass Conference & Exhibition, Paris, France, 17-21 October.

BERC. (2011). *Wood Boiler Systems: Overview*. (http://www.biomasscenter.org/images/stories/Wood_Boiler_Systems_electronic.pdf).

Bezzon, G., and Dilcio Rocha, J. (2000). *Pyrolisis. Industrial Uses of Biomass Energy, The Example of Brazil*, Taylor & Francis, London.

Boerrigter, H. (2006). *Economy of Biomass-To-Liquids (BTL) plants, An Engineering Assessment*. (http://www.thermalnet.co.uk/docs/2G-1%20ECN-C-06-0191.pdf).

Brechbill, S., and Tyner, W. (2008). “The economics of biomass collection, transportation, and supply to Indiana cellulosic and electric utility facilities,” Working paper #08-03, Department of Agricultural Economics, Purdue University, (http://ageconsearch.umn.edu/bitstream/6148/2/wp080003.pdf).

Brem, G. (2005). *Biomass Co-firing: Technology, Barriers and Experience in EU.* (http://gcep.stanford.edu/pdfs/RxsY3908kaqwVPacX9DLcQ/brem_coal_mar05.pdf).

Campbell, K. (2007). *A Feasibility Study Guide for an Agricultural Biomass Pellet Company*, Agricultural utilization Research Institute.

Canalis, P., Royo, J., and Sebastian, F. (2003). “Influence of co-combustion in the efficiency of a pulverized coal boiler,” (http://circe.cps.unizar.es/acvcoco/es/pdf/ 6doc_6.pdf).

Carolina Pacific, LLC. (2009). *Clean Power from the Americas to Europe*. (http://carolina-pacific.com/1.html).

Carter, J. M. (2010). North Carolina Biomass Availability and Pellet Production from Mixed Forest Understory for Bioenergy Industry. (http://repository.lib.ncsu.edu/ir/bitstream/1840.16/6395/1/etd.pdf).

Cassidy, D., and Zophy, K. (2004). Southern Pine Management. A Landowner's Guide. **(**http://forestandrange.org/southernpine/index.htm).

Conrad, J. L., Bolding, M., and Chad, M. (2011). "Virginia's Woody Biomass Market: Opportunities and Implications," *Southern Journal of Applied Forestry* 35(2), 67-72.

Council of Industrial Boiler Owners. (2003). *Energy Efficiency & Industrial Boiler Efficiency. An Industry Perspective.* (http://cibo.org/pubs/whitepaper1.pdf).

DiGiacomo, G., and Taglieri, L. (2008). "Renewable energy benefits with conversion of woody residues to pellets," *Energy* 34, 724-731.

Dougherty, D., and Wright, J. (2012). "Silviculture and economic evaluation of eucalypt plantations in the Southern U.S.," *BioResources* 7(2), 1994-2001.

Duijn, C. (2004). *Torrefied wood mit Resthout en andere Biomassastromen*, Presentation held at "Praktijkdag Grootschalige Bio-energie Projecten", SenterNovem.

Engineering ToolBox. (2010). "Heating values of standard grades of coal," (http://www.engineeringtoolbox.com/coal-heating-values-d_1675.html). EIA. 2012.

EPA. (2007). *Biomass Combined Heat and Power Catalog of Technologies.* (http://www.epa.gov/chp/documents/biomass_chp_catalog.pdf). U.S. Environmental Protection Agency. Combined Heat and Power Partnership.

Estcourt, G., and Jack, M. (2012). "Potential to reduce the delivered costs of forest residue derived bioenergy," (http://www.bioenergy.org.nz/documents/Workshops/Wellington/

Potential%20to%20reduce%20the%20delivered%20costs%20of%20forest%20-%20G%20Estcourt-M%20Jack.pdf). EECA (FIDA) Funded Project.

Evans, A. M., and Perschel, R. T. (2009). "An assessment of biomass harvesting guidelines," Forest Guild, January 2009. (http://www.csbp.org/files/Evans%20An%20Assessment%20of%20Biomass%20Harvesting%20Guidelines%2001%202009.pdf).

Gast, C. H., Jelles, S. J., de Jong, M. P., Konings, A. J. A., Saraber, A. J., Vredenbregt, L. H. J., and Witkamp, J. G. (2007). "Technische grenzen maximaal meestoken," KEMA Consulting, 07-2346.

Gilbert, D. (2007). Eucalyptus, Foxtail Millet, Red Algae, and novel microbial communities added to growing bioenergy and carbon cycling portfolio. (http://www.jgi.doe.gov/News/news_6_8_07.html).

Good, J., Nussbaumer, T., Delcarte, J., and Schenkel, Y. (2006). *Determination of the Efficiencies of Automatic Biomass Combustion Plants*, International Bioenergy Agency, IEA Bioenergy Task 32.

Gonzalez, R., Treasure, T., Phillips, R., Jameel, H., and Saloni, D. (2011a). "Economics of cellulosic ethanol production: Green liquor pretreatment for softwood and hardwood, greenfield and repurpose scenarios," *BioResources* 6(3), 2551-2567.

Gonzalez, R., Treasure, T., Phillips, R., Jameel, H., Saloni, D., Abt, R., and Wright, J. (2011b). "Converting eucalyptus biomass into ethanol: Financial and sensitivity analysis in a co-current dilute acid process, Part II," *Biomass and Bioenergy* 35(2), 767-772.

Green, A., Zanardi, M., and Peres, S. (2000). *Thermal Conversion of Biomass. Bioenergy: Vision for the New Millennium*. Science Publishers, Inc. Plymouth, U.K.

Green Circle Bio Energy Inc. (2011). *Pellet Specifications*. (http://www.greencirclebio.com/products.php).

Gruenspecht, H. (2012). *Annual Energy Outlook 2012. Early Release Reference Case*. (http://www.eia.gov/pressroom/presentations/howard_01232012.pdf).

Hoadley, R. B. (2000). *Understanding Wood: A Craftsman's Guide to Wood Technology*, The Taunton Press, Newton, CT.

Hoque, M., Sokhansanj, S., Bi, T., Mani, S., Jafari, L., Lim, J., Zaini, P., Melin, S., Sowlati, T., and Afzal, M. (2006). *Economics of Pellets Production for the Export Market*. CSBE/SCGAB 2006 Annual Conference, Edmonton, Alberta, July 16-19.

IEA. (2009). *Co-firing database.* (http://www.ieabcc.nl/database/cofiring.html).

IEA Bioenergy. (2009). *Deliverable 4: Technical Status of Biomass Co-firing*. (http://www.ieabcc.nl/publications/09-1654%20D4%20Technical%20status%20paper%20bio mass%20co-firing.pdf).

IEA Bioenergy. (2011). *Biomass Combustion and Co-firing: An Overview.* (http://www.ieabcc.nl/publications/t32.pdf).

Kiel, J. (2005). "Co-utilization of coal, biomass and other fuels," Presented at JRC-Integration & Enlargement Workshop on the Perspectives for Cleaner Fossil Fuel Energy Conversion Technologies in an Enlarging EU, Petten, the Netherlands, 10-11 November 2005, ECN.

Kiel, J. (2007). "Torrefaction for biomass upgrading into commodity fuels," (http://www.ieabcc.nl/meetings/task32_Berlin_ws_system_perspectives/03_Kiel.pdf).

Kim, H., Kim, S., and Dale, B. E. (2009). “Biofuels, land use change, and greenhouse gas emissions: some unexplored variables,” *Environ. Sci. Technol.* 43(3), 961-967.

Kofman, P. D. (2006). “Quality wood chip fuel,” Available at: http://www.coford.ie/media/coford/content/publications/projectreports/cofordconnects/finalfuelquality.pdf). Coford Connects.

Kofman, P. D. (2007). “Delivery and storage of wood chip fuel,” (http://www.woodenergy.ie/media/woodenergy/content/faq/Delivery%20and%20storage%20of%20wood%20chip%20fuel.pdf).

Lako, P. (2010). “Biomass for heat and power,” (http://www.iea-etsap.org/web/E-TechDS/PDF/E05-Biomass%20for%20HP-GS-AD-gct.pdf). IEA ETSAP - Technology Brief E05.

Levi, E. K., Sarunac, N., Bilirgen, H., and Caram, H. (2006). “Use of coal drying to reduce water consumed in pulverized coal power plants,” (http://www.netl.doe.gov/technologies/coalpower/ewr/water/pp-mgmt/pubs/lehigh/41729%20Final.pdf).

Lipinsky, E. S., Arcate, J. R., and Reed, T. B. (2002). “Enhanced wood fuels via torrefaction,” *Fuel Chemistry Division Preprints* 47(1), 408-410.

Livingston, W. R. (2005). “A review of the recent experience in Britain with the co-firing of biomass with coal in large pulverised coal-fired boilers,” Presented at IEA Exco Workshop on Biomass Co-firing, Copenhagen, 2005.

Livingston, W. R. (2008). “Advanced biomass co-firing technologies for coal-fired boilers,” (http://ecosse.org/jack/research/sustainable/biomass/ICCS.pdf).

Maciejewska, A., Veringa, H., Sanders, J., and Peteves, S. D. (2006). "Co-firing of biomass with coal: constraints and role of biomass pre-treatment," (http://library.wur.nl/way/bestanden/clc/1880856.pdf). DG JRC Institute for Energy.

Mahmudi, H., and Flynn, P. C. (2006). "Rail *vs*. truck transport of biomass," *Applied Biochemistry and Technology* 129(1), 88-103.

Marinescu, M., and Bush, T. (2009). "Wood to energy: Use of the forest biomass for wood pellets," (http://edis.ifas.ufl.edu/pdffiles/FR/FR26900.pdf).

McClure, N. (2006). "Forest biomass as a feedstock for energy production," (http://www.gabioenergy.org/ppt/McClure--Forest%20Biomass%20as%20a%20Feedstock%20for%20Energy%20Production.pdf). Georgia Forestry Commission.

McNeel, J., Wang, J., Wu, J., and Goff, T. (2010). "Woody biomass sustainability for bioenergy production in West Virginia," (http://www.ncfap.org/documents/BEADII/WVUBiomassGChallengeBEADII.pdf).

Melin, S. (2011). "Torrefied wood: A new emerging energy carrier," Wood Pellets Association of Canada. Presented to: Clean Coal Power Coalition CCPC. (http://www.pellet.org/linked/2011-03-09%20ccpc%20presentation%20(2).pdf).

Milbrandt, A. (2005). "A geographic perspective on the current biomass resource availability in the United States," Technical Report. NREL/TP-560-39181.

Miles, P. D. (2004). "Fuel treatment evaluator: web-application version 1.0," (http://ncrs2/4801/fiadb/fueltreatment/fueltreatmentwc.asp). U.S. Department of Agriculture, Forest Service, North Central Research Station, St. Paul, MN.

Moran, J. C., Granada, E., Porteiro, J., and Miguez, J. L. (2004). “Experimental modeling of a pilot lignocellulosic pellets stove plant,” *Biomass and Bioenergy* 27, 577-583.

Nicholls, D., Monserud, R. A., and Dykstra, D. P. (2009). “Biomass utilization for bioenergy in the western United States,” *Forest Products Journal* 58(1/2), 6-16.

Oliveira Rodrigues, T., and Rousset, P. L. A. (2009). “Effects of torrefaction on energy properties of *Eucalytus grandis* wood,” *Cerne, Lavras* 15(4), 446-452.

Overend, R. P. (2004). “Heat, power and combined heat and power,” *Bioenergy Options for a Cleaner Future.* Elsevier, London, 63-102.

Perlack, R., Wright, L. L., Turhollow, A. F., Graham, R., Stokes, B. J., and Erbach, D. C. (2005). “Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply,” (http://www.osti.gov/bridge).

PFI. (2011). “Residential/commercial densified fuel standards,” (http://pelletheat.org/wp-content/uploads/2011/11/standards-table.jpg).

Phanphanich, M., and Mani, S. (2009). “Drying characteristics of pine forest residues,” *BioResources* 5(1) 108-121.

PiR (The Swedish Association of Pellet Producers). (2006). “Statistik,” (http://www.pelletsindustrin.org).

Pirraglia, A., Gonzalez, R., and Saloni, D. (2010a). “Wood pellets: An expanding market opportunity,” *Biomass Magazine* June 2010.

Pirraglia, A., Gonzalez, R., and Saloni, D. (2010b). “Techno-economic analysis of wood pellets production for U.S. manufacturers,” *BioResources* 5(4), 2374-2390.

Pirraglia, A., Gonzalez, R., Saloni, D., Wright, J., and Denig, J. (2012a). “Fuel properties and suitability of *Eucalyptus benthamii* and *Eucalyptus macarthurii* for torrefied wood and pellets,” *BioResources* 7(1), 217-235.

Pirraglia, A., Gonzalez, R., Denig, J., and Saloni, D. (2012b). “Technical and economic modeling for the production of torrefied ligno-cellulosic biomass for the U.S. densified fuel industry,” *Bioenergy Research*, Under review.

Pirraglia, A., Gonzalez, R., Saloni, D., and Denig, J. (2012c). “Technical and economic assessment for the production of torrefied ligno-cellulosic biomass pellets in the U.S.,” *Bioresource Technology*, Under review.

Pirraglia, A., Gonzalez, R., Saloni, D., and Wright, J. (2012d). “Freeze tolerant Eucalyptus biomass: A study of characteristics and suitability for solid fuels production,” *Biomass and Bioenergy*, Under review.

Quarterly Coal Report. (2012). *Quarterly Coal Production.* (http://205.254.135.7/coal/production/quarterly/).

Ragauskas, A., Williams, C. K., Davison, B. H., Britovsek, G., Cairney, J., Eckert, C. A., Frederick Jr., W. J., Hallett, J. P., Leak, D. J., Liotta, C. L., Mielenz, J. R., Murphy, R., Templer, R., and Tschaplinki, T. (2006). “The path forward for biofuels and biomaterials,” *Science* 311, 484-489.

Repellin, V., Govin, A., Roland, M., and Guyonnet, R. (2010). “Energy requirements for fine grinding of torrefied wood,” *Biomass and Bioenergy* 34, 923-930.

Scandinavian Pulp, Paper, and Board Testing Committee. (1992). *Wood Chips for Pulp Production. Bulk Density*. (http://www.nordstand.com/upload/NSP/SCAN-test%20Methods/Series%20C/CM%2046-92.pdf).

Sokhansanj, S. (2011). *2011 DOE Biomass Program Review Universal Project Abstract. Feedstock Treatments for Thermal Reactors*. Oak Ridge National Laboratory.

Sondreal, E. A., Benson, S. A., Hurley, J. P., Mann, M. D., Pavlish, J. H., Swanson, M. L., Weber, G. F., and Zygarlicke, C. J. (2001). "Review of advances in combustion technology and biomass co-firing," *Fuel Process. Technol.* 71, 7-38.

Southern Pine Council. (2011). "Using southern pine," (http://www.southernpine.com/ using-southern-pine.asp).

Stokes, S.C. (2003). "Coal-fired power plant emissions factsheet," (http://www.minorityhealth.org/ehhstrp/Coal%20Fired%20Power%20Plant%20Fact%20Sheet%201.pdf).

The Joint Genome Institute. (2011). "Eucalyptus Grandis genome," (http://www.phytozome.net/eucalyptus.php).

University of Pretoria. (2011). "Eucalyptus tree genome deciphered: Key to new possibilities for renewable bioproducts," *ScienceDaily* (http://www.sciencedaily.com /releases/2011/05/110512104214).

USDA-FS (U.S. Department of Agriculture - Forest Service). (2000). "The national atlas of the United States of America," (http://www.fia.fs.fed.us/library/maps/docs/ forestcover.pdf).

USDA-FS (U.S. Department of Agriculture - Forest Service). (2003). *A Strategic Assessment of Forest Biomass and Fuel Reduction Treatments in Western States.* (http://www.fs.fed.us/research/infocenter.htm).

USDOE. (2011). “Biomass for electricity generation,” Federal Energy Management program (FEMP). (http://www.wbdg.org/resources/biomasselectric.php).

USDOT. (2000). “Comprehensive truck size and weight study,” (http://www.fhwa.dot.gov/reports/tswstudy/TSWfinal.htm).

Valero, A. (2003). “Co-firing of low-rank coal and biomass: A chance for biomass penetration in the renewables,” International Conference on Renewable Energy and Power Quality. Vigo, Spain. April 9-12. (http://cibo.org/pubs/whitepaper1.pdf).

Veijonen, K., Vainikka, P., Järvinen, T., and Alakangas, E. (2003). *Biomass co-firing – an efficient way to reduce greenhouse gas emissions*. (http://ec.europa.eu/energy/renewables/studies/doc/bioenergy/2003_cofiring_eu_bionet.pdf).

Wieck-Hansen, K., Overgaard, P., and Larsen, O.H. (2000). “Co-firing coal and straw in a 150 MW power boiler experiences,” *Biomass and Bioenergy* 19(6), 395-409.

Wiltsee, G. (2000). “Lessons learned from existing biomass power plants,” National Renewable Energy Laboratory. (http://www.nrel.gov/docs/fy00osti/26946.pdf).

World Coal Institute. (2007). “Coal conversion facts,” (http://www.worldcoal.org/coal/).

World Coal Institute. (2009). “The coal resource: a comprehensive overview of coal,” (http://www.worldcoal.org/coal/what-is-coal/).

Wright, J. (2010). “Wood-based biofuels, biomass, and bioenergy: Opportunities and challenges in Louisiana,” *Bioenergy Forest Plantations* April 23, 2010.

11. APPENDIX

11.1 Appendix A

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