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IS DENSIFIED BIOMASS FUEL FROM AGRO-FORESTRY WASTE A
SUSTAINABLE ENERGY OPTION?

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in Mechanical Engineering in the
College of Engineering
at the University of Kentucky

By

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Lexington, Kentucky

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Engineering

Lexington, Kentucky

2012

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ABSTRACT

IS DENSIFIED BIOMASS FUEL FROM AGRO-FORESTRY WASTE A SUSTAINABLE ENERGY OPTION?

Raw biomass material is bulky, high in void fraction, and very low in transportation efficiency. Furthermore, biomass dissipates quickly in harsh environments of high heat furnaces because of its relatively low calorific value (BTU/lb) and has grinding or size degradation properties highly dissimilar from commonly-used fossil fuels like coal. Therefore, the development of transformational technologies are necessary to convert raw biomass into high-value and useful products of high hardness and calorific value without requiring excessive process energy.

This thesis investigates the sustainability of densified biomass fuels. In addition, a procedure that converts raw biomass from agro/forest industry waste into a fuel source known as semi-carbonized densified biomass (SCDB) is shown to have the necessary performance qualities that are conducive to applications involving the harsh conditions of high heat furnaces. The SCDB is produced at temperatures between 115-230°C and pressures between 8-25 MPa. The raw biomass is transformed into a densified fuel source with maximum compressive strengths between 60-200 MPa and calorific values between 18-23 MJ/kg, which are essential to operating in high heat furnace environments. The procedural steps and equipment used to manufacture this densified fuel source are outlined in detail along with experimental results and discussions of initial testing.

KEYWORDS: Densified Biomass, Agricultural and Forestry Industry Wastes, Renewable/Sustainable Fuel, Semi Carbonized Densified Biomass, Biomass Transformational Production Technique

William A. Linnig III

05/30/12

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TABLE OF CONTENTS

ACKNOWLEDGMENTS	iii
TABLE OF CONTENTS.....	iv
LIST OF TABLES	viii
LIST OF FIGURES	ix
CHAPTER 1	1
1.0 Introduction	1
1.1 Energy Allocation in the United States	2
1.2 Biomass and Its Potential	4
1.3 Research Objective.....	7
1.4 Outline of Thesis	8
CHAPTER 2	9
2.0 Literature survey	9
2.1 What is Biomass.....	9
2.1.1 Cellulose	12
2.1.2 Hemicellulose	13
2.1.3 Lignin.....	13
2.1.4 Thermo-Chemical Reaction of Cellulose, Hemicellulose, and Lignin	14
2.2 Types of Land Available in the United States.....	17
2.2.1 Forest Land	19

2.2.2	Grassland Pasture and Range.....	20
2.2.3	Cropland.....	20
2.2.4	Special Uses	22
2.2.5	Miscellaneous Other Uses.....	23
2.3	Reasons for Potential Inaccuracies in Acreage of Land Classifications	23
2.4	Trends in Land Usage	24
2.5	Which Types of Land Are More Useful in Biomass Harvest?	27
2.6	Sectors of Available Biomass Residues	28
2.6.1	Agricultural Biomass	28
2.6.2	Forest or Wood Biomass.....	29
2.6.3	Energy Crop Biomass	30
2.7	Assumptions Made to Calculate Abundance of Biomass	30
2.8	Quantity of Biomass Generated Annually	31
2.8.1	Agricultural Biomass	32
2.8.2	Forest or Wood Biomass.....	33
2.8.3	Energy Crop Biomass	36
2.9	Potential Strain on Food Supply and Other Markets.....	38
2.10	Carbon Cycle	40
2.10.1	Geological Carbon Cycle.....	41
2.10.2	Biological Carbon Cycle: Photosynthesis and Respiration	42

2.10.3	Carbon Neutral.....	43
2.10.4	Strategies to Balance the Carbon Cycle.....	46
2.11	Political and Economic Policy.....	48
2.11.1	The 1992 Energy Policy Act.....	49
2.11.2	The 2002 Farm Bill.....	50
2.11.3	The Energy Policy Act of 2005	52
2.11.4	The Energy Independence and Security Act of 2007	53
2.12	Solid Biomass Fuels Available in the Market	54
2.12.1	Charcoal	55
2.12.2	Pelletisation.....	60
2.12.3	Briquettes of Raw Biomass.....	62
2.12.4	Torrefaction.....	64
CHAPTER 3	.....	66
3.0	Semi Carbonized Densified Biomass (SCDB).....	66
3.1	Experimental Procedure: SCDB Production Process.....	67
3.1.1	Heating and Cooling Process	69
3.2	Experimental Apparatus.....	70
3.2.1	Chipper.....	70
3.2.2	Cutting Mill.....	71
3.2.3	Oven.....	73

3.2.4	Moisture Analyzer	74
3.2.5	Balance.....	75
3.2.6	Reaction Cylinder and Shop Press	76
3.2.7	Ceramic Electric Tubular Furnace	77
3.2.8	Thermo Controller	78
3.2.9	Overall Setup of Experimental Apparatus	79
3.3	Experimental Result and Discussion.....	80
3.3.1	Results.....	80
3.3.2	Discussion.....	82
CHAPTER 4	.....	84
4.0	Conclusion and Discussions.....	84
4.1	Contribution of this Thesis.....	85
REFERENCES	.....	86
VITA	.....	91

LIST OF TABLES

Table 2.1	Effect of carbonization temperature on yield and composition of charcoal.	
Source: (FAO, 1983)	.....	58
Table 3.1	SCDB Reaction conditions	81
Table 3.2	Proximate Analysis of SCDB (ASTM d5142)	82

LIST OF FIGURES

Figure 1.1: Supply Sources and Demand Sectors of Energy in the United States in 2009. Source: (USDOE, 2009)	3
Figure 2.1: Major Elements of Biomass.	11
Figure 2.2: Arrangement of Cellulose, Hemicellulose, and Lignin in Biomass Source: (Murphy et al., 2005)	12
Figure 2.3: Basic 2D illustration of biomass structure before thermo-chemical reactions.	15
Figure 2.4: Hemi-cellulose effect occurs during thermo-chemical reactions.	16
Figure 2.5: Lignin effect occurs during the final stages of thermo-chemical reactions.	16
Figure 2.6: Acres of Each Land Category in the United States. Source: (Nickerson et al., 2011)	19
Figure 2.7: Available biomass residues organized by the type of residue. Source: (Milbrandt, 2005)	37
Figure 2.8: Available biomass residue organized by where the residue originates. Source: (Milbrandt, 2005)	38
Figure 2.9: Visualization of the Carbon Cycle. Source: (Remer, L. 2001)	43
Figure 2.10: Picture of Manufactured Charcoal Final Product.....	57
Figure 2.11: Charcoal Briquettes. Source: (Google images, 2012)	60
Figure 2.12: Wood Pellets Formed by Extrusion. Source: (Google images, 2012)	62
Figure 2.13: Biomass Briquettes. Source: (Google images, 2012)	63
Figure 2.14: Biomass which has undergone Torrefaction Process. Source: (Google images, 2012)	65

Figure 3.1: Process chart of SCDB formation from agricultural waste.....	68
Figure 3.2: Heating and cooling production process for elapsed time.	70
Figure 3.3: Earthquake 3” chipper and shredder. Source: (Earthquake, 2012)	71
Figure 3.4: Retsch SM300 cutting mill. Source: (Retsch, 2012).....	72
Figure 3.5: Biomass before and after the two step grinding process.....	72
Figure 3.6: Thermo Scientific Precision drying oven.....	73
Figure 3.7: AnD MX-50 Moisture Analyzer. Source: (AnD MX-50).....	74
Figure 3.8: AnD GF-200P Balance. Source: (AnD GF-200P, 2012)	75
Figure 3.9: Greg Smith Equipment 20 ton air/hydraulic shop press with gauge. Source: (Greg Smith Equipment, 2012).....	76
Figure 3.10: Asahirika Seisakusho Co., Ltd. ceramic electric tubular furnace type ARF- 50K.....	77
Figure 3.11: Asahirika Seisakusho Co., Ltd. Thermo Controller Type AMF-N.....	78
Figure 3.12: Production process of SCDB.....	79
Figure 3.13: SCDB produced from various agricultural wastes.	80

CHAPTER 1

1.0 Introduction

What will we think of next? Everyday people come up with fascinating ideas that push the boundaries of science and technology. As technologies advance, different applications begin to present themselves. What was once unimaginable can be common practice today using newer technology. With every development in technology comes an ever increasing demand for energy.

As the world evolves into a global industrial society and away from an agrarian society, devices that will require energy input in our homes and businesses will become even more prevalent. This will cause a greater demand for all forms of energy. Other driving forces in the increasing demand for energy are industrialization. Businesses and factories will require significant amounts of energy to operate and, as developing economies industrialize, their demand for energy will increase as well. Wealth in emerging markets such as China and India also increase the demand for energy (USEIA, 2011). As more people acquire the ability to afford household appliances, automobiles and modern conveniences, the demand for energy will continue to rise. Globalization also creates a factor for increasing the demand for energy. The world is becoming a smaller place via the internet, which creates markets that are more accessible further distances from base operation. Transportation of products and materials over these further distances will result in an increase in demand for energy. Additionally, there has been an increase in the world's population which in turn raises the energy demand to maintain the current standard of living (USEIA, 2011).

Much of the world's energy resources are used to generate electricity (USEIA, 2011). In order for electricity to be generated we must harness forms of energy, each with their own particular advantages and disadvantages. The advantages and disadvantages concerning each form of energy range from availability of resources, environmental costs, economic production costs, how it can be applied to certain systems, social-political tensions and sustainability. This thesis will explore the potential for biomass as a self-sustaining form of energy that will be competitive in terms of these mentioned advantages and disadvantages with respect to electrical power production.

1.1 Energy Allocation in the United States

To get a better look at how energy resources are allocated in the United States, the U.S. Energy Information Administration, which is a part of the Department of Energy, broke down the United States energy consumption of 2009 into supply sources and demand sectors (USDOE, 2009). The demand sectors consisted of four areas of energy consumption which include transportation, industrial, residential and commercial, and electric power. Electric power consumed the largest portion of energy with 41% of the country's energy and transportation consumed the next closest amount which was around 28% (USDOE, 2009). The percentages of supply sources of energy used were shown to have been 37% petroleum, 25% natural gas, 21% coal, 9% nuclear and 8% renewable. (USDOE, 2009) From these values it can be seen that the major forms of energy utilized today are petroleum, natural gas and coal, but what is most important is their relationship to our topic of generating electrical power from biomass.

In order to understand where biomass would fit into the market for forms of energy to create electrical power, it would be helpful to look at the percentage breakdown of all the other forms of energy that are being used for this same purpose. The dominant form of energy to create electrical power in the United States is coal with 48% of the market share, followed by 22% nuclear, 18% natural gas, 11% renewables, and 1% petroleum (USDOE, 2009). From these statistics provided by the U.S. Department of Energy, it is seen that the demand sector's greatest consumer of energy resources is electrical power generation and the greatest supply source of this demand sector is coal. Since coal is such a pivotal part of electrical energy we must demonstrate how biomass can be interchangeable with or even surpass coal as a form of energy on performance and many other areas of concern. A visual representation is presented in Figure 1.1 of how supply sources and demand sectors of energy interact..

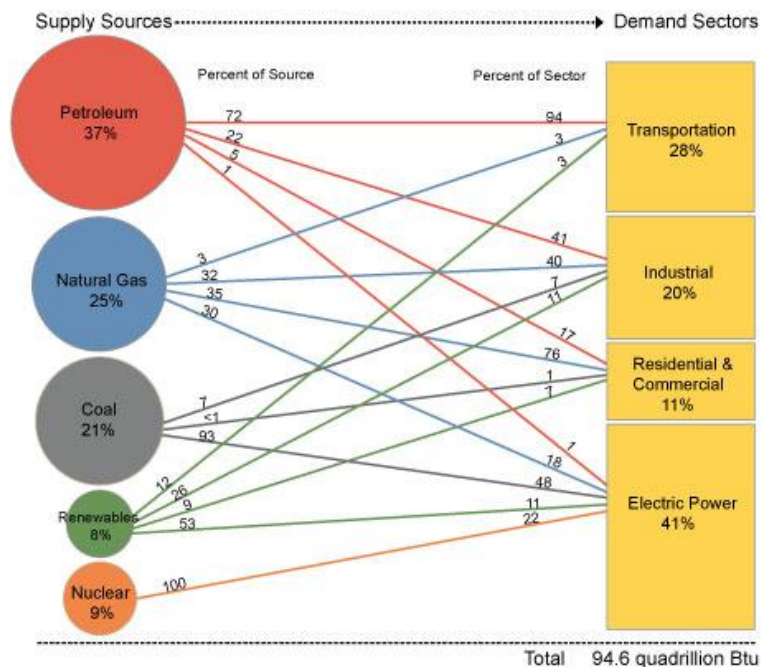


Figure 1.1: Supply Sources and Demand Sectors of Energy in the United States in 2009.

Source: (USDOE, 2009)

1.2 Biomass and Its Potential

Biomass is simply a material made from biological organisms that can be burned to produce heat for electricity generation. One advantage of biomass is that it can be made from agricultural waste and forestry residuals; another is that biomass is incredibly abundant on many farmlands and much of what could be used as an energy source is currently burned off in fields and unutilized. Using agricultural waste and forestry residuals as energy sources will create a new market for farmers and other independent craftsmen who acquire stockpiles of agricultural waste as a byproduct of their trade. Farmers can generate more revenue for themselves while providing a more greener and sustainable form of energy to society. Since farmers will be gaining a new market, they would also be less dependent upon a productive crop yield from year to year and less affected by droughts or other unforeseen environmental occurrences. The revenue generated from biomass will help smaller, independently-owned farms to sustain a profitable business in times of duress.

Due to such an abundance of agricultural waste, biomass would be expected to remain cheap in its raw, unprocessed form and to be a sustainable form of energy. This sustainability may allow many nations to be energy independent and, as a result, to be able to reallocate funding in budgets to other areas of concern. There are several geopolitical ramifications in becoming energy independent as well. For example, the United States depends on much of its energy from the supply of Middle East oil. By using a home grown form of sustainable, biomass energy the United States could re-strategize its presence in this volatile area of the world.

Another incentive for using biomass as an energy source is that it is carbon neutral which eliminates concerns for greenhouse gas emissions or global warming (Remer, 2001). Also, due to the more-clean nature of the combustion byproducts of biomass, there will be less need for pollutant scrubbers. Removing these types of equipment from large scale combustors would be expected to lower their overall cost of installation and operation, and to decrease the amount of capital investment required for building electrical production processes.

The greatest adversary to biomass becoming a major energy source to generate electricity is coal. Currently, coal is the most utilized form of energy to generate electricity in the United States with 48% of the market for resources used. Coal in the United States is cheap and abundant, and it has an admirable energy density. Many factories and power plants use coal because it is the best “bang for their buck.”

When looking at coal from a production perspective it is an incredibly useful form of energy but when looking at coal from an environmental perspective it is a very poor choice. For example, during combustion it gives off formidable amounts of greenhouse and acid gas emissions, such as CO₂, SO_x and NO_x, and creates huge quantities of other pollutant byproducts such as fly ash, bottom ash and flue-gas desulfurization sludge. All of these byproducts contain unwanted amounts of mercury, uranium, thorium, arsenic, and other heavy metals (USEPA, 2007) which are incredibly dangerous to human and environmental health. Two other notable pollutants include radiation from the fly ash emitted from coal power plants and the formation of acid rain (USEPA, 2007). To counteract the effects of the byproducts produced from coal, additional environmental control steps are necessary. For example, scrubbers are used to control sulfur dioxide and

greenhouse gas emissions from electricity production systems; if CO₂ was to be controlled, even larger scale scrubbers would be necessary. Such equipment requires extensive capital investment and high operational costs. In other words, coal by itself may be relatively inexpensive, but to operate with coal and meet increasingly-stricter environmental standards, the other production costs along its life cycle during electricity production must be factored in to provide a more realistic assessment of the its true costs.

With the world becoming “green” oriented, governments have begun giving companies tax breaks for using greener technologies and methods. Coal is on the opposite side of the spectrum when it comes to eco-friendly forms of energy; this fact could add to potential costs of operating coal fired power plants. Because of having a reputation of an unclean and unhealthy form of energy, many people have pushed for tougher governmental regulations on coal power plants. As a result, energy producing companies using coal have had to allocate additional funds toward legal fees to represent themselves as well as push for their own policy initiatives. These litigation fees are piled onto additional costs of marketing departments which must become creative in developing persuasive campaigns against the conception of coal being an unhealthy form of energy. Capital must be invested into commercials and infomercials that aim to ease the public’s environmental health concerns. Litigation and marketing costs must be quantified and factored into the equation when selecting a form of energy to produce electricity.

1.3 Research Objective

The main objective of this thesis is to investigate the sustainability and potential of densified biomass as an energy resource. Also explored is the production of a densified biomass fuel known as semi carbonized densified biomass (SCDB).

Biomass in its raw state, collected as a residue from other operations in which it would have been discarded as an unutilized waste, is bulky, high in void fraction and very low in transportation efficiency. Consequently, the development of transformational technologies which expends minimal input energy and converts raw biomass into a high-value densified fuel source are needed to make biomass a viable energy resource.

There is an array of transformational technologies that convert raw biomass into a high-value form of fuel but often these solid fuels do not have enough calorific value compared with coal and/or coal coke. Therefore, such solid fuels normally perform poorly relative to coal under the severe conditions of combustion, a result of which is to make it difficult for such solid biomass fuels to be competitive even when considering all of the life cycle costs of coal for electricity production.

The proposed SCDB technology aims to create a solidified biomass consisting of semi-carbonized solid matter as a result of processing in which the raw biomass material is pressure-formed while being heated under a substantially sealed-up condition. The SCDB has a maximum compressive strength from 60 to 200 MPa and a calorific value from 18 to 23 MJ/kg. Therefore, the SCDB has high mechanical strength, high density, reasonably high calorific value and low void fraction to be useful in high heat power production furnaces.

1.4 Outline of Thesis

The main objective of this thesis is to investigate the potential of SCDB to be utilized as a sustainable fuel source as a supplement or in competition to coal during electricity production. In order to investigate this potential a variety of topics must be discussed.

Chapter 2 of this thesis outlines a comprehensive literature review which begins with an explanation of the composition of biomass and what makes biomass an attractive resource for manufacturing a densified fuel. An assessment of land availability for unutilized biomass from agricultural and forest industries is presented. Because the availability of land is vital to the sustainability of raw biomass residues, a brief review is presented on current land usages. The literature review continues by examining how land is defined and what types of residues originate from certain types of land. Discussed also are the information used and assumptions made to quantify the current availability of biomass without creating fluctuations in other markets that maintain economic balances. A brief review of the carbon cycle is presented. Because the production of biomass-based fuels would be closely connected with agriculture, power generation and the concomitant environmental concerns, the political and public policy considerations regarding biomass as an energy resource are presented. Finally, current solid biomass fuel production processes are reviewed.

Chapter 3 presents the production technique for SCDB. The experimental procedure, the experimental apparatus, and results and discussions are presented. Lastly, Chapter 4 is a summary of the thesis.

CHAPTER 2

2.0 Literature survey

2.1 What is Biomass

Biomass is biological material derived from living, or recently living, organisms. Often plant-based materials are thought of as the exclusive energy source in the context of biomass for energy, but biomass can also apply to animal-based materials such as manures or fats. However, for the purpose of this thesis, biomass will refer solely to plant-based materials.

The abundance of unutilized biomass from agriculture and forest industries represents an immense potential that could be harnessed and processed into a fuel source. It represents a renewable and sustainable form of energy. By looking simply at the waste biomass that is unutilized by these industries, a more accurate assessment can be made of the amount of available biomass that would not affect the current economic balances of the agriculture and forest industries.

Biomass collected from agriculture is mostly the residue of crops that have been harvested and processed. If farmer's can find other value added uses for these residues that have sufficient economic value to them, they would embrace these uses. Now, most of these residues are left unutilized although they could be used in biomass-to-electricity processes. For example, corn is harvested and removed from the stalk. The corn goes on to be processed as food or other products; the stalk is considered a residue of the corn and has no value other than to become an organic residue that decomposes in fields before the next planting. As such, the stalk becomes a natural compost that helps to

replenish the soil; in other cases, the stalk is burned. The approach to be examined is to use the unutilized cornstalk residue as a biomass precursor with a goal to process it into a densified fuel source. By this approach, a new market is created for a farmer and value is created in something that would have been a waste. This same concept can be used in forest industry waste. Raw timber is processed into lumber, and the shavings and clippings of it can be used in other applications. After no more applications for these woody residues are possible, they can be potentially used as biomass.

The state of biomass when it is collected as residue from fields, the forest or a saw mill is a very ineffective fuel source, especially in a high heat furnace useful for electricity production. Biomass in its raw state is high in void fraction, low in hardness and calorific value, and therefore must be processed into a different form to remedy these ineffectual characteristics. The densification of biomass into a useful fuel source would allow biomass to be utilized during electrical power generation.

What makes raw plant-based biomass attractive for manufacturing into a densified fuel source is the plant's molecular components and their thermo-chemical reaction with one another when subjected to heat and pressure. The molecular components include cellulose, hemi-cellulose, and lignin, with the contributions of these for wood-based biomass comprising of 40–60% cellulose, 20–40% hemicellulose, and 10–25% lignin (USDOE, 2006). The thermo-chemical reaction of these three molecular components gives SCDB the necessary hardness and calorific value to sustain harsh high heat furnace environments.

Figure 2.1 shows a pictorial view of the three major molecular components, and a detailed view of their arrangement is shown in Figure 2.2. The following subsections explain each molecular component in greater detail.

Major Elements of Biomass

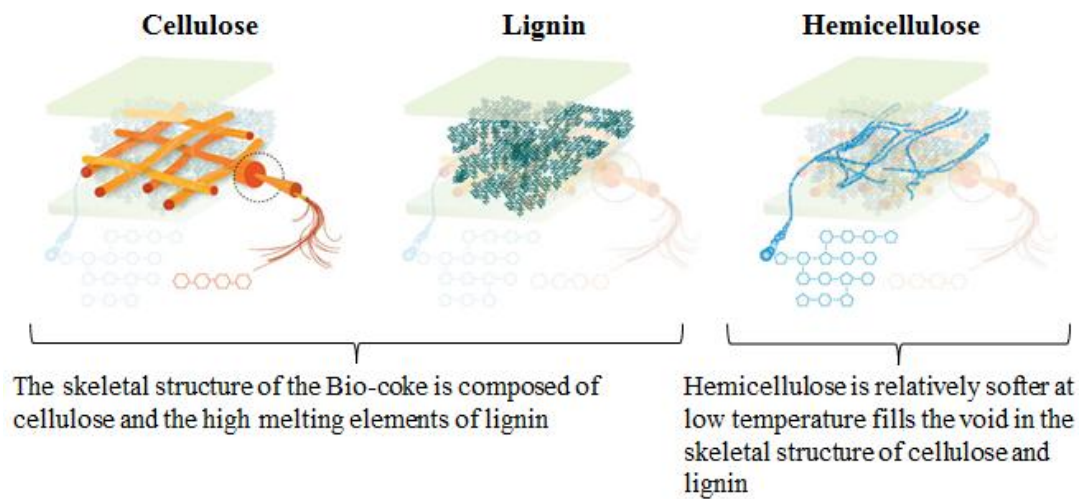


Figure 2.1: Major Elements of Biomass.

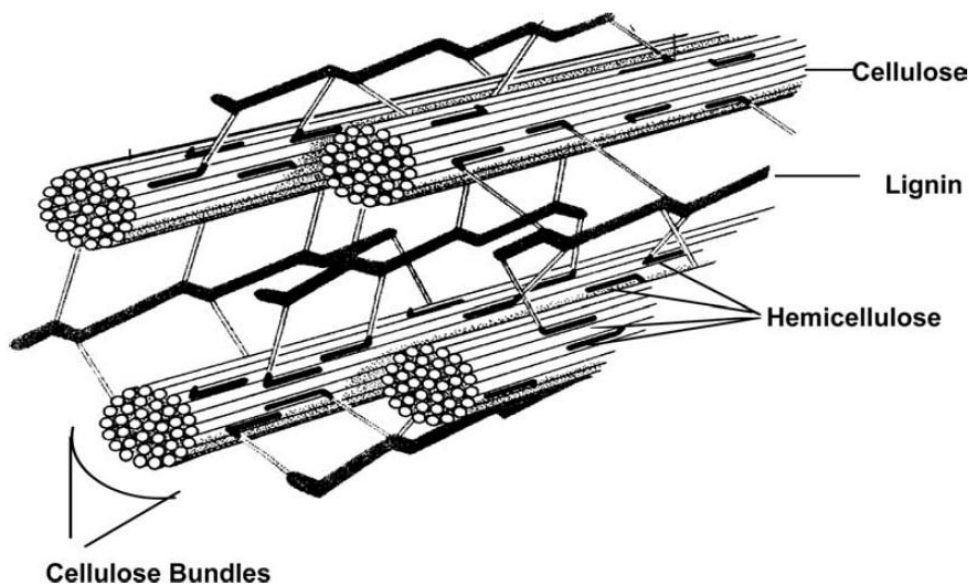


Figure 2.2: Arrangement of Cellulose, Hemicellulose, and Lignin in Biomass Source:
(Murphy et al., 2005)

2.1.1 Cellulose

Cellulose is a long chain of linked sugar molecules that gives wood its extraordinary strength. It is the main constituent of plant cell walls. It is a natural, long chain polymer made by the linking of smaller molecules of D-glucose residues that are joined by $\beta 1 \rightarrow 4$ glycosidic bonds (Tumuluru et. al, 2010). Cellulose forms crystalline microfibrils that are surrounded by amorphous cellulose inside the cell (Chen et al., 2004). The structural integrity of cellulose is due to hydrogen bonding that occurs between glucose monomers. According to Nelson and Cox (2005), cellulose is considered to be an abundant source of carbon in biomass. For hot pressing of wood material, Zandersons et al. (2004) concluded that the strength of the binding depends on

converting cellulose to an amorphous state. It is mentioned that because cellulose is semi-crystalline in structure, the highly hydrogen-bonded cellulose cannot be dissolved easily in conventional solvents and is impossible to melt before it burns. Additionally, although cellulose alone is not a suitable adhesive, this limitation can be overcome when hydrogen bonds are broken.

2.1.2 Hemicellulose

Hemicellulose is any of several heteropolymers present in almost all plant cell walls. While cellulose is crystalline, strong, and resistant to hydrolysis, hemicellulose has a random, amorphous structure with little strength. Hemicellulose contains $\beta 1 \rightarrow 4$ -bonded D-xylan as the main chain, with branches made up of L-arabinose, D-glucose, D-galactose, 4-O-methyl-D-glucuronic acid, D-mannose and L-rhamnose (Shambe et al., 1985). Hemicellulose found in the cell wall is more of a heteropolysaccharide, which is a combination of many sugars other than simple glucose. Its amorphous structure is due to branching and it is more easily hydrolyzed than cellulose, or it can be dissolved in alkali solution. Some researchers believe that natural bonding may occur due to the adhesive degradation products of hemicellulose (Tumuluru et. al, 2010).

2.1.3 Lignin

Lignin is a random network polymer with a variety of linkages based on phenyl propane units (Zandersons et al., 2004). While its structure is complex, lignin is derived from two amino acids, phenylalanine and tyrosine (Nelson et al., 2005), both of which contain aromatic rings. The lignin molecule provides complements the structural properties of cellulose, such as acting as glue to the cellulose fibers. The presence of

lignin in plant materials helps to form pellets without binders; for example, Van Dam et al. (2004) reported that lignin exhibits thermosetting properties at working temperatures of $>140^{\circ}\text{C}$ and acts as intrinsic resin in binderless board production. Hence, lignin is the component that permits adhesion in the wood structure and acts as a rigidifying and bulking agent (Anglès et al., 2001). Also, moisture contents of about 8–15% in biomass promotes a reduction in the softening temperature of lignin to $100\text{--}135^{\circ}\text{C}$, accomplished by plasticizing molecule chains (Tumuluru et. al, 2010). The adhesive properties of thermally softened lignin are thought to contribute considerably to the strength characteristics of briquettes made of lignocellulosic materials (Granada et al. 2002).

2.1.4 Thermo-Chemical Reaction of Cellulose, Hemicellulose, and Lignin

According to Hiroyuki, et al. (2011), the skeletal structure of SCDB is composed of cellulose and the high melting elements of lignin. When biomass is heated, lignin softens and may melt, resulting in thermosetting and the hemicellulose, which is relatively softer at low temperatures in comparison to cellulose and lignin, also contributes to the self-bonding properties by filling in voids between the skeletal cellulose and lignin structures. Also, hemicellulose has adhesive properties that promotes the hardening of the SCDB skeleton.

The presence of free water and the temperature used during the formation of SCDB have significant impacts on the structure of SCDB. The free water and elevated temperatures help to soften hemicelluloses and lignin, and control the reactivity of the main elements (Satoru et. al., 2011). For biomass, densification can be accomplished at moderate

temperatures and pressures with the resulting SCDB product having high mechanical strength, high density, high calorific value and low void fraction (Hiroyuki et. al, 2011).

A rudimentary 2-D illustration of the thermo-chemical reaction stages of woody biomass molecular components is shown in Figure 2.3, Figure 2.4 and Figure 2.5. The basic molecular structure is shown in Figure 2.3 before it begins the thermo-chemical reaction. As the thermo-chemical reaction occurs, the hemicellulose softens and fills the voids between the skeletal cellulose and lignin, shown in Figure 2.4. Lastly, the lignin effect takes place, as is shown in Figure 2.5, in which it acts as a natural binder once cooled and thermosetting has occurred.

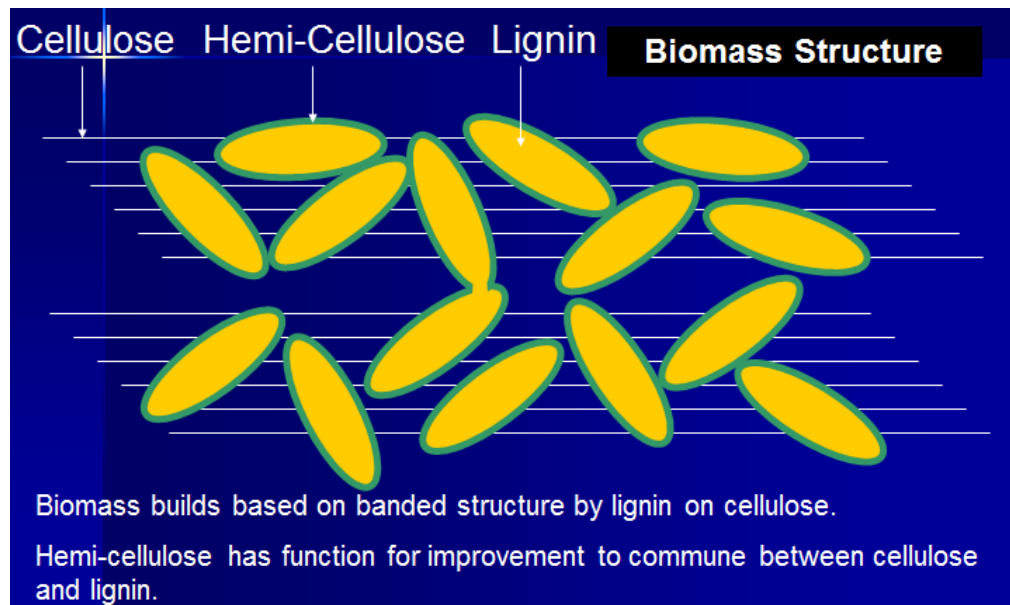


Figure 2.3: Basic 2D illustration of biomass structure before thermo-chemical reactions.

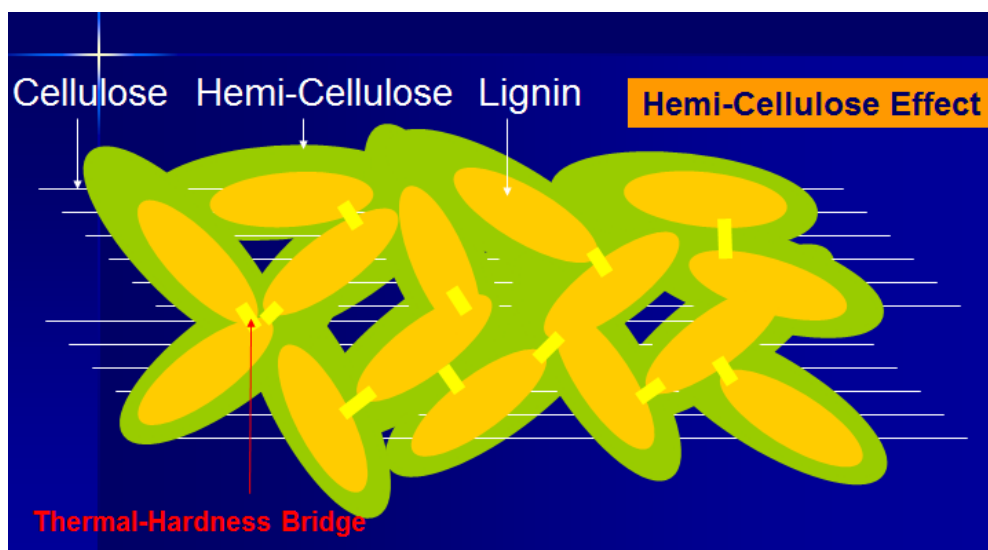


Figure 2.4: Hemi-cellulose effect occurs during thermo-chemical reactions.

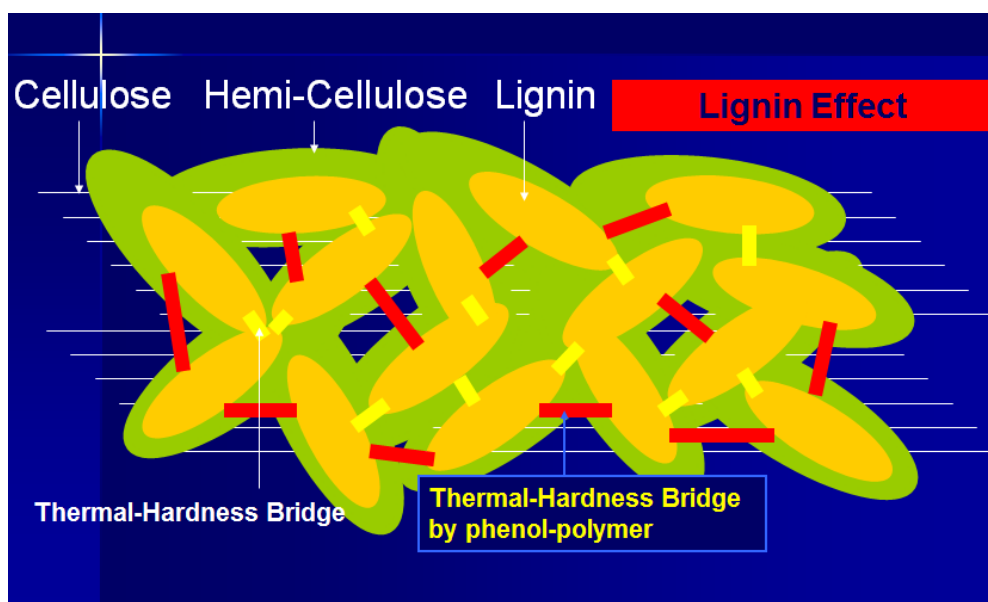


Figure 2.5: Lignin effect occurs during the final stages of thermo-chemical reactions.

2.2 Types of Land Available in the United States

To extract value from things discarded as waste, the value of the energy expended must never exceed the value gained. If the input effort outweighs the value gained, then the process only creates more waste as opposed to more value. Harvesting and processing of biomass into a fuel source is no different. Hence, a vision for biomass is for it to become a viable option to reduce dependency on fossil fuels while creating a clean and renewable fuel source. If harvesting and processing raw biomass into fuel requires more effort and energy than gained in the product of processing, researchers should look elsewhere for viable options for energy production.

Since biomass is harvested from agricultural crops and forests, its potential is dependent on annual harvests which, in turn, is dependent on the amount and current usage of available land. By understanding the usage of available land in the United States one can begin to generalize scenario cases for annual biomass harvest. If the greatest harvest potential is relatively low compared to the energy consumption needs of society, then operating harvesting and processing schemes at even the maximum efficiency would be unproductive relative to lessening the planet's fossil fuel dependencies. In other words, the focus of exploring whether biomass is a potentially abundant energy source is to discover a sustainable path that can supplant fossil fuels and other non-renewables. If the potential of biomass isn't significant, then other solutions must be examined.

Besides the importance of total land area on estimating biomass availability, the type of land that can be harvested is also important. These types have been formulated and classified by the Economic Research Service (ERS), a source of major land use

estimates in the United States for over 50 years (Vesterby, 2001). The ERS draws data from the U.S. Census Bureau, public land management and conservation agencies, and other sources (Nickerson et al., 2011). The data are synthesized by the state government to estimate use within several broad classes and subclasses of agricultural and nonagricultural land. These classifications include (in order of largest-to-smallest): forest use land; grassland pasture and range; cropland; special uses; and, miscellaneous other uses.

These state government estimates were started in 1945 and have been consistently published at roughly 5-year intervals, corresponding with the Census of Agriculture. Within this thesis are presented results from the most recent 2007 inventory of U.S. major land uses. First, the overall projections for each land class are presented. Then, after a quick overview is presented, the definitions that classify these types of land are explained in greater detail.

The United States has a total land area of nearly 2.3 billion acres (Nickerson et al., 2011). In 2007, the major land uses were forestland at 671 million acres; grassland pasture and rangeland at 614 million; cropland at 408 million; special uses (primarily parks and wildlife areas) at 313 million acres; miscellaneous uses (like tundra or swamps) at 197 million acres; and urban land at 61 million acres. A visual representation of how the United States total land area is categorized is presented in Figure 2.6.

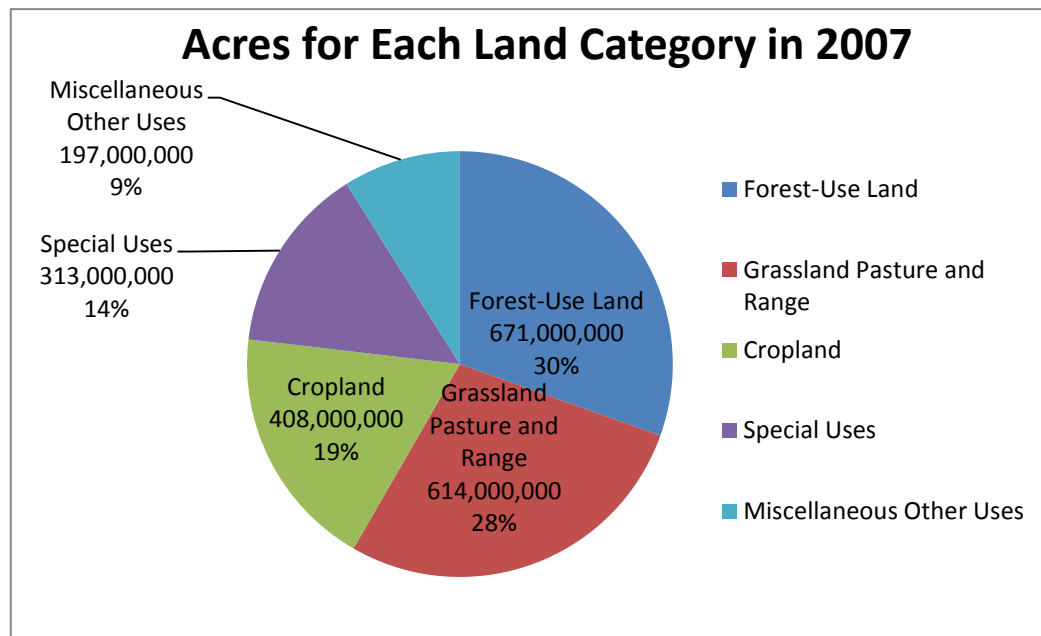


Figure 2.6: Acres of Each Land Category in the United States. Source: (Nickerson et al., 2011)

2.2.1 Forest Land

Forest-use land totaled 671 million acres as of 2007 (Nickerson, 2011). This value excludes estimated forest land in parks, wildlife areas and similar special purpose uses and provides a realistic approximation of the land that may be expected to serve normal forest uses as opposed to having forest cover (Vesterby, 2001). Forest-use land is the main contributor to forest land and the US Forest Service has defined it as “land at least 10 percent stocked by trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated. Forest land includes transition zones, such as areas between heavily forested and non-forested lands that are at least 10

percent stocked with forest trees and forest areas adjacent to urban and built up lands.”
(Powell et al., 1993)

2.2.2 Grassland Pasture and Range

Grassland pasture and range totaled 614 million acres in 2007; it includes all open land used mainly for pasture and grazing, including shrub and brushland types of pasture, grazing land with sagebrush and scattered mesquite, tame and native grasses, legumes, and other forage used for pasture or grazing. Due to the diversity in vegetative composition, grassland pasture and range are not always clearly distinguishable from other types of pasture and range (Nickerson et al., 2011). At one extreme, permanent grassland may merge with cropland pasture, or grassland may be found in transitional areas with forested grazing land. The estimates in this report are composites of data from the National Resources Inventory (NRI), Census of Agriculture, the Bureau of Land Management, USDA Forest Service, and several other Federal agencies. Of the 614 million acres classified as grassland pasture and range, 409 million acres were within farms (USDA/NASS, 2009a).

2.2.3 Cropland

Total cropland totaled 408 million acres in 2007 and included five components: cropland harvested; crop failure; cultivated summer fallow; cropland used only for pasture; and idle cropland.. It also included an upward adjustment to conform to data on principal crops harvested in each State as reported by the National Agricultural Statistics Service for 2007 USDA/NASS, 2009a). These census’ estimates were about 98 percent of the estimate for the same crops from NASS(USDA/NASS, 2009b). The Census of

Agriculture data are derived from a census of all farm operations that produce, or normally would produce and sell, \$1,000 or more of agricultural products annually.

Three of the cropland acreage components - cropland harvested, crop failure, and cultivated summer fallow - were collectively termed “cropland used for crops”, or the “land input to crop production”. Annual estimates of cropland harvested are based on both census data and a series on principal crops harvested as maintained by NASS. Annual estimates of crop failure are based on differences in planted and harvested acreage of principal crops from the NASS data series. Annual estimates of cultivated summer fallow historically have been based on fragmentary data from a variety of sources; since the late 1970s, these estimates have been based on data from the Census of Agriculture and unpublished NASS data (Nickerson et al., 2011).

Cropland harvested includes row crops and closely sown crops; hay and silage crops; tree fruits, small fruits, berries, and tree nuts; vegetables and melons; and miscellaneous other minor crops. Recently, farmers have double-cropped about 4% of this acreage.

Crop failure consists mainly of the acreage on which crops failed because of weather, insects, and diseases, but does include some land not harvested due to lack of labor, low market prices, or other factors. Crop failure is calculated using the difference between cropland planted and cropland harvested. However, some cropland planted is not intended to be harvested. For example, the acreage planted as cover crops or for soil improvement is not intended for harvest and is excluded from crop failure. In recent years, crops have failed on about 2-3% of the acreage planted for harvest.

Cultivated summer fallow refers to cropland in sub-humid regions of the West that are cultivated for one or more seasons to control weeds and accumulate moisture before small grains are planted. This practice is optional in some areas, but it is a requirement for crop production in the drier cropland areas of the West. Other types of fallow, such as cropland planted for soil improvement but not harvested and cropland left idle all year, are not included in cultivated summer fallow but are included as idle cropland.

Cropland pasture is generally considered to be in long-term crop rotation. This category includes acres of crops hogged or grazed but not harvested and some land used for pasture that could have been cropped without additional improvement. Cropland pastured before or after crops were harvested was included as harvested cropland and not cropland pasture. Estimates in this land-use category were derived from the Census of Agriculture (USDA/NASS, 2009a).

Idle cropland includes land in cover and soil-improvement crops and cropland on which no crops were planted. Some cropland is idle each year for various physical and economic reasons. Acreage diverted from crops to soil-conserving uses (if not eligible for and used as cropland pasture) under Federal farm programs is included in this component. Cropland enrolled in the Federal Conservation Reserve Program (CRP) and Wetlands Reserve Program (WRP) is included in idle cropland.

2.2.4 Special Uses

Special-use areas are comprised of highways, roads, and railroad rights-of-way and airports; Federal and State parks, wilderness areas and wildlife refuges; national

defense and industrial areas; and farmsteads and farm roads. Estimates are based on reports and administrative records of the Census Bureau and Federal and State land management and conservation agencies (Nickerson et al., 2011).

2.2.5 Miscellaneous Other Uses

Miscellaneous other land comprises of industrial and commercial sites in rural areas, cemeteries, golf courses, mining areas, quarry sites, marshes, swamps, sand dunes, bare rocks, deserts, tundra, rural residential, and other unclassified land. Urban land is reported as a separate category (Nickerson et al., 2011).

2.3 Reasons for Potential Inaccuracies in Acreage of Land Classifications

Because the United States has such an abundance of land, it can be extremely challenging to determine an acreage value for each land classification. Not only does the amount of land make it difficult to make an accurate assessment on total acreage, the complexity by which land transitions between classifications can also be problematic. Because landscapes are so unique, it is difficult for researchers to encompass the entire spectrum that nature has to offer by creating only a few types of land classifications. In order to simplify such a wide array of land, researchers have had to develop assumptions and definitions for types of landscapes so that distinguishable and quantifiable characteristics could be defined. It is possible that a certain piece of land could fit into the definition of two classifications; it is these instances in which total acreage numbers may become skewed. The accuracy in a land classification's total acreage is, therefore, related to an ability to reliably define styles of land and land use without having any overlap into other classifications.

In order to quantify the total acreage for large areas of land like in the United States, it is too difficult for one group of researchers to independently acquire accurate data to interpret. Similarly, because committees and groups of researchers don't have the funds or resources to examine the total of all land uses in United States, they may cross reference their findings with other research groups. Thereby, a difficulty of data comparison can arise because not every group can be expected to create their assumptions and definitions in a completely identical fashion. This cross referencing of data from group to group can create several inconsistencies in the accuracy of the total acreage values.

2.4 Trends in Land Usage

If solid biomass is a technology designed for the future and is based upon available land and the amount of harvest it can produce, then researchers must make projections as to what the landscape could look like in the future. Of all the types of land, forest, cropland and grasslands are the most effective for producing raw biomass; thereby, if sustainable production of biomass energy is to occur sufficient amounts of these lands must be available. Without a sufficient amount of these main types of land, solid biomass could not become an abundant resource. However, projecting how much raw biomass land resources will be able to produce in the future is a very complicated task because there are so many variables that play a role in how land is used.

Some of these key variables are technology- and institution-related, and must be incorporated into fundamental assumptions (Alig et al., 2003). In addition, cropland, forest land and grassland can compete for the same land base and are all subject to

conversion to developed uses. Outcomes of this competition may be influenced by public policies and government regulations seeking to enhance certain services such as clean water and wildlife habitat as urban populations increase. Similarly, technological developments, such as genetic improvements in planting stock, are difficult to forecast and may affect land use outcomes through impacts on agricultural and forest productivity. The only hard data that can be utilized for projecting land availability are the trends in each land class which have been estimated in the ERS “Major Land Uses” series (Nickerson, 2011). The ERS has been collecting data since 1945 and is the most trusted and acknowledged source for land use statistics.

Trends for forest-use land, which does not include the forest area counted under special uses, increased 20 million acres (3%) from 2002 to 2007 due mainly to increases in timberland on non-Federal land in many regions. Total acreage for forest-use land also grew due to better classification of forestland in some states (Nickerson et al., 2011). However, between 1949-1997, forest-use land trended downward 14% as a result of land reclassification from forest-use to special-use areas. Urbanization of forested land in the southern regions of the US also contributed to the decline, and may have been greater if various Federal and State programs had not provided incentives for private landowners to plant trees (Smith et al., 2009).

In 2007, total grazing land, which is comprised of cropland pasture, grassland pasture and range, and forest land grazed, accounted for 777 million acres (Nickerson et al., 2011). This value was the lowest amount since the ERS’s “Major Land Uses” series began in 1945; total grazing land declined by about 243 million acres (~24%) between 1949-2007. Over the most recent five year period (2002-07), cropland pasture declined

by another 26 million acres, while the estimated acreage of grassland pasture and range increased by 27 million acres. These offsetting fluctuations are in large part due to methodological changes instituted in the Census of Agriculture for estimating cropland pasture.

Overall, the trends for total cropland acreage has remained relatively constant since World War II, but has declined slowly in recent decades. A drop from 478 million acres in 1949 to 444 million acres in 1964 was mostly the result of acreage reduction programs associated with eliminating surplus production (Nickerson et al., 2011).

Cropland acreage was at or above 455 million acres in each census year between 1969-1997. Between 1997 and 2002, total cropland dropped 13 million acres (~3%) to 442 million acres, and then dropped another 34 million acres (~8%) from 2002 to 2007. Most of this decrease, i.e. 26 million acres, can be explained by changes in operational assumptions for estimating cropland pasture. However, with the change in methodology, the estimate of total cropland acres is below any previous estimate since the ERS began.

According to the USDA's 1997 National Resource Inventory (Alig, R., et al. 2003), 11 million acres of US forest, cropland and open space were converted to urban and other developed uses between 1992-1997. Forest land was the largest source of land converted to developed uses, eg urbanization. Additional conversion to urban and other developed uses is expected in the next 50 years as the US population is projected to increase by 120 million people; the fastest population growth is projected in the West and South. Growth in population and income increase the demands for use of land in residential, urban, transportation and related uses. Therefore, an overall net loss in forest area in the US has occurred since the early 1950's as a consequence of a combination of

factors, which in the most recent decades has been mainly conversion to urban and developed uses.

2.5 Which Types of Land Are More Useful in Biomass Harvest?

Some types of land produce greater raw biomass harvests (tonnage per acre) than others. One of the major reasons for this distinction is associated with human resources, eg although forest land is much larger than agricultural land, agricultural land has a greater biomass resource potential because of a higher level of human management. However, high productivity doesn't necessarily translate into sustainability.

Forestlands, especially those held publicly, will always be managed less intensively than agricultural lands because forests are expected to provide multiple benefits that include wildlife habitat, recreation, and ecological and environmental services (Perlack et al., 2005). Contrarily, active cropland, and to a lesser extent idle cropland and cropland pasture, is intensively managed, with crops and management practices changing on a year-to-year basis with land moving in and out of active production.

Forest land is also more difficult to harvest in comparison to agricultural land because of access issues. For example, roads and pathways in forest land are often dictated by rough terrain that is not conducive for optimizing the harvest of raw biomass. Trucks, large equipment and other forms of machinery are difficult to utilize if no convenient or well-prepared access routes exist deep into the forest. This lack of access and the inability to use large equipment increase the energy input for harvesting. If the

level of input is large relative to the return on value, it is more beneficial to operate or harvest elsewhere.

2.6 Sectors of Available Biomass Residues

Because solid biomass can be produced from so many different forms of residues, they have been classified into three main categories. These categories consist of agricultural biomass, forest or wood biomass, and energy crop biomass (USDOE, 2011). These categories are not universal, but most groups involved in biomass utilization efforts stay relatively close to them. They do not comprise of the entire spectrum of available biomass residue but make up an overwhelming majority. The fact that it is difficult to classify all the types of biomass residue may demonstrate the unbelievable potential for biomass. One of solid biomass's many advantages is that it can be developed from so many sources, some of which may still be undiscovered.

2.6.1 Agricultural Biomass

Agricultural biomass is predominantly crop residues that are considered waste from harvesting crops such as barley, canola, corn, cotton, dry beans, flax seed, oats, peanuts, peas, potatoes, rice, rye, safflower, sorghum, soybeans, sugar cane, sunflower, and wheat. These residues are just a few of the most abundant sources of crop residue. several others exist. For example, residues could include animal waste and fats although they are such a small portion of the overall resource base, and animal manure (waste) can be best utilized as a fertilizer to replenish the soil as opposed to being used for solid biomass.

2.6.2 Forest or Wood Biomass

Forest biomass consists of several key contributors such as forest residue, unused primary mill residues, secondary mill residues and urban wood wastes. Forest residues are comprised of logging residues and other removals; logging residues are the unused portions of trees cut, or killed by logging, and left in the woods. Other removals are considered trees cut or otherwise killed by cultural operations (e.g. pre-commercial thinning, weeding, etc.) or land clearings and forest uses that are not directly associated with round wood product harvests (Milbrandt, 2005). Forest thinning operations are typically designed to reduce risks and losses from catastrophic fires and improve forest health, but also are used for harvest of raw biomass (USDoE, 2011).

Primary mill residues are composed of wood materials of any size and bark generated at manufacturing plants (primary wood-using mills) when round wood products are processed into primary wood products like slabs, edgings, trimmings, sawdust, veneer clippings and cores, and pulp screenings (Milbrandt, 2005). Secondary mill residues include wood scraps and sawdust from woodworking shops such as furniture factories, wood container and pallet mills, and wholesale lumberyards.

Urban wood waste residues consist mostly of woody components derived from Municipal Solid Waste (MSW), and construction/destruction (C&D) waste wood. The MSW source consists of a variety of items, ranging from organic food scraps to discarded furniture, packaging materials, textiles, batteries, appliances, yard clippings and other materials. C&D wood waste is accumulated during the construction of new buildings and

structures, the repair and remodeling of existing buildings and structures, and the demolition of existing buildings and structures (USDoE, 2011).

2.6.3 Energy Crop Biomass

Dedicated energy crops (switch grass, willow, hybrid poplar, etc.) can often be economically grown on land that is not suitable for conventional crops and can provide erosion protection for land within agricultural set asides or the Conservation Reserve Program (CRP). The CRP is a voluntary program for agricultural landowners, and is administered by the USDA Farm Service Agency. It provides technical and financial assistance to eligible farmers and ranchers to address soil, water and other related natural resource concerns on their lands (Milbrandt, 2005).

2.7 Assumptions Made to Calculate Abundance of Biomass

To quantify the availability of raw biomass in units of dry tonnes per year and the economics of its production and use, assumptions have to be made that deal with a wide range of factors, like available man hours for harvest, projected precipitation patterns, pricing of biomass per tonne, pricing of materials currently made out of biomass residues, political policy, economic environment and unforeseen issues that could affect biomass supply. Therefore, it is difficult to achieve significant accuracy of the overall abundance of available biomass and its operational sustainability.

One approach that has been used to gain an understanding of biomass's potential abundance is to assume a best case scenario of acquiring biomass. This assumption takes the maximum value of biomass abundance to be comprised of the sum of residues that are currently being used and the residues that are being discarded. The available unused

biomass is the just the sum of all residues that have no current use or perceived economic value, and are being discarded. These two values, i.e. amounts of residue used and not used, would still include many assumptions that may affect accurate predictions but involve the least number of assumptions and, therefore, are the easiest to accurately quantify.

Once again, biomass is such an enticing form of an energy commodity because it can be created, harvested, or recycled from so many resources. The resources that create biomass not only have potential as an energy commodity, but also for a multitude of other purposes and products. It is then logical to ask the question, “Where are certain resources more valuable?” After a discussion of the allocation of resources is brought up, an immense amount of economic ramifications must be addressed; supply and demand curves have to be adjusted for the wide array of markets that potentially will be affected; and, social, political and economic policy have to updated to ensure regulation and to increase economic viability. With all of these unforeseeable impacts on the marketplace, it is difficult to make assumptions that would accurately project an available biomass value. Hence, projections typically are based on currently used and unused biomass residues, values of which also give the best case and worst case scenario values for analyses.

2.8 Quantity of Biomass Generated Annually

In a report titled, “A Geographic Perspective On the Current Biomass Resource Availability in the United States” (Milbrandt, 2005) by the National Renewable Energy Laboratory of the U.S. Department of Energy, currently used and unused biomass

residues were assessed and projected on a basis potential available biomass residue that would not be used for any other application. The unit of measure in the report was bone dry tonnes per year. Their assumptions for each type of residue and their findings for contemporary unused, available raw biomass residue are discussed in the following.

2.8.1 Agricultural Biomass

2.8.1.1 Crop Residue

The following crops were included in the analysis: corn, wheat, soybeans, cotton, sorghum, barley, oats, rice, rye, canola, beans, peas, peanuts, potatoes, safflower, sunflower, sugarcane, and flaxseed (Milbrandt, A., 2005). The quantities of crop residues that could be available in each county were estimated using total grain production, crop to residue ratios, moisture contents, and the amount of residue left on the fields for soil protection, grazing and other agricultural activities. All estimates were developed using the total grain production by county for 2002 as reported to the U.S. Department of Agriculture. Although the amount of biomass compost that must remain on fields for erosion control differs by crop type, soil type, weather conditions and the tillage system used, it was assumed that 30% residue cover was practical for soil protection. The consumption of stover during animal grazing was estimated to be between 20%-25%, and it was assumed about 10%-15% of the crop residue was used for other purposes such as bedding, silage, etc. Using these assumptions, estimates and data, it was found that about 35% of the total residue could be collected as biomass, making the total available crop residue of 157,194,000 Bone Dry Tonnes per year within the United States.

2.8.2 Forest or Wood Biomass

2.8.2.1 Forest Residue

Forest residue includes logging residues and other removals, where logging residues are considered the unused portions of trees cut, or killed by logging, and left in the woods (Milbrandt, 2005). Other removals are considered trees cut or otherwise killed by cultural operations (e.g. pre-commercial thinning, weeding, etc.) or land clearings and forest uses that are not directly associated with round wood product harvests; it does not include volume removed from the inventory by reclassification of timberland to productive reserved forestland.

The data on forest residues by county was derived from the USDA Forest Service's Timber Product Output database for 2002 and data on the volume (cubic feet) of logging residues and other removals by county was collected from the Timber Products Output Mapmaker version 1.0 (McKeever, 1998). The following volume conversion factor was used for computations:

1 mcf= 0.0125 MBDT where 1 mcf= 1000 ft³ and 1 MBDT = 1000 bone dry tons

After these pertinent assumptions were made, the total availability of total forest residues was 56,612,000 Bone Dry Tonnes per year within the United States.

2.8.2.2 Primary Mill Residue

Primary mill residues are composed of wood materials (coarse and fine) and bark generated at manufacturing plants (primary wood-using mills) when round wood products are processed into primary wood products, like slabs, edgings, trimmings,

sawdust, veneer clippings and cores, and pulp screenings. It includes mill residues recycled as byproducts as well as those left un-utilized and disposed as waste (Glenn, 1998).

The total value of primary mill residue sums those residues recycled as byproducts (fuel or fiber) as well as those left un-utilized and disposed as waste. The unused value depicts mill residues not being used for any byproduct and includes mill residues burned as waste or landfilled.

Primary mill residue data by county was derived from the USDA Forest Service's Timber Product Output database for 2002 (Milbrandt, 2005). Data on the volume (cubic feet) of primary mill residues by county was collected from the Timber Products Output Mapmaker version 1.0. The following volume conversion factor was used for computations (NEOS Corp., 1998):

$1 \text{ mcf} = 0.0125 \text{ MBDT}$ where $1 \text{ mcf} = 1000 \text{ ft}^3$ and $1 \text{ MBDT} = 1000 \text{ bone dry tons}$

For the US, the total primary mill residues were 77,125,000 Bone Dry Tonnes per year, of which 1,606,000 Bone Dry Tonnes per year were considered unused.

2.8.2.3 Secondary Mill Residue

Secondary mill residues include wood scraps and sawdust from woodworking shops such as furniture factories, wood container and pallet mills, and wholesale lumberyards (Milbrandt, 2005.). The data on the number of businesses by county was gathered from the U.S. Census Bureau, 2002 County Business Patterns and data on the size of companies (number of employees) and assumptions on the wood waste generated

by a company were derived from Wiltsee's study (Graham et al., 1996). According to this publication, a pallet and lumber company can be expected to generate about 300 tons/year of secondary mill residue whereas a small woodworking company typically would generate between 5-20 tons/year of wood waste. The results for the US are then 2,615,000 Bone Dry Tonnes per year of available total secondary mill residues.

2.8.2.4 Urban Wood Residue

Urban wood residues that were considered in this study were MSW wood from chips, pallets and yard waste; utility tree trimming and/or private tree companies; and construction and demolition wood.

The data on MSW wood and yard waste per capita by state was collected from the BioCycle Journal (NEOS Corp., 1994). Then, county population data (U.S. Census Bureau, 2000) with assumptions from Wiltsee's study were used to estimate the total MSW generation by county. Accordingly, wood is between 3% and 5% of total MSW, depending on whether wood and yard waste separation and recycling is practiced.

Utility tree trimming and/or private tree companies use data on forestry support activities and electric power distribution business establishments by county, information for which is gathered from the U.S. Census Bureau, 2002 County Business Patterns. The assumption that a single tree service crew typically generates about 1,000 tons/year of wood waste (Schmidt et al., 2000) was used to calculate the wood waste generated by utility tree trimming and private tree companies. The amount of construction/demolition (C/D) wood was estimated using the following equation adopted from Wiltsee's analysis (Wiltsee, G., 1998): $C/D \text{ wood (tons/year)} = 0.09 * \text{Population}$

Milbrandt's (Milbrandt, 2005) results while using the Wiltsee study to base their assumptions determined the United States total urban wood residues were 30,902,000 Bone Dry Tonnes per year.

2.8.3 Energy Crop Biomass

2.8.3.1 Conservation Reserve Program (CRP) Land Residue

Data on the CRP acres by county was gathered from the USDA's Farm Service Agency, and the amount of energy crops that could be potentially grown and harvested on CRP lands as calculated by Milbrandt (Milbrandt, 2005). Data also have been developed by the Oak Ridge National Laboratory using a median estimated yield (dry tonnes/acre/yr) for un-irrigated energy crops (switchgrass and short rotation woody crops such as willow and hybrid poplar). This report's results for the US total CRP land residues were divided into two categories, switchgrass and willow/hybrid poplar. Switchgrass was estimated at 83,572,000 Bone Dry Tonnes per year and willow/hybrid poplar was estimated at 61,323,000 Bone Dry Tonnes per year.

Figure 2.7 shows a side by side comparison for the three main types of biomass residues and their respective tonnes per year that are currently unutilized. Overall, the total amount of currently unutilized biomass residues is 393,824,000 tonnes per year with agricultural biomass making approximately 40% of that total. The second most abundant form of available biomass is from energy crops associated with the Conservation Reserve Program lands - ~37%. Finally forest biomass comprises the least of the three forms of available biomass with approximately 23%. Figure 2.8 shows a more detailed comparison of the origin of unutilized biomass residues.

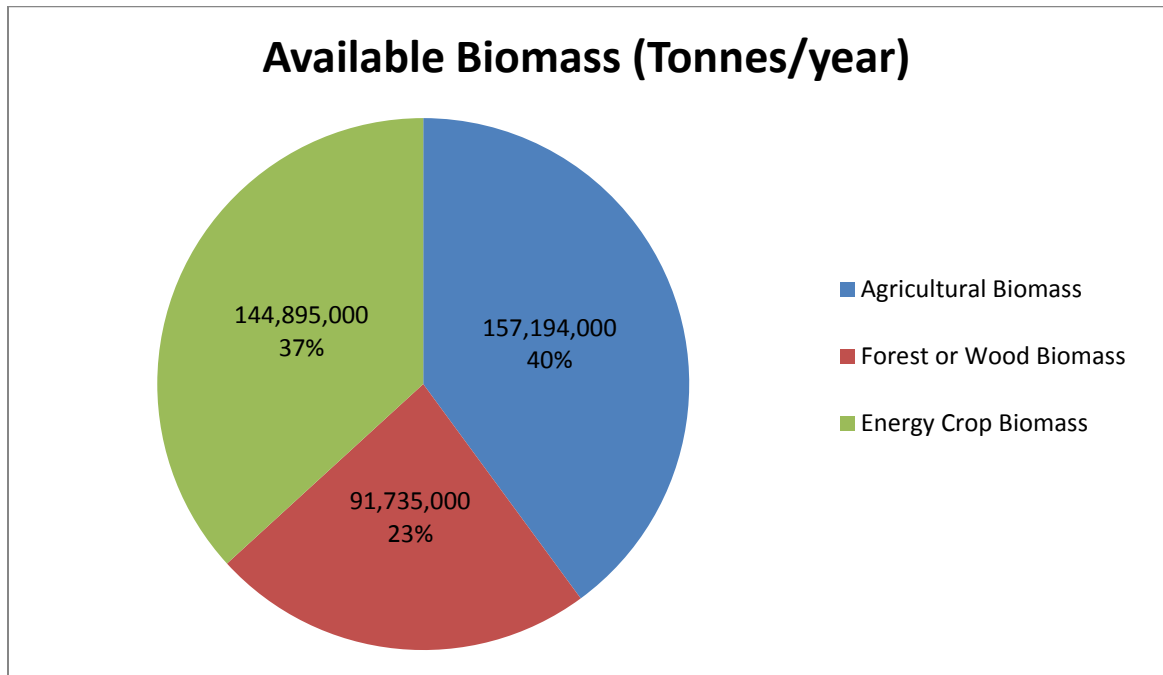


Figure 2.7: Available biomass residues organized by the type of residue. Source: (Milbrandt, 2005)

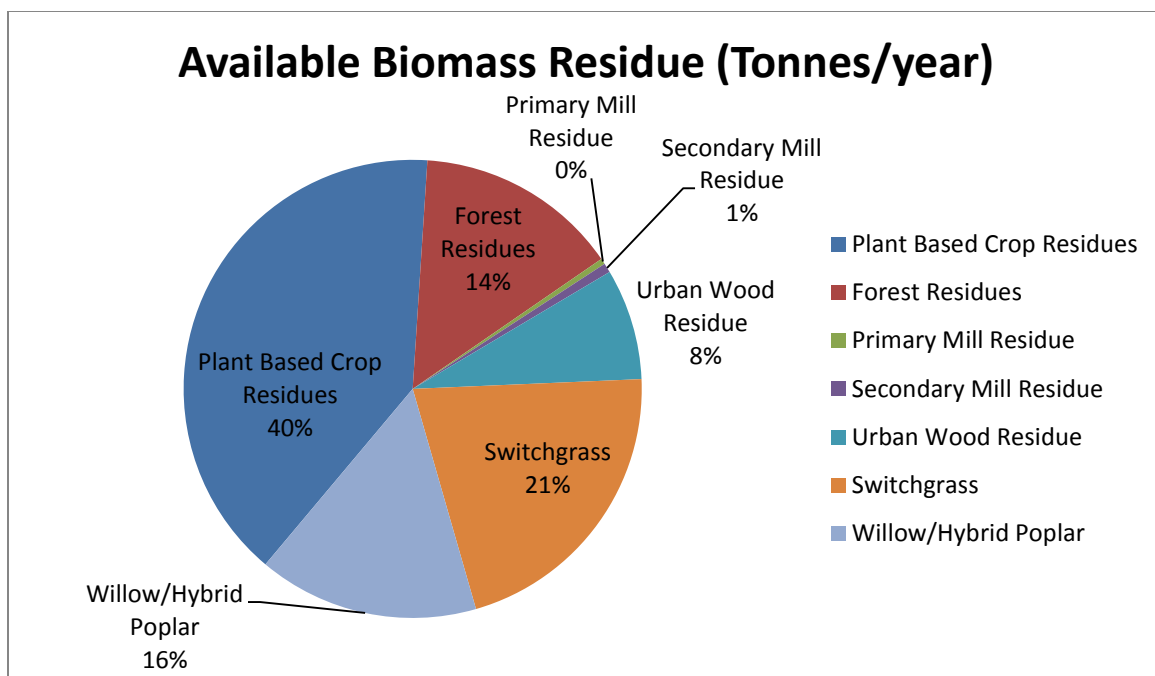


Figure 2.8: Available biomass residue organized by where the residue originates.

Source: (Milbrandt, 2005)

2.9 Potential Strain on Food Supply and Other Markets

Because a majority of available biomass comes from agricultural residues, one must consider if the harvesting of the residues would impact food supply and other markets that agriculture penetrates. Agriculture casts a large shadow in the US marketplace and any additional or unbalancing costs in the production of agricultural products can impact or drive pricing fluctuations in other marketplaces. In the US, the primary, shadow-producing crop is corn. According to the National Agricultural Statistics Service, which works in accordance with the United States Department of Agriculture, approximately 12.4 billion bushels of corn was harvested in 2011 in the US on 91.9 million acres (USDOA, 2012). The reason for such a large corn production of corn is its wide array of application possibilities and potential. Although it is mostly used for

livestock feed and ethanol biofuel production, its organic composition can be altered for a variety of other critical products such as fillers for plastics, packing materials, insulating materials, adhesives, chemicals, explosives, paint, paste, abrasives, dyes, insecticides, pharmaceuticals, organic acids, solvents, antifreeze and soaps. If the supply and demand curve of corn was impacted, then all the derivatives of it also would see pricing fluctuations. This type of effect may be expected to ripple through the marketplace if agricultural residues were to become an important commodity for energy production.

The Energy Independence and Security Act of 2007 intends to increase the supply of alternative fuels by setting a mandatory Renewable Fuel Standard (RFS) requiring transportation fuel sold in the U.S. by 2022 to contain a minimum of 36 billion gallons of renewable fuels, including advanced and cellulosic biofuels and biomass-based diesel (USDOE, 2009). President Obama has acknowledged support for advanced biofuels as part of his commitment to “invest in a clean energy economy that will lead to new jobs, new businesses and reduce our dependence on foreign oil.”

Due to the Energy Independence and Security Act of 2007, an increasing amount of the corn harvest is becoming to be allocated to the production of biofuels for transportation. This reallocation of resources will potentially create a power struggle between utilizing the corn harvest for meeting biofuel demand or for meeting the demands of the various markets corn serves otherwise. One solution to these diverse needs would be to simply grow more corn; two options are available to accomplish this feat. Farmers would need to either use more land to plant their crop or continually grow crops on the same land. Both options would increase the total amount of harvested corn, which in turn would raise the supply to meet the demand and lower prices in all sectors,

and also create more solid biomass residue. This residue could be used by farmers as a way to re-fertilize their fields or as maintenance for preventative soil degradation, but also it could be collected and potentially sold as a source of biomass energy.

The scope of this paper deals with solid biomass, but the food supply and how it is affected is directly linked to making biofuels for transportation purposes. Currently, biofuels primarily are made from the corn kernels rather than from the stalks and husks of the corn. Biofuels for transportation could be made from these waste products produced during corn harvesting, but the technology for it is not as advanced as that for using the corn kernel by itself. However, a substantial portion of the available solid biomass is within these wastes and food supply prices would not be directly impacted by its harvesting. Solid biomass residue is created regardless of how a crop is applied or used in the marketplace.

2.10 Carbon Cycle

Carbon (C), the fourth most abundant element in the universe, is considered the building block of life (Remer, 2001). From fossil fuels to DNA, carbon is the fundamental element that anchors all organic substances. On Earth, carbon cycles through the land, ocean, atmosphere and the Earth's interior through a major biogeochemical cycle. This biogeochemical cycle includes the circulation of chemical components through the biosphere, from or to the lithosphere, atmosphere, and hydrosphere. Following carbon in this cycle is known as the carbon cycle. It can be divided into two categories: the geological, which operates over large time scales

(millions of years); and the biological/physical, which operates over shorter time scales (days to thousands of years).

2.10.1 Geological Carbon Cycle

Billions of years ago, the carbon content of the Earth steadily increased as planetesimals (small bodies that formed from the solar nebula) and carbon containing meteorites bombarded the Earth's surface (Remer, 2001). Since those times, a process called weathering, which takes carbonic acid (a weak acid derived from the reaction between atmospheric CO₂ and water) has slowly but continuously combined with calcium and magnesium in the Earth's crust to form insoluble carbonates (carbon-containing, inorganic chemical compounds). Then, through the process of erosion, the carbonates are washed into the ocean and eventually settle to its bottom. The cycle continues as these materials are drawn into Earth's mantle by subduction where tectonic plates descend beneath one another at the edges of continental plates known as fault lines. The carbon is then returned to the atmosphere as CO₂ during volcanic eruptions. The balance between weathering, erosion, subduction, and volcanic eruptions is the geological carbon cycle. It has been controlling atmospheric CO₂ concentrations over time periods of hundreds of millions of years.

The oldest geologic sediments suggest that, before life evolved, the concentration of atmospheric CO₂ may have been one hundred times that of the present, providing a substantial greenhouse effect during a time of low solar output. On the other hand, ice core samples taken in Antarctica and Greenland have led scientists to hypothesize that

atmospheric CO₂ concentrations during the last ice age (20,000 years ago) were only half of what they are today.

2.10.2 Biological Carbon Cycle: Photosynthesis and Respiration

Biology also plays an essential role in the movement of carbon in and out of the land and ocean through the biological functions of photosynthesis and respiration (Remer, 2001). Nearly all forms of life on Earth depend on the production of sugars from solar energy and CO₂ (photosynthesis) and the metabolism (respiration) of those sugars to produce the chemical energy that enables growth and reproduction. During photosynthesis, green plants absorb solar energy and remove CO₂ from the atmosphere to produce carbohydrates (sugars). Animals effectively “burn” these carbohydrates through the process of respiration, which is essentially the reverse of photosynthesis. Respiration releases the energy contained in sugars for use in metabolism and reduces the carbohydrate “fuel” back to CO₂. This circulation of carbon throughout photosynthesis and respiration processes is known as the biological carbon cycle. The amount of carbon taken up by photosynthesis and released back to the atmosphere by respiration each year is 1,000 times greater than the amount of carbon that moves through the geological cycle on an annual basis.

Photosynthesis and respiration also play an important role in the long-term geological cycling of carbon. The presence of land vegetation enhances the weathering of soil, leading to a slow but long-term uptake of CO₂ from the atmosphere. In the oceans, some of the carbon taken up to make shells of calcium carbonate (CaCO₃) settles to the bottom (after an animal dies) to form sediments. During times when

photosynthesis exceeded respiration, organic matter slowly built up over millions of years to form coal and oil deposits. All of these biologically facilitated processes represent a removal of CO₂ from the atmosphere and storage of carbon in geological sediments. A more illustrative view of the carbon cycle and how each component interacts with one another is given in Figure 2.9.

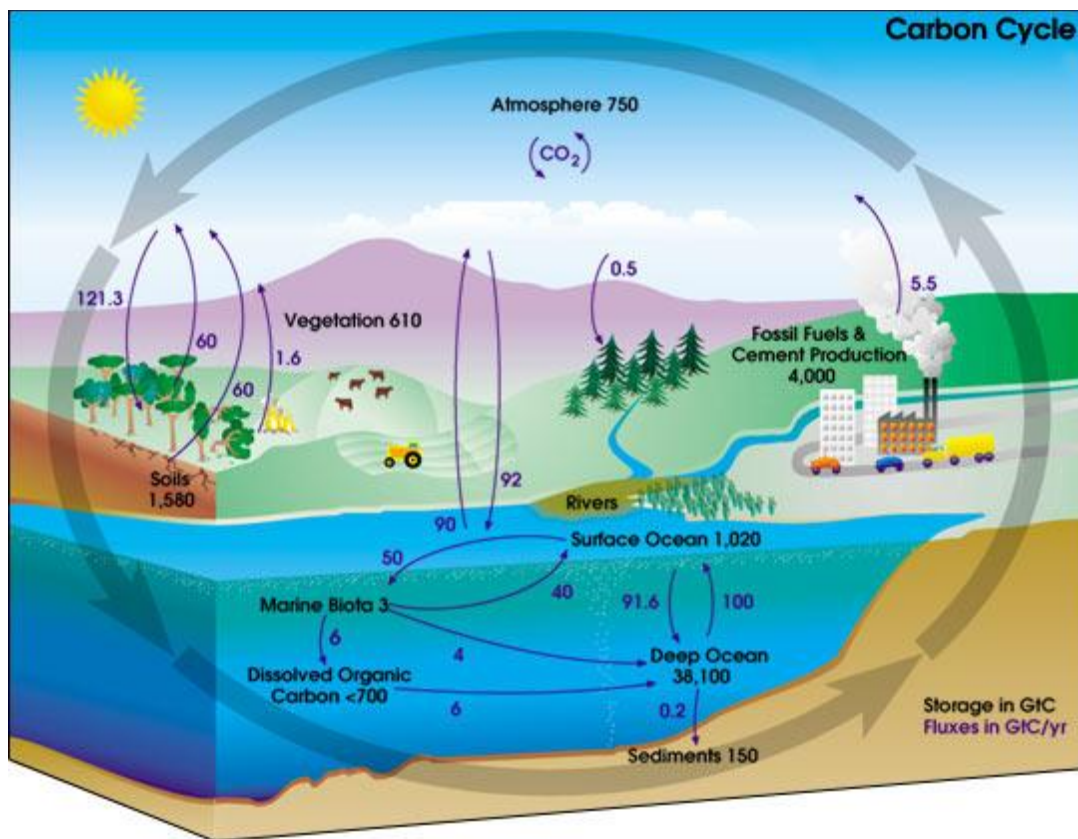


Figure 2.9: Visualization of the Carbon Cycle. Source: (Remer, L. 2001)

2.10.3 Carbon Neutral

The carbon cycle is a continuous process that is incredibly complex. Carbon can be exchanged during so many different modes of interaction between the Earth's

geological and biological cycles that it is too difficult to simulate into a simplified model. The time domain over which the carbon exchange occurs is just as complex. The geological component of the carbon cycle can take place over millions of years, whereas the biological component of the carbon cycle typically takes place over an organism's lifespan; the timescale of the biological component is minuscule relative to the geological component.

Carbon neutral is a term that describes the concept of having no net flux of carbon content throughout the biosphere. This means that carbon is free to be exchanged and flow throughout the biosphere, but every entry into the biosphere must always have the same amount of carbon exiting. Our planet is perpetually changing and evolving, so the concept of having an overall carbon neutral balance is impossible to achieve. The forces of nature - through the shifting of plate tectonics, volcanic eruptions and severe weather patterns - all impact the carbon neutral concept.

The concept of a carbon neutral interaction in terms of human endeavors is primarily discussed with respect to the burning of fossil fuels. Since it is impossible for nature to be carbon neutral on its own, it is difficult to accurately measure mankind's effect or "carbon footprint" on the carbon cycle. One approach to this, however, is to measure emissions caused by the consumption of fossil fuels. For example, if no carbon is released during the combustion of a fuel, the process is said to have been carbon neutral. Especially when burning the predominant fossil fuel - coal, carbon neutrality does not exist.

Achieving carbon neutrality when burning coal is extremely difficult in a technical sense, and is ineffective in a relative time domain sense. For example, coal can be simplified as being carbon buried underground and not been exchanged through the carbon cycle for millions of years. Without human interaction, it would have stayed underground for millions of years in the future; with human interaction, all of a sudden it is burned and released into the atmosphere, thereby adding another entity into the ongoing carbon cycle.

The burning of densified biomass is much more carbon neutral than the burning of coal. Biomass is organic matter that was created from CO₂ within the atmosphere. Once the densified biomass is burned, its carbon emissions will go back into the atmosphere. The carbon's transition in form with respect to time for the burning of biomass can be considered carbon neutral relative to the burning of coal.

2.10.3.1 Comparison of Coal Emissions to Biomass Emissions

An important factor when considering densified biomass in favor of coal is the comparison of their greenhouse gas emissions. CO₂ is the key player in this conversation but sulfur oxide and nitrogen oxide emissions are important as well.

When comparing CO₂ emission levels per kg of fuel consumed during combustion, densified biomass produces lower CO₂ levels than coal. However, densified biomass has a smaller energy density than coal, which means more densified biomass than coal would have to be consumed to create the same amount of energy. As explained by Evans, (Evans, 2008): “Fossil fuels will split the total CO₂ emissions between the point of manufacture and the point of use with densified biomass fuels emitting less CO₂

at the point of use and more at the point of manufacture.” Analyzing CO₂ emissions further would be dependent upon the application and the amount of energy necessary to complete such application.

Biomass typically has a very low sulfur content compared to that of most coals and oil (Evans, 2008). The sulfur content in wood is about 0.01% dry matter (dm), in bark 0.02-0.1% dm and in needles 0.04-0.2% dm. When burning biomass, the total amount of sulfur dioxide emissions will be very small as compared to coal. For example, coal can emit 20,000 mg sulfur dioxide per kg of coal whereas wood emits 30 mg of sulfur dioxide per kg of wood. Hence, the combustion most biomass would not require any specific sulfur emissions control equipment.

Also, biomass typically has a low nitrogen content. The dry mass of wood and bark contain only 0.1-0.5% nitrogen while the content of needles is higher at 0.5-2% dm. In comparison, the nitrogen content of coal varies from 0.8 to 1.2%.

2.10.4 Strategies to Balance the Carbon Cycle

By understanding the carbon cycle and the fluctuations in atmospheric CO₂ concentrations that fossil fuel emissions are creating, many people have become proactive in trying to sequester carbon from the atmosphere or from combustion sources in an attempt to restore carbon cycle balance. A most rudimentary but natural strategy to help restore the “carbon budget” would be to replant forest plants and other vegetation that have been harvested for lumber or harvested during for farming. A simple approach would be to replant a tree for every tree that is removed; this approach is considered a “closed loop”. The United States government created legislation to push this “closed

loop” strategy in the 1992 Energy Policy Act which set up a tax credit (for taxable corporations) and a production payment (for tax-exempt public agencies) for the use of “closed-loop biomass” in new energy production facilities (Hughes, 2000).

A recent, more innovative approach to balance the carbon cycle is known as bio-char, which is simply charcoal or biomass derived carbon black. The application of bio-char to soil has been proposed to establish a significant, long-term sink for atmospheric CO₂ (Lehmann et al., 2006). Simply put, bio-char is carbon that was recently in the atmosphere and phase shifted to being a part of a plant’s decomposing composition. Allowing the biomass to decompose, the carbon will quickly phase change in the carbon cycle and is not necessarily “locked in” to one phase or the other. However, by charring the biomass, with production techniques similar to charcoal, the carbon in biomass is locked to a solid state and will be difficult to quickly phase into the atmosphere again. This bio-charring technique is conversely relative to the creation of greenhouse gases by burning fossil fuels.

Bio-char has the potential to both reduce greenhouse gas emissions and increase the sequestration of greenhouse gases, and its application to soils can deliver immediate benefits through improved soil fertility and increased crop production (Lehmann et al., 2006). Conversion of biomass carbon to bio-char instead of burning it leads to a sequestration of about 50% of the initial carbon compared to less than 3% after burning, and its biological decomposition occurs over a relatively long period (<10–20% after 5–10 years), yielding a semi-stable soil carbon.

2.11 Political and Economic Policy

Political and economic policies are pivotal to the success of densified biomass fuel penetrating the marketplace as a sustainable and renewable energy source. Coal's ability to deliver large amounts of inexpensive energy is difficult to replace, but its unhealthy environmental impacts are increasing and it is a finite resource. Oppositely, densified biomass fuels are sustainable and carbon neutral that could produce enough energy to be utilized in conjunction with coal. However, it will be necessary to promote densified biomass through governmental incentives that give electrical power companies the ability to compete in the market dominated by 'cheap' coal while promoting a renewable energy source. The "bottom line" in business is the primary concern for viability; if no economically beneficial reason exists to switch to an environmentally friendly fuel such as densified biomass, then no company ever will.

Governmental incentives must be fair and accurately accessed. Tax payers' money should not be spent in vain just for government and politicians to say that certain amounts of energy are produced from clean, renewable sources. If incentives from legislature are too large, then tax payers will be paying for the power companies cost to run a business as opposed to the power companies paying for their own natural resources to run their business. In other words, tax payers would be paying on both ends of the operation - for the incentives to the power companies for using densified biomass, for the cost of what they were already paying for with just fossil fuels, and for the electricity itself. If incentives are too low, densified biomass will not succeed in the power production marketplace because the utility companies would be unable to make profits.

Densified biomass has not received as much attention as biofuels for transportation within federal legislation because of the dependence of the US on foreign oil and the impact that biofuels have on that dependence. However, at the fundamental level densified biomass is linked to liquid biofuels because both are or can be produced from the same types of plants; in the case of corn, the kernels can be used for liquid biofuel production and the stover for densified biomass production. Also, the land that is dedicated to growing feedstock for liquid biofuels production could be the same land from which raw biomass residue is harvested for densified biomass production. In other words, it seems plausible to declare that federal legislation providing incentives to produce liquid biofuels was not expansive enough, or without the necessary foresight, to also provide incentives to produce densified biomass. Hence, given below are descriptions of some of the most prominent pieces of federal legislature that affect the market of densified biomass as well as biofuels for transportation.

2.11.1 The 1992 Energy Policy Act

The 1992 US Energy Policy Act established a tax credit (for taxable corporations) and a production payment (for tax-exempt public agencies) for the use of “closed-loop biomass” in new energy production facilities. This credit, found in Section 45 of the Internal Revenue Code, has not been used because no dedicated energy crop has yet been converted to electric power or liquid fuel in a new energy conversion facility (Hughes, 2000).

The fact that the “closed-loop biomass” tax credit has never been used is due, in part, to a poor definition of what constitute a “closed loop biomass” and a dedicated

energy crop. The logical misconception was that only biomass which has been grown for the sole purpose of fuel production could reduce greenhouse gases and be renewable. This position is simply not the case because biomass residue can be collected from a variety of sources that were grown with no intention of them being for biomass energy production. Those residues that would typically go unused would not classify as a “closed loop” biofuel or dedicated energy crop because they were grown as an agricultural crop and therefore unable to receive credit authorization.

Any biomass feedstock that comes from a source that is being replaced at least as fast as it was originally grown is considered to be used in a “closed loop”. Contrary to the phrasing of Section 45, it is not necessary that the biomass is grown as a dedicated energy crop for the carbon to be 100% recycled with no net addition to the atmosphere. Nevertheless, the wording of Section 45 only provides eligibility for tax credits or production payments if a crop is grown strictly as an energy crop. Clearly, the bioenergy community has interest in the revision of Section 45 to permit the use of biomass wastes as a fuel for the production of electricity to meet the closed loop definition. Some lobbying has been done on this point, but its success has not been productive at this point.

2.11.2 The 2002 Farm Bill

Title IX of the 2002 Farm Bill, commonly known as the Energy Title, created a series of provisions to expand production of bioenergy and bioproducts and promote energy conservation (USDOA, 2012). Section 9006 established the Renewable Energy Systems and Energy Efficiency Improvements Program. It authorized USDA loans, loan guarantees, and grants to farmers, ranchers and rural small businesses to purchase

renewable energy systems and to make energy-efficient improvements. This program strives to help rural America reduce energy consumption and costs; assist the U.S. in meeting its energy needs; stimulate rural economic development; create new jobs; and develop new uses for agricultural products and waste materials. Congress provided \$23 million to fund the program in each of the 2003, 2004, 2005 and 2006 fiscal years. Section 9006 grant requests could not exceed 25% of the eligible project costs, grant applications for renewable energy systems were to be no more than \$500,000, and applications for energy efficiency improvements could not be more than \$250,000. In the fiscal years of 2003 and 2004, a total of \$44 million in grants was awarded to 281 agricultural producers and rural small businesses in 33 States.

Section 9008 reauthorized the Biomass Research and Development Act of 2000 and provided \$75 million in funding to the Commodity Credit Corporation for 2002 through 2007. In the last 3 years, the program has awarded \$40.8 million for 39 research, development and demonstration projects on biobased products, bioenergy, biofuels, biopower and related processes.

In addition to these two farm bill programs, Section 9002 provided funding for the testing of biobased products and established a Federal procurement program for biobased products. Section 9004 established the Biodiesel Fuel Education Program to make competitive grants to eligible entities to educate governmental and other entities, and the public, about the benefits of biodiesel fuel use.

The Bioenergy Incentives Program operated by the Commodity Credit Corporation provided incentive payments to encourage increased purchases of eligible

commodities for the purpose of expanding production of ethanol and biodiesel and supporting new production capacity of these biofuels. The program provided over \$500 million in awards between 2001 and 2005. Up to \$60 million was available for the program in the 2006 fiscal year.

2.11.3 The Energy Policy Act of 2005

The Energy Policy Act of 2005 placed a great deal of emphasis on the development of biofuels for transportation as opposed to biomass fuels for power production. With an emphasis on biofuels, raw biomass residue could become more available from the efforts dedicated to growing energy crops but power companies have no incentives to adopt the use of biomass as a primary or even supplementary fuel source.

Title XVII called for the Secretary of Energy to establish a program that provided guaranteed loans for energy projects which "employ new or significantly improved technologies as compared to commercial technologies", including renewable energy technologies (USDOE, 2012). Section 932 required the Secretary of Energy to solicit proposals for cellulosic biorefinery demonstration projects that could produce biofuels, in addition to chemicals power, ensured geographical distribution of projects that could be replicated and did not require Federal funding after construction reached completion.

Section 1501 established a Renewable Fuel Standard (RFS) that mandated all gasoline sold in the US to contain 7.5 billion gallons of renewable fuels by 2012. Furthermore, by 2013, the renewable fuels used should contain 250 million gallons of fuel derived from cellulosic biomass. Section 1342 provided a tax credit equal to 30% of the cost alternative refueling property, up to \$30,000 for business property. Qualifying

alternative fuels are natural gas, propane, hydrogen, E85, or biodiesel mixtures of B20 or more. Buyers of residential refueling equipment can receive a tax credit for \$1,000.

Section 1344 extended the existing tax credit for biodiesel producers through 2008, and for the Volumetric Ethanol Excise Tax Credit (VEETC) through 2010. The credits were \$0.51 per pure gallon of ethanol blended or \$0.51 per percentage of ethanol blended (i.e., E10 is eligible for \$0.051/gal; E85 is eligible for \$0.4335/gal); \$1.00 per gallon of agro-biodiesel; and \$0.50 per gallon of waste-grease biodiesel. If the biodiesel fuel was used in a mixture, the credit amounts to \$0.05 per percentage point of ethanol or agro-biodiesel used or \$0.01 per percentage point of waste-grease biodiesel.

Section 1345 allowed a tax credit of \$0.10 per gallon to small agro-biodiesel producers for up to 15 million gallons and, to be eligible, a producer must produce less than 60 million gallons of biodiesel per year. Small ethanol producers were allowed a \$0.10 per gallon production income tax credit. Also, Section 1347 changed the definition of a "small ethanol producer" to include a production capacity of up to 60 million gallons (instead of the up to 30 million gallons originally established by Congress in 1990).

2.11.4 The Energy Independence and Security Act of 2007

The Energy Independence and Security Act of 2007 was predominantly comprised of efforts to develop biofuels for transportation rather than biomass for power production. Section 207 authorized \$500 million for the fiscal years 2008 through 2015 for a grant program that: shall make awards to the proposals for advanced biofuels with the greatest reduction in lifecycle greenhouse gas emissions compared to the comparable motor vehicle fuel lifecycle emissions during calendar year 2005; and shall not make an

award to a project that does not achieve at least an 80 percent reduction in such lifecycle greenhouse gas emissions (USDOE, 2012).

Section 223 authorized \$25 million for each of fiscal years 2008 through 2010 for grants toward research, development, demonstration and commercial applications of biofuel production technologies in states with low rates of ethanol production. It also included low rates of production of cellulosic biomass ethanol, as determined by the Secretary. Section 224 amended Section 932 of the Energy Policy Act of 2005 by adding "The Secretary shall establish a program of research, development, demonstration, and commercial application for increasing energy efficiency and reducing energy consumption in the operation of biorefinery facilities." Section 234 authorized \$25 million for establishing a competitive grant program, in a geographically diverse manner, for projects submitted for consideration by institutions of higher education to conduct research and development of renewable energy technologies. Each grant made could not exceed \$2 million.

2.12 Solid Biomass Fuels Available in the Market

Biomass in its raw state, collected as a residue from operations in which it would have been discarded as an unutilized waste, is a difficult resource from which to produce energy. It is bulky, high in void fraction, and very low in transportation efficiency. Furthermore, it is relatively low in calorific value when compared to fossil fuels like coal. Therefore, the development of a transformational technologies are needed that convert raw biomass into high-value products.

Transformational technologies are available to convert raw biomass into a high-value forms of fuel for diverse applications. Factors such as manufacturing input costs, moisture content, product hardness, energy content, usage emissions and applications tend to guide raw biomass toward discrete forms of bio-carbonized densified fuel (BCDF).

When analyzing the operational procedures to manufacture raw biomass into BCDF sources one must understand two processes that are often used - pyrolysis and carbonization. Pyrolysis is the thermochemical decomposition of organic matter at elevated temperatures without the participation of oxygen. Carbonization is the conversion of organic matter into a carbon or carbon containing residue (Demirbas, 2001). Simply put, pyrolysis is a process used to change organic matter and carbonization is the final state of the organic matter; pyrolysis does produce organic matter with level of carbonization. Understanding how these two terms work together is necessary for understanding the varieties of densified biomass fuels available. Below are a few types of densified biomass fuels.

2.12.1 Charcoal

Mankind has been using wood for thousands of years to cook food, stay warm and make tools. Wood is combustible in harsh environments and abundant in many parts of the world, making it a great fuel source for early humans. Sixty percent of all wood taken from the world's forests is believed to be burnt as fuel - either directly or by first converting it into charcoal. The proportion of fuel wood used to make charcoal is

estimated to be around 25%, or about 400 million cubic meters per year throughout the world (FAO, 1983).

As mankind began working with metals, a need for higher fire temperatures was necessary. Man learned to manipulate wood as a natural fuel source into a form of bio-carbonized densified fuel, thus creating charcoal. Once wood was manufactured into charcoal, blacksmiths could raise temperatures of their furnaces to manipulate metals that would change history and eventually spark the industrial revolution.

Charcoal is the solid remaining when wood is carbonized or pyrolysed under controlled conditions in a closed environment such as a charcoal kiln (FAO, 1983). Control of the entry of air during pyrolysis or carbonization is accomplished to ensure the wood does not merely burn to ashes, as in a conventional fire, but decomposes chemically to form charcoal. Air is not required during pyrolysis, and advanced technologies for charcoal production do not allow any air to be admitted, resulting in higher yields since no wood is burned and a control of product quality is facilitated.

Once the pyrolysis is started, it is self-sustaining and produces considerable heat. The pyrolysis or thermal decomposition of the cellulose and lignin within wood does not start until the wood is raised to a temperature of about 300°C.

In traditional charcoal kilns or pits, some of the wood is burned to dry the remaining wood and raise the temperature of wood charge. However, success in increasing the yields of high quality charcoal has been accomplished by using the heat of pyrolysis, normally wasted, to raise the temperature of the incoming wood such that burning of wood does not occur. In general, additional heat is needed to replace heat

losses through the walls and other parts of the equipment. Furthermore, the combustible gases given off during carbonization can be burned to provide the extra heat needed to dry the wood. All carbonizing systems have higher efficiency when dry wood is used because the removal of water requires large inputs of heat energy.

Pyrolysis creates charcoal, consisting mainly of carbon with small amount of tarry residues, the ash contained in the original wood, combustible gases, and a number of chemicals mainly acetic acid and methanol. In addition, a large amount of water is given off as vapor during the drying and pyrolytic decomposition of the wood. When pyrolysis is completed, the charcoal, having arrived at a temperature of about 500° C, is allowed to cool without access of air. It is then safe to handle is ready for use (FAO 1983). Figure 2.10 shows charcoal in its final product state.

Several methods exist for manufacturing charcoal at large production capacities that are also economically friendly. Additionally, several types of kilns have been



Figure 2.10: Picture of Manufactured Charcoal Final Product

designed, fabricated and used that have minimal manufacturing input costs. Hence, making charcoal is a very popular option as a fuel supply for people in undeveloped areas of the world. However, the quality of the kiln has a huge impact on the quality of charcoal it produces; if it allows too much oxygen to contact the wood the product yield will suffer. Table 2.1 shows the effects of carbonization temperature on the quality of charcoal produced.

Table 2.1: Effect of carbonization temperature on yield and composition of charcoal.

Source: (FAO, 1983)

Carbonization Temperature	Chemical analysis of charcoal		Charcoal yield based on oven dry wood
	% of fixed carbon	% volatile material	(0% moisture)
°C			
300	68	31	42
500	86	13	33
700	92	7	30

In developing countries, charcoal is used as the domestic fuel of choice for cooking and heating, and is also an important industrial fuel (FAO, 1983). Large amounts are used in foundries and forges; in the extraction and refining of metals, especially iron, and in other metallurgical and chemical applications. Also, the export of charcoal can be a profitable industry in developing countries with abundant forest resources.

Advantages of the production of charcoal as a densified fuel source are predicated upon wood's natural abundance and low input production costs. Creating it is a highly effective value-adding process. However, if it is used in the harsh environments of high heat furnaces typically used for coal in large power production facilities, its limited mechanical strength and hardness, and an inability to withstand the high temperatures and to burn too quickly, immediately point to its excellent characteristics as a fuel source for low-to-medium heat applications rather than high heat applications.

2.12.1.1 Charcoal Briquettes

As charcoal is produced and handled, fractions of the charcoal will break off from the lump coal. This is significant because charcoal fines have a much lower purity than lump charcoal. Along with small fragments of charcoal, the fines contain mineral sand and clay picked up from the earth and the surface of the fuel wood and its bark. Fine, powdered charcoal produced from bark, twigs and leaves has higher ash content than normal wood charcoal (FAO, 1983). Much of the undesired high ash material can be separated by screening the fines and rejecting undersize material passing a 2 to 4 mm screen. This fine material may still contain more than 50% charcoal depending on the level of contamination but, it is difficult to find uses for it.

Charcoal briquettes are made from the charcoal after mixing with a binding agent and then pressing into briquettes; this processing imparts value to the charcoal. Because charcoal lacks plasticity, stable briquettes could not be formed without the binding agent. Preferably, the binder should be combustible, although a non-combustible binder that is effective at low concentrations can be suitable. Starch is a preferred binder although it is

usually expensive; highly plastic clays are suitable if not more than about 15% by weight is used (FAO, 1983). The press for briquetting must be well designed, strongly built and capable of pressing the mixture of charcoal and binder sufficiently for it to be handled through the curing or drying process. The added value imparted by producing briquettes must justify the capital and running costs of the press and of the binder.

Successful briquette operations are found mostly in developed countries, an example of which is the carbonization of sawdust and bark using rotary multiple hearth furnaces and producing between 25-50 tons of fine charcoal per day (FAO, 1983). When briquetted, this charcoal, intended for barbecue grilling, can be sold in retail outlets. The furnace gases are burned to produce steam for electrical power, thus transforming waste sawdust and bark into two useful products, electric power and charcoal briquettes. Air pollution and waste disposal problems are minimized at the same time. Figure 2.11 shows a picture of charcoal briquettes.



Figure 2.11: Charcoal Briquettes. Source: (Google images, 2012)

2.12.2 Pelletisation

Pelletisation can be used with raw biomass after it is ground to a desirable size and placed in a mold and pressed under light-to-medium amounts of pressure. Typically,

pressure-induced temperature increases cause some of the biomass moisture to evaporate and changes in the molecular composition of the lignin. These effects result in the lignin acting as a binder, thus improving pellet transportability and combustibility. Some forms of raw biomass do not contain sufficient amounts of lignin; in these cases, an additional binding agent will have to be mixed into the raw biomass grind before it is compressed (Tumuluru et al., 2010).

Binders produce a more durable product, help to reduce wear in production equipment and increase the abrasion-resistance of the pelleted fuel. Although binders are acceptable in most pelleted biomass, their constituency must be specified to the pellet user because of potential unwanted side effects such as the release of sulfur fumes during use. For example, the most commonly used binder for pellet making is lignosulphonates, or sulfonate salts made from the lignin in pulp mill liquors (Tabil et al. 1997).

Pellets can also be made using manual techniques, eg a crank and screw press. This approach, often used in isolated, rural areas of the world, creates value-added fuel from wood residues and lowers manufacturing input costs. The resultant fuel is used for anything from cooking to staying warm in remote homes without electrical power.

Pellets can also be extruded using specially adapted dies from which the raw biomass is densified through a small openings at the end of the press or crank/screw system. Figure 2.12 shows a picture of biomass pellets formed by extrusion.



Figure 2.12: Wood Pellets Formed by Extrusion. Source: (Google images, 2012)

2.12.3 Briquettes of Raw Biomass

The production of raw biomass briquettes is very similar to pelletization. Typically, they are manufactured using hydraulic, mechanical or roller presses and have densities generally between 900 to 1300 kg/m³. They are a clean, green fuel that can be used in furnaces, boilers or open fires (Tumuluru et al., 2010).

Unlike pellet mills, briquetting machines can handle larger-sized particles and wider moisture contents without the addition of binders. Some advantages of briquettes are the ease of charging the furnace and uniform size and shape. They have increased calorific value because of a reduction in the inherent moisture content, and combustion characteristics with reduced entrained particulate emissions. Also, furnaces that use other larger-sized solid fuels can use briquettes. A main disadvantage of using biomass briquettes or pellets in industrial furnaces is ash slagging due to the alkali content in briquettes made from biomass (Ndiema et al. 2002); however, all biomass fuels have

different slagging characteristics than fossil fuels like coal, and this issue can be solved with appropriate up-front design considerations.

During biomass briquetting, compression under high pressure and temperature is used. This processing causes the biomass particles to self-bond and form briquettes due to thermoplastic flow. Lignin within the biomass is more effective as a binder under the high temperatures and pressures used during briquetting.

One of the most common forms of raw biomass that has been transformed into a briquette is sawdust. Once the sawdust is manufactured into a briquette, it is commonly referred to as ogalite, which is a Japanese term because of their prominent role in ogalite's development. Figure 2.13 shows a picture of biomass briquettes.



Figure 2.13: Biomass Briquettes. Source: (Google images, 2012)

2.12.4 Torrefaction

“Torrefaction is a form of pyrolysis in the relatively low temperature range of 225 - 300°C, which aims to produce a fuel with increased energy density by decomposing the reactive hemicellulose fraction.” (Prins, 2005) Torrefaction gives BCDF’s greater transportability as well as increasing its ability to produce more substantial amounts of energy per unit mass.

During torrefaction, most of the smoke-producing compounds and other volatiles are removed, resulting in a final product that has approximately 70% of the initial weight and 80–90% of the original energy content (Arcate, 2000 and 2002). Thus, torrefaction treatment yields a solid uniform product with lower moisture content and higher energy content compared to the initial biomass.

Throughout the initial heating process, most of the water is removed and thermo-chemical reaction processes are begun (Tumuluru et al., 2010); the temperature at which the thermo-chemical reactions proceed is over 160°C and can also result in the formation of CO₂ (Zanzi et al., 2002). Between 180-270°C, the reaction becomes more exothermal and the degradation of hemicellulose continues. Then, the biomass begins to brown and give off additional moisture, CO₂ and large amounts of acetic acid with some phenols that have low energy values (Zanzi et al., 2002). The major reactions in this temperature range is the decomposition of hemicelluloses, and to a lesser degree the lignin and cellulose (Shafizedeh 1985; Williams and Besler 1996). At about 280°C, the reaction becomes entirely exothermic and gas production intensifies, resulting in the formation of carbon monoxide, hydrocarbons like phenols and cresols, and other, heavier products.

Using these relatively mild conditions enables the reaction product to retain most of the energy within the raw biomass and simultaneously to lose its hygroscopic properties; temperatures over 300°C are not recommended because pyrolysis reactions are initiated (Bourgeois and Doat, 1985).

There are many advantages in the pretreatment of biomass using torrefaction before densification. Torrefaction minimizes variability that can be caused by differences in types and species of the raw materials, climatic and seasonal variations, storage conditions and time (Lehtikangas, 1999). Additionally, torrefaction increases biomass physical characteristics like grindability and pelletability, and reduces hydrophobicity. Figure 2.14 is a picture of biomass that has undergone torrefaction and pelletization.



Figure 2.14: Biomass which has undergone Torrefaction Process. Source: (Google images, 2012)

CHAPTER 3

3.0 Semi Carbonized Densified Biomass (SCDB)

SCDB is a form of solidified biomass fuel that can be utilized in extreme furnace conditions within massive power production operations. SCDB production methods create a fuel source in which a substantial portion of the moisture content and volatile components of the raw biomass have been removed, leaving a composition of mostly a densified, porous, carbon fuel source. The purpose of creating a SCDB is to effectively convert biomass into a high energy content, sustainable fuel with environmentally friendly impact.

Currently, most densified biomass for coke applications does not have the high calorific value typical nor the hardness of coal coke. If SCDB could be manufactured that had the same advantages which coal delivers without its downsides, then the SCDB would be a huge success.

SCDB is a result of processing in which raw biomass material is pressure-formed while being heated under substantially sealed-up conditions. The semi-carbonized solid is produced by carbonizing the raw biomass material without releasing combustible gas or liquid. The pre-semi-carbonized or semi-carbonized solid has a maximum compressive strengths between 60-200 MPa and a calorific values between 18-23 MJ/kg. The pre-semi-carbonized or semi-carbonized solid matter has an apparent specific gravity near $1.20\text{-}1.38\text{ g/cm}^3$.

3.1 Experimental Procedure: SCDB Production Process

First, the SCDB production process involves grinding the biomass to a desired size. During this grinding, two types of size degradation tools are used: a chipper (Figure 3.3) is used to reduce the size of large biomass material before feeding into a cutting mill (Figure 3.4) which reduces the size further to about 2mm.

The ground biomass is dried using a drying oven (Figure 3.6); the drying time depends on the initial moisture of the biomass and the desired moisture content for producing SCDB from each feedstock or mixture of feedstocks. After drying, the moisture content is determined using a moisture analyzer (Figure 3.7), and the weight of the biomass fed into a specially built reaction cylinder is measured using an electronic balance (Figure 3.8).

The reaction cylinder is loaded with the proper weight of crushed raw biomass and is placed on a shop press (Figure 3.9). A piston is inserted into the hollow of the reaction cylinder with small clearance between the inner and outer periphery of the cylinder and piston. A heating element is wrapped around the reaction cylinder and used for heating while the crushed raw biomass is being pressurized. The pressure and temperature conditions used promotes the decomposition of lignin, cellulose and hemicellulose and initiates low-temperature reactions to occur between cellulose and lignin while maintaining their skeletons, thereby producing a semi-carbonized solid material. To monitor the temperature of the biomass during this process, thermocouples are inserted into the cylinder and readings are collected using a data acquisition system. After a predetermined heating period, the heating element is removed while maintaining

the pressure. The cylinder assembly is then cooled to room temperature using a circulation fan.,

The design of the experimental apparatus prevents the release of steam and gasified components generated during heating; these gaseous components are trapped within the semi-carbonized solid matter. A schematic of this torrefaction process is illustrated in Figure 3.1.

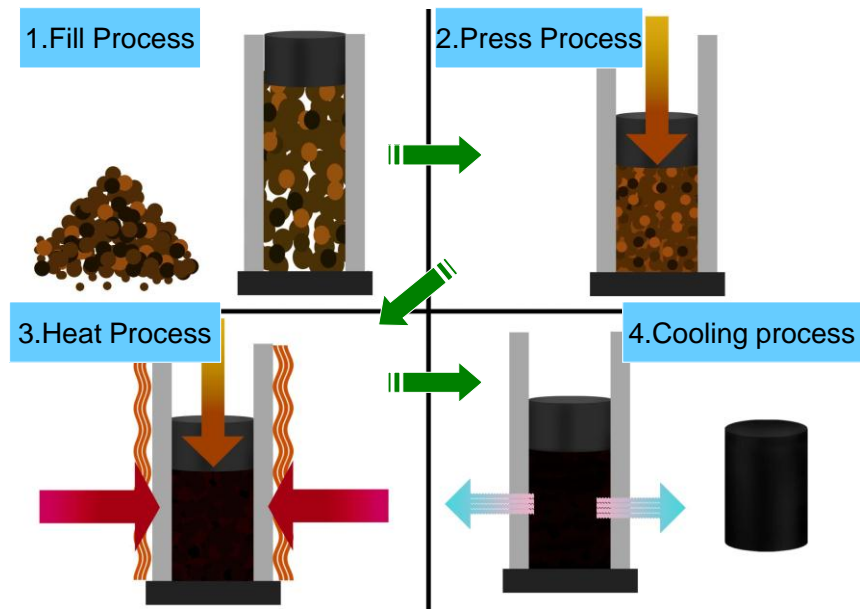


Figure 3.1: Process chart of SCDB formation from agricultural waste.

3.1.1 Heating and Cooling Process

The reaction temperatures used were between 115-230 °C and the pressures were 8-25 MPa. In general, these conditions are crucial to the production of a valuable SCDB because heating and cooling are key factors for cellulose, hemicellulose and lignin reactions to occur that give SCDB value. Hence, the temperature-time sequencing is broken into three different time zones: the heating time zone; the retention time zone; and, the cooling time zone.

During the heating time zone, biomass is heated until a preset temperature is achieved at the pressure used. In general, this loading pressure is kept at 20MPa during this heating time zone and approximately 15 minutes are needed to reach the preset temperature.

During the retention time zone and after reaching the preset temperature, the temperature and loading pressure are held at the preset values, and the time of reacting the biomass is measured. As soon as the retention time zone is completed, the cooling time zone is started. For the work herein, the loading pressure was always kept at 20 MPa. Typically, the duration of the cooling time zone was about 20 minutes. A visual representation of these three different time zones can be seen in Figure 3.2.

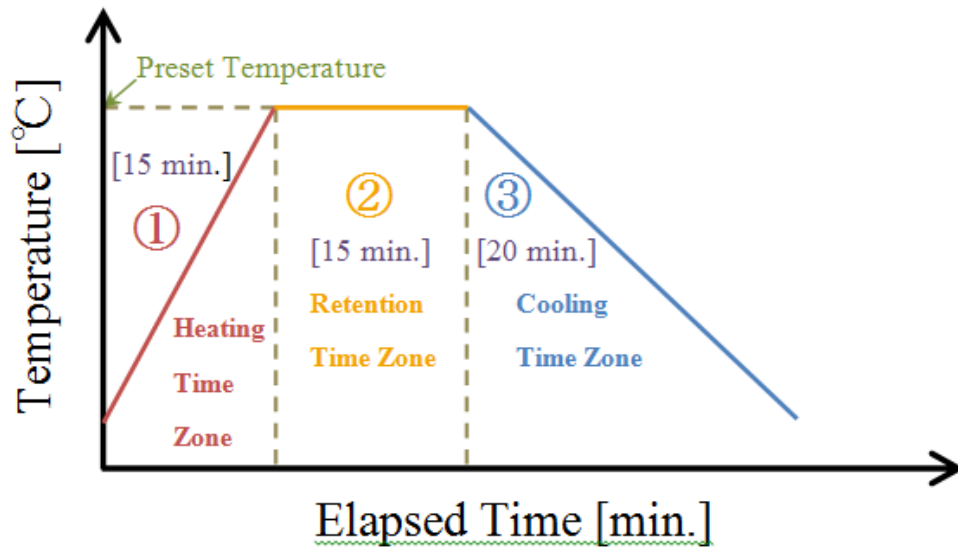


Figure 3.2: Heating and cooling production process for elapsed time.

3.2 Experimental Apparatus

Sub-sections of 3.2 identify each piece of equipment used during the experimentation, give their specifications and describe their use.

3.2.1 Chipper

To be transformed into a highly dense and calorific form of fuel, raw biomass must be ground or reduced in size. The goal is to have the comminuted raw biomass uniform in size with roughly a 2 mm top size. A cutting mill could be used to produce this size range with good uniformity, but cutting mills cannot process larger input sizes typical of raw biomass. Therefore, a chipper was used first to to reduce the size of the raw biomass that could be processed using a cutting mill.

The Earthquake 3" chipper (Figure 3.3) and shredder was used for preparing the raw biomass to be fed into the cutting mill. The Earthquake 3" chipper and shredder uses a Briggs & Stratton Intek IC 206cc, 8.50 ft-lbs torque engine that is capable of chipping materials up to 3" in diameter down to a 20:1 waste reduction ratio (Earthquake, 2012). The size of the output biomass is then within the specs of the input biomass size for the cutting mill being used.



Figure 3.3: Earthquake 3" chipper and shredder. Source: (Earthquake, 2012)

3.2.2 Cutting Mill

The second phase of grinding raw biomass to achieve uniform ground size of 2 mm was to use a Retsch SM300 cutting mill (Figure 3.4). It uses a high torque 3 kW drive and has a capacity to reduce material from 60 x 80 mm to an output size as low as 0.25 mm. For this study, the final raw biomass fineness was 2mm. A picture of the biomass (hay) material before and after grinding is shown in Figure 3.5.



Figure 3.4: Retsch SM300 cutting mill. Source: (Retsch, 2012)



Figure 3.5: Biomass before and after the two step grinding process.

3.2.3 Oven

After raw biomass had a top size of 2 mm, it was dried using a Thermo Scientific Precision drying oven shown in Figure 3.6 (Thermo Scientific, 2012).. The drying time depended on the initial moisture of the biomass and the desired moisture content for producing SCDB for each feedstock or mixture of feedstock.



Figure 3.6: Thermo Scientific Precision drying oven.

3.2.4 Moisture Analyzer

After the biomass has been drying in the oven, its moisture content is measured using the AnD MX-50 moisture analyzer (AnD MX-50, 2012). It uses 400W straight halogen lamp heating system with SRA filter and SHS weighing technology to accurately measure the moisture of samples having greater than 5 grams and smaller than 51 grams in weight with standard deviation of 0.02%. A picture of the AnD MX-50 can be seen in figure 3.7.



Figure 3.7: AnD MX-50 Moisture Analyzer. Source: (AnD MX-50)

3.2.5 Balance

After the biomass has proper moisture content, the weight to be placed within the reaction cylinder has to be obtained. Hence, sample weights were measured using a AnD GF-200P balance. It has a maximum capacity of 210 grams and a resolution of 0.001 grams (AnD GF-200P, 2012). A picture of the AnD GF-200P balance can be seen in Figure 3.8.



Figure 3.8: AnD GF-200P Balance. Source: (AnD GF-200P, 2012)

3.2.6 Reaction Cylinder and Shop Press

The reaction cylinder was a specially built cylinder, specific details of which cannot be given due to intellectual property concerns. However, it had a simple piston/cylinder design with a polished cylinder surface. There were also a few specially built accessories that accompanied this cylinder to create seals, and a piston. After the reaction cylinder was loaded with <2 mm sized biomass, the reaction cylinder was placed on the shop press and pressure was applied to the reaction cylinder that was based on the type of biomass feedstock being used. The shop press used to apply this pressure was a Greg Smith Equipment 20 ton air/hydraulic shop press with gauge shown in Figure 3.9 (Greg Smith Equipment, 2012).

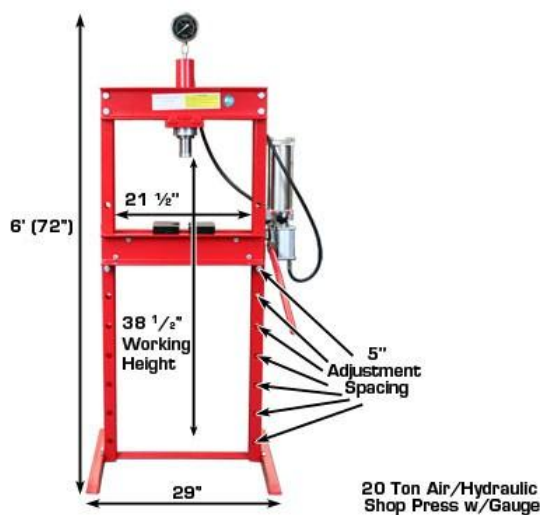


Figure 3.9: Greg Smith Equipment 20 ton air/hydraulic shop press with gauge. Source: (Greg Smith Equipment, 2012)

3.2.7 Ceramic Electric Tubular Furnace

The heat applied to the reaction cylinder was facilitated by a specially built Asahirika Seisakusho Co., Ltd. ceramic electric tubular furnace type ARF-50K, see Figure 3.10. It used AC voltage at 120 V with a power output of 700 W.

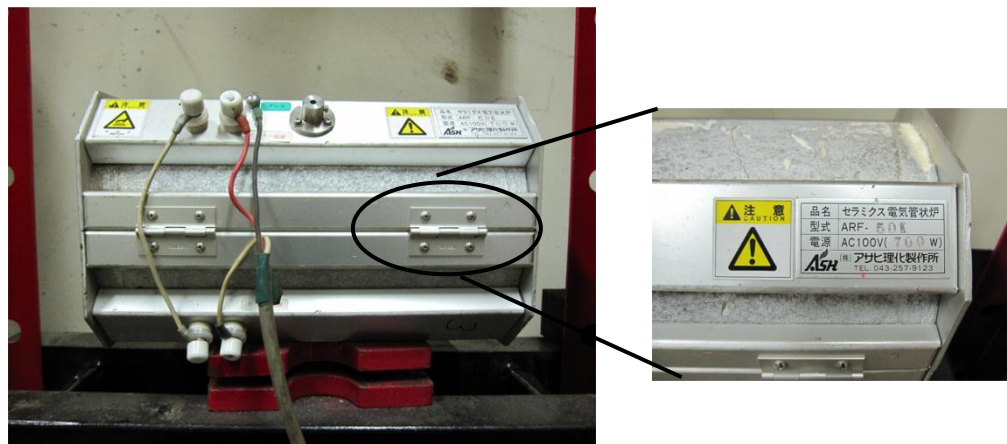


Figure 3.10: Asahirika Seisakusho Co., Ltd. ceramic electric tubular furnace type ARF-50K

3.2.8 Thermo Controller

The temperature of ceramic electric tubular furnace was controlled by the thermo controller, Type AMF-N, manufactured by Asahirika Seisakusho Co., Ltd. Thermo Controller – see Figure 3.11. It used AC voltage of 120 V and a current of 15 A.



Figure 3.11: Asahirika Seisakusho Co., Ltd. Thermo Controller Type AMF-N.

3.2.9 Overall Setup of Experimental Apparatus

All of the equipment discussed in the previous sub-sections were used in conjunction with one another for the production of high value SCDB fuels. The use of a minimum amount of equipment and few production steps is encouraged if input process steps and costs are to be decreased; however, the use of too few steps during production may not give the SCDB the necessary hardness or calorific value. A picture of the equipment being used together in the making of a SCDB can be seen in Figure 3.12.

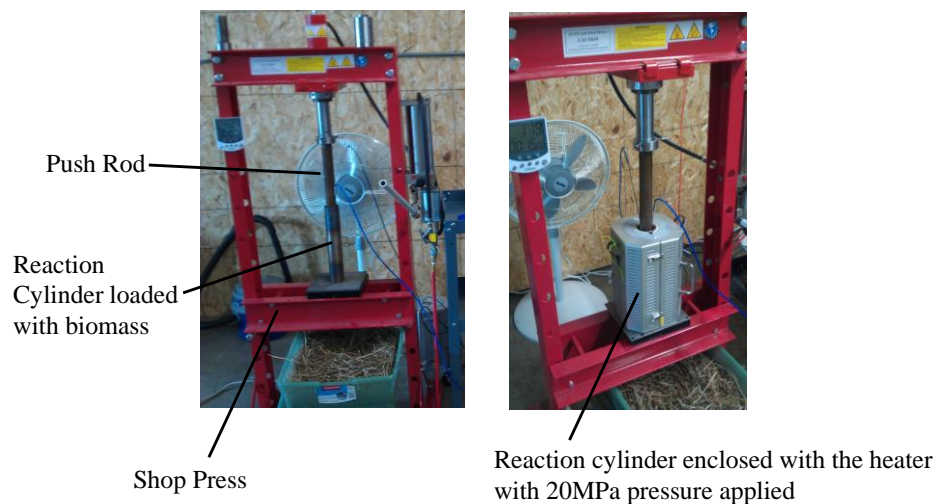


Figure 3.12: Production process of SCDB.

3.3 Experimental Result and Discussion.

3.3.1 Results

Figure 3.13 shows pictures of some of the SCDB produced from hay, corn husk, corn cob, pine wood, tobacco stalk, 50-50 mixture of tobacco stalk and pine wood, and a 50-50 mixture of pine wood and corn cob. Apart from pine wood which required very high moisture content to produce suitable SCDB products, the requirements for the other biomass materials were all fairly similar. The reaction temperature range used was 150-170 °C and the moisture content ranges were between 3-15%. Other biomass materials tested but which are not shown in Figure 3.13 were palm nutshell, palm nut husk, and a 50-50 mixture of palm nutshell and corn husk. The moisture contents of the SCDB products and reaction temperatures used are summarized in Table 3.1.

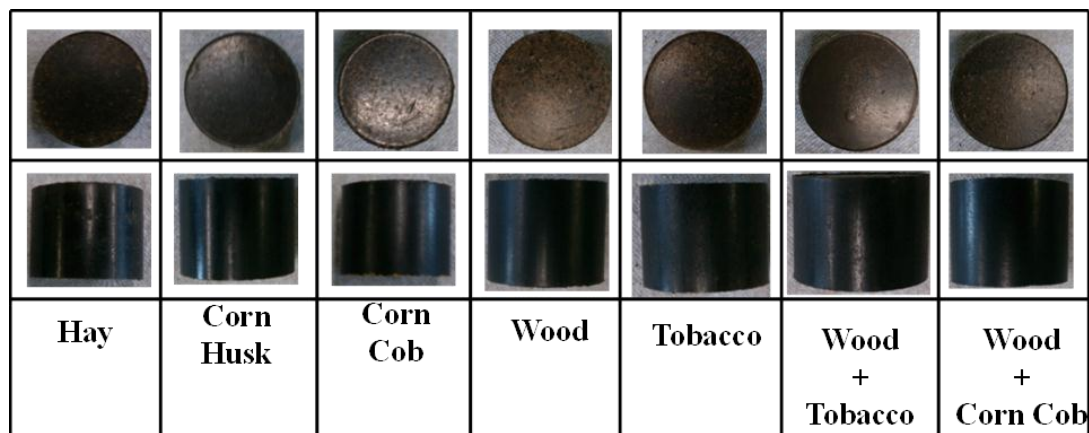


Figure 3.13: SCDB produced from various agricultural wastes.

Table 3.1: SCDB Reaction conditions

Biomass	Moisture Content	Reaction Temperature
Hay	3-5%	160-170 °C
Corn Husk	3-5%	145-165 °C
Corn Cob	3-8%	150-160 °C
Pine Wood	10-15%	140-160 °C
Tobacco Stalk	3-8%	145-155 °C
Palm nut shell	1-5%	170-180 °C
Palm nut husk	1-5%	170-180 °C
Wood + Tobacco	2-7%	150-160 °C
Wood + Corn Cob	4-8%	150-160 °C
Palm nut shell + husk	1-5%	170-180 °C

Both proximate and ultimate analyses were performed on the SCDB. A proximate analysis, as defined by ASTM, is the determination by prescribed methods of the moisture, volatile matter, fixed carbon (by difference) and ash. The ASTM D5142 Standard Test Methods for Proximate Analysis of the Analysis Sample of Coal and Coke by Instrumental Procedures was used. Proximate analyses for some of the SCDB produced are shown in Table 3.2.

Table 3.2: Proximate Analysis of SCDB (ASTM d5142).

Feedstock	Moisture (%wt)	Ash (%wt)	Volatile	Fixed Carbon (%wt)	Calorific Value (Btu/lb)
Hay	4.92	8.22	70.35	16.52	7622.00
Corn Cob	9.87	1.58	69.31	19.23	7269.00
Corn Husk	10.8	3.71	73.36	12.13	6952.00
Wood	13.43	1.80	68.29	16.48	7303.00
Palm nutshell	1.50	5.99	72.79	19.72	8301.80
Palm nut husk	2.27	7.30	74.08	16.35	8892.40
wood*	3.52	2.50	74.10	20.40	
palm nut/husk*	2.90	7.32	71.71	18.06	8479.00
Hay+wood	8.45	4.94	69.31	17.30	8340.34

3.3.2 Discussion

What makes SCDB different from other forms of densified biomass is that the processing to create SCDB uses pyrolysis to carbonize the biomass under a sealed-sample condition, trapping combustible gases and liquids. Most other forms of densified biomass are made when these combustible gases and liquids evolve from the system during processing. This difference imparts the SCDB desirable qualities for cofiring with coal and coke. For example, although solidified biomass can be added as a partial substitute fuel in high-efficiency coal boilers, the loss of boiler efficiency caused by the typical high moisture contents of biomass fuel can be mitigated by the use of SCDB. Cofiring of 15% biomass with coal can reduce greenhouse gas emissions by 18%. Furthermore, early test results with woody biomass cofiring showed as great as a 30% reduction in the emission of oxides of nitrogen, a main precursor for smog and ozone pollution.

The SCDB may also be suitable for use in iron casting or iron making as alternative coke to be mixed with coal. By adding metal particles to the raw biomass material when charging the barrel with the material, the mixture of the raw biomass material and the metal particles can absorb heat efficiently and homogeneously form pre-semi-carbonized or semi-carbonized solid matter. Furthermore, the metal particles added to the raw material and accordingly contained in the SCDB become molten metal in casting or iron-making process upon melting. Therefore, by adding particles of metals adjusted beforehand in mixing ratio of metals to the biomass material, adjustment of ingredients in iron casting or iron making can be achieved.

CHAPTER 4

4.0 Conclusion and Discussions

The objective of this thesis was to examine the potential of biomass for energy production and to experimentally study the production of SCDB. To examine the potential, an extensive literature review was conducted that included wide array of topics that concern biomass availability and sustainability. There are many publications that have been written about biomass and its untapped potential but they often focus on one aspect of the biomass topic. For a sustainable production, issues associated with the environment, government, business, economics, agriculture and food supply must be addressed; these issues were investigated in this thesis. Too often a detailed look at an isolated topic skews the big picture of how eloquently intertwined this wide array of topics truly are.

The topics that were reviewed and discussed included: molecular composition of biomass before and during thermo-chemical reactions; types of land usage; biomass availability and assumptions made to arrive at the availability; effects of biomass on food supply; the carbon cycle; and political policy. Additionally, a detailed look at the available forms of densified biomass present in the market, their production processing and applications were also discussed.

The thesis also presented data on the production of a relatively new densified fuel, SCDB, which is a semi-carbonized solid matter produced through a process in which raw biomass material was pressure-formed while being heated under a substantially sealed-up condition. The SCDB was produced by carbonizing the raw biomass material without

releasing combustible gas or liquid. This production technique helps to produce a densified biomass fuel that may be more capable of enduring the severe conditions associated with coal-fired furnaces.

From the investigation conducted, it can be concluded that biomass as an energy resource can be a sustainable process. However, one big question remains to be answered, and that is whether biomass energy is economical and can be made so with appropriate technology, incentives and enlightened planning.

4.1 Contribution of this Thesis

In summary, this thesis provided the research community with a potential sustainable use of biomass as an energy resource by proposing an innovative manufacturing technique that creates a densified biomass fuel. This new form of SCDB remedies consistent problematic performance characteristics associated with other production techniques used to create densified biomass. This research has shown that setting the heating temperature to 115-230 °C and the pressure of pressure-forming to 8-25 MPa, raw biomass can be transformed into a densified fuel source with a maximum compressive strength from 60 to 200 MPa and a calorific value from 18 to 23 MJ/kg. These performance characteristics would give pre-semi-carbonized or semi-carbonized solid matter high hardness and calorific value, without requiring excessive process energy, to operate in the harsh environments of high heat furnaces.

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