ECOLOGICAL AND ECONOMIC COSTS AND BENEFITS OF THE USE OF PYROLYSIS AS A CLIMATE CHANGE MITIGATION TECHNIQUE IN THE NEOTROPICAL DEVELOPING WORLD

by

BRIAN F. SNYDER

(Under the Direction of C. Ronald Carroll)

ABSTRACT

One of the most promising technologies for net atmospheric carbon removal is biomass pyrolysis. Biomass pyrolysis is the thermal decomposition of organic material in the absence of oxygen. It is generally endothermic but it results in high energy syngas, a liquid bio-oil and biochar, a carbonaceous material which when added to soil stimulates plant growth. Here, the economic potential of small-scale pyrolysis in the neo-tropical developing world is investigated using a net present value framework. Biomass costs are estimated using waste biomass, jaragua grass, short-rotation woody crops, and biomass from artificial wetland systems in Costa Rica. Costs are computed with and without consideration of the environmental services associated with the modeled systems. When environmental services are appropriately valued, the costs of biomass from artificial wetland systems becomes negative; that is, operators of artificial wetlands used for water services would be expected to pay for biomass harvesting. Using the computed biomass costs, pyrolysis system costs are computed for fast and slow pyrolysis and compared to gasification. Fast and slow pyrolysis systems break even at carbon credit prices exceeding 0-5 $/ton, but gasification systems do not break even under most realistic assumption sets. The emergetic costs of pyrolysis systems are also evaluated. Emergy is a measure of the energy and resources required to produce a product, and can be considered a theoretical alternative monetary or accounting system that allows for a more holistic valuation of goods and services than either an exchange (money) or value (exergy) system. The results indicate that the transformities (or emergetic efficiency) of pyrolysis production systems using waste biomass are similar or less than those of geochemical hydrocarbon production systems. Since geologic fossil fuel production is emergetically efficient, this result is promising and suggests that unlike other biomass based alternative energy systems (e.g. ethanol), pyrolysis may be ecologically beneficial when measured holistically. Pyrolysis is a carbon negative technology (i.e. it creates a long term carbon sink) which creates the potential for a cap and trade system in which there is differentiation between carbon neutral and carbon negative credits. The economics of such a system are discussed.

INDEX WORDS: Pyrolysis, Biochar, Carbon negative, Emergy, Costa Rica, Net present value, Wetland valuation, Cap and trade, Jaragua grass

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DEDICATION

To my wife, Sara, for the constancy of her patience and love.

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PREFACE

In 1973, H.T. Odum recognized the "unity of the single system of energy, ecology and economics" (Odum, 1973). Since Odum, much work has been aimed at integrating ecology and economics, but the two fields tend to have fundamentally different value systems (Odum and Barrett, 2005; Nelson, 2010). Economics is generally cornucopian and places value on increasing the standard of living for humans (Nelson, 2010) while ecology often emphasizes scarcity and generally places an inherent value on natural systems beyond their use as natural resources (Nelson, 2010; Leopold, 1949). Global climate change is one of the world's most pressing environmental problems, but as a result of these differences in worldview, ecologists and economists may have different ideas about the technologies and policies most suitable for addressing climate change (Fitzpatrick and Spohn, 2009) and a trans-disciplinary approach including ecology, engineering and economics is required.

There are an assortment of technologies for producing electricity and liquid fuels with little or no carbon dioxide emissions. Solar, wind, geothermal, hydrokinetic and biomass energy can be used to produce electricity while biomass can be used to produce fuels either through conversion to ethanol, biodiesel or bio-oil via pyrolysis. All of these technologies have existed for decades, yet they have been underutilized because conventionally derived energy (coal, natural gas, oil) is usually less expensive than alternative energy. When alternative energy becomes less expensive than conventional energy the use of alternative energy sources will increase, as occurred with wind derived power in the western United States beginning in the early part of the 21st century (Wiser and Bollinger, 2009). Therefore, those concerned about the effects of energy consumption on climate change should be especially concerned with the costs of alternative technologies.

There are two primary options for policy makers interested in changing the economics of alternative energy production: carbon taxes and cap and trade programs. Both of these instruments make conventionally produced energy more expensive while potentially providing additional revenue or tax credits for alternative energy producers. Currently, much of the world follows the Kyoto protocol, a cap and trade program, that places CO_2 emission caps on the developed world (called Annex I countries) and allows emitters to trade CO_2 credits among projects in the developed world or with projects in the developing world (non-Annex I countries). Therefore, renewable energy projects have the opportunity to generate income both from the energy they create and from the CO_2 they do not emit.

Currently, carbon credits are relatively inexpensive, however, the U.S. and China, the world's two largest carbon dioxide emitters, do not participate in cap and trade programs. If either of these countries joins an international cap and trade program, demand for carbon credits and the price of carbon credits may increase. Thus, technologies that have not been economically viable may eventually become viable and it is important to understand the carbon price at which specific technologies become economically attractive.

Biomass based energy is one of the better utilized carbon neutral energy sources in the developed world and is heavily utilized in the developing world. Unlike most other renewable energy sources, biomass has the benefit of being dispatchable (i.e. it can be turned on) and can therefore compete with fossil fueled sources of electricity such as coal and natural gas. In 2007, 53% of the U.S.'s renewable energy consumption came from biomass. However, as a fraction of total electrical generation, biomass accounted for just 0.0275% of U.S. generation (EIA, 2009).

Furthermore, unlike wind generated electricity, the generation of biomass powered electricity has not increased significantly in recent years. Thus, biomass represents one of the most promising sources of growth for carbon neutral energy production.

One of the most ecologically interesting technologies for carbon neutral energy production and net atmospheric carbon removal is biomass pyrolysis. Biomass pyrolysis is the thermal decomposition of organic material. It is a generally endothermic process but it results in high energy syngas, a liquid bio-oil and char, a carbonaceous material which, when added to soil, stimulates plant growth. There are several types of pyrolysis which differ in their reaction temperatures and the proportions of the three main products. Pyrolysis has been well studied, especially fast pyrolysis which yields larger fractions of bio-oil, however its economics, particularly the economics associated with slow or conventional pyrolysis which results in larger fractions of char and which may be of more interest for the generation of carbon credits, has been less well documented and is likely to be dependent on the specifics of the study system.

Here, the economic potential of pyrolysis in the developing world is investigated. Chapter 1 describes the technical literature with an emphasis on reactor designs and products in order to inform the models developed later. Chapter 2 describes the opportunities for bioenergy utilization in one neo-tropical country, Costa Rica. Estimates of biomass costs are developed in Chapter 3 based on a net-present value model and include ecological-economic benefits and payments for environmental services. In Chapter 4, a net-present value model of the costs of three types of small scale pyrolysis is developed. Chapter 5 uses an emergy approach to address the costs of pyrolysis systems in an ecocentric, rather than market-oriented context. Finally, Chapter 6 discusses the political actions that might make pyrolysis, along with other carbon negative technologies, more economically attractive and Chapter 7 provides brief conclusions.

The focus of this work is on small scale pyrolysis because it is likely to be associated with the greatest net carbon reduction due to reduced transport distances, allows for distributed electrical generation, and it is most appropriate for the developing world (Demirbas and Demirbas, 2007). Large scale pyrolysis may be more appropriate for the developed world. Costa Rica is used as a model system because it is a non-Annex I nation, has high productivity and large amounts of biomass wastes potentially available for use, a well-developed payment for environmental services program, relies on hydroelectricity, a threatened resource, for the vast majority of its electricity needs, and is committed to carbon neutrality by 2021.

Chapter 1: The Processes and Products of Pyrolysis

1.1. Introduction

Biomass is one of the only sources of dispatchable or baseload low-carbon electricity and low-carbon transportation fuels. A great deal of recent attention has been focused on bioenergy, particularly in its ability to produce liquid fuels, either via fermentation to ethanol or by the creation of bio-diesel from soy or algae and the cofiring of biomass with coal to produce electricity (Haswell, 2009). Comparatively little commercial attention has been directed to the use of pyrolysis for the production of electricity or liquid fuels.

Pyrolysis is the thermal decomposition of organic material and is accomplished by the heating of carbonaceous material in the absence of oxygen. There are a number of types of pyrolysis classified by the temperature of the reaction and residence time (the length of time the carbonaceous parent material is allowed to react). These processes result in different amounts of the three main products: biochar, syngas and bio-oil. The proportion of the products also depends on the characteristics of the parent material, reactor type and other factors, and the relative proportions of these three products determine the ecological and economic costs and benefits of pyrolysis systems.

1.2. Pyrolysis System

The pyrolysis reactor is one part of a supply chain for converting a biomass feedstock into a marketable energy, carbon storage or chemical product (Figure 1.1). This system includes biomass suppliers (either agricultural producers or waste streams), a logistical chain for transporting the biomass feedstock to the reactor, the pyrolysis reactor itself, a distribution system for transporting products, and the end users of those products. The type and scale of the pyrolysis reactor determines the composition of this system. In order for a pyrolysis system to be economically viable, each part of the supply chain must be present and function efficiently.

In its simplest form, an agricultural producer would transport biomass to a local pyrolysis reactor connected to the electrical grid. Any syngas or bio-oil produced would be converted to electricity through combustion in an internal combustion engine connected to an electrical generator. Produced char would be used in local agriculture and produced electricity would be sold to the grid operator. Carbon credits would be verified and provided either to a third party financier or sold on a climate exchange. As pyrolysis systems increase in size, the complexity of the system must also increase.

Pyrolysis can also be used to manage waste streams including plastics, tires, municipal waste, sewage and agricultural waste. We focus specifically on biomass and include agricultural wastes, but do not discuss the use of pyrolysis on other waste streams.

1.3. Pyrolysis Processes

There are three main categories of pyrolysis: slow or conventional pyrolysis, fast pyrolysis, and gasification[1]. Table 1.1 shows the basic properties of these methods and their end products. In all three types of pyrolysis an organic material is heated in the absence of oxygen. Due to the lack of oxygen, the parent material does not combust, but instead the bonds in the parent material break and a thermal decomposition occurs in which the parent material is modified into a complex mixture of compounds (McKendry, 2002).

The end products separate into a solid and vapor phase with the vapor made up of condensable and non-condensable portions. The solid portion is typically a fine charcoal. The

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[1] Gasification may be more accurately described as a process that uses pyrolysis along with oxidation.

condensable portion is generally recovered as a liquid (bio-oil); the non-condensable portion is a syngas. The pyrolysis process is endothermic, although individual reactions may be exothermic.

In conventional pyrolysis, biomass is slowly heated (less than 2° C/s) to approximately 500°C. The residence time is long, approximately 5 to 30 minutes which allows the components of the vapor phase to continue reacting with one another. A variety of reactor designs may be used (Mohan et al., 2006). Slow pyrolysis typically yields roughly equal portions of each of the three major pyrolysis products (Bridgwater, 2007) and is used to produce the maximum possible char yield.

Fast pyrolysis also occurs at about 500°C, however, much faster heating rates are used and residence times are on the order of several seconds rather than the several minutes used in slow pyrolysis. Fast pyrolysis maximizes the yield of bio-oil, with 60 to 75% of the products being bio-oil, 15 to 25% being char, and 10 to 20% being gases (Mohan et al., 2006). However, a variety of factors including the particle size, heating rate, and biomass type can significantly influence the yields of the different products (Li et al., 2004).

Gasification is used to produce high fractions of syngas. It uses long residence times and high temperatures of approximately 800°C. Unlike most pyrolysis processes, gasification typically uses a source of oxygen in the reaction, either in the form of steam or air. As a result, gasification may or may not be classified as a type of pyrolysis. Gasification systems can be more efficient than combustion and are of particular interest as a means of generating electricity from coal and natural gas. Gasification produces approximately 85% syngas, 5% oil and 10% char (Bridgewater, 2007).

1.4. Chemical Reactions

Biomass used in pyrolysis systems is composed of cellulose, hemicellulose and lignin, the major components of plant cell walls. Cellulose is a glucose-based polysaccharide and decomposes to form the monomer levoglucosan at 300 to 400°C. At 500°C, the levoglucosan vaporizes to form condensable and non-condensable gasses, but little char. Hemicellulose is more reactive than cellulose and begins to undergo decomposition at 130 to 194°C. Hemicellulose produces more gas than cellulose, but like cellulose pyrolysis, it produces little char. Most of the char produced from pyrolysis is formed from lignin. The decomposition of lignin can begin at 280°C, continuing to 450 to 500°C.

The Broido-Shafizadeh model (Figure 1.2) is used to describe the reactions occurring during pyrolysis. Figure 1.2 shows the pyrolysis of cellulose, but the same reaction pathways apply for lignin and hemicellulose. Two main pathways for chemical reactions occur during pyrolysis: dehydration and depolymerization.

During dehydration, the molecular weight of the fuel is reduced and char and water vapor are formed. Following dehydration, decarboxylation and carbonization occur. As the heat rate and temperature increase, the components of syngas (low molecular weight volatile compounds) such as H_2, CO, CO_2, are formed. Dehydration occurs under conditions of slow heat rates, low temperatures (< 300°C), and long residence times. Dehydration is exothermic (Bridgewater et al., 2001).

De polymerization reactions occur at temperatures above 300°C. During these reactions, the fuel is de-polymerized to form levoglucosan and condensable gasses. The condensable gases may remain in the reaction chamber where they may undergo secondary reactions, or may be removed from the reactor to form bio-oil. Depolymerization is endothermic (Bridgewater et al., 2001).

Depolymerization has higher activation energies than dehydration and thus occurs at higher temperatures. Dehydration reactions are typical of slow pyrolysis while depolymerization reactions are typical of fast pyrolysis.

1.5. Reactor Types

1.5.1. Charcoal

Pyrolysis has been used for centuries in the production of charcoal. Traditionally, charcoal is produced in a batch process in an earthern, brick or steel kiln (Figure 1.3). Historically, charcoal production has received a poor environmental reputation because of its role in deforestation (Hofstad, 1997) and because the volatile products of the pyrolysis reaction are vented to the atmosphere (Pennise et al., 2001; Bailis et al., 2005). Charcoal production is inexpensive and some attention has focused on the use of low-technology methods of charcoal production in the developing world, but it is not considered here.

1.5.2. Slow Pyrolysis

Because of the long residence times, conditions for slow pyrolysis are relatively simple. There are a number of reactor designs which vary in the way in which they transfer heat to the biomass particles. The simplest reactor type is fixed-bed, batch pyrolysis which has been frequently used in laboratory studies. In fixed-bed pyrolysis the reactor and reaction is static; the biomass is fed into the chamber and the chamber is externally heated to initiate the reaction. Heating may also occur internally by allowing limited combustion. The condensable and non-condensable gasses are captured and the char is removed after the batch is processed. A rotary kiln or rotating screw system are also commonly employed and allow for a continuous process and better control of biomass residence times than static units.

1.5.3. Fast Pyrolysis

In pyrolysis optimized for bio-oil production (fast pyrolysis), heat must be transferred rapidly and the char which forms on the outside of the biomass particle must be removed during the reaction. As a result, reactor designs must be complex. Fast pyrolysis reactors are generally either ablative or fluidized bed (Briens et al., 2008).

Ablative reactors use some mechanical means of keeping biomass particles moving against an externally heated wall. For example, in a cyclone reactor a gas stream with suspended biomass particles enters a cyclone tangentially. This creates a vortex which keeps the biomass particles moving against the cyclone wall (Briens et al., 2008). Similarly, biomass particles can be introduced into an externally heated rotating cone which uses centrifugal forces to keep the biomass against the cone wall. Ablative process can use larger biomass particles than other pyrolysis reactor designs and no carrier gas is necessary.

Fluidized bed reactors inject biomass particles into a bed of a hot, usually inert material such as sand along with an inert fluidizing gas. In a circulating fluidized bed (Figure 1.4), the sand (or other carrier) is heated in a separate combustion chamber and then fed into the reactor. The carrier is then cycled out of the reactor and back into the combustion chamber. In other fluidized bed designs, the carrier is not recycled. (Briens et al., 2008). Both of the largest fast pyrolysis corporations, Ensyn and Dynamotive, use a fluidized bed system (Mullaney et al., 2004).

1.5.4. Gasification

In gasification, biomass is first pyrolysized to release char and volatiles; biomass not pyrolysized and char from the pyrolysis reaction is oxidized providing heat for the system. The CO_2 and H_2O from oxidation are then reduced to form CO and H_2. The production of this syngas can allow for an increase in overall system efficiency because the syngas may then be burned more efficiently than the parent material.

In fixed bed gasification systems, biomass is fed into the top of the system and travels down through several zones in the reactor including a low temperature drying zone, a pyrolysis zone, and very high temperature oxidation and reduction zones (Figure 1.5). A gasification agent, typically air, is introduced either at the bottom (updraft gasifiers), some distance above the bottom (downdraft gasifiers), or both (twin fire gasifiers).

1.5.5. Batch Versus Continuous Systems

Pyrolysis systems may be either batch or continuous systems. In a batch system, the reaction is periodically stopped to introduce new feedstocks while in continuous systems the reaction may continue indefinitely, and is limited only by maintenance requirements. Most existing pyrolysis systems used for research are batch systems but the continuous process is more labor and energy efficient as the system does not cool between batches. Most large scale and many small scale commercial systems are expected to be continuous systems.

1.6. End Products

The end products of pyrolysis depend on the parent material, the pressure and temperature of the reaction, residence times, particle sizes, and heating rates. Biomass used in pyrolysis reactions is composed primarily of cellulose, hemicellulose, and lignin but the proportion of each compound differs significantly among feedstocks. Each component decomposes differently, and the proportion of each component in a feedstock determines the char, bio-oil and gas yields.

1.6.1. Char

Bio-char is a fine biologically derived charcoal. The distinction between charcoal and biochar is arbitrary and dependent on the intended application and the production method; char that is intended for combustion is typically called charcoal, char intended for carbon management or soil improvement is typically considered biochar (Brown, 2009). The lower heating value (LHV or net calorific value) of char depends on the process and feedstock, but is generally on the order of 32 MJ/kg (Diebold and Bridgewater, 1997).

Of the three main pyrolysis products, biochar has the potential to not just offset carbon dioxide emissions, but to remove carbon dioxide from the atmosphere by forming a storage sink, making pyrolysis of biomass a potentially carbon negative technology. When used as a soil additive, biochar can increase crop productivity (Lehmann, 2007) by improving nutrient and water retention, increasing cation exchange capacity (Laird et al., 2009), and increasing mycorrhizal and microbial growth (Warnock et al., 2007; Laird et al., 2009). Char can be thought of as similar to activated charcoal, which is widely used for adsorption.

The half-life of biochar in the soil is not well known, but it is thought to be on the order of centuries to millennia. Biochar was intentionally applied to soils in the Amazon Basin (terra preta) over 1,000 years ago; these soils currently contain 2.5 times as much carbon as adjacent non-amended soils (Figure 1.6; Glaser et al., 2001). Given that the effects of climate change are on the timescale of decades, biochar added to the soil could be thought of as a relatively long-term carbon sink.

1.6.2. Syngas

The syngas derived from pyrolysis consists primarily of H_2 , CO, CO_2, and CH_4. Syngas can be used to power the pyrolysis reactor and may be combusted to produce excess electricity for sale. In theory, the H_2 in syngas can also be captured and could be used to power fuel cells or hydrogen-powered internal combustion engines for transportation applications. In general, higher yields of syngas are associated with higher temperatures and long vapor residence times (Li et al. 2004). Syngas production is maximized in gasification reactors (Bridgwater, 2007).

1.6.3. Bio-oil

Bio-oil often is considered the most economically promising products of the pyrolysis system. Bio-oil is a complex mixture of organic compounds and water. Bio-oil is entirely different from bio-diesel produced from soybeans, animal fats, or algae. Despite its name, it is hydrophilic, immiscible in petroleum based oils and contains 15 to 30% water (Bridgewater, 2002). It has an energy content that is approximately half of the energy content (LHV = 13 to 18 MJ/kg) of diesel fuel (40% by weight; 60% by volume).

Bio-oil can be used directly without further processing; however, the low energetic value precludes its use as a transportation fuel and while raw bio-oil has been shown to be operational in diesel engines, there are concerns about the effects of the oil on the engine, the flow of the oil in cold temperatures, and other technical problems (Briens et al., 2008). In raw form, bio-oil may be used to power the pyrolysis process or to generate electricity in a fixed generator.

After processing, bio-oil has a number of potential uses. Processed bio-oil could be utilized as a transportation fuel, especially as a blend with diesel fuel, or may produce high value products such as liquid fuels, fertilizers, acetic acid, food flavorings, and adhesives. Currently, the best known use of processed bio-oil is the food flavoring liquid smoke (Briens et al., 2008).

However, refining of bio-oil is unlikely in the small scale, developing world context modeled here.

1.7. Commercial Reactors

There are a large number of existing pyrolysis research reactors, both at academic and commercial research facilities, but, excepting charcoal production kilns and gasification systems, a limited number of reactors can be said to be operating at a commercial scale. Here, we discuss selected commercial reactor designs which are at least at the prototype stage of development. Some systems are intended to be scaled up while others are intended for modular or small scale use. It should be noted that in the past ten years, players in the pyrolysis market have had limited success in realizing development goals, and therefore companies' development goals may be viewed speculatively.

1.7.1. Fast Systems

Dynamotive

Dynamotive is arguably the most successful pyrolysis firm. It is traded on the over-the-counter market and has a market capitalization of $32 million (as of April 2011), but according to recent financial statements, has not yet made a profit. Dynamotive has two large scale pyrolysis systems in West Lorne and Guleph Ontario, Canada. The West Lorne plant is capable of processing 130 t of biomass per day, and the Guleph system is capable of processing 200 ton (t) per day, however, the Guleph plant was idled in 2008 and has not yet restarted production. The West Lorne plant is coupled with a 2.5 MW generation facility which sells power to the electrical grid.

The Dynomotive system uses a finely ground feedstock (under 2 mm) heated to between 450 and 500°C in a fluidized bed reactor. The char is then separated and collected and the gases are fed into a quenching system which condenses the bio-oil and allows the syngas to flow back into the reactor. Dynamotive is primarily interested in energetic applications for the products of pyrolysis and is investigating the use of bio-oil as a transportation fuel and char as a substitute for coal as well as a soil amendment. Table 1.2 shows the proportions of the main end products of the Dynamotive system given different feedstocks.

Ensyn

Ensyn, like Dynamotive, is a relatively large pyrolysis company and has a 100 t per day circulating fluidized bed fast-pyrolysis system operational in Renfrew, Canada (Figure 1.7), as well as several smaller plants in the U.S. The Ensyn system is a fast pyrolysis fluidized bed system called Rapid Thermal Processing (RTP). The RTP system results in 65 to 75% bio-oil. Ensyn, along with UOP (a Honeywell subsidiary), formed Envergent Technologies to commercialize the RTP process. Envergent Technologies estimates that the capital costs for a 400 t per day system integrated into an existing refining system are $21 to $49 million and a with a bio-oil production cost of $0.41 per gallon (assuming $40/ton feedstock cost). Envergent Technologies plans to offer 100 to 1000 t per day facilities. Table 1.3 shows the proportions of the main end products of the Ensyn system given different feedstocks.

Biomass Technology Group

Biomass Technology Group-Biomass to Liquid (BTG-BTL, a subsidiary of BTG) has built a 24 t per day demonstration rotating cone fast pyrolysis reactor. According to the company, it is capable of producing 70% bio-oil by weight. The BTG reactor can use biomass with up to 10% water and a 6 mm particle size and produces excess process heat which can be used for drying biomass. In their system the char is combusted to heat the fluidized bed sand and thus provide energy for the reactor. BTG is building a 120 t per day system in the Netherlands to demonstrate the technology, but their primary business model is to license and provide technical support and components for their reactor design.

Renewable Oil International

Renewable Oil International has developed 5 and 15 t per day fast pyrolysis units and has plans for 50 and 200 ton fast pyrolysis units. The larger units are expected to generate 57% bio-oil, 27% char and 15% syngas using a woody feedstock and to cost \$3.4 and \$15 million respectively (Sorensen, 2010). The smaller of the units is designed to be periodically mobile and built on the bed of two semi-trailers. Table 1.4 shows the output and energetic values from the Renewable Oil system and compares the energetic values to conventional fuels. Energetic values vary by feedstock and pyrolysis system, but are generally similar to those provided in Table 1.4.

1.7.2. Slow Systems

Pacific Pyrolysis

Pacific Pyrolysis (formerly BEST pyrolysis) uses a slow pyrolysis system that may be coupled with char gasification for the production of varying quantities of syngas and char. Pacific has built a 300 kg/hr demonstration plant and is currently working with clients to build modular 48 or 96 t per day slow pyrolysis units. Biomass is fed from a dryer to the pyrolysis kiln. Both the dryer and the kiln are powered by the combustion of syngas. The kiln has only two significant end products, syngas and char. The syngas is cleaned and combusted in an engine for the production of electricity, while the char is either collected as a soil amendment, or gasified for the creation of syngas to power the kiln and dryer. Depending on the feedstock and process conditions, Pacific claims that char accounts for between 25 and 70% of the end product (by weight). Despite the fact that they have built small scale reactors, Pacific does not intend to commercialize small scale technology. The smallest reactors Pacific hopes to sell are 48 to 96 t per day systems due to economies of scale, especially related to safety issues (Wednt, 2009).

Biogreen

Biogreen is a process developed by a French engineering company, ETIA. The Biogreen system is a small to medium scale system capable of performing a variety of pyrolysis reactions by varying the operating conditions within the reactor. The system uses an electrically heated screw conveyor to heat the biomass at a variable temperature and control the reaction time. Biogreen systems are available from 2.5 m^3/h to 7.5 m^3/h, on the order of 25 to 75 t per day and cost approximately \$1.2 to \$3.3 million depending on size.

Eprida

Eprida has built a small (25 to 50 kg/h; 0.6 to 1.2 t per day) slow pyrolysis reactor that is designed to produce primarily char and syngas. The Eprida system is a variation on conventional pyrolysis in which 30% of the H_2 produced as syngas is used to create NH_3. This ammonia is then combined with CO_2, water and the char from pyrolysis to create ammonium bicarbonate and additional energy. This ammonium bicarbonate is bonded to the char and creates a fertilizer called ECOSS. Eprida hopes to build a 1.2 t per day commercial reactor that generates 10 kW of excess electricity with a capital cost of \$75,000.

1.7.3. Gasification Systems

There are a number of small and mid-scale biomass gasification systems that have advanced to commercial or near commercial status.

Community Power Corporation

Community Power Corporation provides 25, 50 and 75 kWe (10^3 Watts of electric capacity) gasification systems for off and on-grid applications. Community Power offers a modular downdraft gasification system; biomass enters the top of the reactor where it is dried and flows downward into a higher temperature, pyrolysis zone. As the pyrolysis products continue downward, air is added and the char from the pyrolysis is combusted. The ash, char and gas is then fed through a cooling and cleaning system where heat is removed from the products and the residual char and ash are removed. The gas is then burned in a gas or diesel generator set to produce electricity.

1.8. Scale

Pyrolysis is a readily scalable process and economies are likely to exist at both large and small scales. At a small scale (< 1 t/h biomass input), pyrolysis is amenable to rural electrification where systems would be close to biomass sources, reducing transport costs. The char from these systems could also be used in the local community or by the pyrolysis operator, reducing both transport and marketing costs. It is also possible that small scale systems would be mobile, allowing a periodic relocation of the system to follow biomass production. Small scale systems are not physically large and could be built in an assembly line process and shipped to the end user mostly pre-assembled; this would lead to further cost reductions. Small scale systems are likely to be designed to either maximize char and/or electrical production, either through bio-oil or syngas combustion. Due to processing requirements, small scale systems are less amenable to bio-oil production.

Medium and large scale systems (> 1 t per h biomass input) are likely to be more diverse and may include both fast and slow pyrolysis and gasification systems optimized for char, bio-oil and/or syngas. Large scale systems may be collocated with bio-oil refining operations to upgrade bio-oil into a more attractive product.

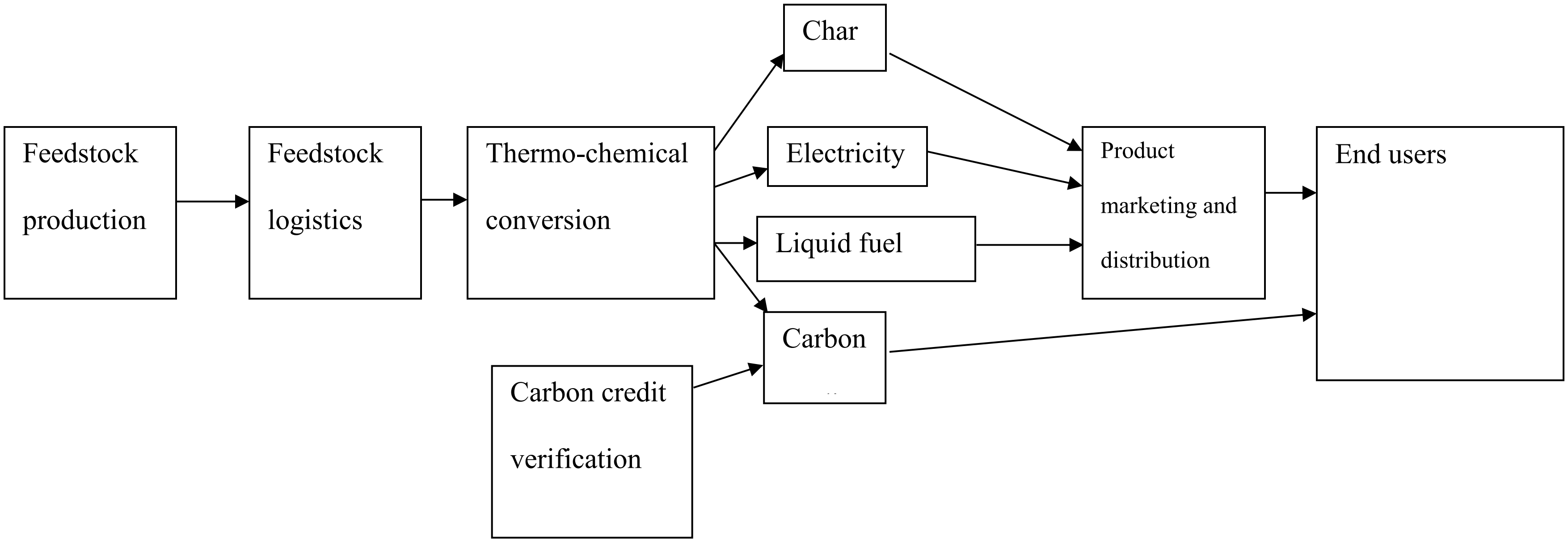

Figure 1.1 Pyrolysis system

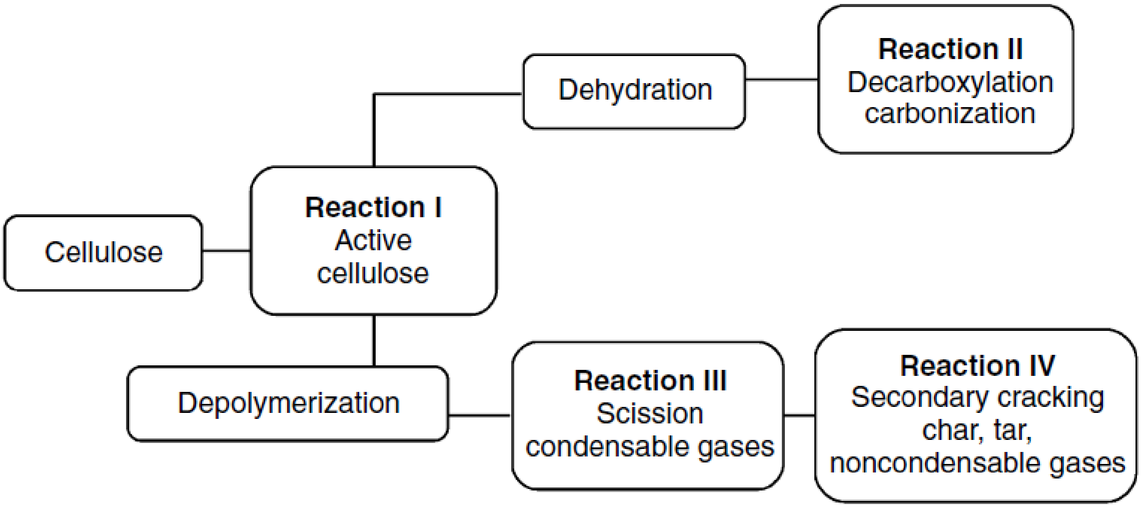

Figure 1.2 The reactions occurring during the pyrolysis of cellulose Source: Basu, 2010

Figure 1.3 A kiln used for traditional charcoal production

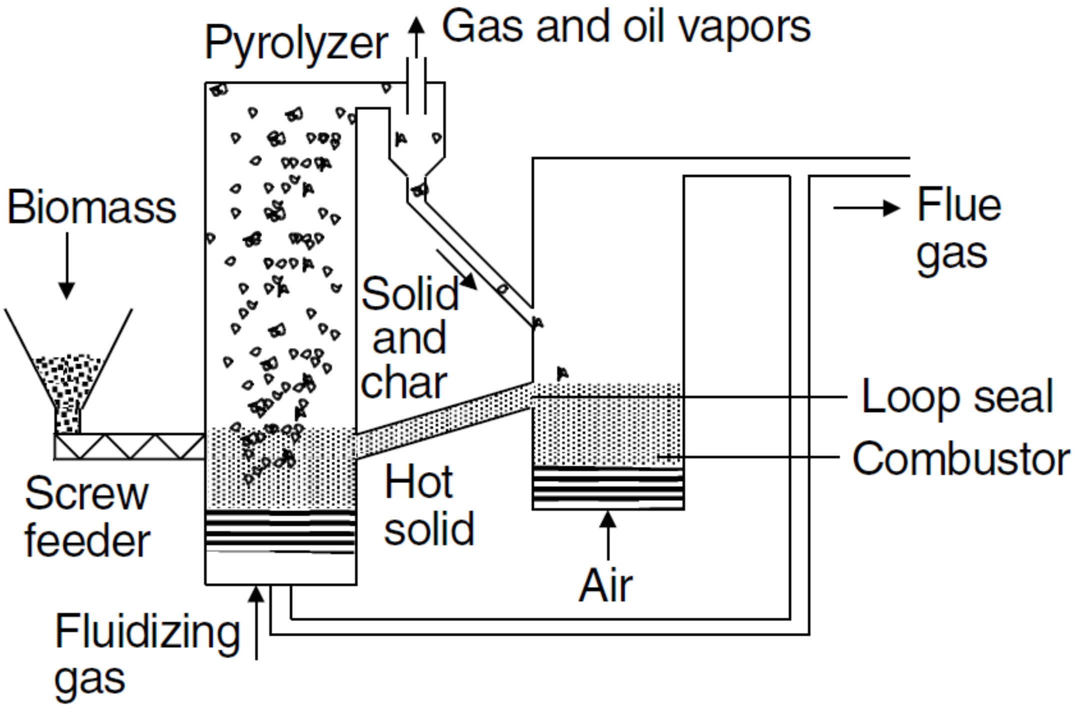

Figure 1.4 Circulating fluidized bed fast pyrolysis system Source: Basu, 2010

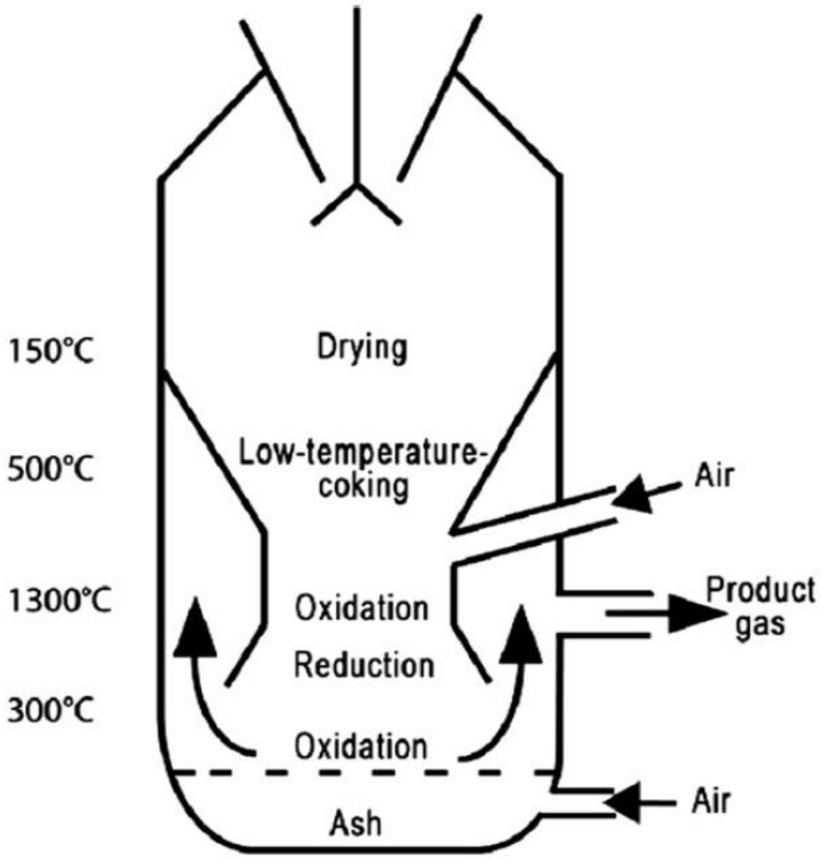

Figure 1.5 Gasification system Source: Kramrieter et al., 2008.

Figure 1.6 Left, an oxisol (nutrient-poor), right, a terra preta (fertile) soil

Figure 1.7 Ensyn fast pyrolysis system Source: Ensyn

Table 1.1 Types and end-products of pyrolysis Source: Bridgewater, 2007; Laird, 2009

Mode	Temperature °C	Residence Time (sec)	Liquid (%)	Gas (%)	Char (%)
Fast	500	1	50-75	12-25	13-15
Slow	400	>300	30	35	35
Gasification	800	>60	5	10	85

Table 1.2 Products from Dynamotive fast pyrolysis system using different feedstocks

Feedstock	BioOil yield (Wt%)	Char yield (Wt%)	NCG yield (Wt%)
Corn Hulls	80.4	12.1	6.8
Spruce	73.8	8.1	16.3
Larch	72.9	12.7	10.3
Sugarcane bagasse	72.7	14.8	8.2
Pine/Spruce Mix	70.3	14.3	13.4
Western Cedar	68.8	14.1	7.1
Switch Grass	58.7	13.8	13.4
Wheat Straw	58.7	13.8	13.4

Table 1.3 Products from the Ensyn RTP system

Biomass Material	Bio-oil Yield (wt%)	Gross energetic value (MJ/t)
Hardwood	70-75	17,200-19,100
Softwood	70-80	17,000-18,600
Hardwood Bark	60-65	16,700-20,200
Softwood Bark	55-65	16,700-19,800
Corn Fiber	65-75	17,600-20,200
Bagasse	70-75	18,900-19,100

Table 1.4 Products from Renewable Oil International system

	Yield %	Energy content (MJ/t)	Energy content of comparable product (MJ/t)
Bio-oil	60	18,600	crude oil: 40,000-45,000
Char	24	27,900	coal: 30,000
Syngas	15	10,500	natural gas: 54,000

Chapter 2: Opportunities for Bioenergy Utilization in Costa Rica

2.1. Introduction

Costa Rica is well regarded for its recent environmental record. It has led the world in payment for environmental services programs, uses primarily non-CO_2 emitting forms of electricity, has protected and reforested large amounts of land, and has developed significant numbers of high-tech and service industry jobs which are generally less environmentally destructive than heavy industry or large-scale commercial agriculture. Recently, Costa Rican officials announced plans to make the country carbon neutral by 2021. Costa Rica is also one of the most economically developed nations in Latin America. The per capita GDP (adjusted by purchasing power parity) is approximately $11,000, slightly above the world average and it is considered to be among the most democratic and stable nations in the world (Marshall and Cole, 2009).

However, Costa Rica also faces significant challenges. Costa Rican electricity production relies heavily on hydroelectricity which has significant environmental impacts and is susceptible to drought and climate change. The economy, while diversifying, still relies heavily on agriculture which produces large amounts of wastes, much of which is untreated, and poverty, while low by Latin American standards, is still a problem with 2% of the population living on less than $1 per day and 9% of the population living on less than $2 per day (Cox et al., 2007).

From the perspective of bioenergy projects, Costa Rica is particularly interesting. It is a non-Annex I party to the Kyoto Protocol allowing firms in Costa Rica to generate Clean Development Mechanism (CDM) carbon credits. It has high net primary productivity, and agricultural waste streams can be utilized as feedstocks. Further, the stability of its government lowers risk for foreign investors seeking to develop CDM projects. Despite these advantages, as of 2010 only 6 of over 2100 registered CDM projects were in Costa Rica.

Access to reliable energy sources is critical to economic development (Casillas and Kammen, 2010) and particularly important in Costa Rica. Costa Rican policy makers seek to attract foreign investment to the country, particularly high tech manufacturing facilities (Spar, 1998). Electrical costs and reliability will be key factors determining the ability of Costa Rica to continue to attract foreign investment and diversify the economy. Here, we discuss energy use in Costa Rica, its constraints and its future growth in the context of development and the opportunities for bioenergy use.

2.2. Energy Use

In much of the developed world electricity use has stabilized or declined in recent years due to conservation, reduced population growth, and the movement of manufacturing to the developing world. In the developing world, population and manufacturing growth is high and consumers purchase new electricity-demanding goods; in many places, this has led to rapid energy demand growth (Suri and Chapman, 1998). Figure 2.1 shows the distribution of sources of electrical generation and electrical generation growth in Costa Rica. From 1990 to 2005, electrical generation doubled. Most of the electrical generation growth in Costa Rica is hydroelectric, however, there is also a growing proportion of electricity produced from solar, wind and geothermal sources. Costa Rica produces approximately 1000 GWh of electricity from geothermal sources, 200 GWh of electricity from wind power and 70 GWh of electricity from biomass and waste annually. Together, these non-hydroelectric renewable energies account for 15 to 20% of generation, but the 70 GWh of biomass based electricity is equivalent to approximately 0.7% of electrical generation. Wind power is particularly promising because trade winds are strongest in the dry season when river flows are low.

Traditional thermal sources (oil, coal and natural gas) provide approximately 6% of Costa Rican electricity generation, and from 2004 to 2008, the proportion of generation associated with conventional thermal sources increased from 2 to 6%. In order to improve electrical reliability, the nation's electricity regulator, *Instituto Costaricense de Electricidad* (ICE) has planned to increase the proportion of electricity generated from conventional thermal sources to 20% by 2016. This may be at odds with the government's desire to make Costa Rica the first carbon neutral nation by 2021.

In Costa Rica, all traditional thermal generation is generated from petroleum fuel. No coal or natural gas is used to generate electricity. Since coal and natural gas are typically the least expensive electrical generation options in many global markets, the absence of coal and gas allows alternative energy sources to be more competitive.

Table 2.1 shows the per capita electrical consumption, per capita energy consumption and total energy use in Costa Rica. Both the total energy use and the per capita energy use increased steadily over the 26 year period, however, even in 2006, the per capita energy consumption in the U.S. was approximately 7.6 times the per capita energy consumption in Costa Rica. Electricity accounts for 15 to 16% of energy use; the remainder of energy consumption is due to transportation fuels (50 to 55% of energy consumption) and heat used for industrial processes. As of 2008, Costa Rica used approximately 2,000 kWh per person per year.

2.3. Electrical Costs

In 2008 the average price of electricity for Costa Rican consumers was 9.7 U.S. cents per kWh (¢/kWh) for residential use and 9.3 U.S. cents per kWh for industry (EIA 2011). These costs are comparable with electricity costs in the Southeastern U.S. However, energy prices in Costa Rica have increased in recent years largely due to costs for bunker fuel, and in rural areas that are more heavily reliant on thermal generation, electricity costs are approximately 16 U.S. cents per kWh (Aguero, 2010).

The costs of producing hydroelectric power generally range from 5 to 10 cents per kWh and depend on the geography and hydrography of the site, the scale of the development, regional wage conditions and other factors (Sims et al., 2003; NEA and IEA, 2005). Hydroelectric costs are composed primarily of the capital costs of construction, and operating costs are low compared to fossil fueled power. Thus, the costs of hydroelectric generation are relatively predictable. By contrast, the costs of fuel oil powered generation are unpredictable and are primarily influenced by fuel costs rather than capital costs. Recently, oil costs have been high which has led to increases in electricity rates, and ICE plans to adjust electricity rates every three months based on fuel costs. Thus, Costa Rica is in a unique position in which the costs of renewable energy generation are frequently lower than the costs of thermal energy generation

2.4. Electrical Reliability

Costa Rica has had recent problems with electrical reliability occurring every dry season and peaking in April. From February to May hydroelectric production decreases from 80 to 63% of capacity (U.S. State Department, 2009). Hydrocarbons are used to compensate for this decreased production. In the U.S. and Europe, natural gas is seen as the preferred energy source to back up other power sources because it is quickly dispatchable, and in the current price environment is inexpensive, especially compared to petroleum. The lack of natural gas generation and infrastructure forces Costa Rica to rely on petroleum to backup to its hydroelectric power.

Costa Rica is also seeking to increase wind and solar power production. Both onshore wind and solar power are intermittent and require a backup system in order to maintain a reliable supply of electricity. The use of petroleum as a backup will raise overall system costs for Costa Rican consumers.

2.5. Demand Growth

Several factors impacting electrical demand growth in Costa Rica. First, as the nation develops, per capita residential electrical consumption will increase. Ninety-seven percent of Costa Rica's households have access to electricity, and 91% of households have a refrigerator, 87% have a washing machine, and 42% have a water heater (Huttunen and Lampinen, 2005). As Costa Rica develops, per household electricity consumption will increase as the remaining households purchase refrigerators, water heaters, air-conditioners, televisions, computers and other electricity demanding products.

Additionally, economic development may change the energy intensity of the Costa Rican economy. As a nation's per capita GDP grows, its energy intensity, measured by the energy use per dollar of GDP generated, may remain constant, may increase or may decrease. Over the past 25 years, energy intensity has steadily increased mostly in the world's poorest nations (Haiti, Dominica, Benin, Burundi, Congo, Guatemala); in some cases, this may be due to energy use increasing faster than GDP growth, while in other cases it may be due to energy consumption remaining constant while GDP falls. In other nations, energy intensity has declined dramatically due either to a rapidly expanding economy (e.g. China) or to a transition to less energy intensive industries (U.S. and Europe). Figure 2.2 shows a relative lack of change in Costa Rica's energy intensity since 1980. If Costa Rica continues its present course of development, and the tourism, financial service and high-tech sectors continue to grow, it is likely that energy intensity will decline, moderating demand growth.

The US EIA predicts that electricity demand growth in Latin America will average 2.8% over the next two decades (EIA, 2008). Morey (2006) predicted that electricity demand in Costa Rica will increase between 4.65 and 5.4% per year over the next two decades, and Costa Rica's *Instituto Costaricense de Electricidad* (ICE), the public utility monopoly, expects energy growth to average 5 to 6 % (Hamilton 2008). The growth of electrical demand at rates of between 2.5 and 5.5% per year are shown in Figure 2.3. The 5.5% growth rate most closely matches the observed growth rate over the past three decades and if continued would lead to a tripling of demand in twenty years. This level of demand growth would require significant investments in generation and transmission infrastructure.

Over the past 25 years, the average growth rate of generation capacity was 5% (compared to 5.7% for the growth rate of demand) While 5% is a large annual increase in generation capacity, if consumption continues to increase at 5.7%, generation capacity will eventually need to increase by more than 5%,. The rate of capacity growth needed to satisfy demand is shown in Figure 2.4. Figure 2.4 shows that in order for capacity to keep pace with increasing demand growth, the capacity must roughly triple from about 2000 MW to about 6000 MW. Assuming that each future kW of capacity will cost $2000, Costa Rica may need to spend about $7-8 billion over the next 20 years in order to upgrade its electrical generation capacity, consistent with ICE estimates (U.S. State Department, 2009). This figure does not include upgrades to the electrical grid necessary to transport this increased load. The GDP of Costa Rica in 2009 was $29 billion; for comparison, if scaled to the size of the U.S. economy, a similar investment in the U.S. would be on the order of $4 trillion.

The vast majority of electrical generation in Costa Rica comes from hydroelectricity and hydroelectric power production may decrease due to drought associated with climate change. If this occurs than the capacity may need to increase by more than expected to cover shortfalls in hydroelectric production. Furthermore, additional investments in hydroelectric generation are constrained by the availability of suitable sites and the ecological impacts of dams (Kennedy, 2013).

The costs of meeting increased demand with hydroelectric power are significant. In 2011 Costa Rica opened a large (134 MW) hydroelectric facility at a cost of $4.6 million per MW and in 2018, Costa Rica plans to open the largest hydroelectric plant in Central America, the Reventazón dam at a cost of approximately $1 billion ($3.3 million per MW). While the cost of electricity produced from these plants are not known (e.g. costs on a kWh basis which depend on both the capital and operating costs and finance terms), the capital costs are similar to those of offshore wind systems in Europe which are among the most expensive generators (Kaiser and Snyder, 2012). Recall that the estimate of $7 to $8 billion in required generation investment assumed a capital cost of $2000 per kW ($2 million per MW), roughly half of recent hydroelectric costs.

2.6. Electrical Regulation

The Instituto Costaricense de Electricidad (ICE) is a government-owned vertically-integrated electricity and telecommunications monopoly that is charged with coordinating and planning the electricity and telecommunication sectors in Costa Rica. ICE is responsible for all electricity transmission, 39% of distribution and 78% of generation. The Compañía Nacional de Fuerza y Luz (CNFL) an ICE subsidiary, distributes 42% of electricity and produces 9% of national electricity (Morey, 2006). Together, these two companies are responsible for 100% of transmission, 81% of distribution and 87% of production. Two municipal companies and four cooperatives make up the rest of electricity distribution in Costa Rica. These companies and a few private companies including small hydroelectric projects, sugarcane refineries and wind plants, produce the remaining 13% of electricity in Costa Rica. All of the electricity they produce must be sold to ICE which then transmits to distributors.

The laws that established ICE also established its monopoly by limiting the amount of electricity produced by private industry. In total 30% of electrical production can be generated in non-ICE owned plants, however, half of this must be in Build-Operate-Transfer plants which must be sold to ICE after 20 years of operation, and all generation must be sold to the ICE controlled grid. Additionally, private companies are limited to building plants under 20 MW (or 50 MW for a build-operate-transfer plant).

There has been recent debate about the liberalization of the energy market in support of increasing the diversity of renewable energy generation. A bill under debate (as of 2011), calls for opening 35% of the electrical grid to private renewable generation and to establish a regulated market for the sale of energy.

Recently, ICE has also developed a pilot 5 MW net-metering program in which individuals may generate renewable energy and sell it to ICE. However, the generator does not receive cash, but a credit to be used for the purchase of electricity. In practice, this limits the average amount of electricity a consumer will produce to their average consumption; generating more than this amount will result in the build-up of credits which will never be used.

2.7. Climate Change Impacts on Energy Production

Climate change may have significant impacts on Latin American electrical generation capacity. Latin America in general, and Costa Rica in particular, relies on hydroelectricity to produce large portions of their power. Precipitation anomalies, especially droughts, impact hydropower production. Over the past several decades there have been significant decreases in precipitation in the tropics particularly between 10° S and 30° N (Bates et al., 2008). Table 2.2 shows the precipitation predictions for Latin America (IPCC, 2007). There is considerable variation in the ranges and it is possible that in parts of Latin America increases in precipitation may occur. Overall though, it is thought that Latin America will suffer a sustained decrease in precipitation over land. This decrease is predicted to increase in severity throughout the 21st century. Figure 2.5 shows the predicted global precipitation in the late 21st century. In both models the precipitation in Central America declines, however the extent of the decrease and its precise geographic location is different.

Much of the hydropower generated in Latin America is produced in small systems, in many cases without large reservoirs. As a result, the system has little ability to store water. Therefore, more frequent storms and longer dry periods, would impact production at small-scale sites, even if total precipitation remained constant. This will interact with electrical reliability issues so that even if average rainfall and average hydroelectric generation do not decline, increases in rain variability will increase the needs for backup dispatchable generation.

Climate change may also have impacts on agricultural yields. If rainfall declines, agricultural production will generally suffer. This could cause farmers to irrigate crops, leading to water withdraws from surface water and further reducing water available for hydropower. Furthermore, as crop yields decline and crop prices rise, demand for additional land may create pressures for turning forest into cropland. This would not only release additional carbon into the atmosphere but would reduce the availability of land which could be used for bioenergy growth. Additionally, manufacturing and population changes may also lead to competition for water resources and reduce the water available for hydroelectric generation. Costa Rica has recently experienced significant population growth and the implementation of the Central American Free Trade Agreement along with tax incentives from the Costa Rican government may lead to sustained manufacturing growth in Costa Rica. Combined with the potential for drought due to climate change, it may not be possible for Costa Rica to continue significant growth in its hydroelectric sector without user conflicts.

2.8. Export Opportunities

In the recent past Costa Rica has been both a slight importer and slight exporter of electricity with imports exceeding exports in the dry season, and exports exceeding imports in the rainy season. In the near term, SIEPAC, a regional high voltage transmission line connecting all of Central America, will become operational. The construction of SIEPAC is analogous to the construction of an interstate highway replacing local roads in that it increases the efficiency of electricity transport over large scales. This will create new opportunities for imports and exports into and out of Costa Rica through the creation of a single Central American electricity market.

SIEPAC will allow a firm to sell electricity to a larger market than was previously available; this would create economies of scale so that firms could build larger generators to match the larger market. Due to these economies of scale generation systems that were previously too costly may be feasible. This may include coal-fired generation (Martin, 2010).

SIEPAC is critical for meeting Costa Rica's goals of renewable electricity generation. One of the main problems with solar, wind and some hydroelectric power is intermittency, that is, it cannot respond to demand and is variable in output. One way to address the problems with intermittency is to link renewable energy generators over a wide geographic region so that if generation declines in one region it can be compensated for by increased production in another region (Delucchi and Jacobson, 2011). Due to their size, most countries in Central America lack the capability to geographically compensate for variability in generation, however, the creation of a single larger market may allow for improved geographic compensation particularly for solar and wind power networks which are more locally time-variant than hydroelectricity.

2.9. Opportunities for Bioenergy

Total electricity demand in Costa Rica is expected to increase significantly in the coming years and multibillion dollar investments in generation will be needed to meet demand. Demand will increase due to both increasing population size and an increase in electrical demand per capita. Costa Rican policy makers must decide which generation technologies to encourage and which to discourage. Changes in climate due to CO_2 emissions may impact the future availability of wind and hydropower resources and may require investment in more expensive alternative energy sources.

In 2005, ICE predicted that approximately 4700 MW of new capacity would be required by 2025, consistent with their prediction of a 5 to 6% annual growth rate and historical trends. The demand needs are to be met with a combination of new hydroelectric, wind, geothermal and petroleum generation (U.S. Trade and Development Agency, 2010). The future price of oil is notoriously difficult to predict, however, there is a general consensus that oil prices will remain high relative to their historical average due to increasing demand from Asia and concerns over the ability to increase the production to meet this demand. Therefore, the costs of petroleum based electrical generation are expected to be high. If petroleum based generation remains a backup to hydroelectric production in Costa Rica, high oil prices may not increase average electricity prices significantly, however, a high oil price provides an opportunity for bioenergy. If bioenergy resources are stored for use during the dry season when hydroelectric production declines, bioenergy will not compete with hydroelectric production but with more expensive oil-based electrical production and wind.

Difficulties with reliability and back up energy sources necessitating the need for petroleum-based generation provide a provide a particular market opportunity for bio-oil and biomass based syngas. Both of these energy sources are dispatchable and can be used to provide peaking power. Peaking power is required to meet daily periods of high demand and in market based systems peaking power plants obtain a price premium.

Bio-oil and syngas could also be used by individual consumers for small or medium scale on-site backup generation. A number of facilities require backup power capabilities, especially in areas with frequent power outages. Frequently, consumers are willing to pay a price premium for emergency generation.

Biomass combustion could also be used to back-up renewable energy generation, however, biomass combustion, like coal combustion, is applicable primarily to a predictable, system level support (i.e. base load power). That is, biomass combustion facilities could be operated throughout the dry season, but would likely be unable to react quickly to peak power demands limiting its utility for individuals. However, given the predictability of hydro power production, this power could be valuable.

While biomass combustion is poorly suited to peaking power generation, the use of pyrolysis to make syngas or bio-oil creates an energy supply that is useful for rapidly responding to power needs (i.e. dispatchable) and could be stored to meet future demand. Syngas and bio-oil can both be burned in internal combustion engines, functionally similar to those used for diesel-powered electrical generation. The decision whether to use biomass to generate pyrolysis products or in direct combustion will in part depend on the price difference between baseload and dispatchable power.

2.10. Conclusion

Assuming that Costa Rica requires 6000 MW of renewable electrical generation capacity in 2025, and that the electrical system requires at least 25% of that capacity to be in the form of dispatchable power to compensate for dry periods (similar to the current situation), then approximately 1500 MW of dispatchable, renewable power are required. Furthermore, if the climate becomes more variable, as is widely predicted by most climate change models, the need for dispatchable backup generation will increase, and if Costa Rica seeks to improve electrical reliability or increase the proportion of wind power in the grid, dispatchable energy needs will increase further. Thus, if Costa Rica intends to eliminate the use of bunker fuel for electrical generation, it must find a way to build at least 1500 MW of dispatchable renewable generation. It is possible that pumped hydroelectric facilities may be able to provide some of this need, however, given the current reliance on hydroelectric and climate change issues, pumped hydroelectric storage may not be reliable. Thus, biomass-based generation is the only means of addressing this need. Assuming an investment of $2000/kW of capacity, this amounts to a $3 billion investment in bioenergy facilities.

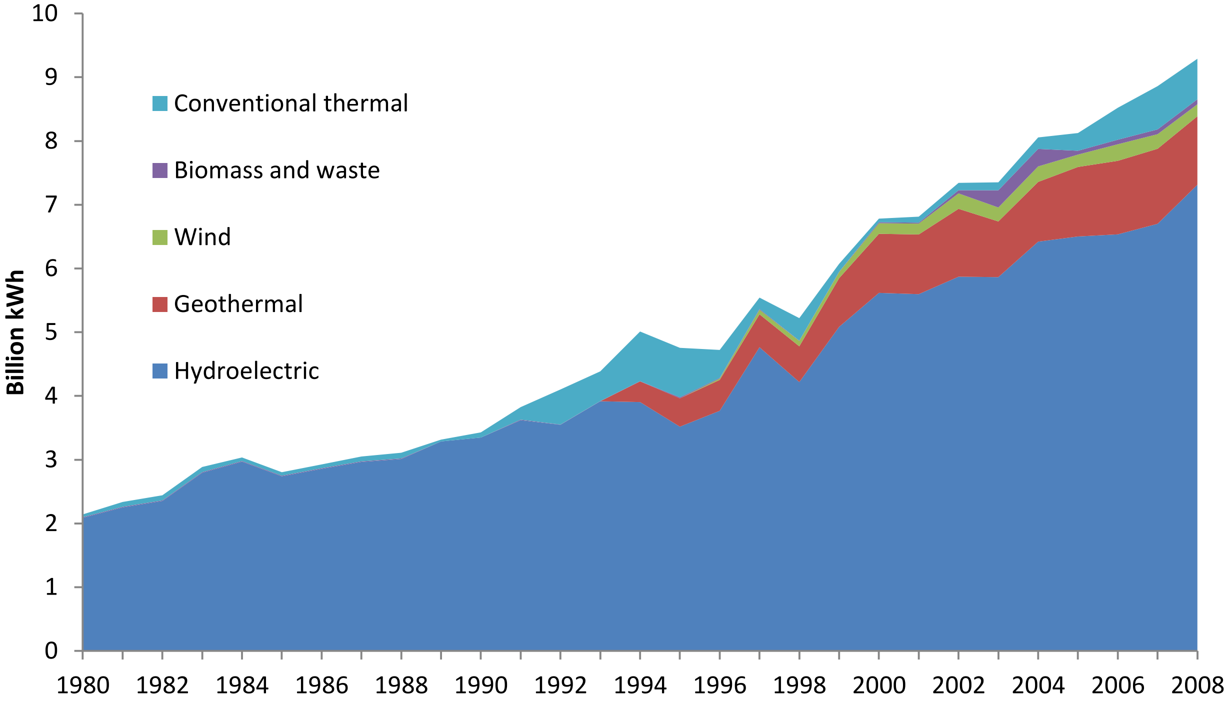

Figure 2.1 Costa Rica electricity generation by type and year Data from EIA, 2011

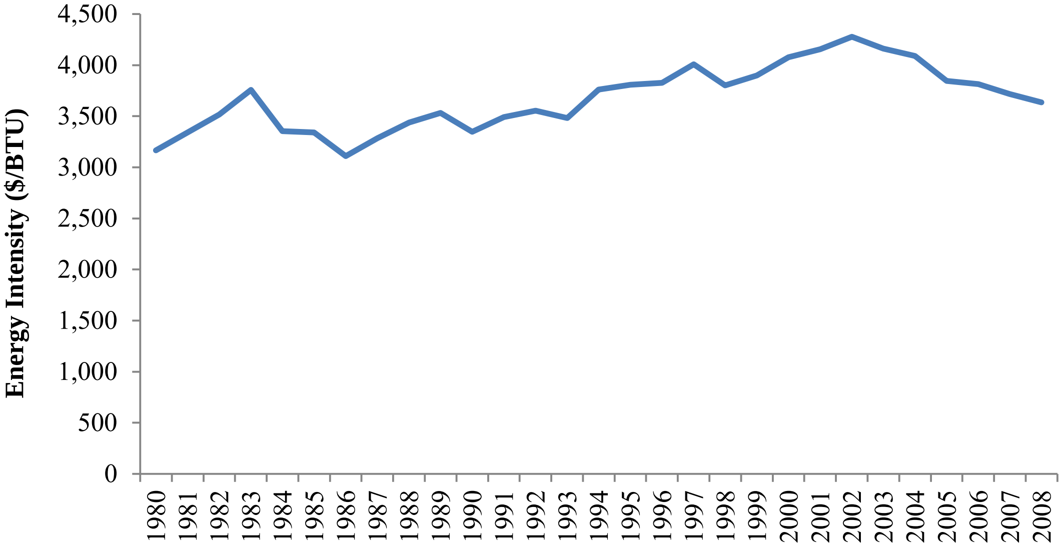

Figure 2.2 Energy intensity in Costa Rica Data from EIA, 2011

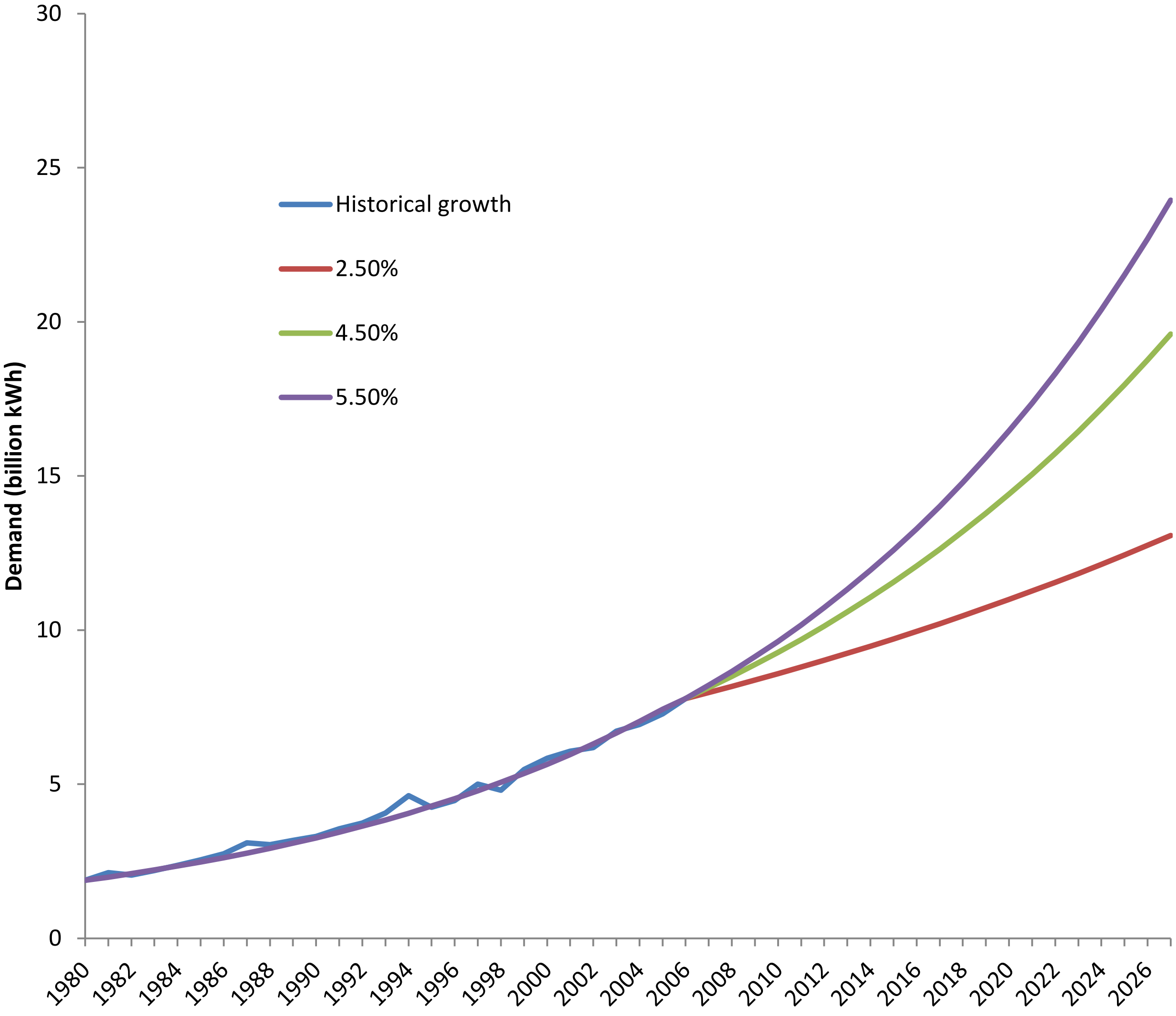

Figure 2.3 Historical Electricity Demand and Demand Growth in Costa Rica 1980 to 2027 Data from EIA, 2011

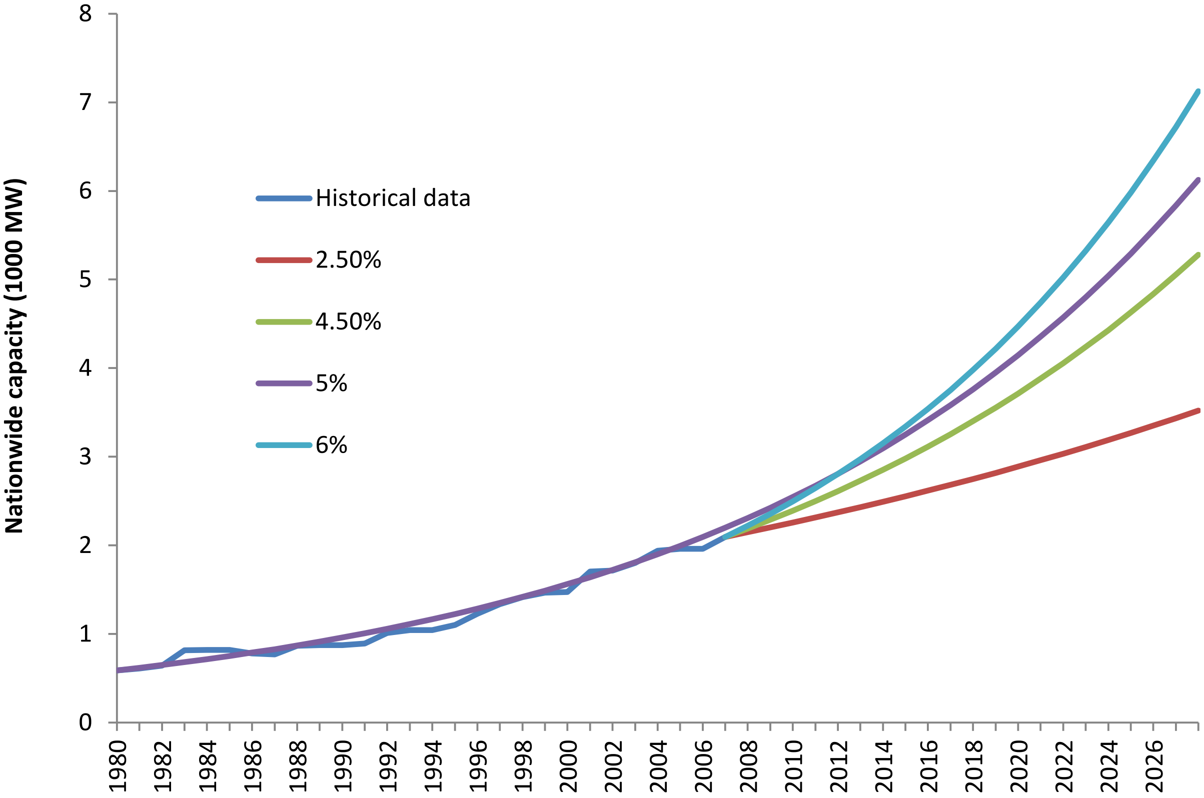

Figure 2.4 Historical electrical capacity and potential capacity growth Data from EIA, 2011

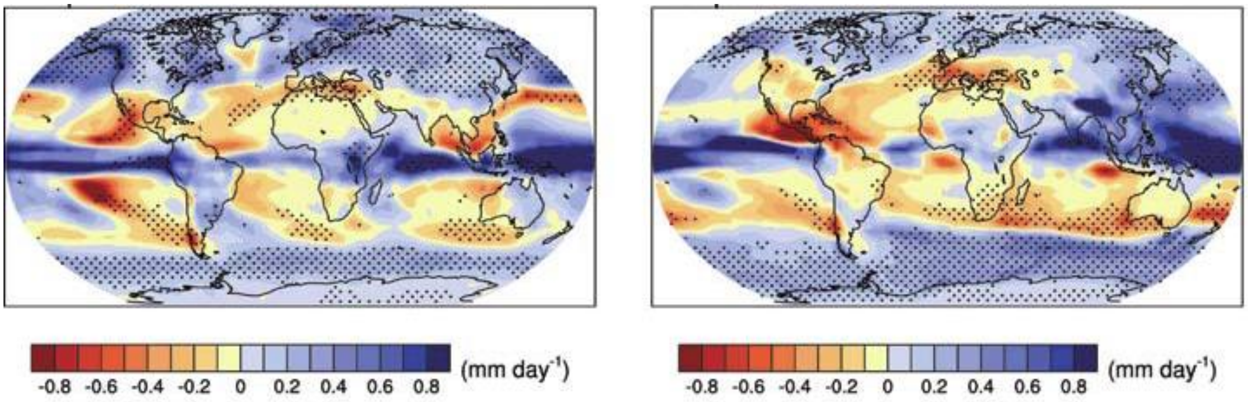

Figure 2.5 The precipitation predictions of two global climate models from 2080 to 2099

Source: IPCC, 2007

Table 2.1 Costa Rican Energy Use

Year	Total Energy consumption (10^9 kWh)	Per capita energy consumption (kWh)	Per capital electrical consumption (kWh)
1980	16.3	7,069	932
1981	16.8	7,112	991
1982	16.4	6,745	1,007
1983	18.0	7,206	1,157
1984	17.3	6,747	1,182
1985	17.4	6,579	1,061
1986	17.1	6,269	1,075
1987	18.9	6,750	1,089
1988	20.5	7,119	1,081
1989	22.2	7,526	1,123
1990	21.8	7,203	1,133
1991	23.3	7,498	1,233
1992	25.8	8,142	1,293
1993	28.3	8,712	1,352
1994	30.7	9,275	1,512
1995	32.3	9,560	1,405
1996	32.8	9,506	1,368
1997	36.3	10,311	1,576
1998	37.3	10,411	1,457
1999	41.4	11,350	1,665
2000	44.1	11,882	1,827
2001	45.4	12,033	1,805
2002	47.9	12,482	1,914
2003	49.4	12,675	1,886
2004	50.5	12,763	2,035
2005	50.6	12,585	2,022
2006	52.1	12,766	2,090

Table 2.2 Expected changes in Latin American Precipitation From IPCC, 2007

Change in Precipitation (%)	2020	2050	2080
Dry Season	-7 to +7	-12 to +5	-20 to +8
Wet Season	-10 to +4	-15 to +3	-30 to +5

Chapter 3: Production Costs of Biomass for Bioenergy in the Neotropical Developing World

3.1. Introduction

The two major costs facing all bioenergy producers, including pyrolysis operators, are capital expenditures for reactors and biomass costs. Even small scale pyrolysis units can use several tons of biomass per day. If this biomass is not locally produced, its transportation will emit carbon dioxide which will reduce the overall carbon reduction efficiency of a project. Furthermore, to the extent that biomass for bioenergy competes for land with food production, its use can be controversial (Pimentel et al., 2006).

The cost of biomass for bioenergy is constituted by both production costs and transport costs. For biomass grown specifically for bioenergy applications the costs of production can be high. For example, the farm gate costs of growing switchgrass in the western and Midwestern U.S. have been estimated to range between 49 to 114 $/t (Perrin et al., 2008; Duffy et al., 2001). At this cost, biomass is significantly more expensive than coal on an energetic basis. As of early 2010, the spot price of coal was approximately 2.2 $/GJ. At 50 $/t of biomass, the cost of biomass energy would be 5 $/GJ, assuming an energy content of 10 GJ/t, commensurate with a crop residue with a relatively high moisture content. Even at this relatively high coal price, biomass would need to cost under 22 $/t to be competitive. In other cases, crop residues, animal wastes or other non-valued forms of biomass may be used. In these cases, the cost of production is simply the cost of collection (Sokhansanji and Turhollow, 2002). Note, however, that these "non-valued" potential feedstocks may in fact have value for soil nutrition.

While there have been a number of theoretical and field studies of biomass production costs in the developed world (Perrin et al., 2008; Duffy et al., 2001; Sladden et al., 1991; Hallam et al., 2001; Eplin, 1996), there has been relatively little attention on the tropical developing world. Given the low labor costs and high productivity in the tropical developing world, coupled with the Clean Development Mechanism of the Kyoto protocol, biomass for bioenergy production may be more feasible in tropical developing countries.

Estimates of transport costs for biomass also exist. Rogers and Brammer (2009) estimated transport costs of biomass in the UK to range from 6 to 30 \$/t depending on distance. Searcy et al. (2007) estimated costs for woodchip transport to increase linearly with distance from 3 to 10 \$/t for distances from 1 to 100 km. Sokhansanj and Turhollow (2002) developed a model of transport costs to a location 8 km away and found costs to range from 6.1 to 8.6 \$/MT. However, they assumed low fuel prices (0.37 \$/L), high capital costs, and high labor costs. Perlack and Turhollow (2003) estimated the costs of transport of corn stover to range from 4.23 \$/T to 10.62 \$/T for transport to a facility 5 km away. However, in all of these cases, the authors modeled a utility scale operation in the developed world. The costs of transport for decentralized systems in the developing world are likely to be very different due to different road conditions, vehicles and transport distances (Ruan et al., 2008).

Here, we estimate the costs of transporting biomass a variable distance and producing biomass from several sources. We first model the costs of waste agricultural residues assuming that they are provided for free to the bioenergy system; thus the costs of waste agricultural residues simply becomes the transport costs of the residues plus the labor costs of collection and handling. Transport costs then serve as an input to estimates of other biomass costs. We develop estimates of the costs of biomass grown in an artificial wetland, and two bioenergy crop systems. We then develop a holistic estimate of biomass costs by discounting the costs in consideration of the environmental services associated with the modeled systems.

In all models we envision a small scale system commensurate with bioenergy and/or biochar production on the scale of a small rural town or agricultural cooperative. We focus specifically on Costa Rica, but intend the analysis to be applicable to many neotropical developing world systems. This leads to technical details that are quite different from those envisioned in the developed world for utility scale biomass production (Rogers and Brammer, 2009; Badger, 2002).

3.2. Methods

We develop a number of estimates of the costs of biomass for bioenergy. In each case we use a spreadsheet-based net present value (NPV) model of cash flows. Net present value is the total current value of a series of cash flows and is equal to

$$NPV = R_0 + \sum \frac{R_t}{(1+i)^t}$$

where R is the cash flow at time *t* and *i* is the discount rate. R_0 is negative and represents the initial capital investment. R_t may be negative or positive and is the difference between operating revenues and expenses, minus depreciation. NPV allows for a simple determination of costs and is the preferred method for many of our study systems (Herbohn and Harrison, 2000; Bryan et al., 2008).

In general, we assume throughout the models that land costs, when applicable, are equal to the opportunity costs of alternative uses established in the literature. Previously, some studies of forestry projects in Costa Rica have ignored opportunity costs and have treated land costs as a separate investment decision (Streed et al., 2006). Thus, one could assume that the land for any forestry or bioenergy project is purchased and appreciates at a rate equal to cost of capital required to purchase the land. This allows for the removal of land costs from the models, significantly simplifying them. However, this does not adequately treat the concept of opportunity costs: the costs or profits associated with a foregone opportunity. Opportunity costs are often difficult to determine and highly variable, but we employ a mean of $60/hectare/yr for as an average cost (Wunscher et al., 2008).

Throughout the paper we generally assume low discount rates, between 0 and 10%. Very low discount rates (below approximately 2%) can be considered negative as they do not account for inflation and inflation is not accounted for elsewhere in the model. Low discount rates of 2 to 3% can be considered to be effectively 0; that is, they discount for future inflation, but do not discount for the opportunity costs of money or costs of capital; these low discount rates might be acceptable discount rates of return for some publicly financed systems development grant funded systems. We assume a tax rate of 0%, commensurate with a not-for-profit entity.

3.3. Waste Agricultural Residues

Agricultural residues are frequently cited as one of the most promising sources of biomass for bioenergy. In the U.S., the most frequently mentioned agricultural residue for use in bioenergy applications is corn stover (leaves and stalks) which is often left on fields after harvesting. Most frequently, corn stover is discussed as a feedstock for cellulosic ethanol. However, there are several often overlooked issues with using crop residues for bioenergy. The costs of collecting a dispersed residue can be significant. Sokhansanj et al. (2002) estimated the costs of collecting corn stover using machinery as 21.60 $/t and the efficiency as 40%. Additionally, when a crop residue is removed from a field it removes a nutrient input to the field; this lost nutrient input would result in a cost to the farmer, either in the form of lower crop yield or increased fertilizer use (McCarl et al., 2009). Increased fertilizer use would also be associated with increased carbon emissions.

In the developing world, the disposal of agricultural residues is an environmental concern (Ulloa et al., 2003). Agricultural wastes can be deposited in surface water leading to increases in nutrient concentrations, they can be deposited in landfills, or they can be burned leading to air quality issues (Cancado et al., 2006). This is a special problem in the tropics because several of the main cash crops grown in the tropics, notably coffee and sugar, require processing and produce large amounts of concentrated wastes. The primary crops in Costa Rica in 2008 are given in Table 3.1. The agricultural products and land use of Costa Rica are dominated by cash crops especially coffee, bananas, and sugar cane. Table 3.1 also includes productivities of the crops grown in Costa Rica, many of which are quite large.

One of the main potential sources of biomass for energy in Costa Rica and much of the developing neotropics is sugar cane bagasse (the fibers that remain after juice extraction). In 2005 Costa Rica produced 1.3 million metric tons of bagasse (UN FAO, 2008). Much of this bagasse is used for heat and steam in sugar mills (e.g. boiler fuel). Ulloa et al. (2004) estimate that 80% is used, leaving about 400,000 tons. However, the precise quantity of available bagasse is unknown. Restrictive electricity production laws may force many sugar mills to discard bagasse. According to Huttunen and Lampinen (2005), only three of the 16 sugar cane processing facilities in Costa Rica currently co-generate electricity using bagasse. Huttunen and Lampinen (2005) also discuss the El Viejo S.A. sugar mill which upgraded its production process to include co-generation of electricity. Before co-generation, the facility produced 109,000 tons of bagasse per year and used 30% for the production of steam, heat, and some electricity. Following the plant upgrade they now use all of the bagasse produced and generate

6.5 MW of electricity, 4 MW of which are sold to the electricity grid. Thus, it is likely that there is a large amount of bagasse which is either being burned outside of electrical generation systems, disposed of in landfills or dumped into surface waters.

Other potential sources of biomass in Costa Rica include swine and cattle manure, wastes from animal slaughtering, rejected bananas and banana peels, coffee pulp, rice husks, fruit and pineapple husks, and cocoa pods (Ulloa et al., 2004). The nationwide estimated amounts of each of these wastes are listed in Table 3.2. Costa Rica also produces about 4.3 million tons of landfill waste each year. About 60% of this waste is organic (Huttunen and Lampinen, 2005). In total, there are probably several million metric tons of waste biomass available in Costa Rica each year. Given these quantities, small bioenergy producers could choose from a large number of waste biomass sources.

Importantly, many of the wastes generated in Costa Rica are generated in concentrated streams. This fact can increase their adverse ecological impact at the local level but decrease their costs for bioenergy applications because the cost of that 'concentrated' influx of raw material involves the cost of transportation to a bioenergy facility only and not the collection of a residue dispersed across an agricultural field.

3.3.1. Model

We model a cooperative system in which a bioenergy producer travels among nearby waste producers and hauls off their waste at no cost to the waste producer. The model is beneficial for both parties; the waste producers benefit by having their wastes removed and disposed of for free while the bioenergy firm benefits by receiving a free source of biomass. We assume that a small dump truck carries 3 tons of cargo a variable distance from the source to the bioenergy facility. We assume that the truck is limited by weight rather than volume, as is typical for biomass

(Searcy et al., 2007). The truck makes a variable number of trips per day depending on the parameterization and the average distance used in the parameterization. The system operates 4 to 7 days per week in different parameterizations. Labor is assumed to cost $3 per hour. In all parameterizations the capital costs of the truck are $30,000. Maintenance on the truck requires 10% of the purchase cost annually. We assume that the truck is operational 50 weeks per year.

We developed short and long distance parameterizations of three basic scenarios (i.e. six total parameterizations); a base scenario, a maximum throughput scenario and a scenario that includes additional loading costs. Table 3.3 provides a summary of the major assumptions of each parameterization. We parameterized the model using two average distances to examine the effects of travel distance on cost. In all short distance scenarios the average trip distance was 20 miles each way (32 km) while in the long distance scenario the average trips distance was 40 miles (64 km). In the short distance scenario a round trip takes 2.5 hours including half an hour each way for transit and 1.5 hours for loading and unloading. In the long distance scenario the round trip requires 3.5 hours. In the short distance scenarios the truck completed 3 round trips per day but only operated 4 days a week. In the long distance scenario the truck operated 6 days per week but only completed 2 trips per day. This keeps the total number of trips and biomass collected equal in both long and short distance parameterizations.

We also created a maximum throughput scenario intended to maximize biomass collection and thereby reduce the per ton biomass cost. In this scenario the truck and personnel are employed 7 days per week, and complete as many trips as possible per day without exceeding a 12 hour working period. The total hours worked per week in these scenarios are 70 and 73.5 hours in short and long distance scenarios.

Finally, we modeled a scenario in which loading costs are required. The scenarios described above assume that the equipment costs of loading the biomass onto the truck are negligible. This could be reasonable if a waste producer (i.e. a sugar mill or a swine farm) had an already established logistical system for disposing of wastes. However, loading might require the purchase, use and maintenance of additional machinery. In this scenario, we assume a front end loading tractor is purchased for an additional $30,000 and that the tractor uses 9 L of fuel per hour of operation and requires 10% of its purchase price in annual maintenance.

Note that the calculated costs may be for wet or dry biomass; presumably the moisture content of the biomass would range from 50% if it were recently harvested to 15% if it had been air dried for a long period. Ideally, the bioenergy producer would plan their waste pickups to maximize the proportion of dry waste collected. We assume the water content is 25%.

3.3.2. Results

The results of the parameterizations are shown in Table 3.4. The costs range from 8 to 24$ per ton. The costs with loading are approximately 60% to 80% greater than the costs without loading and the increased distance increases costs by about 4 to 4.5$ per ton, or between 22% and 54%. Fuel costs make up the majority of costs in almost every case, with the exception of the short distance baseline model. We examined the sensitivity of the model to changes in fuel and labor costs. In both cases, responses were linear. For every $1 increase in fuel costs the break-even price of biomass increased by $1.11 while for every $1 increase in hourly labor costs the break-even price increased by $0.83. We also examined the sensitivity of the model to changes in the discount rate. Discount rate had relatively little impact on the overall cost of biomass transportation (Table 3.5).

The costs are somewhat higher than those estimated for transport in the U.S. but generally of the same order of magnitude. There are several reasons why this might be the case. Most notably, the midwestern U.S., the area in which corn stover transport costs have been modeled, has a very high density of corn farms and as a result the average distance that bioenergy producers would need to travel would be much lower. In our model, halving the distance reduces the costs by slightly over $4 per ton. Furthermore, the midwestern U.S. has a well-developed grid-like road infrastructure which would decrease the time and thus labor costs required for transport. Additionally, the present model was designed for small scale use while most previous models have focused on utility scale use. Utility scale use may allow for economies of scale, primarily associated with larger vehicles.

One way in which bioenergy producers in the tropics may be able to reduce their overall costs is through circuitry. In the above model we assumed that a truck would go to a single waste source, load, and return to the bioenergy facility. However, an alternative method would be to purchase a larger truck and visit multiple, nearby source locations before returning to the bioenergy facility. To examine this possibility we modified the model to account for the purchase of a larger truck (a 9 ton dump truck purchased for $80,000) and assumed that each day it made a 40 mile trip one way, collected waste from three nearby waste producers while traveling another 20 miles, then returned to the bioenergy facility. We used other assumptions of the long distance maximum throughput model, but found that circuitry actually increased the average delivered cost by approximately $1.9 per ton due to the increased capital costs of the truck and increased operating costs associated with fuel. Thus, circuitry does not seem to lower costs considerably.

Finally, we examined the effects of changing the truck size from 3 to 9 tons in the short distance high throughput scenario. We increased the cost of the truck and allowed for increased loading time associated with a larger truck. Increasing the size of the truck reduced the costs from 8.3 \$/ton to 4.6 \$/ton. This scenario delivered 9,450 ton of biomass per year and was the most efficient scenario. The feasibility of this scenario depends upon the concentration of waste suppliers near the bioenergy firm and is commensurate with a medium scale bioenergy facility. This value set a reasonable lower bound on the transport cost of biomass, and suggests the economies of increasing project scale.

Fuel makes up approximately 50% of annual costs (depending on the specific scenario) and therefore assumptions about the costs of fuel are critical to the overall cost of transport. Earlier models of biomass transportation costs assumed much lower fuel costs, however, recent fuel price increases make these assumptions seem unrealistic. Here, we assumed fuel prices of 3 \$/gallon. Given uncertainties with global oil supplies, this price seems an optimistic average over a ten year period.

The model may overestimate costs by assuming that the truck depreciates to zero over the life of the project. All of the trucks modeled are designed for heavy, long-term use and it is likely that the truck could still have significant value after 10 years. This would increase the NPV of the project and reduce the average transport costs. However, given the heavy use that is assumed in the models, depreciation of the truck is expected to be significant and the impact of this assumption is likely small and conservative.

3.4. Constructed Wetlands

A potential source of biomass for pyrolysis or other biomass energy projects would be to harvest biomass from constructed wetlands created for the treatment of wastewater. Wastewater treatment is a major problem in the developing world, including Costa Rica. Of the 2,069 aqueducts in Costa Rica, only 33 have treatment plants and only 416 have disinfecting plants (Pagiola, 2008). In the Tarcoles Basin, the river basin that drains San Jose and almost half of Costa Rica's population, only 4% of wastewater is treated despite regulations to address this (Blomquist et al., 2005). However, San Jose is in the process of building a $45 million wastewater treatment facility with a treatment capacity of 243,000 m^3 per day.

One feasible alternative for wastewater treatment in the developing world is the construction of artificial wetlands. Artificial wetlands are man-made wetlands that enahnce the environmental services of natural wetlands and remove environmental contaminants including excess nutrients and pathogens and decrease turbidity and oxygen demand (Kivaisi, 2001). In the temperate developed world, constructed wetlands are generally lagoons dominated by emergent macrophytes while in the tropics constructed wetlands are often dominated by floating aquatic plants such as water lettuce (*Pistia stratiotes*) and water hyacinth (*Eichhornia crassipes*). These floating plants need to be harvested regularly in order to allow for oxygenation of the water (Kivaisi, 2001). Thus, there is an opportunity to construct artificial wetlands for the provisioning and use of two ecosystem services: the treatment of wastewater and the production of biomass for bioenergy. Although several authors have investigated the multi-service properties of artificial wetlands (Costa-Pierce 1998, Greenway and Simpson 1996), to our knowledge the costs associated with the provisioning both of these ecosystem services simultaneously have not been investigated.

3.4.1. Model

In order to estimate the costs of biomass production in an artificial wetland we created a NPV model of a hypothetical 10,000 m^2 lagoon wetland. The wetland has an inflow rate of 2,500 m^3

per day (Nahllik and Mitsch, 2006) and a wet biomass production of 136 kg/m^2/yr (Hayes et al., 1987). The costs include capital costs of construction, labor costs associated with maintenance and harvesting, and the opportunity costs of land. Depreciation was constant over 20 years and a discount rate of 5% was used. A summary of assumptions is given in Table 3.6. Two very similar parameterizations were developed that differed only in labor costs and the capital costs of construction. In all other respects the models used identical parameters. The wetland creates two products of value, cleaner water and biomass, and we use the model to estimate the points at which the net present value of the facility equals zero at different values of the two products.

Artificial wetlands create other ecosystem services as well which could be given a market value (for example habitat value, fish protein, air quality, or aesthetic value) but these are ignored in the present analysis.

Note that the capital costs of construction of the lagoon system are similar, on a normalized basis, to the industrial water treatment facility under construction in San Jose, Costa Rica. The facility in San Jose is designed to treat 240,000 m^3 per day at a capital cost of $45 million, while the lagoon system is designed to treat 2,500 m^3 per day at a cost of $150,000 to $450,000. Thus, the lagoon system is approximately 1% of the size and at most 1% of the cost of the industrial system.

3.4.2. Results

The hypothetical constructed wetland provided secondary treatment to 91,250 m^3 of water per year and produced 1,360 tons of wet biomass. This is not enough biomass to fuel a small scale pyrolysis system, so any system that plans to use wetland derived biomass as a biofuel would need to harvest biomass from several artificial wetlands or a single larger wetland. Alternatively, a wetland using emergent macrophytes such as cattails would produce significantly more biomass; however, such systems are not used in Costa Rica. Additionally, due to the low biomass yields, transportation costs of biomass from the wetland to the pyrolysis system would need to be included since a pyrolysis system could not be collocated with an artificial wetland and produce enough biomass.

Given that there are two products produced from the wetland model, there is no single break-even cost of biomass; instead, the break-even costs of biomass depend on the value of treated water. Figure 3.1 shows the break-even points for the artificial wetland construction model. The cost of producing biomass in the absence of water related ecosystem service benefits is relatively high, between 51 and 83 $/ton. However, when the value of water related ecosystem services are considered, the costs of producing biomass drop considerably. If the value of clean water is between 0.075 and 0.124 $\$/m^3$, the biomass can be given no value and the operation can still be profitable. In Section 3.7 we discuss the value of water treatment services.

Figure 3.1 also shows that if the value of water exceeds 0.125 $\$/m^3$, then a water treatment system integrated into a bioenergy system could provide biomass at a negative value. That is, if water treatment is given a value above 0.125 $\$/m^3$, then a water treatment system could subsidize a bioenergy system or pay a bioenergy system to harvest its excess biomass.

3.5. Jaragua Grass

A third method of providing biomass for bioenergy is to convert land from other uses for the production of bioenergy crops. This method has been controversial as it may either remove land from other agricultural uses, or convert native forests or grasslands to bioenergy plantations. Nonetheless, bioenergy crops could provide carbon neutral or carbon negative energy and may be more economically efficient than other sources of biomass.

3.5.1. Model

Jaragua grass (*Hyparrhenia rufa*) is an introduced and invasive (Simoes and Baruch, 1991) perennial grass in Central America commonly used for grazing cattle. It grows rapidly and can tolerate low nitrogen soils. It is often grown un-irrigated and unfertilized, and can tolerate low nitrogen soils; optimum growth is achieved with 112 kg N and 56 kg P per hectare (UN FAO, 2010). It generally outcompetes weeds, has few pest problems and can withstand temporary flooding and dry seasons of up to 6 months. It is frequently burnt during the dry season to stimulate regrowth (Daubenmire, 1972). Jaragua grass can be thought of as a tropical analog of switchgrass which has been heavily investigated for its bioenergy potential; despite this, jaragua grass has not been considered as a bioenergy crop in the academic literature.

We built an NPV-based model of the costs of crops grown on a 1,000 ha plantation for bioenergy purposes. Since jaragua grass is perennial, we modeled the costs of establishment as capital costs rather than annual costs. We assume that establishment will consist of conventional tilling followed by broadcast sowing and harrowing (UN FAO, 2010). Jaragua grass can be established after burning or less intensive tilling, but we assume conventional tilling is used since it can be slow to establish (UN FAO, 2010). Establishment costs consisted of labor and seed. Seed was assumed to be sown at 20 kg/ha (UN FAO, 2010). Additional capital costs included the costs of machinery and land. The necessary machinery was assumed to be similar to that needed for switchgrass and consisted of a tractor and a baler. We did not include the costs of a tiller as establishment would only occur once and it would make little economic sense to purchase establishment equipment for a single use. Instead we assumed that the necessary establishment equipment would be rented. We included the costs of land as rental costs equal to the opportunity costs associated with alternative land use systems.

We assumed that the biomass would be grown without fertilizer to allow for comparisons between tree plantations and jaragua grass and because fertilizer use would complicate net energy and net CO_2 calculations for bioenergy production. Jaragua grass is known to grow well without fertilizer, although modest fertilizer application does increase yields. Herbicides are not applied as *H. rufa* outcompetes most other grasses, and, since it is used for biomass production, low levels of weeds are not a major concern.

Annual costs consisted of harvesting costs which consisted of labor, and fuel costs. We iterated the model over a 15 year period. The discount rate was 3 to 10% and we assumed a constant rate of depreciation of capital expenditures to zero. This assumes that the crop would need to be replanted every 15 years. Revenues consisted of biomass and we determined the cost of producing biomass when NPV was set to zero. This gives the farm-gate cost of *H. rufa* production, to which transport costs must be added. We parameterized the model with pessimistic and optimistic assumptions (Table 3.7) in order to develop a range of farm gate costs.

3.5.2 Results

Under pessimistic assumptions the break-even price of dry biomass is 34.5 $/mt. The cost of production drops to 14.3 $/mt using optimistic assumptions. This suggests that the cost of production of jaragua is relatively low compared to the costs to produce switchgrass in the U.S. which are about 50 $/mt (Perrin et al., 2008) This is likely due to the low costs of land and labor employed in the model and the relatively high productivity of the tropics.

3.5.3 Model Limitations

The productivities reported in the literature are highly variable and range up to 18,000 kg/ha, however the highest productivities assume some fertilization. To our knowledge, there have not been studies on the productivity of unfertilized Jaragua grass, and it may not be able to achieve the growth rates assumed in the model without fertilization.

3.6. Mixed-species Tree Plantations

In temperate regions, short rotation woody crops (SRWCs) such as pine and poplar have been widely investigated for their use in bioenergy applications (Baral and Guha, 2004). The forestry of SRWCs for bioenergy has not been as thoroughly investigated in the tropics, but poplar clones and eucalyptus have been studied as possible SRWCs (Swamy et al., 2006) primarily as a potential substitute to the logging of rainforests. As a result, the emphasis has been on high-value species. The value of the wood is not important from a biomass perspective, and species choice is predicated primarily on growth rate.

In Costa Rica, members of the genus Eucalyptus may be the most appropriate fast growing tree species, however, they can have significant environmental impacts associated with water demand and a government backed attempt at planting eucalyptus in the early 1990’s failed (Munoz 2002). Thus, it seems unlikely that there would be popular support for eucalyptus-based bioenergy crops in Costa Rica. Mixed species timber plantations with native species may be more appropriate, at least given current knowledge. This may sacrifice some biomass production but may have less environmental risk and a greater public acceptance. Furthermore, Costa Rica has government programs that offer to pay landowners for the establishment or maintenance of native species forests, and polycultures of native species have generally been shown to outperform monocultures of the same species (Piotto et al., 2003). Therefore, we chose a polyculture of three native tree species: *Terminalia amazonia*, *Virola koschnyi*, and *Dipteryx panamensis*. These species are commonly planted on small farms in Costa Rica with short dry seasons, are relatively fast growing, and have been shown to grow well in polyculture without fertilization (Redondo-Brenes and Montagnini, 2006).

3.6.1. Model

Academic models of financial performance of forestry regimes are either designed for smallholder or industrial forestry applications. The models for these two systems differ markedly in their assumptions and structure (Venn et al., 2000). In order to provide a consistent supply of biomass a pyrolysis system would need either a very large number of smallholder operations or a few industrial scale systems. We chose to model a small scale (10 ha) biomass forestry system and to assume that a large number of these might be established interspersed around a pyrolysis facility. Small scale systems have a number of advantages over large scale systems: small scale systems are more amenable to the growth of native mixed-species plantations since they are less reliant on machinery and automation, they may not require pesticides and herbicides since they are more likely to use native species at lower densities and have higher biodiversity than monocultures, they are less subject to poaching, they may have lower capital costs if they are associated with already established nearby farms, and they can use lower-technology and less expensive methods of management, for example using oxen teams instead of tractors or skidders for skidding logs, weeding by hand instead of with pesticides or using manure instead of chemical fertilizers (Harrison and Hebrohn, 2003; Venn et al., 2000; Streed et al., 2006).

We parameterized two models with optimistic and pessimistic assumptions. We assumed the costs of establishment to be $900 to $1,200 per hectare in optimistic and pessimistic scenarios, respectively (Streed et al., 2006; Venn et al., 2000). Establishment consists of land preparation, purchasing seeds and seedlings, and planting. We assume that no fertilizer is used[2], although the application of fertilizer, especially as manure, is unlikely to have a significant impact on either the financial performance or the carbon budget since fertilizer is generally only applied in the establishment year. Labor costs are assumed to be $3 per hour in both scenarios. As in the jaragua grass model, we modeled land costs as rental costs and equal to the opportunity costs of land. Additional capital costs occur in the form of equipment and tools, primarily a tractor to be used for general movement around the plantation and hauling biomass. Additional tool costs consist of a chainsaw, shovels, and other minor equipment.

In years following the establishment but before harvesting, we assumed that the only costs were labor, which was again budgeted at $3 per hour. We assumed that 500 to 1,000 hours of labor per year were needed (Streed et al., 2006; Venn et al., 2000) for weeding, dead tree replacement and general management in the first year following establishment and that this declined to 200 hours in subsequent, non-thinning years. Additional annual costs consisted of fuel for the tractor and replacement seedlings and tools and were budgeted at $100 per hectare per year.

Thinnings were conducted in years 3, 6 and 9 and the remaining trees were harvested in year 12. Thinning removed 5 or 10 metric tons/ha in the pessimistic and optimistic parameterizations, respectively (Redondo-Brenes and Montagnini, 2006; Piotto et al., 2003). In thinning years we assumed that labor requirements returned to 500 to 1,000 hours. The final harvest removes 182 t/ha and requires 2,000 hours of labor. Revenues consisted of payments from the payments for environmental services program and we determined the cost of biomass production when NPV was set to zero.

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[2] This assumption allows for consistency with the Jaragua grass model as well as the growth data used to parameterize this model.

3.6.2. Results and Discussion

As a source of biomass, smallholder tropical forestry is not cost effective. The break even costs in the optimistic and pessimistic scenarios were 49 and 104 $/ton, respectively. At these prices the PES payments make up a very small proportion of overall revenue (5.4 % in the pessimistic scenario and 10.7% in the optimistic scenario).

The high costs were largely due to the high capital costs which were heavily influenced by the purchase of a tractor. However, the purchase of a tractor specifically for a smallholder operation is unlikely to be necessary. Instead, oxen could be used or a tractor could be purchased in a cooperative framework with other nearby users with significantly positive effects on NPV (Streed et al., 2006). Removing the budget for a tractor in year 1 and replacing it with a $10,000 allowance for a 1/3 portion of a cooperatively owned tractor, reduces the break even prices to 17.8 $/t in the optimistic scenario and 44.6 $/t in the pessimistic scenario.

Unlike the other biomass production systems discussed above, a forestry system produces a product (wood) that has significant value outside of the bioenergy industry. Thus, bioenergy facilities would need to pay at least as much for the wood as mills interested in using the wood for more traditional uses would be willing to pay. However, the value of wood to mills declines with the size of the trunks or boards and therefore bioenergy producers may be able to buy small trees from thinning or branches and foliage from clearings. This would make these wood products similar in cost to the agricultural residues discussed above.

3.7. Payment for Environmental Services

Payment for environmental services (PES) programs seek to correct market failures in which ecosystem services are not valued by traditional economic systems. Costa Rica is one of a few nations with a PES program. PES programs seek to provide monetary value from an ecosystem service user to an ecosystem service provider. For example, a landowner may be compensated for leaving land as forest, rather than deforesting it, by a hydroelectric company which uses water that runs through a forest for the generation of electricity. They function much like carbon markets in that they create private wealth for the creation or maintenance of a public good. In the polyculture system described in Section 3.6 above, we already incorporated payments from the Costa Rican PES system as agroforestry is currently capable of receiving such credits in the Costa Rican system. Here we describe the PES payments for waste disposal or water treatment under a theoretical system in which those services were appropriately valued.

The models described above create services (waste disposal and water treatment) that are, in general, not appropriately valued by the economies in the developing world. Frequently in the developing world, including Costa Rica, water is left untreated and wastes are often not properly disposed of and eventually enter surface waters causing obstructions to flow and increased nutrient levels, and major public health problems (Blomquist et al., 2005).

Strictly defined, neither waste disposal or water treatment by artificial wetlands are actually an ecosystem services. Ecosystem services are generally the services provided by natural ecosystems, not constructed ecosystems or human activities. Constructed wetlands mimic natural wetlands and their ecosystem services, while waste removal and disposal allows natural ecosystems to provide ecosystem services without impairment. However, both have been subject to ecological economic valuation in the past (Jin et al., 2006; Chen et al., 2009) and both can be considered environmental services, if not ecosystem services. Here, we adopt a broad definition of ecosystem services and use the terms ecosystem and environmental service interchangeably.

Costa Rica's PES program is currently aimed at only forest conservation, however, it is the intention of the program that eventually all beneficiaries of ecosystem services will pay for the services they receive (Pagiola, 2006). While water resources are an important target of Costa Rica's PES, no payments have been made for waste management or artificial wetlands. However, during the voluntary phase of the Costa Rica PES program (which ended in 2011), potable water providers were a part of the ecosystem service users. Therefore, it is reasonable to expect drinking water providers to pay for the reduction of wastes in water, either through water treatment or waste management. In order for waste management or water treatment to be included under the PES system, the law would need to be amended. However, water quality is a major environmental issue in Costa Rica and the developing world in general, and the use of the PES system for waste management may be reasonable.

3.7.1. Valuing Ecosystem Services

There are several ways to value ecosystem services. Among the more common are contingent valuation, avoided cost methods, replacement cost methods, and factor income methods (Farber et al., 2002). The contingent valuation method is essentially a survey methodology in which investigators ask individuals how much they would be willing to pay for a specific action (Gilpin, 2000). For example, investigators might ask respondents how much they would be willing to pay (WTP) for some improvement in water quality in a local river, or the maintenance of an area as primary forest. The contingent valuation method has important applications, however, it relies on public knowledge and works best for services that are generally well understood by the public, like ecotourism and aesthetic value. It may undervalue services that are more abstract or poorly understood, for example nutrient impacts on water quality, as respondents may not understand the impact of the ecosystem service on their quality of life. It has not been commonly used to measure the value of water supply related ecosystem services (DeGroot et al., 2002).

The replacement cost method attempts to determine the cost of alternative sources of ecosystem services. For example, a wetland might be valued as the cost to build a water treatment plant with a similar efficiency. The replacement cost method is not as proficient at valuing recreation or aesthetic value. The avoided cost method is similar to the replacement cost method in that it seeks to estimate the costs that would have been incurred in the absence of the ecosystem function. For example, part of the avoided costs of having a functional avian ecosystem might be reduced pesticide costs associated with avian predation on insects. These methods have been more traditionally used in the assessment of water related ecosystem services (DeGroot et al., 2002).

Benefit transfer is a well described practice of transferring estimated benefit functions from one study area to another area (Wilson and Hoehn, 2006). Depending on the socio-economic differences between the two areas the estimated benefit may or may not be adjusted. The reliability of benefit transfer is limited to the reliability of the original benefit estimation (Brookshire and Neill, 1992). Benefit transfer studies have been aided by the advent of online databases of ecological valuation studies (McComb et al., 2006).

3.7.2. Agricultural waste collection

While there is significant academic literature on the valuation of municipal solid wastes, there is little literature on the valuation of agricultural residue collection. Parra et al. (2008) conducted a contingent valuation study and found that farmers in Spain would be willing to pay, on average, approximately 14 $/t for a basic waste management system and an additional 4 $/t for a system that utilized crop residues for compost or desalination. The study conducted by Parra et al. is of relatively similar scope to the hypothetical waste management system described above. In both cases, a small dump truck is used to collect agricultural waste residues and generates value from these residues. However, transfer of this benefit to the agricultural sector in Costa Rica is difficult due to the very large differences between the two countries. Benefit transfer across international boundaries has been conducted (Brouwer and Bateman, 2005) and despite its difficulties, benefit transfer from the developed to the developing world is frequently conducted, typically with error rates of 20 to 40% (Ready and Navrud, 2006). Most typically, international benefit transfer is accomplished by converting currencies using purchasing power parity and multiplying by the ratio of per capita GDP. Transferring a benefit of 18 $/t in Spain using this method gives a Costa Rican WTP of approximately 6.4 $/t.

In the developed world, the large scale disposal of waste in surface water or by open air incineration is generally not tolerated. The producers of waste are generally required to pay for its disposal, a basic application of the polluter pays principle (PPP; Gilpin, 2000). If we assume that generators should pay to dispose of their wastes, then the ecological value of the service provided by agricultural waste collection becomes its cost. Therefore, from an avoided cost perspective, we can assume that the value of the ecological service provided by waste removal is equal to the minimum cost of the service, which, from the models above is estimated to be approximately \$5 to \$8 per ton[3]. This assumes that the generated wastes cannot be disposed of responsibly (i.e. without causing air or water pollution) for lower cost.

3.7.3. Water treatment

The value of water treatment is critical to the artificial wetland model as cleaner water is the primary product of the model. The valuation of wetlands has been well studied. For example, a

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[3] This value does not include the value of disposal which may create additional ecological value. Thus, the estimate is conservative.

2006 meta-analysis contained 190 studies and 215 separate observations (Brander et al., 2006). Unfortunately, the estimates obtained are highly variable and range over approximately 5 orders of magnitude from 1 to 100,000 \$/ha/yr (Brander et al., 2006). Among 12 South and Central American studies, the average value was 170 \$/ha/yr. However, the ability to predict the value of a wetland based on predictor variables, and the ability to estimate the value of an unknown wetland based on the value of a different wetland is poor (Brander et al., 2006).

Ghermandi et al. (2009) expanded on the work of Brander et al. (2006) with similar results. Ghermandi et al. (2009) also developed a smaller sample set of 18 studies of constructed wetlands (as opposed to all wetlands). In these studies the value of the wetlands ranged from 101 to 8,013,754 \$/ha/yr. However, values for wastewater services were relatively high, generally several thousand dollars/ha/year. As in previous studies, regressions developed to predict generalized constructed wetland values were not statistically significant and explain less than 50% of the variance in cost. Thus, the ability of a general model to estimate the value of artificial wetland services is limited.

The valued constructed wetland most similar to the present case is likely a constructed wetland built to treat the primary effluent from an ornamental fishpond in Hangzhou, China (Yang et al., 2008). Using the avoided cost method, and converting the value using the per capita PPP GDP, gives a value of 1.6 \$/m^3.

Barton (2002) conducted a contingent valuation survey in two locations on the west coast of Costa Rica. He surveyed residents about their willingness to pay for significantly improved water quality and found that on average a household would pay approximately \$11.7 to \$32.3 annually. Assuming that the average Costa Rican uses 14 m^3 of water per year for domestic use (Pacific Institute, 2008) and that the average household consists of 4 people (Barton, 2002), then the cleaned water may be valued at 0.21 to 0.57 $\$/m^3$. This is slightly beyond the point at which the value of biomass from a constructed wetland may equal zero.

A final way to estimate willingness to pay for water quality improvement in Costa Rica is to use information on payments made under the PES program. The standard payment under the PES program is approximately 45 \$/ha for forested land. Assuming an average rainfall of 2.5 m/yr, then the value of a m^3 of water through the PES program is approximately 0.0018 $\$/m^3$, far less than that estimated by the willingness to pay method. From the perspective of the constructed wetland model, this value of water treatment is negligible. Note, however, that this is a value for water supply into rivers, rather than for water treatment.

Thus, it is possible to support a wide range of values for the water treatment associated with a constructed wetland. The best estimate is likely that of Barton (2002) as it was conducted in an economically similar area and measured WTP on an identical parameter, namely a significant but qualitatively defined improvement in local water quality. Barton's estimates suggest that the people of Costa Rica may be willing to pay for an improvement in water quality associated with a constructed wetland, independent of any benefit gained from harvesting biomass from that wetland. Note, however, that if rainfall becomes less plentiful, the supply of clean water will decline and the willingness of individuals to pay for water treatment services may increase.

3.8. Conclusions

For an economy in which the degradation of public resources by private firms was prohibited by law (i.e. degrading water quality through the disposal of wastes in surface water), the costs of waste removal and disposal would be borne by waste producers. Thus, the costs of transporting waste biomass to a bioenergy user should be zero or nearly zero from the perspective of the bioenergy firm. That is, they should be capable of charging the waste producer at least the costs of transport. Furthermore, the limited contingent valuations studies that exist suggest that Costa Ricans may be willing to pay the approximate minimum cost of agricultural waste disposal. One can therefore make a credible argument that the costs of waste biomass for a pyrolysis system is zero, nearly zero, or negative.

The costs of biomass production from an artificial wetland are heavily dependent on the value given to water treatment. There is evidence to suggest that the costs associated with the establishment of a constructed wetland for water quality improvement and biomass provision would willingly be borne by the citizens of Costa Rica.

Given the large quantities of biomass available as waste and the potential for artificial wetlands to provide biomass supplies, it seems reasonable to assume that the costs of biomass for bioenergy applications in Costa Rica could be limited to the costs of waste transport. While these transport costs should reduce to zero or nearly zero in a system that appropriately assigned externalities, in reality, the costs of agricultural waste transport will likely be approximately 5 to 20 \$/t. Similar transport costs would likely be borne for most bioenergy crop applications, depending on the geographical dispersion of the operations.

Given these quantities of wastes and the value of environmental services associated with water treatment or waste removal, it would seem to make little sense to pay additional costs for growing bioenergy crops, either as jaragua grass or SRWCs. SRWCs, in particular, are extremely expensive and likely infeasible for bioenergy in Costa Rica. Jaragua grass may be feasible if the optimistic assumptions are realistic and the crops were to be collocated with a bioenergy system so that transport costs were effectively zero.

From an ecological and economic perspective, it may be beneficial for bioenergy projects to utilize the non-specific nature of bioenergy reactors to process multiple sources of biomass into bioenergy, for example, taking biomass from multiple local waste inputs. In this way, bioenergy producers could use local sources of the cheapest biomass, adding more expensive biomass sources as the cheaper sources are depleted. This would limit both carbon and monetary transportation costs and help to ensure biomass supply even in the event that a single source of biomass was reduced for at a given time. However, the outputs of pyrolysis depend significantly on the feedstock, therefore, if multiple waste streams were to be used they would need to be combined to form some type of constant mixture. This would add logistical difficulties, but would seem plausible.

Since the pyrolysis outputs differ depending on the biomass input, the actual choice of input will depend not just on the costs of the feedstock but on the output of the feedstock in the actual system. Thus, pyrolysis developers would be required to test feedstocks in alternative commercial systems before selecting an optimal pyrolysis system.

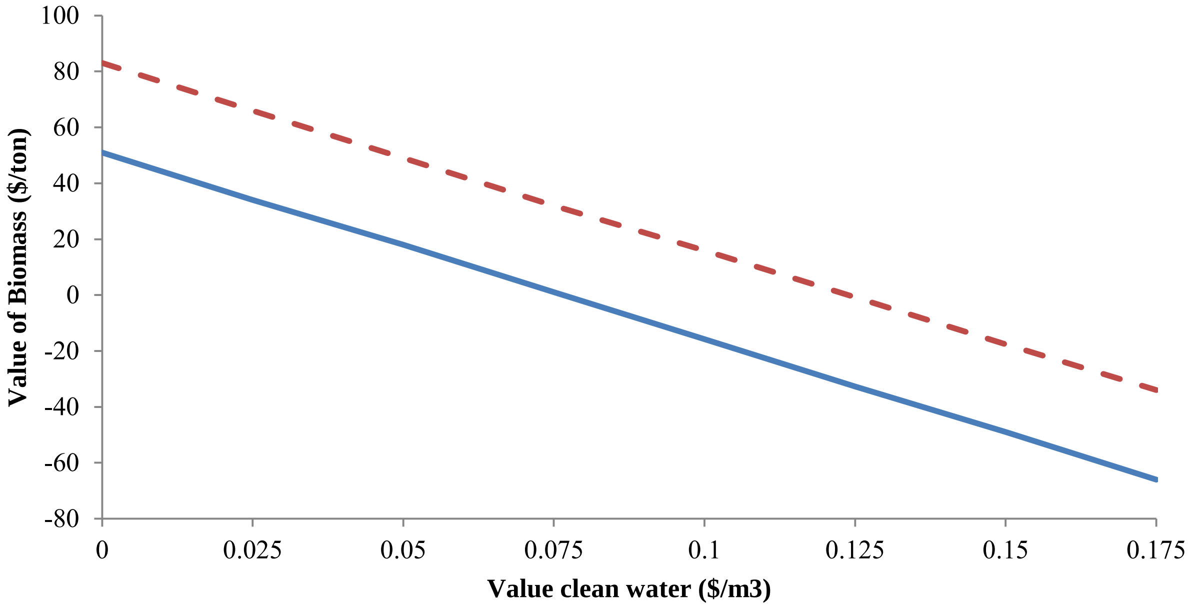

Figure 3.1 The break-even costs of biomass and water purification through artificial wetland construction. Solid line assumes low capital costs of construction and low labor costs while dashed line assumes high capital costs and high labor costs.

Table 3.1 Harvested area, yield per hectare and total production of major crops in Costa Rica

Data from UN FAO, 2008

Crop	Area harvested (ha)	Yield per hectare (kg/ha/yr)	Total production (10^6 kg/yr)
Sugar cane	48,000	87,916.67	4,220.00
Bananas	42,700	55,096.44	2,352.62
Pineapples	38,500	31,168.83	1,200.00
Oil palm fruit	52,625	14,821.85	780.00
Oranges	23,000	14,191.30	326.40
Cassava	20,000	15,000.00	300.00
Other melons (incl. cantaloupes)	10,102	24,144.03	243.90
Rice, paddy	48,439	3,117.32	151.00
Coffee, green	113,387	1,163.71	131.95
Watermelons	3,576	25,881.71	92.55
Plantains	11,000	6,966.82	76.64
Potatoes	2,205	24,092.97	53.12
Tomatoes	1,000	42,424.00	42.42
Guavas, mangoes	8,200	5,000.00	41.00
Onions, dry	1,367	28,057.27	38.35
Papayas	617	57,641.82	35.57
Avocados	4,847	5,059.01	24.52
Lemons and limes	1,200	20,000.00	24.00
Maize	6,359	3,464.07	22.03
Yams	3,595	5,657.30	20.34
Grapefruit	2,130	8,938.50	19.04
Coconuts	4,000	3,620.25	14.48
Beans, dry	14,000	735.79	10.30
Cabbages and other brassicas	1,322	7,345.69	9.71
Ginger	700	10,924.29	7.65
Strawberries	60	31,666.67	1.90
Raspberries and other berries	47	14,574.47	0.69
Cocoa beans	3,050	147.54	0.45
Seed cotton	300	1,000.00	0.30
Groundnuts, with shell	175	1,234.29	0.22
Tobacco, unmanufactured	70	1,942.86	0.14
Sesame seed	217	622.12	0.14
Pepper (Piper spp.)	84	1,480.95	0.12
Cotton lint	300	366.67	0.11
Cottonseed	241	394.19	0.09

Table 3.2 Costa Rican Agricultural wastes in thousand metric tons Data from Ulloa et al., 2004

	Thousand tons	Percent used	Thousand tons available
Cattle Slaughtering	54	35	35.1
Swine Processing	5	11	4.45
Fish and Shrimp processing	14	69	4.34
Swine manure	117	0	117
Banana peels	32	30	22.4
Rejected bananas	324	55	145.8
Coffee pulp	350	18	287
Rice husks	54	10	48.6
Orange and pineapple husks	39	1	38.61
Cocoa pods	35	2	34.3

Table 3.3 Assumptions of the waste transport model

Parameterization	Short distance	Long distance	Short distance max throughput	Long distance max throughput	Short distance w/ loading	Long distance w/ loading
Capital costs						
Truck	30,000	30,000	30,000	30,000	30,000	30,000
Front loader					30,000	30,000
Operating Costs						
Hourly wage	3	3	3	3	3	3
Days per week	4	6	7	7	4	6
Hours per week	30	42	70	73.5	30	42
Cost of fuel ($/g)	3	3	3	3	3	3
MPG	12	12	12	12	12	12
One way distance	20	40	20	40	20	40
Trips per day	3	2	4	3	3	2
Distance per day (miles)	120	160	160	240	120	160
Maintenance	3,000	3,000	3,000	3,000	6,000	6,000
Total labor costs	4,500	6,300	10,500	11,025	4,500	6,300
Total fuel costs	6,000	12,000	14,000	21,000	6,000	12,000
Tractor costs						
Hours used per trip					1.5	1.5
Fuel cost per year					6,480	6,480
Total annual costs	13,500	21,300	27,500	35,025	22,980	30,780
Tons per trip	3	3	3	3	3	3
Wet tons per year	1,800	1,800	4,200	3,150	1,800	1,800
Moisture content	0.25	0.25	0.25	0.25	0.25	0.25
Dry tons per year	1,350	1,350	3,150	2,362.5	1,350	1,350

Table 3.4 Results of the waste transport model

Parameterization	Short distance	Long distance	Short distance max throughput	Long distance max throughput	Short distance w/ loading	Long distance w/ loading
Cost per wet ton ($)	11.06	15.39	8.074	12.41	19.89	24.23
Proportional distribution of annual costs						
Labor	33%	30%	38%	31%	20%	20%
Fuel	44%	56%	51%	60%	54%	60%
Other	22%	14%	11%	9%	26%	19%

Table 3.5 Sensitivity of the transport model to changes in discount rate

Discount Rate	Short distance	Long distance	Short distance max throughput	Long distance max throughput	Short distance w/ loading	Long distance w/ loading
0	10.8	15.2	8.0	13.0	19.4	23.8
5	11.2	15.6	8.1	13.2	20.2	24.5
10	11.6	16.0	8.3	13.5	21.0	25.4
20	12.5	16.8	8.7	14.0	22.7	27.1

Table 3.6 Assumptions used in constructed wetland model

Parameter	Value	Source
Production	1360 Mg/year/ha	Hayes et al., 1987
Construction costs	15 or 45 \$/m^2	Chen et al., 2009 Yang et al., 2008 Manninio et al., 2008
Size	10,000 m^2	Nahlik and Mitsch 2006
Labor costs	3 or 4 \$/h	U.S. State Department 2011
Harvest rate	1/month	Nahlik and Mitsch 2006
Opportunity Costs	56\$/ha/yr	Wunscher et al., 2008

Table 3.7 Parameterization of the jaragua grass models

	Pessimistic	Optimistic	Citation
Seed application rate (kg/ha)	20	20	FAO
Hectares	1000	1000	
Cost seed (\$/kg)	4	1	Collected locally by hand; FAO
Tractor	50000	35000	John Deere
Baler	10000	15000	John Deere
Discing rental	2000	2000	
Labor required in establishment (hrs/ha)	1.6	0.9	Epplin 1996
Cost labor (\$/h)	4	3	
Land costs (\$/ha)	60	60	Wunscher et al., 2008
labor for harvesting (hrs/ha)	0.9	0.9	Epplin 1996
Fuel use per hour (L)	9	9	John Deere
Cost of fuel (\$/L)	0.8	0.8	
Biomass/ha (kg)	3500	7000	FAO, Holman and Tiemann 2008
Harvesting efficiency	0.8	0.8	Epplin 1996

Chapter 4: A Net Present Value Model of the Costs of Small Scale Pyrolysis in the Tropics

4.1. Introduction

Pyrolysis is a carbon negative technology for generating saleable energy products. The majority of commercial and academic interest in pyrolysis has been focused on the large scale production of liquid fuels in the developed world. However, future energy use in the developing world will be a major determining factor in future CO_2 emissions and global climate change. Per capita energy demand will grow more rapidly in the developing world than in the developed world and there are more people living in the developing world than the developed world. To 2030, the U.S. Energy Information Administration predicts that total energy consumption will increase at a rate of 1% per year among the 30 Organization for Economic Cooperation and Development (OECD) members, but 3% among non OECD members (EIA, 2011). Therefore, it is prudent to focus not only on the developed nations currently producing the most greenhouse gases per capita, but also the developing economies that pose both a challenge and an opportunity to reduce CO_2 concentrations below forecasted levels. Here, we analyze the economic costs of generating electricity, carbon credits, and other marketable goods by pyrolysis and we compare the costs of systems at different scales and with different end products.

4.2. Previous Economic Studies of Pyrolysis

Several recent studies have estimated the costs of pyrolysis systems. Because pyrolysis creates different products which are of varying interest to different researchers, the unit of analysis varies between studies; some studies have examined the break-even costs of electricity, while others have studied the break even costs of bio-oil, biochar and/or carbon credits (Table 4.1). While pyrolysis may be cost competitive under some circumstances, results depend on the specifics of the model system and the assumptions made by the researchers and generalizations about costs are not meaningful.

Peacocke et al. (2004) studied the costs associated with two fast pyrolysis systems. Their model assumed that the operator purchased biomass in the form of woodchips at the market price in the UK, used a fast pyrolysis system to create bio-oil and then combusted the bio-oil in an internal combustion engine to produce electricity. They found that the cost per kWh was high and ranged from 0.15 to 0.60 $/kWh, however, there was no assumption about carbon credit revenue (Peacocke et al., 2004).

Bridgwater et al. (2002) studied large scale-fast pyrolysis systems. As in Peacocke et al. (2004), they assumed the pyrolysis was used to produce bio-oil which would then be burned to create electricity. They found that costs of electricity would vary by scale from 0.09 to 0.18 $/kWh (Bridgwater et al., 2002).

Dowaki et al. modeled a larger scale, 27 MW gasification system in Japan and found the cost of energy to be between $0.144 and $0.329 per kWh (Dowaki et al., 2005). However, they assumed high biomass costs and did not consider carbon credits, although they did include a capital costs subsidy associated with biomass-based energy projects in Japan.

Rhodes and Keith modeled a 150 MW, U.S. based gasification system with and without carbon capture and storage (CCS). Without CCS they found the cost of electricity to be just $0.059 per kWh; with CCS, electricity production costs increased to $0.082 per kWh (Rhodes and Keith, 2005). These electricity costs would require a carbon price of $102 and $123 per ton, respectively, to be cost competitive with coal.

Ruan et al. (2008) studied the economics of a small-scale fast pyrolysis system which they envisioned would be owned and operated by an individual farmer. They assumed the farmer would have access to 3000 tons of corn stover per year, 50% of which would be pyrolysized. They assumed relatively high feedstock costs, but relatively low capital costs. At a bio-oil price of 1 $/gallon and a char price of 50 $/t, their model resulted in a net income to the farmer of over $42,000 per year (Ruan et al., 2008).

Sorenson (2010) studied the costs of operating a fast pyrolysis system in Oregon that generated biochar and bio-oil. Since two factors were simultaneously varied there was no single break-even price, but the system was profitable at biochar prices above $16 per ton when bio-oil prices were held at $1.36 per gallon. The system was far more sensitive to bio-oil prices than to biochar prices.

Mullaney et al. (2004) studied the costs of using bio-oil as a replacement for fuel oil. Mullaney et al. did not consider revenue from biochar, but found that the system would only be profitable if feedstock prices were below $9 per wet ton.

Roberts et al. (2009) studied the break-even costs of a slow-pyrolysis system using switchgrass, corn stover or yard waste as feedstocks. They assumed char costs of approximately $40 to $80 per ton and an energetic return of $35 to $55 per ton of feedstock (depending on the feedstock). They found break-even carbon credit prices of $2 per ton CO_2e for yard waste, $40 per ton CO_2e for stover and $62 per ton for switchgrass.

Brown et al. (2011) modeled the profitability of the fast and slow pyrolysis of corn stover assuming an increasing price for gasoline and carbon offsets over the 2015 to 2030 period. When feedstock costs were included, slow pyrolysis was never profitable, but fast pyrolysis was profitable even at high (83 $/t) feedstock prices.

From the perspective of small scale bioenergy in Costa Rica, the results of Nouni et al. may be the most informative. Nouni et al. (2007) studied small scale (5 to 40 kW) biomass gasification projects in rural India and found that the cost of electricity ranged from \$0.16 to \$0.34 per kWh and that biomass gasification becomes cost competitive with diesel generators at diesel prices above 0.80\$/l (Nouni et al., 2007). Commensurate with a developing world system, Nouni et al. used modest feedstock prices and low labor costs (0.3 \$/h).

4.3. Study System

We model small to mid-scale pyrolysis systems in a neotropical developing nation, Costa Rica. In general, novel energy systems are first studied and employed in the developed world and gradually spread to the developing world and most academic attention for the application of pyrolysis has also focused on the developed world. However, the developing world may provide greater opportunities for the employment of alternative energy systems, especially bioenergy systems, for a number of reasons.

In the developed world, the growth of energy use is typically low as nation's economies become less energy intensive and production shifts from the manufacturing sector to the service sector; in contrast, in the developing world energy demand growth can be extreme and in some cases it may be difficult for a country to meet demand with new generation. Unlike much of the developing world, most of the nations of Central America have little or no domestic hydrocarbon reserves or production and as a result, hydrocarbons are frequently more expensive in Central America than in oil producing nations. Meeting growing energy demands in Central America with coal, oil or natural gas is difficult and these nations must use other energy sources to produce electricity.

The neotropical developing world has high rates of net primary productivity, even in the absence of human-provided energy subsidies. This may reduce the costs of bioenergy systems relative to the temperate developed world. The potential absence of human-provided energy subsidies (irrigation and fertilizer) reduces concerns about net energy losses and unintended negative ecological consequences in bioenergy systems. For example, the production of ethanol from corn in the U.S. may or may not provide a positive net energy return (Cleveland et al., 2006; Farrell et al., 2006) and contributes to fertilizer runoff and the Gulf of Mexico dead zone (Donner and Kucharik, 2008).

Central America is dominated by highly degraded soils (UNEP, 1997) and these soils have shown the largest and most consistent benefits from biochar application (Rondon et al., 2007; Kimetu et al., 2008; Lehmann et al., 2003; Stiener et al., 2007). As a result, biochar may have more value in the Central America than in other regions. This may be partially offset by generally higher food prices in the developed world, however, maize is more expensive in Central America than in North America (FAO, 2011) and biochar has been shown to have strong effects on maize production (Rondon et al., 2006).

Costa Rica is particularly appealing as a focal nation due to its status as a non-Annex I party to the Kyoto Protocol. This allows foreign investors from Annex I nations to invest in greenhouse gas control programs in Costa Rica and to apply the carbon credits generated to meet their obligations under the Kyoto treaty. Furthermore, Costa Rica is generally considered to be among the most stable nations in Central America, reducing risk for foreign investors.

Large scale pyrolysis may eventually be successful in the developing world, but small scale pyrolysis may be particularly suited to the developing world. Pyrolysis relies on large inputs of biomass; in large scale systems this biomass may need to be supplied from a large geographic area, adding to cost. In areas with poor road networks, transport costs may increase significantly, and therefore large scale pyrolysis may not be feasible in the developing world.

4.4. Methods

Three related net present value (NPV) models of the cash flows associated with different types of pyrolysis were created. We modeled three small scale systems (five metric tons of biomass per day): a slow pyrolysis system, a gasification system, and a fast pyrolysis system. With the exception of gasification, none of these systems are currently commercially available and therefore important variables were obtained from manufacturer estimates and published literature.

4.4.1. Model Structure

We used standard net-present value (NPV) theory to develop a model of the economic viability and costs of small scale biomass pyrolysis. Net present value is the total current value of a series of cash flows and is equal to

$$NPV = R_0 + \sum \frac{R_t}{(1+i)^t}$$

Where *R* is the cash flow at time *t* and *i* is the discount rate. The model was iterated over a 20 year period. A flowchart of the model system is shown in Figure 4.1; not all sources of income shown in the figure apply to all systems. Costs are composed of capital and operating expenditures. Capital expenditures are one time allocations for the purchase of capital equipment, but may be financed over the life of the system. Operating expenditures are annual costs and may include fixed and variable costs. Each of the models were parameterized with optimistic, pessimistic and expected assumptions. In addition, a “non-profit” parameterization set was used; in the non-profit parameterization, the expected parameters were used for all variables except the discount rate which was assumed to be low and taxes, which were ignored.

In all models, capital costs consisted of the reactor and biomass processing facilities. In the gasification system, the hydrogen produced was assumed to be combusted for electricity. In all scenarios it was assumed that the facility would be placed on land already owned by the operator of the system and the costs or opportunity costs of land were not considered. All capital costs were financed over a five year period through a fixed principal, declining interest loan.

For all systems, the components of operating costs were labor, maintenance, biomass and insurance. The reactor was operational for a variable number of hours per day and days per year depending on the scenario used. Labor needs, biomass tonnage, and maintenance costs of the biomass processing system were a function of the time the reactor was operational. Insurance costs and maintenance cost of the pyrolysis system was a fixed annual percent of capital costs.

Annual revenue was a function of the total biomass input and the proportion of char, syngas, and bio-oil produced, as well as the proportion hydrogen in the syngas. Hydrogen was assumed to be the only source of energy in the syngas and was burned on-site for electricity. Bio-oil and char were both sold to consumers at a fixed price.

Carbon credits were calculated as carbon negative and carbon neutral. Carbon neutral carbon credits were a function of the amount of energy produced by the combustion of bio-oil and/or syngas compared to the baseline production method; carbon negative credits were a function of the weight of char output. Carbon credits could be created by the reduction of fertilizer use from the addition of char to the soil, but these were not considered (Roberts et al., 2010). The model was iterated over 20 years.

4.4.2. Model Assumptions

Product Values

Bio-oil is functionally similar to diesel fuel, at least for the purpose of running stationary generators (Bridgwater et al., 2002) and we assume bio-oil is sold to local consumers for use in backup generators. Recent diesel costs in Costa Rica have ranged from 0.9 to 1.1 $/L (1.1 to 1.3 $/kg: World Bank, 2011). Diesel fuel has 2.3 times the energy content of bio-oil, and we estimate the value of the bio-oil as 43% of the value of diesel fuel, or 0.5 $/kg in the expected scenario (excluding carbon credits). The costs of diesel fuel vary widely over time and it is not possible to confidently predict the price of diesel over a twenty year time frame. However, we assume diesel prices will generally be high, and we consider 0.5 $/kg to be conservative.

The price of biochar is uncertain. A ton of biochar has a similar energy content as a ton of coal (Abdullah and Wu, 2009), and they can be used in similar ways; this would suggest a price of biochar roughly equivalent to coal. Coal prices are highly variable, but in Central America coal imports have recently cost $150 to $250 per ton. However, coal is not widely used in Costa Rica and thus the utility of a coal substitute is questionable. Biochar would derive additional value through carbon credits, but this is addressed separately.

Biochar may be relatively easy to market as a soil amendment, but is likely to be less valuable than is used for energy. Due to the infrastructural and capital requirements of using biochar as an energy source, it may be more difficult to develop a market. For agricultural uses, authors have suggested prices of $120 to $180 per ton, but these prices may be optimistic for farm-scale use in the developing world. Rondon et al. (2006) found a 28% increase in maize productivity using a 20 t/ha application of biochar in eastern Colombian soils. Given the price of maize in Costa Rica, this would yield an extra $681 per hectare and would make the value of char for agricultural purposes approximately 34 $/t. Biochar may be more valuable if used to improve forage production for cattle.

The use of biochar as a soil amendment is the only way to generate carbon negative electricity from pyrolysis, and if carbon negative and carbon neutral credits were differentiated, this may add additional value to the use of char as a soil amendment. Because we are primarily interested in char as a carbon sequestration mechanism we assume an agricultural use and use a range of 25$/t to 50 $/t with an expected value of 35 $/t.

We assume char has additional value as a carbon sequestration mechanism; this value can be captured in the sale price of the biochar and passed to the end user or credits could be retained by the pyrolysis system operator; the selection has important practical implications, but is immaterial for cost modeling.

The value of electricity input into a grid can be difficult to determine and depends on the predictability of the generation and the time at which it is produced. Further, the value of the electricity to a grid producer is less than the retail price due to transmission costs. However, in a small scale system in which the producer consumes the electricity produced, the value of the electricity is the retail price. This method for valuing electricity is the relevant method for production and use by a farm, farm cooperative or village. In Costa Rica, retail electricity prices are on average 9.7 ¢/kWh, but can be as high as 16 ¢/kWh and are expected to increase. Therefore, we used a range of 10 to 17.5 ¢/kWh with an expected value of 12.5 ¢/kWh.

The price of carbon credits are unpredictable. The best way to predict future carbon prices may be to refer to carbon futures contract prices. In carbon futures markets, a buyer may purchase a contract for delivery of a carbon credit at some future time, *t*. The cost to the buyer is fixed at the current market rate and is set by the markets expectation of the price of carbon at time *t*. Thus, the cost of a futures contract for delivery at time *t* is the market expectation of the future cost of that credit. For credits for delivery at the end of 2014, prices ranged from approximately \$15 to \$30 per ton during 2010 and 2011. As of 2012, prices declined, but we assume that as the caps in cap-and-trade systems decline and economies recover from the 2008 recession and 2011-2012 European debt crisis, prices will increase and select a range of 15 \$/t to 45 \$/t with an expected value of 30 \$/t.

Carbon neutral and carbon negative credits were assumed to have the same value. We assume that 70% of the carbon in the char is stable and contributes to climate mitigation. Each ton of soil stabilized char is assumed to create 3.66 carbon credits (44/12). Further carbon credits could be created from reduced use of fertilizer, however, in our model system, biochar is sold to local agricultural users; we assume that these users apply biochar to the soil to increase plant growth and generate carbon credits, but this may or may not be coupled with a reduction in fertilizer use depending on the preference of the end user.

Bio-oil and gas are assumed to displace diesel-fired electricity in back-up generators and carbon credits are created accordingly. Each ton of bio-oil sold offsets 1.4 tons of CO_2 emissions and each kWh of gas-fired electricity offsets 0.8 kg of CO_2 emissions (IEA 2011).

Costs

We developed models of biomass costs that were input into the present model (see Chapter 3); biomass costs of 5, 10 and 20 \$/t were used for the optimistic, expected and pessimistic scenarios, respectively. This is significantly lower than biomass costs used in bioenergy models in the developed world. The costs of transportation of the biomass were included in the costs of the biomass. After delivery to the pyrolysis site, biomass is dried and grinded to a uniform size. A KDS Micronex system or equivalent is used to simultaneously grind and dry the biomass. The system has a capital cost of $300,000, requires 150 kW of power, and has a maximum output of 4 t/h. The KDS system is electrical and requires no external heat source, can process biomass containing up to 70% water and can grind particles to under 2 mm. We assume that labor used for the pyrolysis system is also used to operate the biomass processing system, and that maintenance costs are low, approximately $1-2 per operating hour.

Costs for the pyrolysis system include capital and operating expenditures. Assumed capital expenditures are given in Table 4.2. Slow pyrolysis systems are the least expensive while gasification systems are the most expensive. To facilitate comparisons, all systems are scaled to 5 tons per day. For slow pyrolysis, a system with parameters similar to the Pacific Pyrolysis or Eprida system is modeled. For fast pyrolysis, a system with characteristics similar to the Biogreen or Renewable Oil International system is selected. For gasification, the Community Power Corporation system is used as a model. Since the pyrolysis process is endothermic, an energy penalty equal to 10% of the input material is assumed to be used to power the reaction. For gas products, the electrical efficiency of the system is assumed to be 35% (Hammond et al., 2011). Maintenance costs are assumed to be 4% of the equipment purchase price annually; a miscellaneous charge of $5,000 is included for administrative, marketing and other costs.

Labor requirements for a small scale system are assumed to consist of one manager/operator and one general laborer. Labor costs in Costa Rica are highly proscribed by the government and is based on a daily, rather than hourly rate. Employees may work up to 12 hours per day at minimum daily rate and there are a number of minimum wages depending on the qualifications of the employee. As of 2012, the minimum wage for semi-skilled labor was approximately $17 per day (plus a 26% premium paid to the government for social benefits, plus workers compensation insurance premiums). We assume that one semi-skilled laborer is required whenever the reactor is operating and assume a wage of $24 per shift with each shift lasting eight hours. In the optimistic scenario and expected scenarios, we assume that the employee has other duties not associated with the pyrolysis system allocate 50 and 25% of labor costs to these other duties, respectively. In the pessimistic scenario, operation of the system is assumed to account for all labor costs.

Costa Rican businesses pay corporate income tax on net profits but the tax rate is based on a sliding scale depending on the gross income of the company. Firms with incomes less than approximately $85,000 are charged a 10% tax; firms with income less than $170,000 are charged a 20% tax; and firms with incomes greater than $170,000 are charged a 30% tax.

4.5. Results

4.5.1. Slow Pyrolysis

Under optimistic, expected, and non-profit assumption sets, the NPV of the slow pyrolysis system is positive; under pessimistic assumptions, the NPV of the slow pyrolysis system is negative. In the expected scenario, annual gross revenues are approximately $235,000; 50% of revenue is due to bio-oil sales, 20% is associated with electricity production, 5% is due to char sales, and 25% is due to carbon credit sales. Char-based credits account for 45% of carbon credit production. Approximately 50% of annual costs are due to maintenance of the pyrolysis and biomass preparation systems and biomass purchases and labor costs each account for 15 to 20% of costs.

Taxes and the discount rate have a significant effect on the financial viability of the project; when the discount rate and tax rate are set to zero, the NPV of the expected scenario (e.g. the non-profit scenario) increases from $378,000 to $2.3 million.

Figure 4.2 shows the combination of product prices at which NPV is zero in the expected parameterization. In the figure, combinations of product prices below the lines indicate a negative NPV; combinations above the lines indicate a positive NPV. Even at very low carbon prices (below 2 $/t), the NPV of the model may be positive if the char price is above 40 $/t. At bio-oil prices below 250 $/t, NPV may still be positive if the char price is over 55 $/t.

4.5.2. Fast Pyrolysis

Under expected, non-profit, and optimistic assumption sets, the NPV of the fast pyrolysis model is positive; under the pessimistic assumption set, the NPV is negative. In the expected scenario, the gross annual revenue is approximately $375,000, approximately 60% higher than in the slow pyrolysis model. Approximately 77% of revenue is associated with bio-oil sales and approximately 20% is associated with the sale of carbon credits. Less than 3% of revenue is due to direct char sales, but char does account for nearly 30% of the carbon credits produced.

The NPV of the expected scenario is $1.1 million which increases to $3.3 million under the optimistic assumption set and $4.7 million when the discount rate and tax rate are set to zero (the non-profit scenario). Under pessimistic assumptions, the NPV is -$430,000.

4.5.3. Gasification

The gasification model exhibits significantly more negative results than either the slow or fast pyrolysis models, and the NPV is only positive under the optimistic assumption set. Under the expected assumption set the NPV is -$760,000, and the NPV improves only slightly when taxes and the discount rate are set to zero (to -$646,000). Even under the optimistic assumption set, the NPV is only slightly positive ($228,000).

4.6. Sensitivity

4.6.1. Slow Pyrolysis

Negative biomass prices are possible if the pyrolysis system provides a waste removal service. The model is relatively insensitive to changes in the price of biomass. In the slow pyrolysis model, the break-even price of biomass was 67.5 $/t in the expected parameterization, relative to an expected value of 10 $/t. In the optimistic scenario, the NPV was positive under all reasonable biomass prices, while in the pessimistic scenario, the NPV was negative at all biomass prices greater than -174 $/t. Thus, very large changes in biomass prices are required to change the NPV of the system.

Figure 4.3 shows the NPV of the expected, optimistic and pessimistic scenarios under varying carbon prices. Regardless of the price of carbon, the pessimistic scenario is never profitable. The optimistic and expected scenarios are profitable at all carbon prices, however, the NPV of the expected scenario is nearly zero when carbon prices are set to zero. The slope of the relationship between NPV and carbon prices was not equal in the three scenarios; the expected scenario was the most sensitive to changes in carbon prices and every $1 increase in carbon prices increased the NPV by $12,000. In the optimistic and pessimistic scenarios, each $1 increase in the price of carbon is associated with an approximately $8,000 increase in the NPV.

The relationship between NPV and bio-oil prices is shown in Figure 4.4. In the optimistic scenario, the NPV is always positive, even if bio-oil is given no value; in the pessimistic scenario, NPV is negative at bio-oil prices under $1350 per ton. In the expected scenario, the break-even bio-oil price is approximately $275 per ton. Bio-oil prices of $275 per ton are equivalent to diesel prices of $0.54 per L ($2.04/gal); even if bio-oil must be priced at a significant discount to be marketable, the model suggests that if the expected conditions hold, the pyrolysis system may be profitable.

In the default parameterizations, char was assumed to be an inexpensive agricultural product for use at the farm-scale. Char could also be marketed to consumers as a garden product, equivalent to a "green" fertilizer or as a coal substitute; in these case, the price of char may increase significantly. The results of the model under varying char prices are shown in Figure 4.5. The model is relatively insensitive to changes in char prices, and due to the throughput rates, the model sensitivity is highest in the optimistic scenario, followed by the expected scenario.

4.6.2. Fast Pyrolysis

Figure 4.6 shoes the NPV of the three model parameterizations with a varying carbon price. At carbon prices above 60 $/t, the NPV is positive for all three parameterizations. Figure 4.7 depicts the relationship between the bio-oil price and the NPV. The pessimistic assumption set is never profitable at bio-oil prices below 500 $/t, but the break-even point for the expected parameterization is approximately 200 $/t. Results of the optimistic assumption set are always positive, even when bio-oil is given no monetary value, and the optimistic assumption set is the most sensitive parameterization to price changes. Because char represents a minor proportion of the fast pyrolysis system revenue, char prices have very little impact on the profitability of the system (Figure 4.8).

4.6.3. Gasification

Figure 4.9 depicts the relationship between the carbon price and NPV in the gasification model. At all carbon prices under $100, the NPV is never positive in the expected or pessimistic assumption sets, and the price of carbon must exceed 15 \$/t for gasification to be profitable under the optimistic assumption set.

Figure 4.10 depicts the sensitivity of the gasification model to alternative electricity prices. Because of the increase in throughput and electrical production in the optimistic parameterization, the optimistic parameterization is more sensitive to changes in product prices than the expected or pessimistic parameterizations. The pessimistic parameterization does not exhibit a positive NPV at any electricity price below 0.45 \$/kWh while the optimistic parameterization yields a positive NPV at all electricity prices over 0.075 \$/kWh.

4.7. Limitations

The analysis was conducted in U.S. dollars, but many of the cash flows will be in Costa Rican colones. The capital costs of equipment will likely be in U.S. dollars, income from carbon credits may be in euros or U.S. dollars, and most other cash flows will be in Costa Rican colones. We assumed an exchange rate of 500 colones to one dollar which has been the approximate exchange rate for much of the 2010 to 2012 period. If the dollar strengthens relative to the colon, capital costs would increase for a Costa Rican operator. Since carbon credits are denominated in euros, the euro to colone exchange rate will also be important in determining the feasibility of carbon reduction systems in Costa Rica.

For all three pyrolysis systems, the optimistic scenario had a positive NPV while the pessimistic scenario had a negative NPV; this limits the generality of the results and suggests that pyrolysis may or may not be economically feasible depending on the assumptions used. In reality, neither the optimistic, pessimistic or expected scenarios will exactly reflect the experience of pyrolysis system operators in Costa Rica. Instead, the scenarios are intended to represent the range of possible alternatives and the actual parameterization will reflect a combination of values from the three alternatives presented.

The carbon prices used in the analysis are higher than market levels as of mid-2012 and reflect market expectations from the 2010-2011 period. As of mid-2012, carbon credit futures contracts were approximately 6 to 7 $/t for credit delivery in December 2020. Low carbon prices have a significant negative impact on the NPV of pyrolysis, but, based on the analysis, fast and slow pyrolysis may remain profitable even at very low carbon prices, however, the probability of realizing a negative NPV increases.

A 10% energy loss was required for the slow, fast, and gasification systems. The 10% loss may be appropriate for the slow pyrolysis system because the dehydration reactions typical of slow pyrolysis are exothermic and relatively little exogenous energy may be required to power the reaction. However, gasification and fast pyrolysis may require a larger energy input which would reduce the profitability of the system. The financial effects of the energy loss will depend on the specification of the system and whether char, gasses or another fuel are used to power the reaction. Since biomass costs are low, the effects of increased energy losses are likely to be minimal as long as the capital costs of the system scale with product outputs rather than inputs.

4.8. Conclusions

The models may be used to identify system goals that result in a profitable pyrolysis system. Operators have little ability to control capital costs or market prices, but can control throughput, and to a lesser extent, labor and biomass pricing.

Fast and slow pyrolysis are relatively profitable under the assumptions identified in the parameterization and are economically promising technologies for reducing global carbon dioxide emissions. Small scale gasification is not profitable under the most realistic combinations of the carbon and electricity price.

Despite generally positive results for fast and slow pyrolysis, future market prices are impossible to predict with confidence. The results of the pessimistic parameterization were generally negative and if the pessimistic price environment most closely matches the future, pyrolysis systems will not be profitable. Therefore, while promising, investment in small scale pyrolysis in the tropics remains a high risk investment.

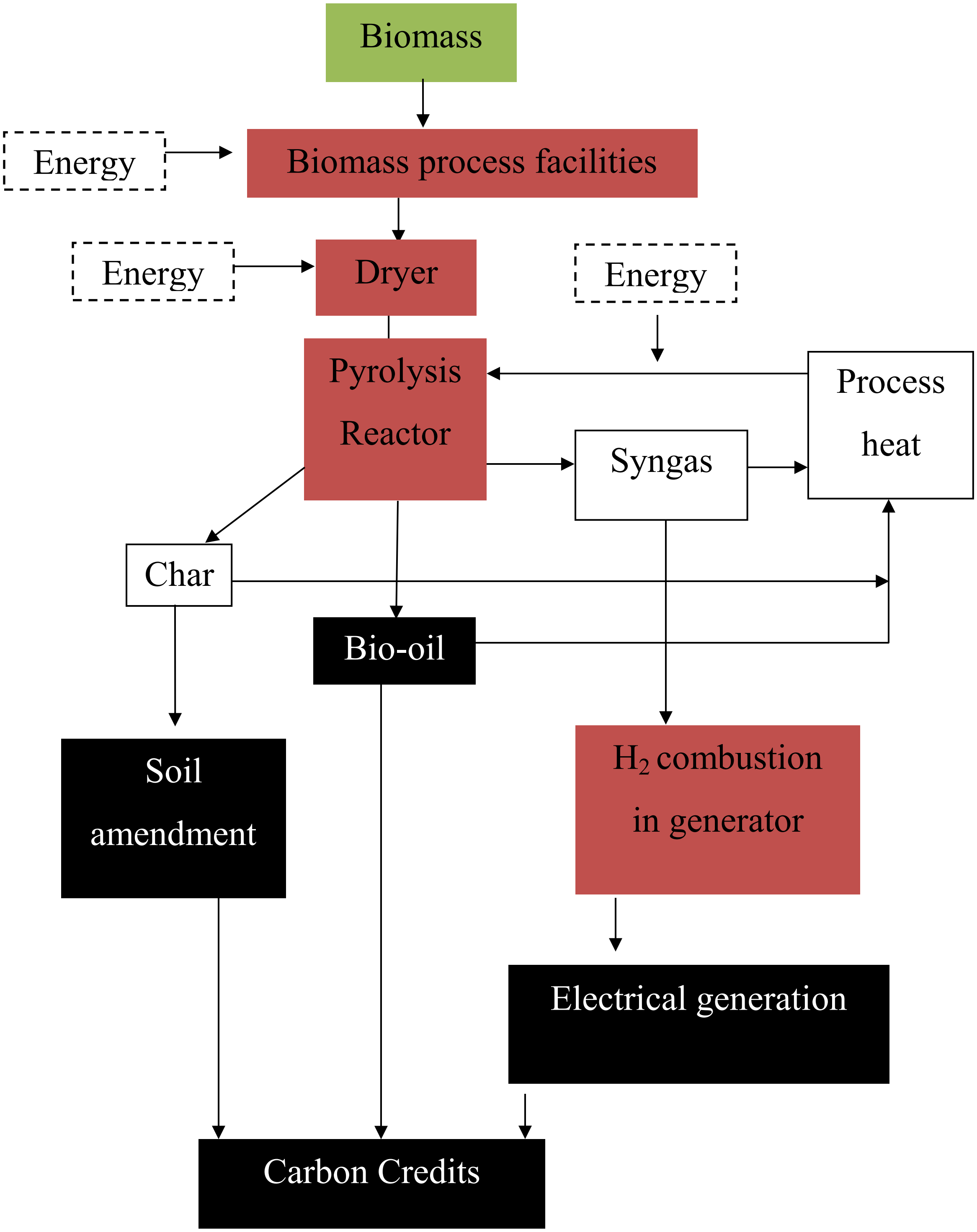

Figure 4.1 Visual representation of the model. Red signifies capital costs, green signifies operating costs, black signifies sources of income

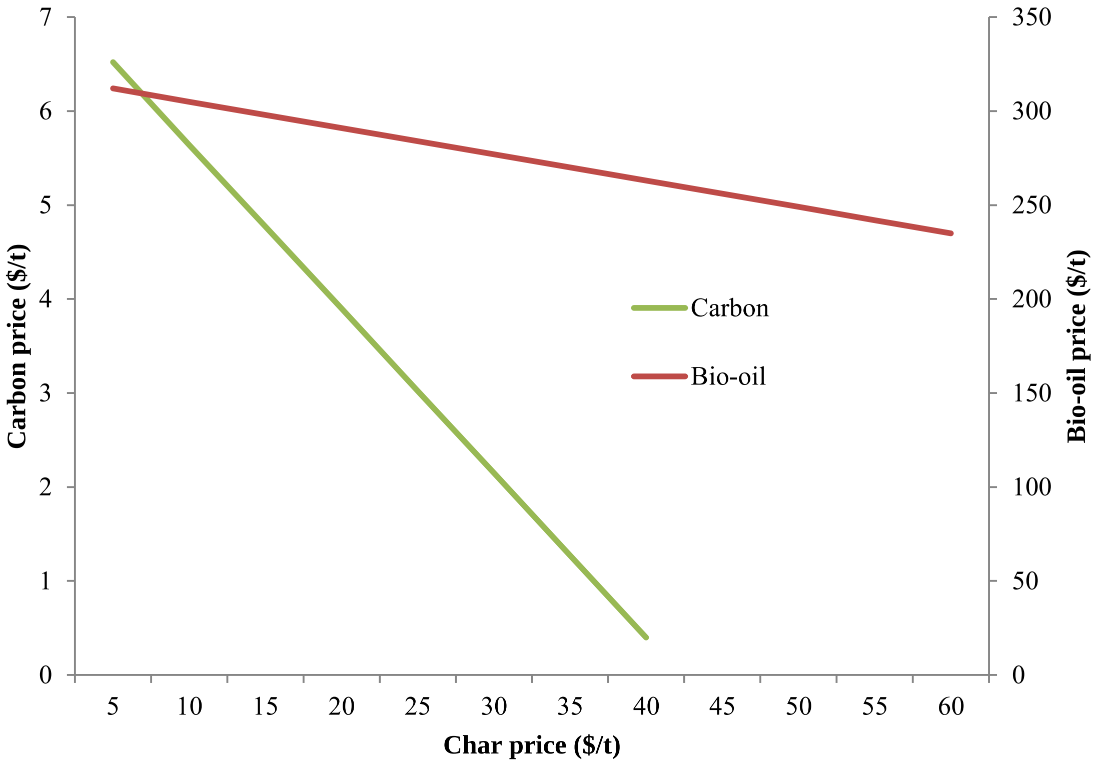

Figure 4.2 Break-even bio-oil, char and carbon prices in the slow pyrolysis model, expected parameterization

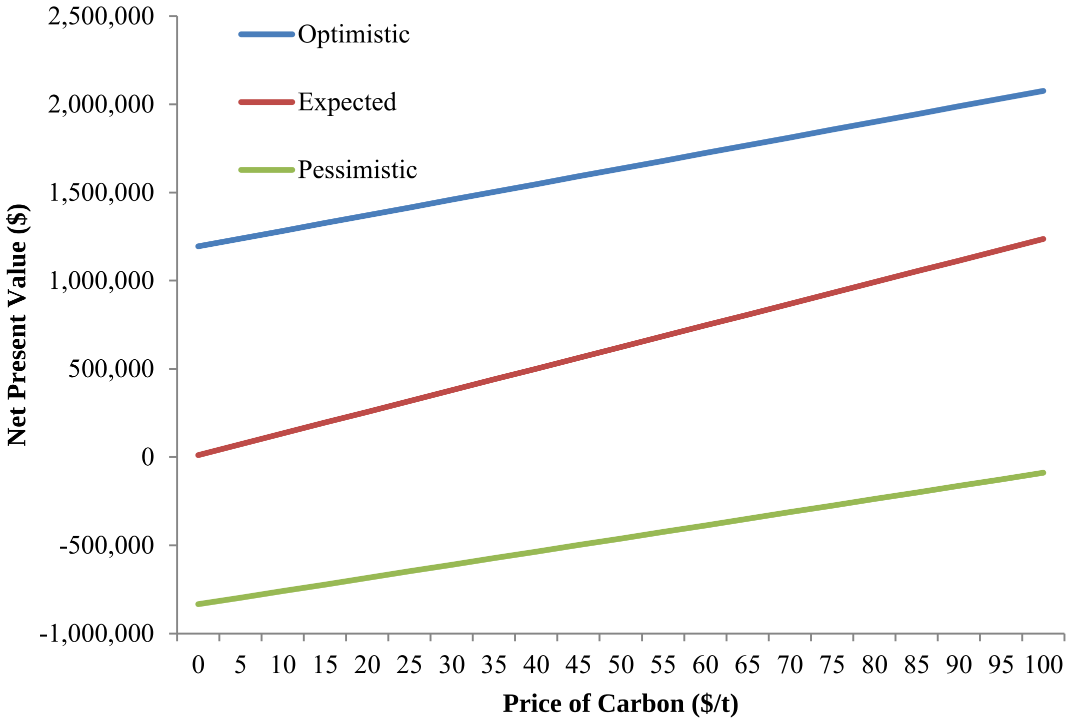

Figure 4.3 Relationship between the carbon price and net present value in the slow pyrolysis model

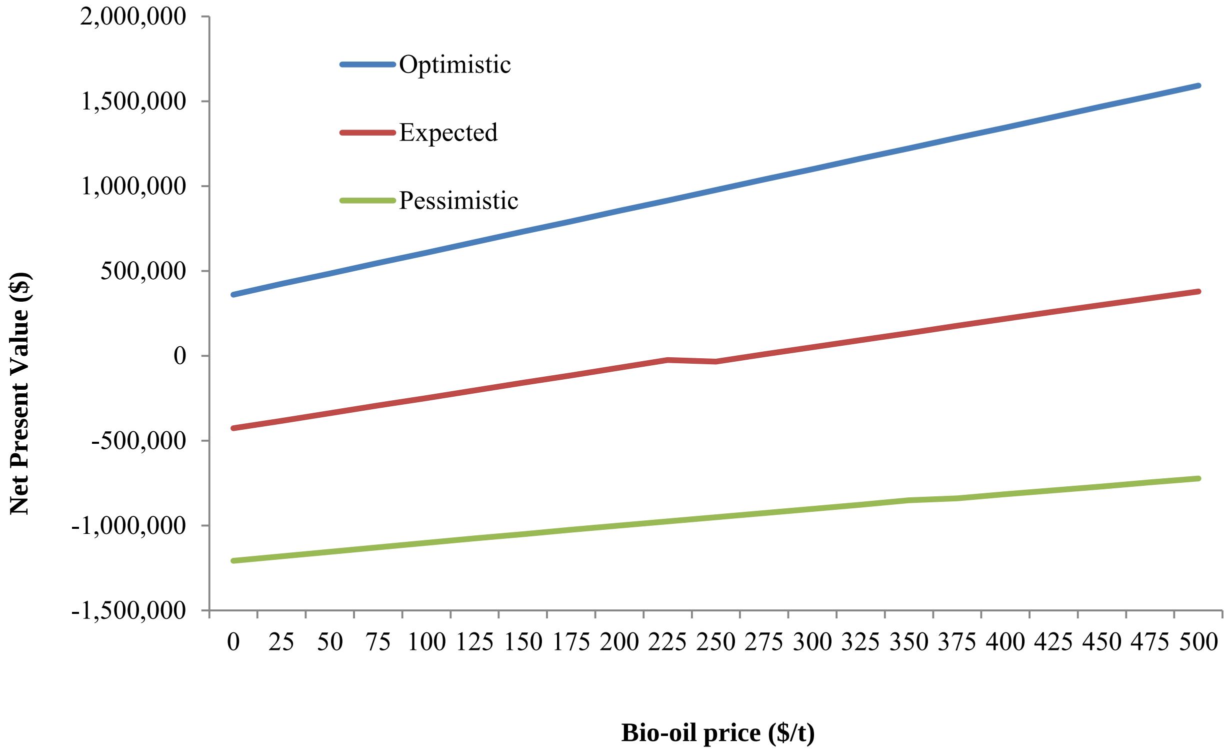

Figure 4.4 Relationship between the bio-oil price and net present value in the slow pyrolysis model

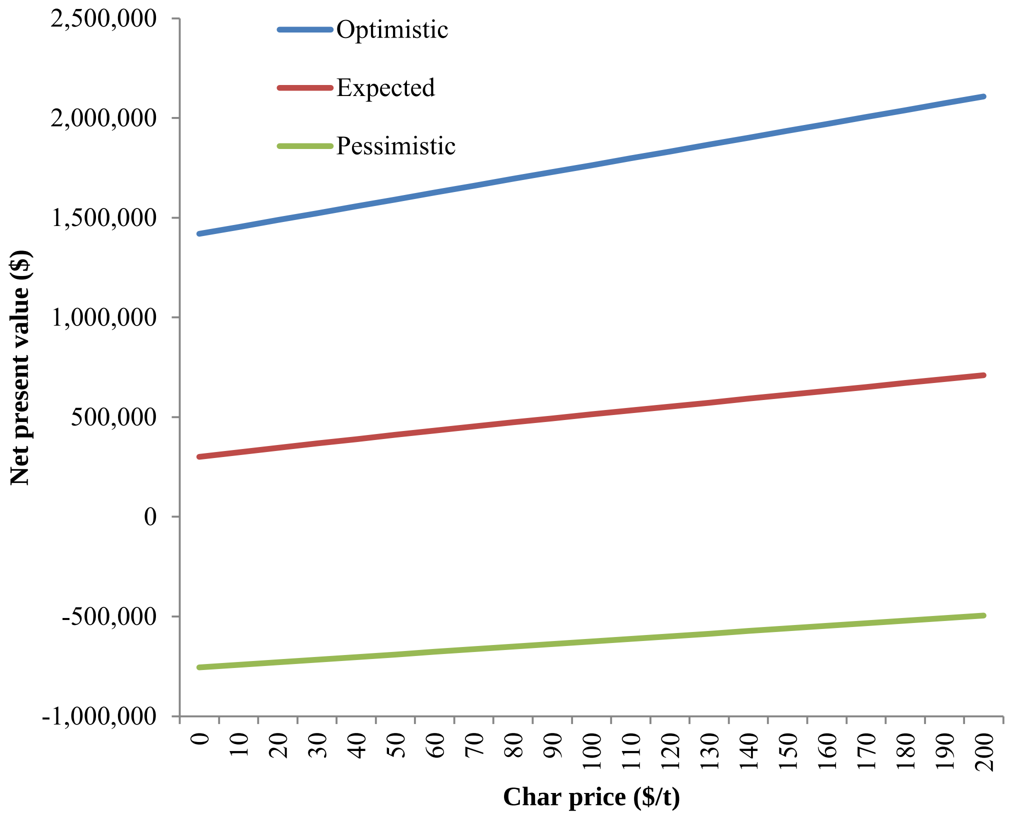

Figure 4.5 Relationship between the char price and net present value in the slow pyrolysis model

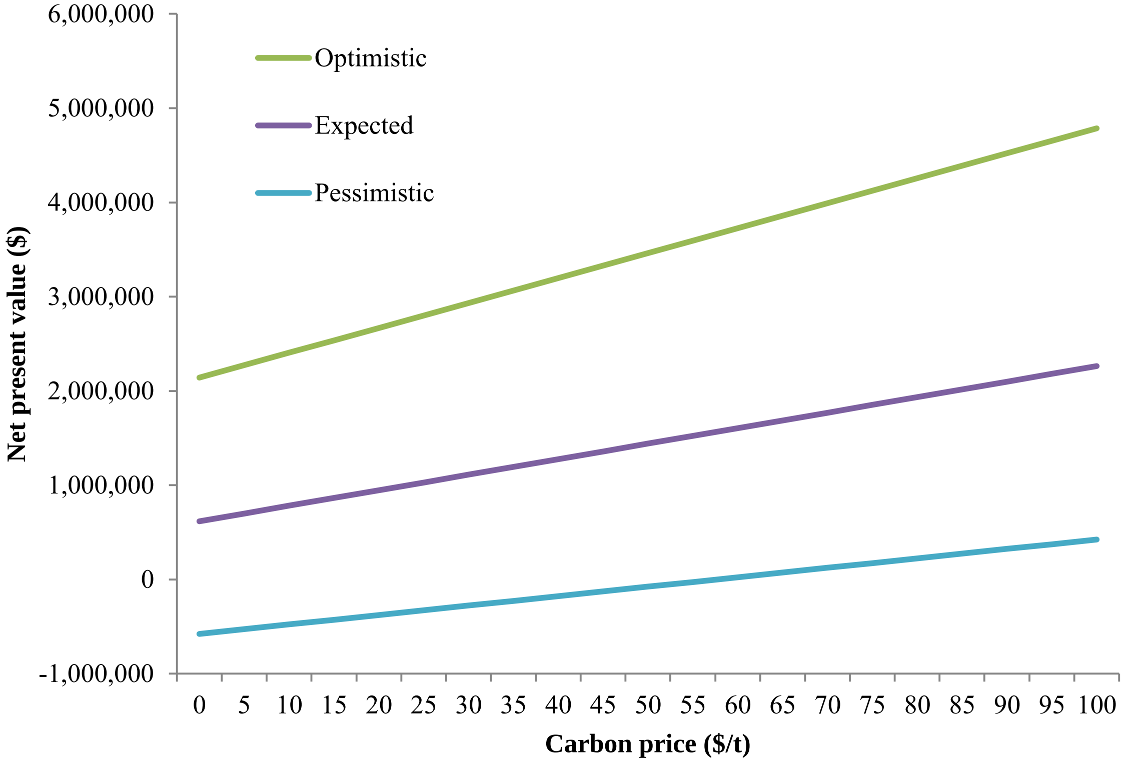

Figure 4.6 Relationship between the carbon price and net present value in the fast pyrolysis model

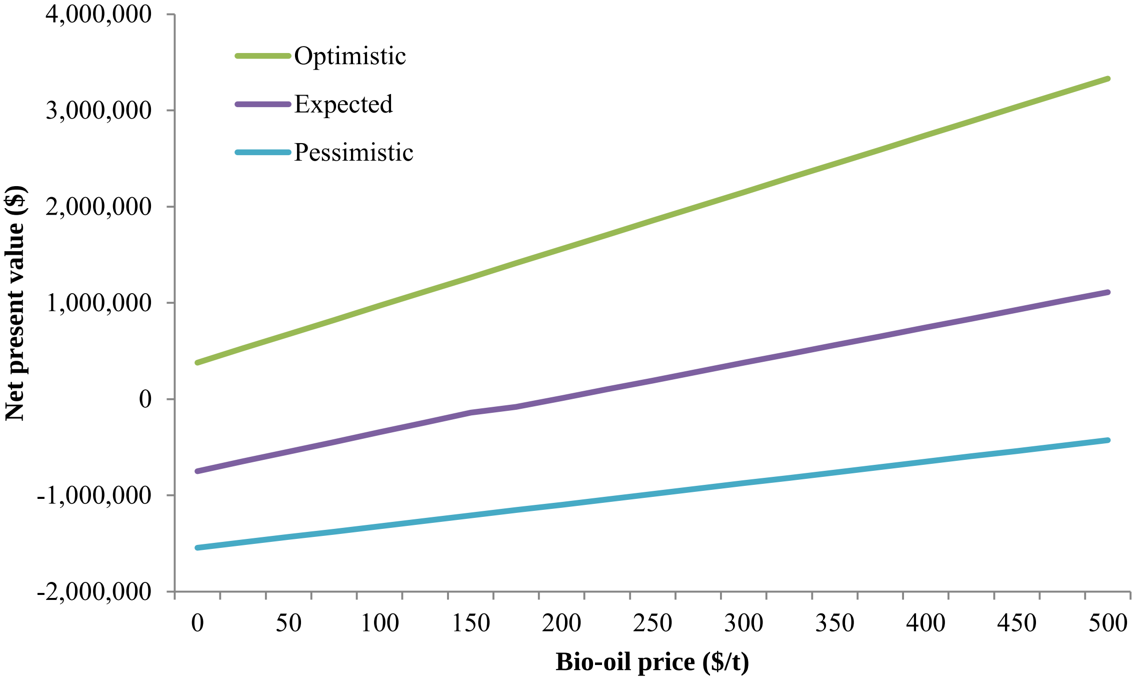

Figure 4.7 Relationship between the bio-oil price and net present value in the fast pyrolysis model

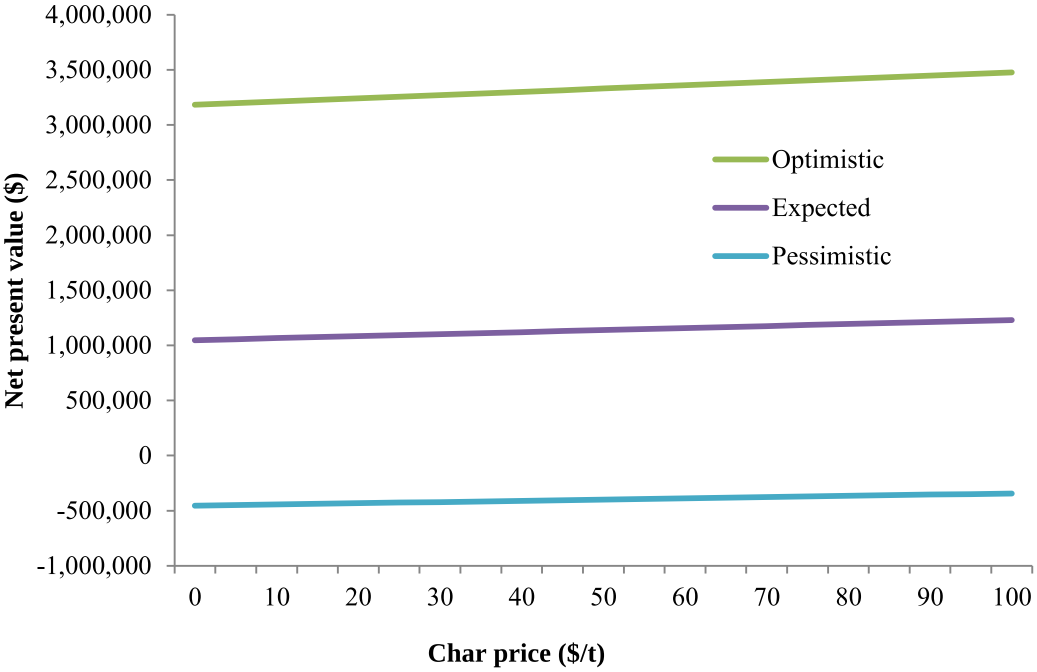

Figure 4.8 Relationship between the char price and net present value in the fast pyrolysis model

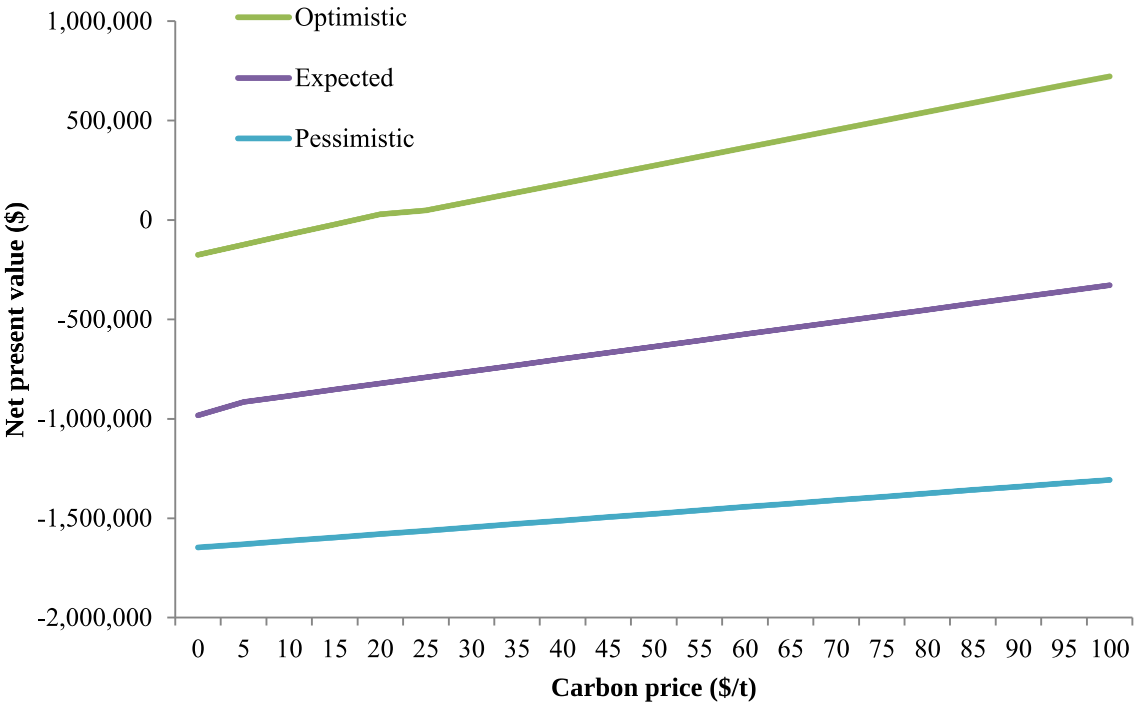

Figure 4.9 Relationship between the carbon price and net present value in the gasification model

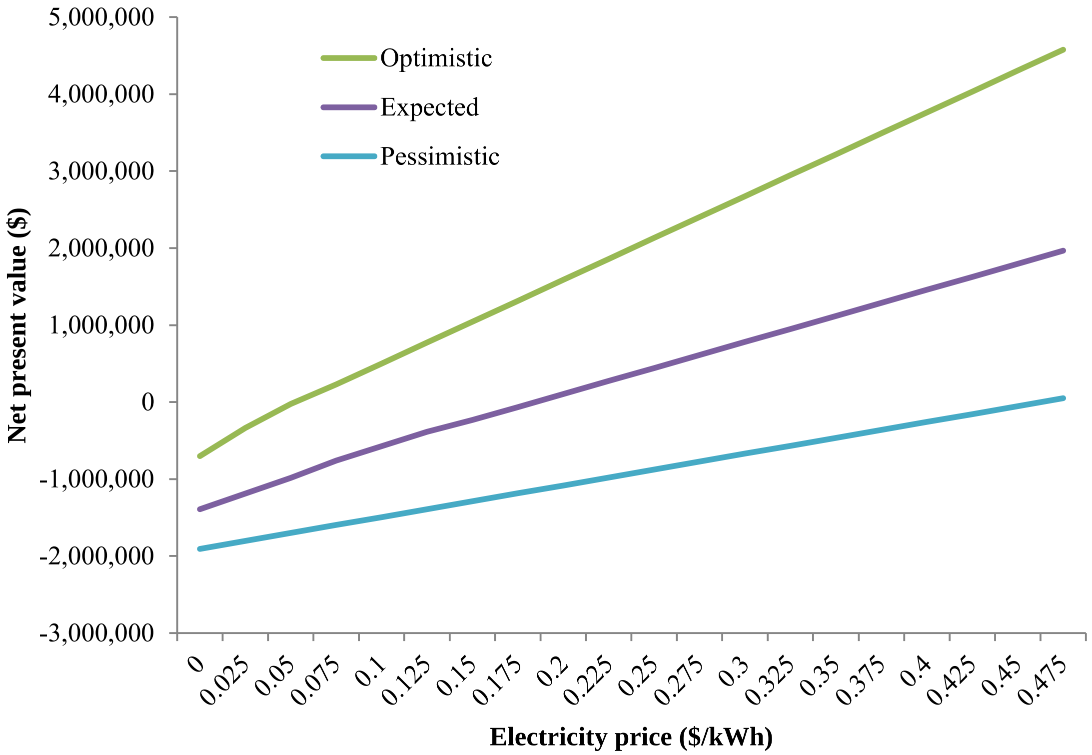

Figure 4.10 Relationship between the electricity price and net present value in the gasification model

Table 4.1 Previous economic studies of pyrolysis

Study	Pyrolysis type	Scale	Capital costs	Biomass price	Results
Peacocke et al. 2004	fast	small large	9,000 $/t/h 900 $/t/h	70 $/t	Break-even electricity price: 0.15 $/kWh Break-even electricity price: 0.60 $/kWh
Bilek et al., 2005	gasification	small	2,000 $/kW	0	Break-even electricity price: 0.10 $/kWh
McCarl et al., 2009	fast or slow	large	1,896 $/kW	59.44 $/t	Break-even electricity price: 0.11 $/kWh
Brown et al., 2011	fast slow	large	$110 million $72 million	83 $/t 0 $/t	IRR = 15% IRR = 8%
Roberts et al., 2010	slow	large	16 $/t	37-43 $/t	Break-even carbon price 2-62 $/t
Farang et al., 2002	fast	large	3,320 $/kW	18 $/t	Bio oil price: 0.89-1.21 $/gal
Ringer et al., 2006	fast	large	$29 million	30 $/t	Bio oil price: 7.62 $/GJ
Sorensen 2010	fast	large	$10 million	45.33 $/t	Break-even: 1.36 $/gal bio-oil; 16 $/t biochar
Bridgewater et al., 2002	fast	large	variable	70 $/t	Break-even electricity price: 0.09-0.18 $/kWh
Ruan et al., 2008	fast	small	266,000 $/t/h	33 $/t	Net income of 42,000 $/yr
Caputo et al 2005	gasification	large	3,125 $/kW	33 $/t	Break-even electricity price: 0.13 $/kWh
Nouni et al., 2007	gasification	small	1,000 $/kW	34 $/t	Break-even electricity price: 0.26 $/kWh
Dowaki et al., 2005	gasification	large	4,850 $/kW	100 $/t	Break-even electricity price: 0.144 to 0.329 $/kWh
Rhodes and Keith 2005	gasification	large	1,250 $/kW	50 $/t	Without CCS, break-even electricity price: 0.059 $/kWh With CCS, break-even electricity price: 0.082 $/kWh

Table 4.2 Cost and output assumptions used in the models

System	Slow	Fast	Gasification
Capital Costs (1,000 $)	400-800	500-1,000	600-1,200
Char Yield (%)	35	30	0
Liquid Yield (%)	25	60	0
Gas Yield (%)	30	0	90
Energy Penalty (%)	10	10	10

Chapter 5: Emergetic Comparison of Bio-oil, Char and Electricity Produced by Fast and Slow Pyrolysis and Gasification: An Ecocentric Model

5.1. Introduction

According to Odum (1971) " all wealth stems from the environment and its myriad systems and processes, and the value of services and commodities should be based on the energy and resources required to produce them, rather than on what someone is willing to pay for them". Emergy is a measure of the energy and resources required to produce a product, and can be considered a theoretical alternative monetary or accounting system that allows for a more holistic valuation of goods and services than either an exchange (money) or value (exergy) system. It is "a universal measure of real wealth of the work of nature and society made on a common basis" (Odum et al., 2000).

Emergy is defined as the total amount of energy of one kind that is directly or indirectly required to make a product or service (Odum, 1988). In emergy analysis, all of the inputs into a system are converted into a comparable energetic unit (the solar emjoule or sej); this allows the comparison and summation of qualitatively different inputs (i.e. human labor and hydrocarbon reserves) in a common currency (Odum, 1996).

Transformity is the critical quantity that allows for the comparison of qualitatively diverse inputs and is defined as the emergy used to create a product per unit energy in the output product. That is, the transformity of product i is given by:

$$Tr_i = \frac{Emergy_i}{Energy_i}$$

Transformity represents the inverse of the emergetic efficiency of a production system and a high transformity may be considered a low "net emergy" yield; that is, a large amount of emergy is required to create each unit of energy. Transformity has the units solar emjoules per joule (sej/J) and can be considered analogous to the price per joule in an ecocentric or emergetic context.

Figure 5.1 shows a standard energy flow diagram used in emergy analysis and Table 5.1 defines the primary indices used in emergy analysis. In emergy accounting, a top-down approach is used. For a given production system, a system diagram is created and a spreadsheet model is used to specify the emergetic flows. The model is parameterized with known energetic inputs and transformities and the emergy flows and transformity of the product is estimated.

The purpose of this chapter is to compare the transformities of bio-oil, char and electricity produced through fast and slow pyrolysis and gasification. Because the comparison is intended to be general, we use a simplified systems diagram to facilitate comparison between the production processes.

5.2. Methods

Two similar systems are modeled. In the first system, waste sugarcane bagasse is used as a feedstock; in the second, unfertilized jaragua grass is grown as a feedstock; the two models are referred to as “waste” and “jaragua” models, respectively. In both models, biomass is transported to the reactor via the transport system described in Chapter 3. Biomass flows into a feeding and processing system and then into the reactor. Services purchased from the economy include fuel for biomass transportation, electricity for feedstock processing, labor, and machinery and equipment. The output of the pyrolysis system are identical to those described in the expected case in Chapter 4. Annual inputs to each system are identical in terms of biomass, labor, electricity, fuel and equipment. Transformities for both models are taken from taken from Alonso-Pippo et al. (2004), Zhang and Long (2010), and Ciotola et al. (2011).

5.2.1 Waste Model

Figure 5.2 shows energy system diagram for the waste model. Biomass is considered to be a byproduct of the sugar production process and is considered to be an energetic input rather than requiring separate inputs for sunlight, water, soil, etc. This simplifies the energy system diagram. The pyrolysis system requires 960 t of biomass per year, consistent with the expected parameterization developed in the models in Chapter 4. Bagasse is assumed to be supplied from a sugarcane processor and transported to a local pyrolysis facility according to the waste transport model developed in Chapter 3. Note that the model in Chapter 3 is for 1350 dry tons per year, while the present model requires 960 tons per year; parameters were adjusted accordingly. The long distance model is used and loading costs are required; 1,482 hours of labor and 13,680 kg of diesel fuel are required for transport each year. As in the model in Chapter 4, 36,000 kWh are required annually for processing, 4,800 hours of labor are required for operation, and a 10% energy loss is required to power the pyrolysis reaction. Material and equipment inputs include the reactor, a truck for biomass transport, material handling equipment, feedstock processing equipment and other miscellaneous steel manufactured goods; we consider 25 tons of manufactured goods to be a conservative overestimate. Equipment inputs are prorated to a 10 year lifespan. Output of the pyrolysis system is provided in Table 5.2 and is consistent with the expected model in Chapter 4.

Fast and slow pyrolysis and gasification are modeled using a single identical system diagram. Differences between fast and slow pyrolysis and gasification in the system are primarily associated with the amount of steel equipment and machinery required and this is likely to be an insignificant factor in the total emergy flows.

5.2.2 Jaragua Model

The jaragua model is similar to the waste model with the exception of energetic inputs associated with growing and harvesting the jaragua grass. Figure 5.3 shows the energy system diagrams for the jaragua model. In the jaragua grass model, the biomass is grown according to the jaragua grass model described in Chapter 3; seed density is assumed to be 20 kg/ha, productivity is 3.5 t/ha, and no fertilizer application or irrigation are used; 275 ha are planted to yield 960 t/y. The site is assumed to receive 2.5 m of rain per year, consistent with the area around Monteverde, Costa Rica. Soil loss is assumed to be 5.5 t/ha per year (Quintiliano et al., 1961). The jaragua grass is reseeded every five years.

5.3. Results

5.3.1 Waste Model

Table 5.3 shows the emergy flows into the waste model system and Table 5.4 depicts the major emergy indicators. The inputs are the same in the slow, fast and gasification systems, and as a result, the indices are the same for all three systems. Biomass represents the largest input and accounts for 73% of the yield. Diesel fuel and electricity are also significant emergy flows, but steel machinery and labor are minor.

Compared to other electricity production systems, a PR of 73% is considered high. For comparison, hydrocarbon production has a PR of 0 while ethanol production has a PR between 11 and 30% depending on feedstock (Brown and Ulgiati, 2004; Dong et al., 2008; Pereira and Ortega, 2010). The EYR of pyrolysis is relatively low (3.6) compared to fossil fuels (coal, 8-10.5; natural gas, 6.8-10.3; crude oil, 3.2-11.1; Odum, 1996). This occurs because of the large nonrenewable emergetic input into fossil fuel systems and suggests that pyrolysis systems may not be cost competitive with fossil fuels.

The ELR and EIR of the model pyrolysis systems are the same because no nonrenewable natural resources were included in the model. Sand is often used as a heat transfer material in pyrolysis systems and could be included as a nonrenewable natural resource; however, the sand is not typically used up during the reaction. Both the EIR and ELR are low indicating a system with minor environmental impacts (low ELR) and a low investment of emergy purchased from the broader economy.

The transformities of the waste system are depicted in Table 5.5 and transformities of fossil fuels and electricity are given in Table 5.6 for comparison. The transformity of char is similar for both the fast and slow systems (53- 63,000 sej/J) and is roughly similar to the transformity for coal. Since the fast pyrolysis system is optimized for bio-ooil production, the transformity of biooil production is much lower via the fast pyrolysis system than the slow pyrolysis system, and in the slow pyrolysis system, the transformity of bio-oil is lower than the transformity of crude oil. The transformity of electricity produced via gasification is roughly equivalent to the transformity through conventional thermal electric production, but higher than the transformity for hydroelectric power.

Since the fast and slow pyrolysis systems are designed to produce several useful products, the total transformity of the system may be a more meaningful measure (Brown and Herendeen, 1996). The total transformities listed in the table are the emergy input per unit energy output, after correcting for the proportional split in energetic outputs; the total transformity applies to all products in the production system. When viewed in aggregate, the transformity of the fast and slow pyrolysis sytems are relatively low, indicating that approximately 32,000 to 36,000 sej of emergy are required for each joule of energy output from the system.

5.3.2 Jaragua Grass Model

Table 5.7 shows the emergy flows into the Jaragua grass model system and Table 5.8 depicts the major emergy indicators. The inputs are the same in the slow, fast and gasification systems, and as a result, the indices are the same for all three systems. Since the system is not fertilized, the PR is high (70%) and rainfall and soil organic matter are the two largest emergy inputs into the system. The EYR of the jaragua model is larger than the EYR of the biomass model and comparable to fossil fuels. The high EYR of the jaragua grass model is due to the low proportion of purchased emergy inputs relative to the renewable and nonrenewable natural resource inputs in the form of rain, sun and soil. The ELR of the jaragua model is slightly higher than the ELR of the waste model, but is still low relative to other biofuel systems (Brown and Ulgiati, 2004; Dong et al., 2008; Pereira and Ortega, 2010).

The emergy input in the jaragua grass model is greater than in the waste biomass model and as a result, the transformities of the jaragua grass model are much higher than those of the waste model (Table 5.9). As in the waste model, the total transformities are the most representative measure of the emergy efficiency of the system, and are slightly higher than the transformities for the conventional fuels depicted in Table 5.6.

5.4. Discussion

The results indicate that the transformities of pyrolysis production systems using waste biomass are similar or less than those of geochemical hydrocarbon production systems. Geochemical hydrocarbon production systems have low transformaties compared to most human-engineered production systems (e.g. fertilizer, ethanol, biodiesel, or chemical production); transformaties are integrative efficiency measures on a geologic time-scale and natural systems are frequently more efficient than human designed systems on this time scale (Zhang and Long, 2010). Therefore, the result that pyrolysis systems may have transformaties similar to or less than those of fossil fuels is promising.

Note that the transformities identified in Table 5.6 represent the geological production process of hydrocarbons, while the transformaties calculated here represent the production process that ends with delivery of the product to a refiner or end user. Therefore, the more relevant transformity for hydrocarbons would include all of the emergy required to extract a hydrocarbon from the earth. This would increase the emergy input per unit of energy output, thereby increase the transformity of hydocarbons.

Alonso-Piping et al. (2004) also conducted an emergetic analysis of small scale fast pyrolysis using waste-biomass with generally similar methods and generally consistent results. Our results are slightly more positive (e.g. lower transformities and high PR ratios) than those of Alonso-Piping et al. because the throughput of our model system was greater and the electricity use in our system was lower.

In Chapter 4, we developed a net present value model of pyrolysis that emphasized the exchange (monetary) costs of pyrolysis. From a practical perspective, the exchange valuation is the most reasonable method for valuing the production of char, bio-oil and electricity produced from pyrolysis (Hau and Bakshi, 2004). Since global monetary systems are not based on emergy costs, the analysis presented here is not relevant to the actual costs and benefits of pyrolysis; however, the emergy flows identified represent the emergetic production costs and correspond to the emergy prices that would be charged in a hypothetical ecocentric market. Under an emergetic framework, the prices for bio-oil, char and electricity produced through waste biomass pyrolysis are less than those for oil, coal and conventional thermal electricity.

In addition to the energetic outputs (bio-oil, char, electricity), the model system may also produce carbon credits, and this is true of many systems studied in emergy analysis. Emergy analysis has not been fully integrated into carbon accounting (Cato, 2011) and the emergy of alternative carbon credit production processes has not been evaluated. Previous emergetic studies of bioenergy systems have generally not been positive and (Ulgiati, 2001; Brown and Ulgiati, 2004; Dong et al., 2008; Pereira and Ortega, 2010) and have exhibited high transformities, low PR ratios and high environmental loading ratios. The use of waste biomass as an input significantly improves the transformity of the production process relative to other sources of bioenergy. The ability of pyrolysis systems to use waste biomass represents a major advantage of pyrolysis over other biologically based energy production systems such as ethanol or bio-diesel and suggests that waste products may be preferred over cropping systems, regardless of the economic costs. The jaragua grass model did not consider the impact of fertilizer inputs on emergy flows, but fertilizer application is likely to further increase transformity (Ju and Chen, 2011).

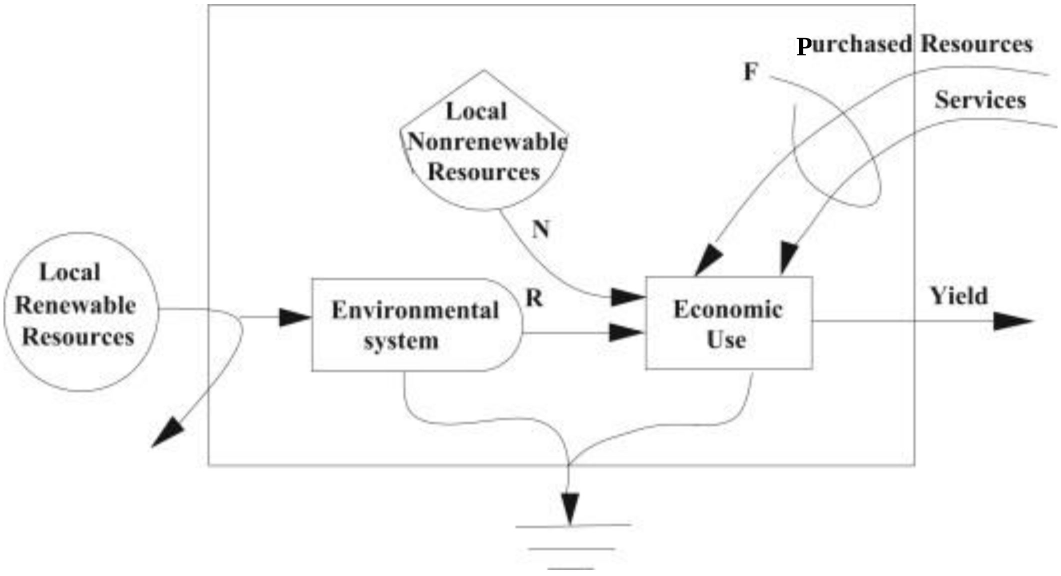

Figure 5.1 Example system diagram used in emergy analysis

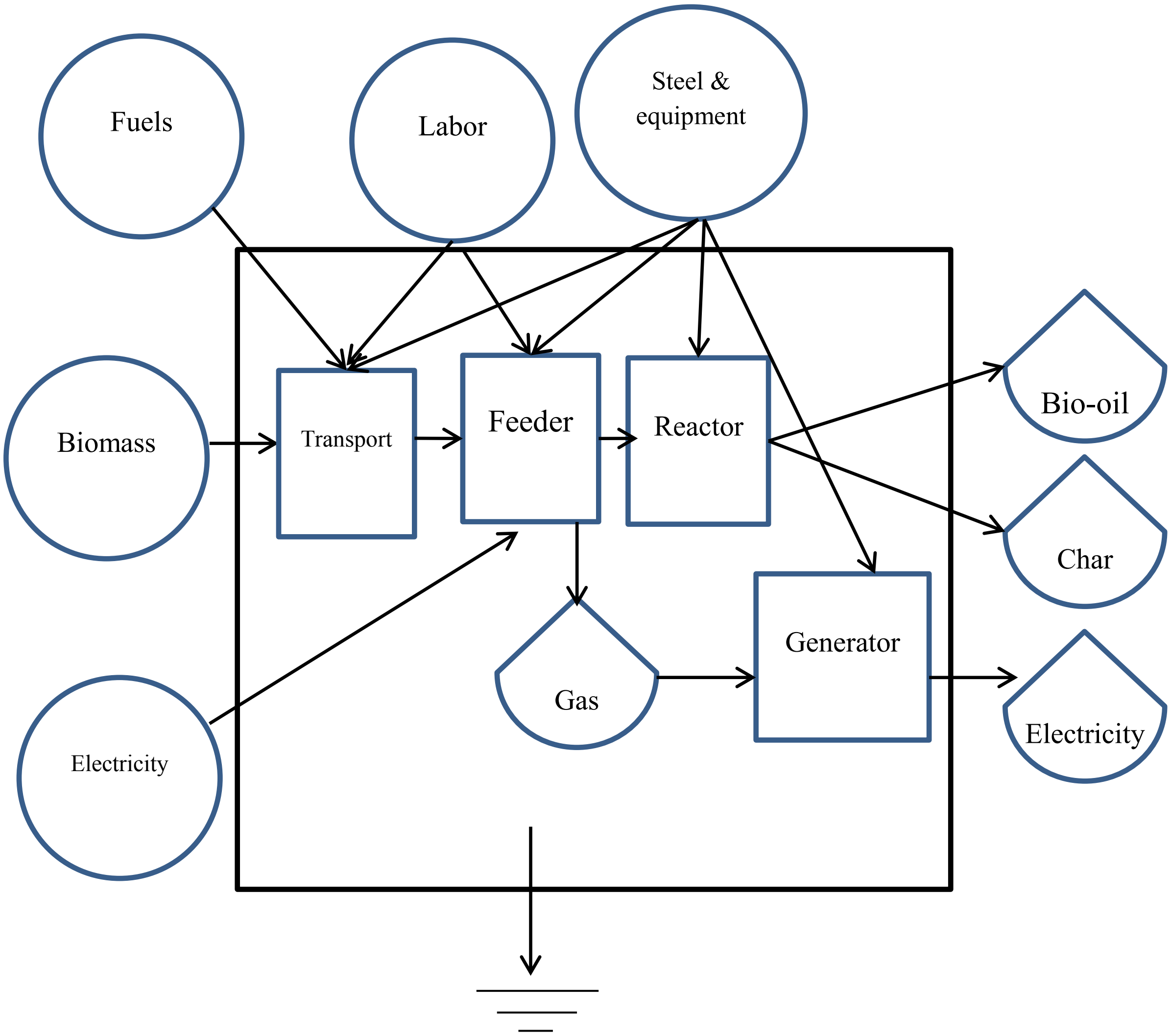

Figure 5.2 Generalized system diagram of a pyrolysis system using waste biomass as a feedstock

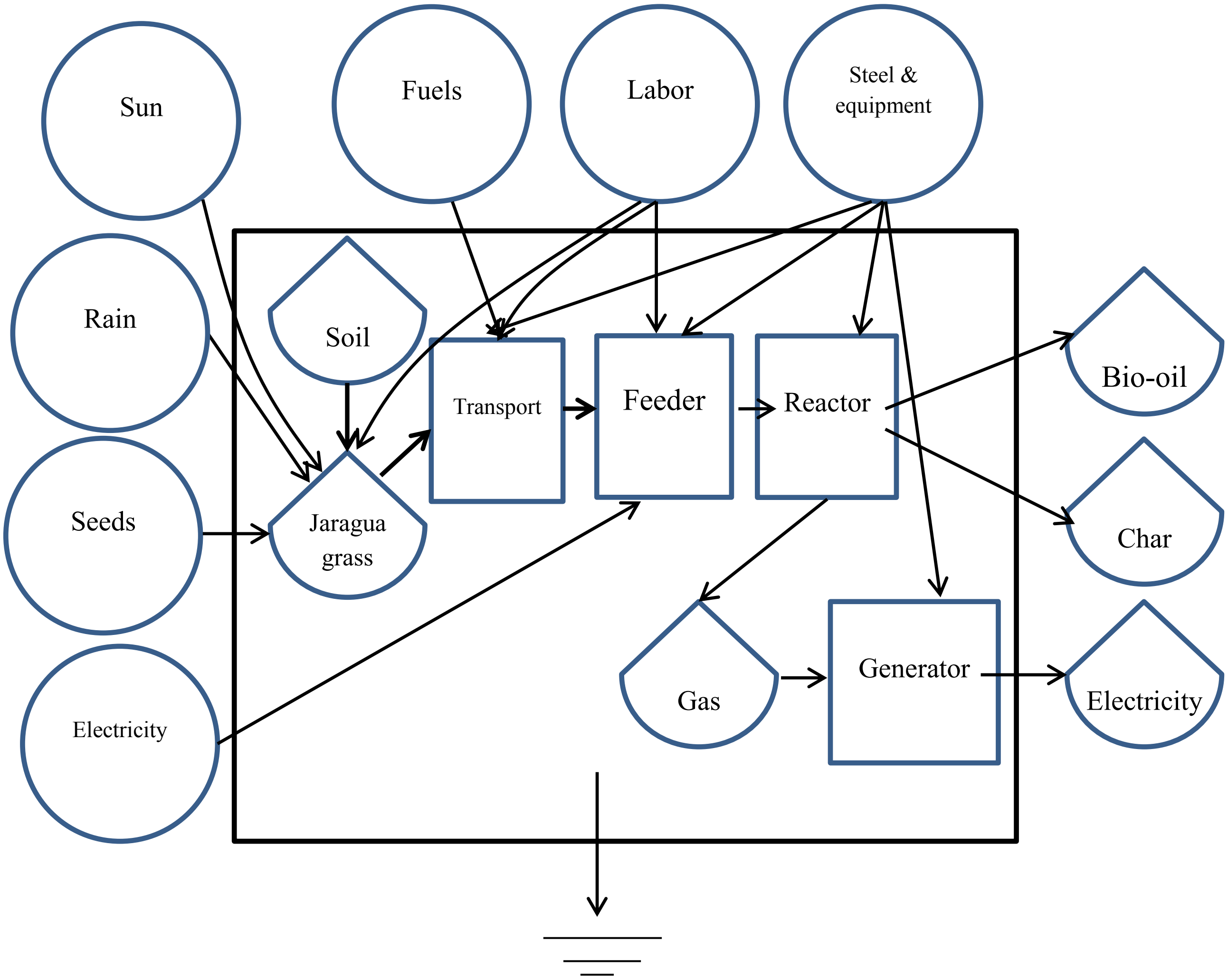

Figure 5.3 Generalized system diagram of a pyrolysis system using cultivate jaragua grass biomass as a feedstock

Table 5.1 The indicies used in emergy evaluation

Name and abbreviation	Definition	Description
Yield (Y)	Y=R+N+F	Summation of all emergy inputs
Percent Renewable (PR)	R/Y	Indicator of the sustainability of a process
Emergy yield ratio (EYR)	Y/F	Emergy yield to purchased emergy costs
Emergy investment ratio (EIR)	F/(R+N)	Ratio of purchased to non-purchased emergetic inputs
Environmental loading ratio (ELR)	(F+N)/R	Measure of ecosystem stress due to production

Table 5.2 Assumed outputs of the fast, slow and gasification systems

System	Fast	Slow	Gasification
Bio-oil (t)	518	216	0
Char (t)	259	302	0
Electricity (kWh)	0	329,196	987,587

Table 5.3 Emergy flows in the waste pyrolysis system

Input	Value	Unit	Energy (J/yr)	Transformity (sej/J)	Emergy flow (sej/yr)
Biomass	960	t/yr	1.52×10^{13}	24,600	3.7×10^{17}
Labor	6,282	h/yr		4.3×10^{12}*	2.7×10^{16}
Electricity	36,000	kwh/yr	1.3×10^{11}	165,000	2.1×10^{16}
Steel & equipment	25	T		1.1×10^{13}**	2.8×10^{16}
Fuel	13,680	kg/yr	1.33×10^{12}	66,000	3.8×10^{16}
Total emergy					4.9×10^{17}

Note: (*) in sej/h; Ciotola et al., 2011; (**) in sej/kg; assumes equipment life of 10 years

Table 5.4 Emergy indicators for a small-scale waste pyrolysis system

Name and abbreviation	Value
Yield (Y)	5.4×10^{17}
Percent Renewable (PR)	0.76
Emergy yield ratio (EYR)	4.2
Emergy investment ratio (EIR)	0.31
Environmental loading ratio (ELR)	0.31

Table 5.5 Transformities (in sej/J) of bio-oil, char and electricity produced through fast and slow pyrolysis and gasification in the waste system

Product	Fast Pyrolysis	Slow Pyrolysis	Gasification
Bio-oil	62,861	15,750	
Char	59,277	50,837	
Electricity		412,139	137,380
Total	30,508	34,806	137,380

Table 5.6 Transformities of conventional energy carriers

Product	Transformity (sej/J)	Source
Coal	67,100	Odum 1996
Natural gas	43,500	Bastianoni et al., 2005
Crude oil	54,200	Bastianoni et al., 2005
Thermal electricity	159,000	Lans 2002
Hydroelectricity	80,000	Lans 2002

Table 5.7 Emergy flows in the jaragua grass pyrolysis system

Input	Value	Unit	Energy (J/yr)	Transformity (sej/J)	Emergy flow (sej/yr)
Sun	6.5 x 10^{13}	j/ha/yr	1.8 x 10^{16}	1	1.8 x 10^{16}
Rain	2.5	m/yr	2.69 x 10^{13}	30,600	1.0 x 10^{18}
Soil loss	5.5	t/ha/yr	1.7 x 10^{12}	124,000	2.1 x 10^{17}
Seeds	5,500	Kg		60,000*	6.6 x 10^{10}
Labor-annual	6,532	h/yr		4.3 x 10^{12}**	2.7 x 10^{16}
Labor-establishment	440	h/yr		4.3 x 10^{12}**	3.8 x 10^{14}
Electricity	36,000	kwh/yr	1.3 x 10^{11}	165,000	2.1 x 10^{16}
Steel & equipment	30	T		1.1 x 10^{13}***	3.4 x 10^{16}
Fuel-annual	15,528	kg/yr	1.33 x 10^{12}	66,000	4.4 x 10^{16}
Fuel-establishment	2,000	kg/yr		66,000	1.1 x 10^{15}
Total emergy					1.4 x 10^{18}

Note: (*) in sej/g; assumes reseeding every five years. (**) in sej/h; Ciotola et al., 2011 (***) in sej/kg; assumes equipment life of 10 years

Table 5.8 Emergy indicators for a small-scale jaragua grass pyrolysis system

Name and abbreviation	Value
Yield (Y)	1.4 x 10^{18}
Percent Renewable (PR)	0.76
Emergy yield ratio (EYR)	10.9
Emergy investment ratio (EIR)	0.10
Environmental loading ratio (ELR)	0.32

Table 5.9 Transformities (in sej/J) of bio-oil, char and electricity produced through fast and slow pyrolysis and gasification in the jaragua grass system

Product	Fast Pyrolysis	Slow Pyrolysis	Gasification
Bio-oil	155,410	372,696	
Char	146,550	125,684	
Electricity		1,018,925	339,642
Total	75,425	86,051	339,642

Chapter 6. Policy alternatives for the expansion of carbon negative technologies under cap and trade systems

6.1. Introduction

Carbon negative technologies are photosynthetically based methods of removing carbon dioxide from the atmosphere and storing it as either living biomass, as carbon in the soil, or in gaseous form in underground reservoirs (Matthews, 2007). There are four main classes of carbon negative technologies. The simplest, reforestation, involves the establishment of new forests which would fix CO_2 from the atmosphere A second alternative is to cultivate crops, particularly low input crops which could be burned for energy production, or potentially turned into liquid fuels; this technique could be carbon negative if significant amounts of carbon are sequestered in the soil. Similarly, no-till low-input or organic agriculture of food crops may sequester carbon in the soil. A third carbon negative technology involves the combustion or gasification of biomass for energy and the capture and storage of the resulting CO_2 (Azar et al., 2006). A final method for removing CO_2 from the atmosphere is to pyrolize biomass creating energy, biochar and other co-products; the biochar is applied to the soil as a carbon sink. With the exception of reforestation, carbon negative credits are not generally accepted by cap-and-trade systems.

By contrast, most technologies for climate change mitigation rely on carbon neutral technologies. The term carbon neutral is used here to refer to a set of technologies which produce some societal want or need (typically energy or agricultural products) in a carbon neutral, nearly carbon neutral, or carbon reduced (relative to a baseline) manner. Major examples of carbon neutral technologies are wind power or biomass fueled power, but the term would also apply to changes in waste handling or disposal or agricultural systems that do not result in the physical removal of carbon dioxide from the atmosphere.

Carbon negative technologies range significantly in cost. Reforestation is among the least expensive carbon dioxide mitigation techniques (Baral and Guha, 2004) while biomass gasification with carbon capture and storage is still in development and thought to be expensive (Azar et al., 2006; Lehmannn and Joseph, 2009). Despite the high cost, carbon negative technologies provide one of the only methods for addressing rapid, unexpected or severe climate change.

There has been academic interest in developing a successor to the Kyoto Protocol (Aldy and Stavins, 2008). The goal of this chapter is narrower: it is to discuss the costs and benefits associated with accepting carbon negative carbon credits in existing cap and trade systems. Specifically, we propose a system in which emitters are required to purchase offsets, some proportion of which are generated by carbon negative technologies with the remainder generated by conventional carbon neutral sources. Over time, the proportion of carbon negative credits required would increase until all carbon credits were generated through carbon negative technologies. For economic reasons, carbon negative credits could be substituted for carbon neutral credits, but carbon neutral credits could not be substituted for carbon negative credits.

We first describe the current context of cap and trade systems including the way in which prices for carbon credits are set by the market. We then describe potential carbon negative technologies that could be included in a cap and trade system, and contrast the effects of carbon negative and carbon neutral credits. We discuss the impact of carbon negative credits on the costs of compliance, and describe concerns about additionality, leakage and permanence. We define a carbon neutral cap and trade system as one that accepts only or primarily carbon neutral offsets, and a carbon negative cap and trade system as one that accepts only carbon negative offsets. This is differentiated from a carbon neutral economy, which we define as a future global system in which no net carbon dioxide is emitted.

6.2. Current Policy Landscape

There have been two main popularly discussed options for policymakers seeking to manage carbon dioxide in the atmosphere (Driesen, 1998). Policy makers may attempt a command and control system or a system of economic incentives. Command and control systems seek to reduce carbon emissions by mandating the behavior of firms or consumers by, for example, mandating gas mileage requirements, the proportions of electrical generation from various sources, or by placing limits on carbon emissions. Command and control systems have been criticized by economists as inefficient (Stavins, 1998) and have been largely ignored or secondary in large scale attempts to regulate carbon emissions[4].

Systems of economic incentives seek to raise the costs of emitting carbon to reduce their use. In principle, they are an application of the polluter pays principle (UN Conference on Environment and Development 1992). Economic incentives may be divided into two classes: fixed cost (carbon tax) and fixed emissions (cap and trade).

A fixed-cost system is a one-time tax on all sources of carbon at their point of sale (Nordhaus, 2006). For example, when a barrel of oil is imported or a ton of coal sold, a tax could be collected. This method is logistically and administratively simple compared to cap and trade systems, where innovation is prizes, as there is no need to certify and account for offsets, and it allows emitters to plan for a fixed price of carbon. However, it does not allow for policy makers to set the amount of carbon emitted as can be done through carbon markets. Instead,

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[4] Note, however, that the Obama administration has undertaken a command and control strategy including raising fuel economy standards and phasing out the construction of coal-fired power plants.

policy makers set the price of carbon and hope that CO_2 emissions drop to an ecologically acceptable level. Carbon taxes are favored by many economists but are politically unpopular due to hostility to taxation in some countries and are less preferred among some environmentalists because they do not tightly control emissions (Murray et al., 2009; Gaunt and Cowie, 2009).

Cap and trade programs are systems in which the government or an intergovernmental organization places a cap on emissions from particular sources and allows firms that exceed their cap to purchase credits from firms that fall under the cap. The credits are generally purchased on an electronic exchange. The government may auction additional credits to raise revenue for the state, or a cap and trade program may be revenue neutral from the perspective of the government (with the exception of enforcement which is a cost for the government). Additionally, companies may produce and sell credits by undertaking or sponsoring a variety of activities which may produce electricity without CO_2 production, sequester CO_2, or destroy or convert particularly harmful greenhouse gases such as methane or HFCs.

6.2.1. Kyoto Protocol

There are a number of mandatory and voluntary agreements under which carbon markets have been formed. The most important is the Kyoto Protocol. The Kyoto Protocol is the basis of the major international cap and trade program; three of the world's four largest emitters of greenhouse gasses (China, India and the United States) are either not signatories or are signatories but are not obligated to cut emissions. As a result, there is significant dissatisfaction with current schemes and a number of policy alternatives have been suggested for altering the Kyoto Protocol (Kemp and Swierzbinski, 2007; Olmstead and Stavins, 2006;Prins and Rayner, 2007).

In addition to the ability to generate credits by falling under the established cap, the Kyoto protocol has two methods for the creation of carbon credits, the Clean Development Mechanism (CDM) and the Joint Implementation (JI). The CDM creates carbon credits called certified emission reductions (CER) while the JI creates carbon credits called Emission Reduction Units (ERU). The difference between the CDM and JI mechanisms are essentially where the emission reduction is created; under the CDM program the emission reduction is created in a non-annex I nation (i.e. the developing world) while under the JI the emission reduction is created in another annex-I nation (i.e. the developing world) while under the J1 the emission reduction is created in another annex nation. CERs and ERUs are interchangeable and can be traded on exchanges such as the European Climate Exchange (ECX).

There are a number of methods by which carbon credits can be created. Figure 6.1 shows the distribution of CDM projects by type (data from http://cdm.unfccc.int/statistics). As can be seen, the majority of CDM projects are energy related with significant proportions also related to waste disposal. Many of these projects are wind, hydro, geothermal, biomass or solar powered electricity projects. Carbon credits may also be created for reforestation and afforestation.

We focus here on the CDM as a model framework for carbon credit governance, however, there are several governmental and inter-governmental organizations that regulate carbon credits and enforce their own rules for what is and is not a carbon credit. To our knowledge, no distinction has been made in any system for carbon negative and carbon neutral credits, but our discussion is general and applies to any current or future cap and trade system.

6.2.2. Supply

The cost of carbon credits sets the overall costs of climate mitigation to society and determines the technologies economically available for mitigation. As for most goods, the production cost of the marginal carbon credit, in theory, will set the price of all credits on the market (Hamilton, 2009). For example, a carbon credit produced from wind power may cost \$2 to produce while one produced by pyrolysis may have a marginal production cost of \$100. The price of carbon credits will not be the average of those two values rather, it is the maximum cost needed to satisfy demand. If demand declines, the expensive production becomes economically unviable and shuts down (McConnell and Brue, 2006).

The variance in carbon credit marginal production costs are typically illustrated through a marginal abatement cost (MAC) curve. Figure 6.2 depicts an example MAC curve; on the y-axis is the carbon price, while the quantity of carbon credits generated is on the X-axis. To generate the MAC curve, the cost of various climate mitigation technologies is computed, along with the total number of credits each technology may generate annually. For example, according to the figure, at an abatement cost of 25 €/ton CO_2 medium cost forestation and CCS with new coal fired power become economically viable, and between 15 and 20 Gt CO_2 are abated per year.

MAC curves may be used to proxy the supply curve, however, the supply curve for carbon credits is likely to be steeper (more inelastic) than is generally depicted in MAC curves due to optimism bias (Holmes et al., 2010). MAC curves frequently depict large emission reductions at low prices, and may include negative costs for some emission abatement technologies (e.g. energy efficiency); in reality, behavioral economic issues, capital constraints, and other factors lead to a much lower volume of credits generated at a given price than is predicted by MAC curves (Holmes et al., 2010; Pfaff et al., 2007; IPCC, 2007).

Figure 6.3 shows a hypothetical inelastic supply curve. Supply can be shifted to the right (an increase in supply at a given price) by technological innovations that reduce the cost of credits. Supply can be shifted to the left (a reduction in supply at a given price) by changing baselines that alter the types of projects which qualify for carbon credits.

6.2.3. Demand

In previous academic studies, demand curves have been thought to be less elastic than supply curves but still relatively elastic (Ellerman et al., 1998; Jotzo and Michaelowa, 2002; Michaelowa and Jotzo, 2005). The demand curve is determined by the caps assigned by the government and the marginal cost of emission abatement (Jotzo and Michaelowa, 2002). A firm will demand credits whenever the marginal cost of reducing its own emissions exceeds the cost of primary (project financed) or secondary (purchased on the open market) credits (Metcalf, 2009). However, caps and the marginal cost curve of within-firm abatement differ by industry making estimation of the demand curve difficult. In general, the demand curve is likely to be non-linear (Figure 6.3) with a high slope at low quantities and high prices and a low slope at high quantities and low prices (Ellermann et al., 1998).

The demand curve may be shifted to the left (i.e. a decrease in demand) due to technological innovations in within-firm abatement, by a reduction in overall economic activity, or by governmental increases in caps. Demand can be shifted to the right by increasingly strict caps, or increasing overall economic activity.

6.2.4. Price Volatility

Carbon credit production is frequently capital intensive and requires long planning times. Similarly, reductions in carbon credit demand require either more generous caps, or investments in emissions abatement by firms, both of which occur slowly. Therefore, there will be time lags between price increases and market responses (either production increases or demand decreases). As a result, a rapid increase in carbon credit costs caused either by speculation, increases in demand or decreases in supply, may not be met with a rapid decline in demand or a rapid increase in production, but a high cost of credits, generating volatility.

Carbon credit markets have a number of similarities with energy commodity markets such as the oil or natural gas market (J.P. Morgan, 2009). Like other energy markets, carbon markets have highly variable production costs, a slow response of producers and consumers to increases in price, and speculation. Over the past several decades the oil and natural gas markets have been highly volatile leading to boom and bust cycles in the oil industry. These cycles are caused by over-investment when prices are high and a lack of investment when prices are low. These boom and bust cycles have been identified as having major negative impacts on the energy industry in terms of infrastructure investment and human capital. Similar volatility in the carbon market would increase investor risk and potentially reduce the number of investors willing to fund credit generating projects.

Despite the young age of the carbon credit markets, their volatility has raised concern among investors and academics and has led to discussion of volatility mitigation strategies (J.P. Morgan, 2009; Metcalf, 2009; Palmer et al., 2008). Figure 6.4 shows the price volatility in the oil and EUA markets. The data for oil prices come from the EIA and are NYMEX traded light sweet crude futures contracts, while the data for EUA prices comes from the European Climate Exchange. A EUA is a European carbon credit similar but not identical to a CER; EUAs are lower risk than CERs (Mansanet-Bataller et al. 2011) and would be expected to show less volatility. EUAs were chosen over CERs due to the longer time period of available data. In both cases the prices are the daily settlement front month future contract price rather than the spot prices; futures prices were used over spot prices due to the length of available data in the futures market. While the variance in price is larger for oil than for EUAs, the coefficient of variation is larger for EUAs than for oil prices (67% versus 29%, respectively), and the difference is highly significant ($p < 0.001$; Verrill and Johnson, 2007). This suggests that carbon credit markets are volatile; policy-makers interested in developing a sustainable carbon management system will need to account and plan for this volatility.

6.3. Existing and Potential Carbon Negative Projects

All carbon negative projects rely on photosynthesis to capture CO_2 from the atmosphere. The captured carbon must then be stored in a long lived reservoir. Storage can be accomplished by the protection of a forest from carbon loss, by combusting the biomass and storing the resultant CO_2 in underground geologic formations, via char applied to soil, or through storage as organic material in soil.

6.3.1. Bioenergy-Soil Organic Material

Carbon may be stored in the soil as organic matter and in the roots of crops through the use of no-till or low-till planting (Murray et al., 2007). In temperate grasslands similar to those used for switchgrass or other cellulosic biomass sources, up to 4.4 tons hectare^{-1} year^{-1} can be stored (Tillman et al., 2006). However, the use of no-till or low-till agriculture is currently not approved as a method for the generation of CDM credits for either bioenergy or food-based agriculture. Crops grown for bioenergy may be especially likely to be grown in systems in which carbon is stored in the soil as bioenergy crops are usually perennial and require little tilling or other energy inputs.

6.3.2. Carbon Capture Storage-Biomasss

Carbon dioxide, once captured from exhaust, could be stored, potentially indefinitely in underground geological formations or as pools in the deep ocean (IPCC, 2005). Carbon capture occurs in a very limited number of fossil fueled power plants in which the CO_2 generated from combustion is scrubbed from exhaust streams. In current applications, the CO_2 is concentrated and sold commercially for use in fire extinguishers and as carbonation in beverages. There are also natural gas fields in which CO_2 is scrubbed from the natural gas stream (e.g. the Sleipner field) and stored in geologic reservoirs as well as enhanced oil recovery systems in which carbon is taken from underground wells and injected into oil reservoirs to raise pressures. Thus, there are both carbon capture systems and carbon storage systems, but with the exception of Sleipner, there is no system that both captures and stores carbon.

Most interest in CCS has been from so called “clean coal” in order to produce nearly carbon neutral electrical production. However biomass could also be combusted or gasified, and the resulting CO_2 captured and stored. This would be carbon negative (Rhodes and Keith 2005), producing electricity and a net reduction in carbon dioxide concentrations.

Currently, CCS is not eligible for carbon credits under the CDM (de Coninck et al., 2009), however, there has been a great deal of discussion among policymakers on the inclusion of CCS methodologies to the CDM (Philibert et al., 2007). If conventionally fueled CCS becomes eligible for carbon credits, and given that biomass fired power without CCS is eligible for carbon credits, then it may be reasonable for biomass fueled power with CCS to be eligible for additional carbon credits for both the biomass combustion and the carbon storage.

6.3.3. Reforestation and Afforestation

Reforestation and afforestation have been studied extensively as a means of producing carbon credits and reforestation projects are allowed and have been implemented under the CDM (see, for example, CDM methodologies AR-AM002, 004-007 and 009-010). Reforestation and afforestation projects receive CDM credits; thus they are the only carbon negative technology that is currently receiving carbon credits. However, unlike other CDMs, reforestation projects are only eligible for temporary credits (called either tCERs or LCERs) which expire either at the end of the compliance period (tCERs) or at some other predetermined date 20 to 60 years in the future (CDM Rulebook 2010) thus ensuring that purchasers of tCERs or LCERs must purchase new credits at some point in the future and depressing the value of these credits relative to normal CERs.

6.3.4. Pyrolysis

When biologically derived material is heated in the absence of oxygen it thermally decomposes and produces a hydrogen rich gas, a complex liquid phase of hydrocarbons and water and a solid high carbon char. The hydrogen and hydrocarbons can be burned to produce electricity and the char can be added to soil as an amendment. When added to soil, the char is long lived, may increase crop productivity and serves as a carbon sink (Lehmannn and Joseph, 2009). The lifetime of the carbon in soil is not known. Pyrolysis could produce carbon credits through the generation of carbon neutral energy and through the storage of carbon in the soil. No pyrolysis projects are currently granted credits under the Kyoto Protocol.

6.4. Shortcomings in the Current Policy System

The Kyoto protocol is severely limited because it does not place emission restriction on large developing nations, and because the United States is not a treaty participant. However, current carbon neutral cap and trade systems are insufficient for completely addressing climate change, even if 100% participation is assumed. Cap and trade systems, as currently constituted, may reduce the growth of CO_2 emissions among participating member states by placing a cost on carbon emissions and making lower carbon alternative more financially attractive. While cap and trade systems incentivize lower carbon economic development, they do not incentivize the actual offsetting of carbon emissions.

6.4.1. The Polluter Pays Principle

In theory, the ultimate goal of cap and trade programs or carbon taxes should be to internalize the costs of carbon to its producers, or to apply the polluter pays principle to carbon dioxide. The polluter pays principle states that the firm or individual causing pollution should be financially responsible for the damage it causes. These costs could include the costs to remove the pollution from the environment and the costs of damages to the environment borne by other users. For example, a company that caused an oil spill could be financially responsible for both removing oil from the water and the damage to fisheries or tourism that resulted from the spill. Applied to CO_2 emissions, the polluter pays principle would require an emitter of one ton of CO_2 to pay for the costs of the removal of one ton of CO_2 from the atmosphere, as well as any damage it causes. If we assume that the marginal environmental impact of one ton of CO_2 is negligible, then the polluter pays principle would require emitters to pay for the removal of CO_2 from the atmosphere.

Cap and trade programs which make the carbon neutral production of societal needs an acceptable carbon credit do not achieve this goal. Instead, these carbon credits are based on the cost of not producing CO_2, rather than the cost of removing CO_2 from the atmosphere. By contrast, the cost of a carbon negative credit reflects the cost of physically removing one ton of CO_2 from the atmosphere.

6.4.2. Effects on CO_2 Concentrations

From the perspective of the atmospheric concentration of $CO_{2,}$ carbon neutral and carbon negative credits have different effects (Table 6.1). Assume a steel producer in the UK emits

1,000 tons of carbon dioxide and is required to buy carbon credits that help to finance a wind farm in China such that the production of electricity from the Chinese baseline electricity production system would otherwise emit 1,000 tons of CO_2. From the perspective of the atmosphere, 1,000 tons of CO_2 have been emitted; this is, of course, less than the 2,000 tons of CO_2 which might exist in the absence of the cap and trade program, but different from the zero tons of CO_2 which would exist if the cost of a carbon credit went to finance a carbon negative, rather than carbon neutral, project.

6.4.3. Long-term Abatement

In the short term, current cap and trade systems may achieve the goal of limiting carbon dioxide emissions; however, the longer-term goal of the international community should be to create a carbon-neutral economic system in which no net carbon is released to the atmosphere. Given the long half-life of CO_2 in the atmosphere, low but chronic annual CO_2 emissions could accumulate in the atmosphere, leading to significant climate change, even if annual emissions are significantly below current levels. Therefore, the only sustainable long-term strategy is to eliminate net carbon dioxide emissions to the atmosphere.

It may be difficult for carbon neutral cap and trade systems to create a global economy in which there are no net carbon dioxide emissions. Assume a global cap and trade system in which all emission sources are regulated and that over time, caps are lowered to zero so that any company that emits CO_2 must purchase offsetting credits. In a carbon neutral cap and trade system, these credits may come from carbon neutral activities, leading to significant annual CO_2 emissions; in a carbon negative cap and trade system, credits would come from the pyrolysis, biomass-CCS, reforestation, or other sequestration activity, and no net carbon would be emitted.

It is possible that carbon neutral cap and trade systems may encourage technological change such that over the long-term, current sources of CO_2 emissions are replaced (e.g. coal is replaced by wind power or gasoline cars are replaced by electric cars); in theory, this could lead to a carbon-neutral economy, without the need for carbon negative credits. However, under cap and trade systems, as emitters shift to cleaner technology, the number of carbon credits demanded declines, reducing prices and making emissions less costly. Simultaneously, as emitters shift away from fossil fuels, demand for these fuels will decline, and prices decrease. If carbon credits and fossil fuels are inexpensive, it is likely that some level of carbon emissions will occur, creating a need for carbon negative offsets.

In the near term, a carbon-negative only cap and trade system is unlikely for political, economic and technical reasons. However, a hybrid system that allowed for carbon negative and neutral credits may allow for an eventual transition to a carbon negative only system.

6.4.4. Rapid Reactions to Climate Change

Current policy approaches to climate change assume that the negative impacts of climate change will accrue slowly and in a generally linear fashion. However, positive feedbacks or tipping points may exist and could cause climate to change over a few years rather than a few decades. One of the most popularly discussed methods for addressing rapid climate change is spreading aerosols into atmosphere to reflect sunlight into space popularly called geoengineering (Goodell, 2010; Wigley, 2006; Aldy and Stavins, 2008). While of significant academic interest (reviewed in Rasch et al., 2008), geoengineering has significant ethical and technical problems (Robock 2009). Carbon negative technologies, particularly pyrolysis and biomass-based carbon capture and storage, provide a lower risk alternative for rapidly addressing climate change, should the need arise (Rhodes and Keith, 2005).

Thus, it would be prudent for society to develop the capacity for rapid large scale implementation of carbon negative technology. This will require financial incentives to private firms investing in commercializing carbon negative technology; existing carbon neutral cap and trade systems do not incentive carbon negative development and lack a mechanism for a response to abrupt changes in climate (Aldy and Stavins, 2008).

6.4.5. Natural Resource Scarcity

Proponents of existing cap and trade systems often implicitly assume that over time, the costs of coal, oil and natural gas will rise relative to the costs of alternative energies, such that at some point in the future, oil, gas and coal will no longer be widely utilized. In part, this assumption depends on natural resource scarcity increasing the future costs of hydrocarbons. For example, climate scientists have warned that the Keystone XL oil pipeline linking the Athabasca oil sands in Alberta, Canada to refineries on the U.S. Gulf Coast, represents a severe threat to the climate because it would increase global oil supplies, decreasing prices. Similar arguments have been made about shale gas in the U.S. (Howarth, 2011).

Ecologists have predicted natural resource scarcity for decades (Ehrlich, 1968), however, due to substitution and technological change, many of these predictions have failed to materialize (Fitzpatrick and Spohn, 2009). Technical progress in oil and gas exploration may lead to hydrocarbon abundance, rather than scarcity and an adequate climate policy should not rely on assumptions about future scarcity of hydrocarbons.

6.5. Effects on Prices

A system that requires the purchase of carbon negative credits may have positive or negative impacts on the price of carbon credits, depending on the cost of carbon negative credit production and the proportion of carbon negative credits required. In this analysis, we assume that carbon negative credits could be substituted for carbon neutral credits.

6.5.1. Effects on Supply

Carbon negative technologies, particularly pyrolysis and biomass-CCS have the potential to store large quantities of carbon (Lehmann, 2007; Rhodes and Keith, 2005). In an MAC curve framework, the acceptance of carbon negative credits would add a broad "block" of emission reduction credits (Figure 6.2) which would reduce the slope of the MAC curve adding low-cost supply and potentially reducing price volatility. However, the placement of this block along the MAC curve determines the impact on credit prices; if the costs of carbon negative credits are competitive with carbon neutral credits, then the addition of supply would shift costs down. Conversely, if the costs of carbon negative technologies were high, then carbon negative credits would not impact supply at most prices.

6.5.2. Effects on Demand

By requiring emitters to purchase a portion of credits as carbon negative credits, the demand for carbon neutral credits would decline. This could reduce overall compliance costs, even if carbon negative credits are more expensive than carbon neutral credits. For example, assume two scenarios: in Scenario A all credits are carbon neutral and cost \$10; in Scenario B, 5% of credits must be carbon negative. Assume an emitter must purchase 100 credits under both scenarios. In Scenario B, assume that the 5% reduction in demand for neutral credits reduces the neutral credit prices to \$7, and that carbon negative credits are \$50. Given these assumptions, the total compliance cost in the two scenario is shown in Table 6.2. In Scenario A, the compliance cost is \$1,000, while the compliance cost in Scenario B is \$915, despite the fact that carbon negative credits add cost.

The effects of a carbon negative policy on the total costs of compliance will depend on the price elasticity of demand. If the price of a carbon credit changes significantly with reductions in demand, then a small reduction in the demand of neutral credits will lead to a cost savings in neutral credits, which may be able to compensate for the added costs of negative credits. Conversely, if prices are insensitive to demand, then small changes in demand may not lead to large changes in the costs of neutral credits, and the overall compliance costs associated with a carbon negative system may increase.

6.6. Additionality, Permanence and Leakage in Carbon Negative Credits

The primary arguments against including carbon negative credits in climate mitigation schemes are related to additionality, permanence and leakage of stored carbon.

6.6.1. Additionality

The principle of additionality is used to determine the eligibility of a proposed CDM project to generate carbon credits. Additionality stipulates that in order for carbon credits to be produced, they must not have been produced under a business as usual scenario. For example, in order to receive carbon credits for the construction of a wind farm, a wind farm cannot be the business as usual scenario. There is debate over how to determine the business as usual scenario (Greiner and Michaelowa, 2003), but it is currently determined using either an investment analysis or a barriers to implementation analysis (Purohit, 2009). In general, activities that are financially viable on their own would not be eligible for carbon credits.

As currently implemented, additionality is a problem for both carbon neutral and carbon negative credits, and may create a market opportunity for carbon negative credits. If the costs of renewable energy technologies decline or the costs of conventional fuels increases, then new renewable energy projects may no longer be eligible to generate carbon credits (Zhang et al., 2005). These carbon credits are typically inexpensive, and their reduction will shift the supply curve to the left, increasing the costs of carbon mitigation. Similar arguments may apply to other project types, for example methane capture and use.

Under the CDM, projects are granted credits for either 10 years, or 7 years with options to renew the crediting period twice. The rate of removal of these low-cost credits from the market will depend on how aggressively the CDM conducts these reviews and assesses additionality. From the perspective of high-cost carbon credit producers, the removal of low cost credits from the market would make high-cost projects more viable, but increase compliance costs to society.

Applied to carbon negative technologies, additionality may be a particular problem for low-till agriculture, particularly agriculture for bioenergy applications as low till agriculture may reflect the business as usual scenario for energy crops. Additionality is less likely to be a major concern for pyrolysis or carbon capture and storage due to the higher costs of these technologies.

6.6.2. Permanence

One of the main concerns of carbon negative approaches to CO_2 management is the risk that the technology does not provide a permanent sink. For example, there is concern that reforested areas will be cut or burned or that char added to the soil or CO_2 sequestered underground will eventually find its way back into the atmosphere. In some cases these concerns are based on scientific ignorance while in others they are based on uncertainty around human action. That is, we do not know the rate at which CO_2 sequestered underground leaks into the atmosphere (scientific ignorance) and we cannot predict the whether a certain area will be clear cut (uncertainty around human action). Conversely, carbon credits associated with renewable energy generation are relatively simple; once a kilowatt-hour of electricity has been produced and consumed it is easy to account for the carbon not emitted via this process.

One solution to this problem is the method already used by the CDM in which LCERs and tCERs are issued. However, these credits expire at a set date, even if the carbon storage still exists. For example, imagine an investor pays to reforest an area and receives LCERs in compensation, set to expire in 30 years. Before the expiry date the LCER must be replaced with another credit type, even if the sink still exists. If the forest is destroyed before the expiry of the LCER, the investor must also buy a new credit (CDM Rulebook, 2012).

This is a conservative method for ensuring permanence, however, it is likely not applicable to pyrolysis or geologic storage as these are stored on a much larger timescale then 20 to 30 years. An alternate solution to the problem of leakage is to create some sort of carbon credit insurance in which the value of carbon credits is discounted by the probability of default (de Figueiredo, 2007). For example, a purchaser of a carbon negative credit could be required to simultaneously purchase an environmental compliance bond, payable to the requisite government or inter-governmental organization. If the stored carbon is released to the atmosphere over a predetermined period, the bond would be paid to the government and the money used for climate mitigation.

6.6.3. Leakage

In the context of cap and trade systems, leakage refers to indirect emissions of carbon dioxide caused by, but physically separated from the emission reduction system. For example, a farm may be converted from conventional to low-till agriculture in order to store carbon in the soil. However, if the crop yield on the farm declines, food prices may increase which could cause the landowners to convert additional land to agriculture, potentially increasing total carbon dioxide emissions.

Leakage is a concern for all carbon reduction systems, but is of special concern for some carbon-negative systems. Leakage associated with reforestation has been relatively well studied with leakage rates estimated to be between 10 and 90% (Murray et al., 2004; Sathaye and Andrasko, 2007; Ewers and Rodrigues, 2008). Leakage from shifting from conventional to conservation tillage has also been studied, but the effects are more modest (5-10%; Murray et al., 2004; Choi, 2004).

Leakage impacts of biochar application or biomass-CCS are less well studied, but leakage could occur. If biomass grown for bioenergy displaces crop production, food prices may increase, leading to the conversion of additional land for agriculture and leakage. However, biomass-based carbon negative projects have the potential to remove large amounts of carbon per hectare of biomass. For example, assume a biomass-CCS program converts 1000 hectares of food cropland to bio-energy crops, and in response, 1000 hectares of non-agricultural forest is converted to cropland, with consequent carbon dioxide emissions. The bioenergy project could produce clean energy and sequester carbon indefinitely, significantly offsetting the original leakage. Furthermore, biomass-based carbon negative projects can use waste biomass rather than bioenergy crops.

6.7. Conclusions

This chapter has advocated for the creation of at least two types of carbon credits, those that produce renewable energy without emitting CO_2 and those that create a sink of carbon. At its most basic level, these two types of carbon credits are differentiated by their ecological impact and their theoretical economics. In the case of the creation of the carbon sink, the carbon credit seeks to correct a market failure in which one actor (a company or nation, a “polluter”) has not internalized the social costs of actions by forcing the polluter to pay for someone else to remove their pollution from the atmosphere. In the case of carbon neutral electrical generation, the polluter is again forced to pay due to their failure to internalize the costs of pollution, but they are not paying an actor to remove their emissions from the atmosphere, instead they are paying another actor to create a product in which the costs of pollution are internalized. Either method can lead to a cost for CO_2 emission and can thereby reduce CO_2 use, but there is a difference in the methods used to achieve this reduction.

However, carbon markets as currently designed are a good stimulus for the transition to a less carbon intensive energy production system. While there is disagreement on the total emission reduction achieved through the Kyoto protocol, alternative energy use has grown dramatically in Europe over the past several years in part due to Kyoto. Thus, it may be reasonable to have two carbon management systems one focused on the transition to a carbon neutral system of energy production and another dedicated to offsetting the carbon currently emitted.

Carbon neutral credits are an artificial social construct; by contrast, carbon negative credits are associated with a physical and observable carbon sink. As a result of the physical nature of carbon negative credits, they have been criticized for a presumed lack of permanence. However, these criticisms fail to recognize that carbon neutral credits are not susceptible to issues of permanence precisely because they are artificial constructs, the validity of which depends entirely on the regulations under which they are granted.

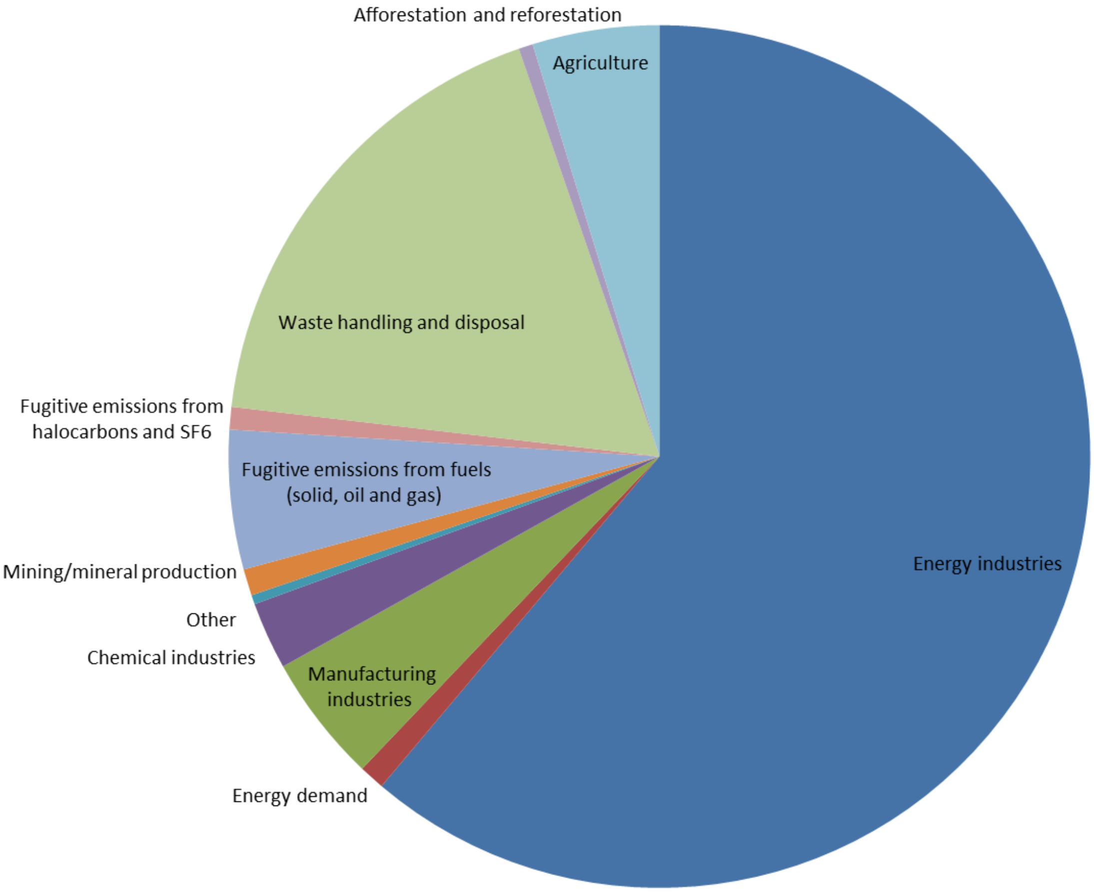

Figure 6.1 Distribution of CDM credits by project type

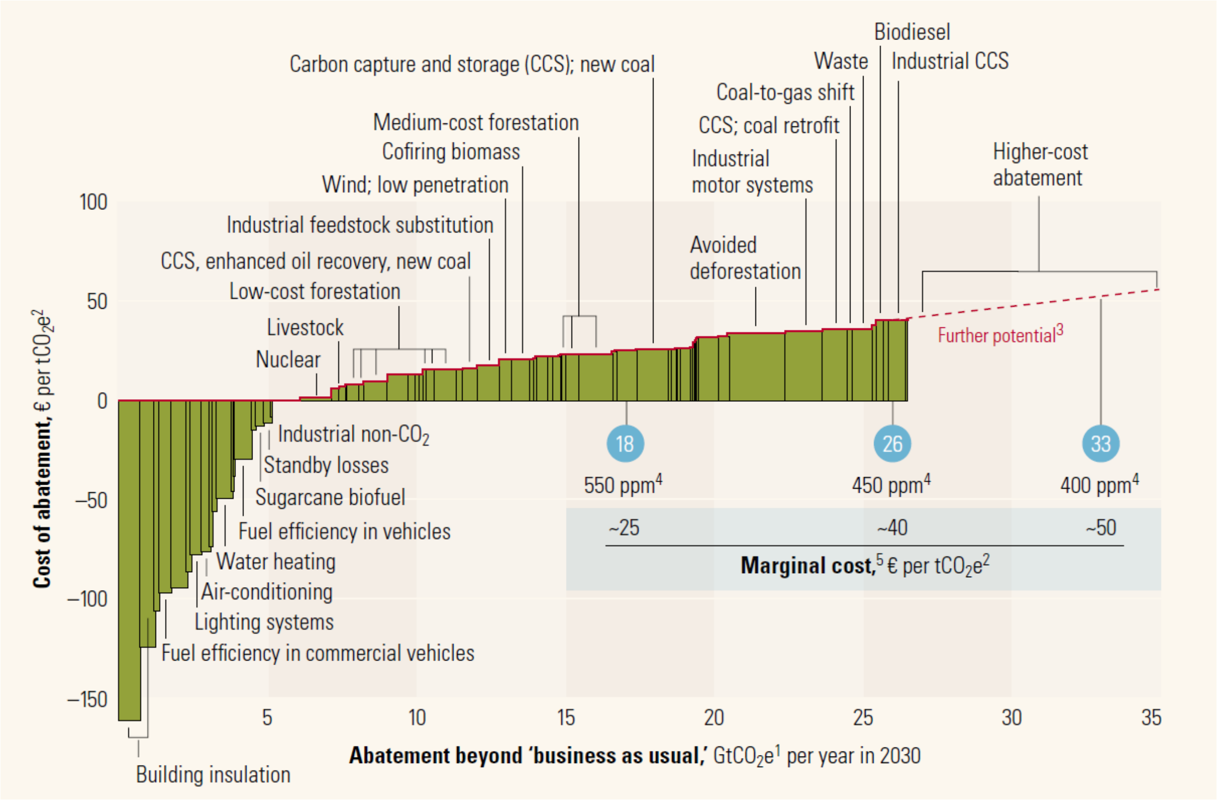

Figure 6.2 Example marginal abatement cost curve (Source: Enkvist et al., 2007)

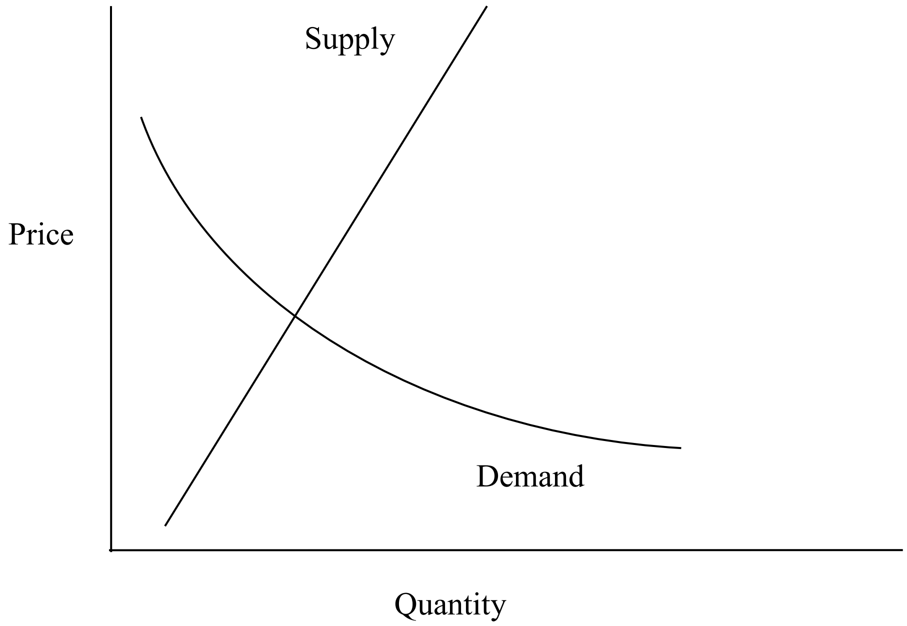

Figure 6.3 Hypothetical supply and demand curves for CERs

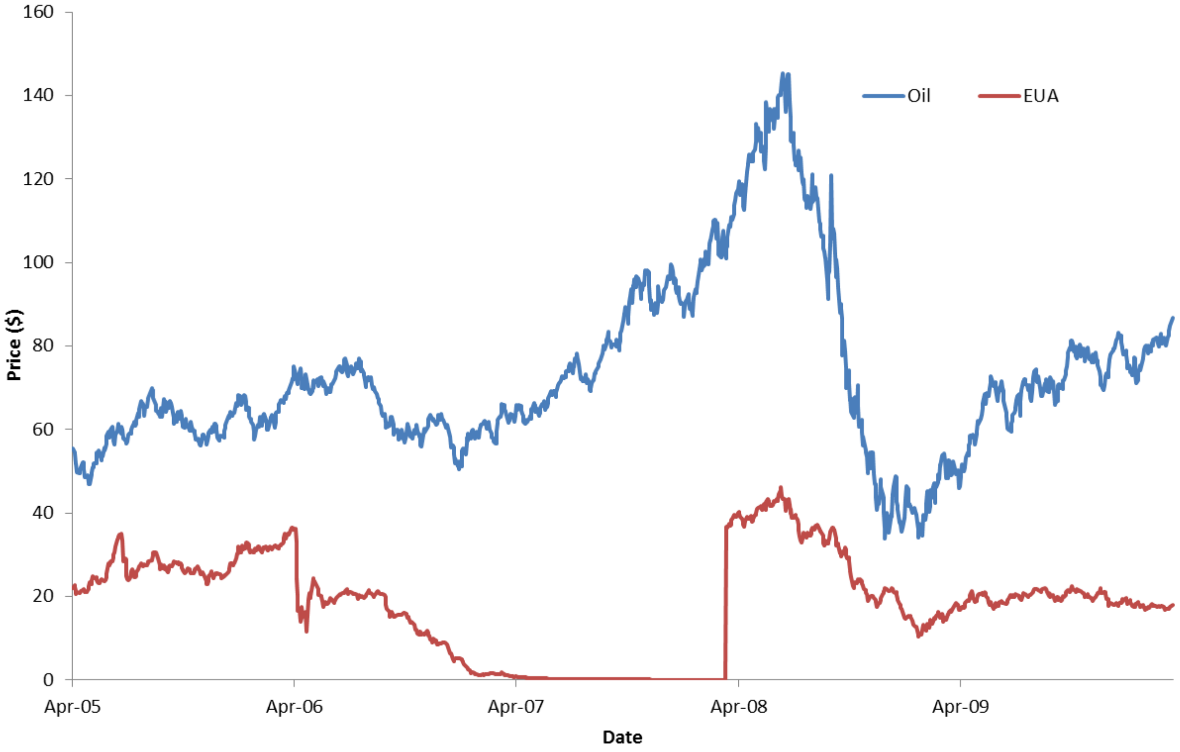

Figure 6.4 Price comparison of oil and EUA

Table 6.1 The difference between carbon negative and carbon neutral credits

Method	Party One’s action	Party two’s action	Net Result
Negative	Emits 1 ton CO_2	Remove 1 ton CO_2	Zero tons emitted to the atmosphere
Neutral	Emits 1 ton CO_2	Doesn’t emit 1 ton CO_2	One ton CO2 emitted to the atmosphere;
No policy	Emits 1 ton CO2	Emits 1 ton CO2	Two tons CO2 emitted to atmosphere

Table 6.2 Effect of carbon negative credits on total compliance costs

	Credits required	Total offsets	Price per offset	Cost	Total cost
Scenario A	100% carbon neutral	100	10	1000	1000
Scenario B	95% carbon neutral	95	7	665	915
	5% carbon negative	5	50	250	

Chapter 7. Conclusions

7.1. Summary of Results

The economic costs of small-scale pyrolysis in the neotropical developing world are relatively modest. Given specified assumptions about capital, biomass and labor costs, slow and fast pyrolysis are moderately profitable under realistic assumptions of future bio-oil, char and carbon prices. Gasification systems were not profitable under most model parameterizations.

Biomass feedstocks represent a major cost facing bioenergy producers, but the models developed indicate the biomass costs in the neotropical developing world may be far lower than those experienced in the developed world. If ecosystem services are appropriately valued, biomass costs in the developing world may be zero or negative.

The small scale of the pyrolysis systems modeled is amenable to application in the developing world and may lower the economic and emission costs of biomass transport. However, small scale projects may experience higher normalized capital expenditures due to an inability to take advantage of economies of scale. However, economies of scale in the capital costs of pyrolysis equipment may exist if demand is sufficient to allow equipment manufacturers to produce systems in an assembly-line manner. That is, while economies of scale may not exist in the size of individual systems, economies may exist if the number of systems ordered each year is sufficiently large. Currently, only a handful of pyrolysis systems are manufactured each year and the costs of a mass produced system are unknown.

The emergetic costs of pyrolysis indicate the costs in an ecocentric framework and illustrate the advantage of using a waste agricultural residue as compared to crops grown for bioenergy use. Unlike ethanol or bio-diesel production, pyrolysis does not require a sugar or lipid-rich feedstock and a variety of cellulose-rich materials may be used. As a result, the emergy costs of pyrolysis systems are much lower than those of bioethanol or bio-diesel.

Current approaches to regulating carbon dioxide emissions using carbon neutral credits may be sufficient in the short term, but are inadequate over the long term. Given the risk of abrupt changes in climate, the development of carbon negative technologies should be a priority for policy makers. One way to stimulate the development of carbon negative technologies would be through the development of a separate carbon negative cap and trade system.

7.2. Technological Optimism and Technological Pessimism

In the inaugural issue of *Ecological Economics*, Costanza (1989) described the debate between technological optimists and technological pessimists. According to Costanza, technological optimists believe that continuous and unlimited economic growth is possible due to the development of new technology. By contrast, pessimists argue that technological development will not be able to circumvent resource and environmental constraints and that economic growth will eventually stop. Pessimists argue that we should undertake policies to reduce resource use to delay the time until Malthusian limits on growth are reached and diminish the negative impacts of those limits on society; optimists argue that Malthusian limits on growth will not apply to human societies, and no such policies are necessary.

Pyrolysis is a technological approach to addressing climate change and carbon dioxide emissions, and is consistent with the optimists' view that new technologies will be developed that will allow resource use and economic growth to overcome environmental constraints. Pyrolysis represents a real carbon offset and if used at an appropriate scale, could allow for the continued consumption of fossil fuels without increasing carbon dioxide concentrations in the atmosphere. However, while the costs of pyrolysis are relatively competitive, pyrolysis does require a subsidy on the price of carbon to be profitable and is thus unlikely to be economically feasible without the policies advocated by technological pessimists, at least under current market conditions.

In the early to mid-nineteenth century, whale oil was widely used for illumination in Europe and North America. At its peak in the 1840's and 1850's, approximately 700 ships killed on the order of 8,000 whales annually. As whale populations declined, whalers had to travel farther to locate whale populations and whale oil prices rose to up to \$2.50 per gallon (on the order of \$50 per gallon in 2010). As a result, interest developed in alternative sources of illumination. In the 1840's Abraham Gesner developed a process for the production of a new fuel, kerosene, by the pyrolysis of coal; in the 1850's, Benjamin Silliman used a distillation process to extract kerosene from crude oil. The development of kerosene provided a high quality substitute for whale oil and reduced the demand for whales, potentially saving some species from extinction (Yergin, 1991). The switch from whale oil to kerosene for illumination can be viewed as a historical example of technological optimism proved correct.

Notably, the switch from whale oil to kerosene occurred in the context of government intervention. Another alternative to whale oil, camphene, had also been developed. Camphene was a combination of turpentine, alcohol, and camphor oil. In 1862, to pay for the U.S. Civil War, the federal government instituted a tax on alcohol, which raised the price of camphene, making kerosene far more attractive and helping to stimulate the growth of the oil industry. Thus, while the development of kerosene provided a high-quality, low-cost substitute for whale oil, its development was stimulated by a favorable government tax policy. By analogy, the pyrolysis of biomass to form char, bio-oil and syngas provides a partial solution to climate change, but the development of the industry will depend on government policy.

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