ESTIMATING A NET ENERGY VALUE FOR BIOFUEL FROM AGRICULTURAL BIOMASS PRODUCED IN HAWAIʻI

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Abstract

Hawai‘i is nearly 92% dependent on fossil fuels for energy. In order to alter this situation, there are a variety of renewable energy options available, one such option is biomass production for conversion to biofuels within the State. This research uses a format of energy analysis used for corn production on the US mainland. A Net Energy Value (NEV) calculation is derived for local biomass production and conversion of banagrass (*Pennisetum purpureum* Schumach). After assessing all energy associated with agricultural production of banagrass, including land preparation, labor, embodied energy of machinery and chemicals, transport of inputs and transport of biomass, various conversion efficiencies are also analyzed. For a 500-acre farm, using non-irrigated, non-prime agricultural land, the energy used for production is about 18,300,000 Btu/acre/year. The banagrass yield produces ethanol with a total energy of about 109,000,000 Btu/acre/year. The energy input of the conversion processes range from 30,000,000 Btu/acre/year to 137,000,000 Btu/acre/year, depending on the efficiency of the conversion assessment, the utilization of co-products for energy production, and accounting for embodied energy of the materials used in the plant itself. Total Net Energy Value ranges from -46,000,000 to 60,000,000 Btu/acre/year.

Keywords: Banagrass, Net Energy Value, Biofuel, Biomass Production, Hawai‘i

Acronyms

DBEDT	Department of Business, Economic Development and Tourism
EPA	Environmental Protection Agency (United States)
GIS	Geographic Information System
HECO	Hawaiian Electric Company
HRS	Hawaii Revised Statutes
IAL	Important Agricultural Lands
IO	Input-Output
LCA	Lifecycle Analysis
LPG	Liquefied Petroleum Gas
MEFA	Material and Energy Flows Analysis
MFA	Material Flows Analysis
NAICS	North American Industry Classification System
NASS	National Agricultural Statistics Service
NEV	Net Energy Value
RMI	Rocky Mountain Institute
USDA	United States Department of Agriculture
WRA	Weed Risk Assessment

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Chapter One – Introduction

Currently, the State of Hawai‘i is nearly 92 percent dependent upon fossil fuels for energy (DBEDT 2009a). Unlike other states, petroleum is the predominant fossil fuel used for energy in Hawai‘i, making up 89% of the total energy consumed in the State. Petroleum has to be imported, largely from sources in the Middle East and Asia (DBEDT 2009b), for electricity generation and fuel production. Recent increases in the cost of petroleum have caused instability in the local economy, fueling the need for alternative energy sources. Though other fossil fuel sources could substitute for petroleum, they face the same problems as petroleum usage, including finite supply, greenhouse gas emissions, and lack of local sources, thus alternative, renewable energy sources are being looked upon as to help solve the State's energy dependency issue.

Because Hawai‘i is amenable to alternative energy production due to its ample solar, wind, wave, and geothermal energy sources, the State has an opportunity to switch to more secure, renewable energy resources. These resources can provide reliable energy solutions, job opportunities, and secure Hawai‘i's energy future. The future energy portfolio should be stable, flexible, and should include a variety of energy sources for both transportation and electricity production. Most renewable sources harness solar energy in some form (biomass, sunlight, wind, wave—the latter two caused by differences in solar radiation), converting it into useful energy carriers (ethanol, biodiesel, electricity, hydrogen) that can be converted into the end-use forms necessary for society (transportation, food preparation and storage, heating, cooling, etc).

Generally, fuel sources provide energy in two main areas: transportation fuel and electricity. Heat is also an area that requires fuel; however, the use of fuel for heating is more prevalent in industrial processes and in colder climates, and will not be examined for this research. Transportation fuels are typically storable liquid fuels—diesel, gasoline, jet fuel, etc. Electricity can be generated from many sources; when generated from a fuel source, electricity generation involves combustion of the fuel to release the energy to create electricity. It can also be generated through the conversion of heat, wind, solar or wave energy. However, many renewable sources of energy cannot provide firm electrical power—consistently available power able to meet changes in electricity demand. There are also technical issues with adding alternative power to standard grid systems (as opposed to smart grids), as this power is not dispatchable, meaning it cannot generate power to meet fluctuations in society's demands. For example, the peak electricity usage in Hawai'i occurs between 5 to 9 pm, which is not during peak sunlight hours (HECO 2010a), reducing the effectiveness of photovoltaic conversion without storage. Thus, Hawai'i's energy portfolio should include storable forms of alternative energy that can efficiently accommodate fluctuations in demand. Biofuels are one type of storable liquid fuel that can satisfy many of Hawai'i's energy needs. They can be used to run electrical generators on and off a grid system and are a transportation fuel.

Biofuel Overview

Biofuels are renewable fuels that have the flexibility of meeting the demands of modern society. Biofuels are solid, liquid, or gas fuels derived from biomass—plant, algae, or animal matter. This research focuses on plant matter used for biofuel production, and will therefore not include biofuels made from used cooking oil or animal products. In the case of plants and algae, biofuels directly convert solar energy into usable energy currencies by creating biomass. This biomass can then either be burned as a fuel for electricity production, or be processed into other fuels like ethanol and biodiesel, which could be used for transportation and electricity generation.

The production of biofuels can be divided into two major areas: feedstock and conversion. Feedstock production involves the agricultural, anthropogenic, or ecological production of the organic material used to create the fuel. The organic material must then undergo conversion to create the fuel. Biofuel feedstocks are often described as either first, second or third generation technology. First generation biofuel feedstocks are crops that are currently being produced and manufactured into biofuels. These feedstocks tend to be food sources, because the commercial production of biofuels from them is a relatively new development. These crops have known yields and existing commercial conversion technologies. Second generation biofuels are those that are made from feedstocks that are residual materials left after production of a main product. These fuels often require cellulosic conversion, to create fuels like ethanol. The yield information for these crops are often known, as the main product produced from the crop is not the biofuel itself; however, conversion information is often less reliable, as these conversion technologies are in the developmental stages. Third generation biofuels are those that are presently in the research and development stage. These feedstocks are grown exclusively for energy purposes and require advancements in technology or crop research before reaching the commercial markets. The yields of these crops for biofuels are often experimental yields, thus they are largely unknown for industrial production (Biomass Research and Development Board 2008).

Typically, agricultural production processes start with land preparation, seed stock production, planting, crop maintenance, harvesting and transport. All aspects of agricultural production are unique to the crop selected. Large amounts of land preparation may not always be necessary depending on the prior use of the land and the methods and machinery that will be employed. Seed stock production can take various amounts of investment in research or special equipment or nutrient needs. In the case of corn, seed is grown at a less efficient rate than the industrial crop and requires different processing, thus often requiring 4.7 times more energy than the crop itself (Shapouri et al.2002). Grass crops can typically use stem cuttings from existing crops to propagate, thus seeding consists of using a specialized piece of machinery to create the cuttings. Crop maintenance depends on the soil type, environmental factors like rainfall and temperature, and nutrient requirements of the selected crop. Irrigation can be a large part of crop maintenance depending on the crop and the desired yield. In the case of sugarcane plantations in Hawaiʻi, irrigation played a key role in production; however, eucalyptus plantations grown on the same land use no irrigation (Coffman 2009). The machinery used throughout the process of feedstock production is varied and tailored to the crop.

Biofuel Conversion

Conversion technologies exemplify a myriad of processes based on the type of biomass stock and the type of fuel being processed. They are a mix of established technologies and new scientific techniques. Adapted coal gasification processes can be used to create bio-gas from biomass, while fermentation, which has been utilized for centuries, can be used to create ethanol from plant sugars and starches. The conversion techniques used to convert plant matter into usable energy (in the form of methane, methanol, hydrogen, ethanol, and biodiesel) include extraction (and esterification), biochemical conversion techniques (digestion, fermentation), and thermochemical conversion (combustion, gasification, pyrolysis). Extraction and transesterification of oils creates biodiesel. Fischer Tropsch conversion can also be used to make a syndiesel fuel. Also, currently being developed are methods involving conversion of cellulosic materials to ethanol, and pyrolysis of biomass to create bio-gas, and other forms of biofuel (methane, methanol, hydrogen, etc).

Extraction

Bio-oil extraction from plant seeds and fruits is traditionally a physical process that removes the plant oil from the seeds using pressure or from fruits through boiling the fruit. Oil seed production is the more accepted method of bio-oil production, and has therefore been studied in greater detail. There are over 350 oil-bearing seed crops identified, though only a few are currently considered for energy conversion. Industrial plant-oil harvesting can be done using physical and chemical processes. Solvent extraction methods utilizing hexane, petroleum ether, chloroform, and methanol are all used commercially, though new methods using CO_2 as a supercritical fluid extraction[1] are currently being studied (Barthet et al. 2002).

The first step for industrial oil harvesting involves removing extraneous materials from the seeds or fruit. For seed oil, the seeds are cracked, dried, rolled into flakes, then pressed or exposed to solvents. If exposed to solvents, the remaining seed materials, called cake or spent flake, and oil after extraction are then separated from the solvent and the solvent is collected for reuse. The spent flake can also be used as fuel (Hyphoma Group 2008). The oil then needs to be refined to remove unwanted materials that could make combustion or further use difficult. This also can be done chemically or physically.

[1] Supercritical fluid extraction uses a liquid that is above its thermodynamic critical point (it is at high pressure and temperature) allowing it to diffuse through solids and dissolve materials like a solvent. Supercritical fluid methods can be found under all three conversion mechanisms, and will be discussed further in subsequent sections.

Bio-oil can also be produced using pyrolysis, which is not currently economically viable, and is therefore only in experimental phase. Pyrolysis involves rapid heating of the plant material in the absence of oxygen, which produces liquid oil and char. The resulting bio-oil must also be further refined before use (Faaij 2006). Pyrolysis will be discussed further in the thermochemical conversion section, as it is a thermochemical biofuel production method, and a part of the gasification method. After extraction, the bio-oil can undergo a variety of chemical reactions to form various types of biofuel. There are many factors contributing to the usability of the produced biofuels and the further refining of which is dependent upon the ultimate use of the product.

Biochemical Conversion

The biochemical conversion of plant biomass into other usable fuels is readily found in nature and, like oil extraction, has been modified for industrial purposes. The natural processes need to be sped up to be economically viable, but the output potentially produces less waste than other forms of conversion. The conversion mechanisms found under biochemical conversion include digestion and fermentation. Like oil extraction, these processes are currently employed by the food and beverage production industry, and in some countries, are used to produce biofuels for large-scale operations.

Digestion processes utilize anaerobic bacteria's natural functions to produce biofuel (usually methane). It is most suited for wet biomass, as these are the conditions that the bacteria function well under. The obvious use for digestion is in organic wastes, thus refuse and animal waste are excellent feedstock materials for this form of biofuel production. This form of biofuel production is usually found as a secondary product from already occurring phenomenon, like landfill gas production.

Plant matter is suited for fermentation as the sugars and starches in the biomass can be used as biofuel production feedstock to create ethanol. Ethanol can also be produced from cellulosic and ligno-cellulosic materials of plants, which are more abundant, lower in value, and less limited by other uses than the crop biomass aforementioned (sugar and starch). Ethanol production from such materials involves more processing of the biomass, as the chemical bonds in the cellulose must first be broken via hydrolysis to produce sugars, which can then undergo fermentation to produce ethanol. The sugars produced by hydrolysis (mostly xylose) are also more difficult to ferment than the glucose typically used by the food industry, and thus the enzymes and bacteria used in the process need to also be further developed to increase efficiency. The extracted lignin can be combusted for power production.

Methodologies to convert cellulose directly to sugar using microorganisms are also available, though such techniques are not yet used for commercial production. Other microorganisms can also be employed in the delignification process, reducing the amount of energy required (Lee 1997). Fungi (including yeast), and bacteria are known to have enzymes capable of breaking down cellulose (cellulases), and certain fungi are also able to break down lignin. The enzymes employed in the production of these biofuels can also be used to derive the fuels without the bacteria; however, the cost of the purified enzymes makes these operations unable to compete with other energy sources.

Thermochemical Conversion

The processes included in thermochemical conversion are combustion, gasification, and pyrolysis. Though they are separate processes, gasification and pyrolysis are often found together to produce fuel gas. Combustion, the most pastoral of the processes, is used in various scales of production all over the world. Combustion of biomass as a fuel for cooking and heating is the original use of biomass for energy. Large-scale combustion can be used for heat generation or steam generation to generate electricity and power.

Gasification of biomass can occur in two ways: direct and indirect gasification. Direct gasification is the conversion to combustible gas of the solid or liquid feedstock using an oxidant gasification agent (another gas). The process requires high temperatures, provided by the oxidation processes. Gasification is a multistep process that involves drying of the biomass, conversion to tar or char (pyrolysis), then reaction with the gasification agent to produce gases. The combustible-gas product, bio-gas, contains carbon dioxide, carbon monoxide, methane, hydrogen, and water. Other products include the remaining tar or char, and trace amounts of other hydrocarbons.

Indirect gasification uses a non-oxidizing gaseous agent (typically steam) in an oxygen free atmosphere and therefore requires an external energy source. It can be favored over direct gasification because the product contains less oxygen and more hydrogen. Other products also include tar and char and trace amounts of other hydrocarbons. The tar and char products can be burned for heat generation, which can fuel the gasification process (Belgiorno et al. 2003, Bridgwater 2006).

Pyrolysis can be used to transform any type of biomass into a biofuel product. This functional diversity makes it useful in the biofuel production process. The temperature and vapor residence times of pyrolysis control the speed and output of the reactions. Low temperature pyrolysis (about 400º C) with long vapor residence times occurs slowly and favors the creation of charcoal. Higher temperatures (about 500º C) with short vapor residence times favor liquid creation (bio-oil). Liquid creation is favored because of the storability and the ease of transport of the product. Longer vapor residence times at this temperature give way to gas production (Bridgwater 2006). Like in gasification, the char or tar produced can be burned to provide heat required for the pyrolysis process minimizing the amount of waste produced. Because fast pyrolysis produces a storable fuel that is more easily transported than the biomass itself, it is currently the most useful of the independent pyrolysis conversion technologies. For fast pyrolysis, the biomass feedstock must first be dried and ground to provide sufficient surface area for quick heating and reaction (Faaij 2006).

Super critical fluid usage, like pyrolysis permeates many aspects of biofuel production. As mentioned earlier, supercritical fluids can be used to extract oils from biomass. Because super critical fluids have high density, high diffusivity, low viscosity, and high compressibility, they dissolve things readily (organics, minerals, biological molecules) and they allow fast chemical reactions. They can completely dissolve biomass and produce bio-gas or bio-oil. Large-scale commercial usage of supercritical fluids currently is employed to decaffeinate coffee. Because supercritical fluids used are typically water and carbon dioxide, they leave no residual solvent that needs to be cleaned from products.

After biomass is converted to biofuel, there are some end-use modifications that are necessary in order to transition away from a petroleum-fuelled economy. The end-use modifications depend on the type of biofuel created, but include modifications to distribution infrastructure, engines and generators, and transportation needs. Though low concentration blends of biofuels have been integrated into the transportation system without many changes to engines and infrastructure, to fully utilize high-concentration blends of biofuel blends efficiently, combustion processes and machinery must be optimized for their use.

Policy Overview

Though biofuels are a feasible solution to Hawai‘i's energy needs in a more secure manner than petroleum, they need to be coupled with appropriate policies to foster their production and use. Recognizing the need to reduce our dependence on foreign oil, the state government has set various policies promoting alternative energy research and use. Because Hawai‘i's electricity and transportation fuels are highly petroleum dependent (DBEDT 2009b), Governor Linda Lingle and the state legislators embarked on an ambitious plan in 2006, the Energy for Tomorrow initiative. This initiative resulted in the ratification of four energy-related bills that year, including the 20 percent by 2020 mandate. This mandate, previously established in 2004 in the Hawaii Renewable Portfolio Standards, adapts the 20 percent of electricity generation from alternative fuels, to be 20 percent of all energy consumption (Rocky Mountain Institute 2006).

In 2008, the Governor then entered in a Memorandum of Understanding with the US Department of Energy to start the even more ambitious Hawai‘i Clean Energy Initiative (HCEI). In addition to other outcomes, the initiative resulted in an energy agreement signed by the State of Hawai‘i, the Division of Consumer Advocacy, and the Hawaiian Electric Industries that established a standard of 70 percent of Hawai‘i's electricity and transportation energy obtained from renewable resources by 2030. To meet these goals, a reduction in energy consumption through energy efficient measures is also expected (HECO 2010b). HCEI set the most ambitious energy goals of any state in the nation.

Because of the push for energy efficiency and renewable energy in policy, adequate tools are necessary for the analysis of various aspects and benefits of such changes. Economic models, baseline information, indicators, analyses, and infrastructure demands and compatibility assessments are all among the necessary tools that must be developed for policy assessment. Alternative energy can be assessed in various ways:

- o Economic or monetary analyses, involving market development, import analyses, pricing mechanisms, and substitution effects, etc;

- o Social analyses, examining social implications of employment creation, potential large-scale agriculture industries, potential change or variations in land-use patterns;

- o Environmental analyses, looking at pollution abatement, ramifications of land-use change, greenhouse gas emissions, etc; and

- o Technological analyses, involving production, conversion, and energy efficiency analyses, which look at the effectiveness of biofuel production and use from various perspectives.

As mentioned previously, the State is promoting the use of alternative fuels in part through the work of the Hawai‘i Clean Energy Initiative (HCEI). Specifically, HCEI promotes research in the compatibility, storage, and efficiency of biofuels in Hawai‘i Energy Company generators. HCEI also promotes the purchasing of locally produced energy (HECO 2010b).

In 1994, the State instituted a mandate of 10 percent ethanol blend in 85 percent of motor vehicle fuel, which went into effect in 2006. The mandate successfully encouraged companies to explore local ethanol production; however, though ethanol could be locally produced, local production facilities have yet to complete the permitting process. Thus, the ethanol required for use is imported from El Salvador (Ethanol Producer Magazine 2008). The difficulty of permitting and siting for conversion operations is currently being addressed by other biofuel policies.

HCEI’s energy agreement promotes biofuel use in the state, stating that “the demand created by the use of biofuels in Hawaiian Electric’s units will provide a strong basis for investment in the local biofuel industry, which, in turn, will bolster Hawai‘i’s agriculture sector and increase our energy independence and security, and retain dollars in the State" (HECO, 2008, p. 14).

Hawai'i Biofuels Summit in 2006 brought together stakeholders to discuss the growth of the biofuel industry in Hawai'i, and lead to the development of the Hawai'i Bioenergy Masterplan, as required by Act 253 of the Session Laws of Hawai'i 2007. The program was underway in 2008 to "set the course for the coordination and implementation of policies and procedures to develop a bioenergy industry in Hawai'i" (Hawaii State Legislature 2007).

Other policies affecting biofuel production, including those relevant to agricultural land, agricultural policy, water use and policy, economic incentives, and permitting are also relevant to biofuel production in Hawai'i. If the State wants to encourage the investment necessary to support the biofuel industry, policies should be aligned with endorsing the biofuel industry. Through the support of this industry, the State could be providing other benefits to the local community and economy. Local biofuel production will keep more of Hawai'i's money in the local economy, provide jobs, and could help stabilize energy costs. In addition to potential benefits of biofuel in improving energy security, the people of Hawai'i can also benefit through the preservation of agricultural land and an agricultural heritage.

Until relatively recently, Hawai'i's agricultural history has largely influenced the government and the daily life of many of its people. Hawai'i's agricultural history began long before western contact, when the principal Hawaiian crops were taro, sweet potato, breadfruit, yams, sugarcane, bananas and coconuts (Clark 1986). Agriculture in Hawai'i then shifted towards large, plantation-style operations after the introduction of western ideas of land ownership and western economics. Eventually, as the cost of land and water increased in Hawai'i, and agricultural products from other countries began to out-compete Hawai'i's agricultural products, the profitability of plantation-style agricultural production declined. Thus the decline in pineapple and sugar has enabled agricultural landowners to petition for other uses of their land. Since 1978 (the start of this statistic), the total acreage of land in agriculture has been decreasing (Hawaii Agricultural Statistics Service, 2007) through petitions to the state land use commission for changes in land zonation.

To resist this loss of prime agricultural land, recent legislation in 2005 created the "Important Agricultural Lands" (IAL) designation because "viable agricultural operations are the key to preserving agricultural lands in Hawaii" (Department of Agriculture 2010). The identification process in HRS §205-44 includes a list of standards that can be used to designate IAL, including land types associated with traditional native Hawaiian agricultural uses, land with sufficient water, and land near appropriate infrastructure. This land designation system is meant to keep agricultural lands active, contiguous and functional. Previous land designation systems in Hawai'i include Land Capability Classification, the Land Study Bureau Overall Productivity Rating, Agricultural Lands of Importance to the State of Hawaii (ALISH) and the Land Evaluation and Site Assessment (LESA), which were meant to identify lands for their productivity, but were not necessarily focused on keeping them zoned for agriculture.

In general, land designation systems identify lands that are important for standard forms of agricultural food production, and allow for a maximization of yield, they do not account for lands that could be important for rain-fed agricultural crops. Nor do they particularly emphasize contiguous agricultural land on a large enough scale that would be beneficial to large-scale crop production (though specifications are made over agricultural land boundaries and emphasis of coordinating zonation with state and county plans), despite promoting such, because the scale of contiguousness varies depending on the scale of the agriculture being promoted.

In order to persuade large landowners to classify their agriculture land under the IAL system, the law allows a reclassification allocation of 15 percent of IAL to other districts (conservation, rural, and urban). Therefore, landowners can choose 15 percent of their total IAL acreage in each county and petition for it to be changed to a different district. For reclassification to urban districts, the proposed urban-zoned land must be consistent with development plans for the area. Instead of changing IAL zoning, petitioners for changes in zoning can also earn credits from IAL designation in the amount of 15 percent of the total IAL acreage to reclassify land in that same county currently zoned as agriculture (but not IAL) to a different use (HRS §205-45).

Ideally, the use of the non-prime agricultural land would be dedicated to the production of locally-used products, through lower-value crops. Because the prime agricultural land is best suited for food production, non-prime land could effectively be used as cropland for energy crops. Because of the rising costs of energy in Hawaiʻi, and the growing public concern over greenhouse gas emission, the use of the agricultural lands for biofuel production is currently a potential option with benefits to society because residents prefer open-space land uses to development (Cox and Vieth 1997).

Thesis Overview

For Hawaiʻi, biofuels can be chosen to convert solar energy to usable energy given the soil type and rainfall and other agricultural production conditions. In feedstock production, agricultural yields and required inputs vary according to the crop and agricultural land used. Differences in genotype based on environmental factors (like slope, soil type, irrigation requirements, precipitation, and solar radiation) contribute to the performance of a crop. Additionally, when producing agricultural crops for biofuels, the crop can be produced for maximum biofuel yield, which may vary from the maximum biomass yield, requiring different conditions for growth, as biofuels are made from the conversion of specific parts of a plant (like starch or oil).

To determine the validity of this option among other renewables, the energy efficiencies of renewable energy sources like biofuels have to be examined to determine their cost-effectiveness and appropriateness for the state. This research will focus on energy efficiency analyses and determining the net energy value of biofuel production in Hawaiʻi, concentrating mainly on biofuel feedstock production, though conversion will be addressed.

The next two chapters contain an overview of energy analysis from the literature, Chapter 2 includes an example energy analysis using corn production and conversion to ethanol in the US, and chapter three discusses the relevant biofuel research and analyses that has already been done in Hawaiʻi. The fourth chapter will detail a methodology used to evaluate energy used in biofuel production in Hawaiʻi, specifically, using banagrass to create ethanol. Results and discussion will follow, followed by conclusions and further research suggestions.

Chapter Two – Literature Review: Energy Accounting

As energy costs increase, the importance of energy analysis is now part of the policy debate. Developments in the interdisciplinary fields of industrial ecology, material flows analysis, emergy analysis, and life-cycle assessment have attempted to quantify the energy in materials and streamline the efficiency of industrial energy and material usage in order to ensure we are using energy and materials efficiently, thereby saving money. With respect to alternative energy, accounting for the energy used to create energy is a way to analyze energy production techniques. This section will explain some methods of energy analyses, and then will focus specifically on energy accounting and calculating the net energy value (NEV) of an energy production process. It will detail some factors of how to account for the energy inputs and assess the energy outputs of a process, and give an example of the NEV calculation and its variability using a topic for which there is much analysis: corn ethanol in the United States.

Energy-Related Analysis Tools and Fields of Study

Industrial Ecology

This field uses ecological principles to analyze industrial systems. It also addresses the system's interaction with society and the environment. It focuses on the flows of materials, energy, and information in order to analyze industrial systems and can help to improve the efficiency of such systems. With respect to energy, this analysis includes the efficiency of heat, energy to do work, and entropy. The field includes entropy in its analysis to imply the irreversibility of processes in production through its accounting for the recycling of materials (Lowenthal and Kastenberg 1998).

Ecological/Green Economics

This field is an integration of economics, ecology, and other natural and physical sciences under the interdisciplinary themes of sustainable development, growth, trade, and earth processes among others. It analyzes the economy as part of a larger system of natural resources and the environment. As part of the relationship between the economy and the environment, energy is used as an indicator for analysis. The efficient use of energy, maximizing of recycling, and efficient material flows are all a part of the analyses that can be done in this field (van den Bergh 2001)

Emergy Analysis

This analysis quantifies the environmental services that society benefits from with respect to a service or commodity. It has a broad view of the system of energy. The system boundaries extend out to the sun, soil, geothermal energy, etc. Referred to as "energy memory," emergy quantifies a system with respect to a common energy unit for various services and commodities within it. There is a maximum emergy principle that states that the system that will out-compete other rival systems will be the one that has the most "useful" work done by emergy sources (useful is specifically used as opposed to most efficient—useful work is self-reinforcing with respect to that energy flow. It represents a change of perspective of value, from one that is based on willingness to pay to one that is based on the resources used to make/provide something (Brown and Herendeen 1996).

Material Flows Analysis or Accounting (MFA)

This method tracks the flows of materials through a specific process. This analysis can be done at various levels of systems—materials can be tracked on a national scale, all the way down to facility-level analyses. Material and energy flow analysis (MEFA) looks at both the energy and the material flows. MFA/MEFA can be used as tools in industrial ecology, or can be stand alone analyses of systems. They can point out inefficiencies in a system or highlight ways in which waste can be reduced (BESR 2004).

Lifecycle Assessment or Analysis (LCA)

This technique is used to analyze the environmental impacts of a product or service by looking at its material and energy inputs and various outputs, products, or releases. It encompasses the entire lifecycle of a product, from the extraction of raw materials used to create inputs for a product or service to make a product to the destruction, dismantling, or recycling, of a product and accounts for waste products and emissions. It can be used to promote sustainable consumption, and reuse of materials. The United State's EPA promotes this assessment because it offers another way to evaluate a good or service that accounts for the environmental costs (EPA 2006).

Energy Sources and System Boundaries

There are various ways energy can be accounted for when looking at a product, service, process, or industry regardless of the accounting method. The most obvious would be to look at the fuel or electricity consumed by a product verses its output. For example, a generator or engine is often analyzed this way. A slightly broader assessment would also account for the labor and transportation costs associated with that product. Together, these first two levels encompass the direct energy associated with the product. To fully encompass total energy associated with efficiency, indirect energy must also be factored into the energy accounting method. Because energy is consumed in the construction, manufacturing, and/or delivery of inputs into any energy conversion technology, this indirect energy can also play a significant role in the overall energy efficiencies. Indirect energy can consist of the energy embodied in any of the inputs used to create a specific product. The system can be expanded yet again to include energy associated with end use modifications associated with the use of a product, or the energy used to dismantle or recycle a product. Also, the energy sources can be expanded and categorized to denote whether the energy is from natural sources (sunlight, water, soil etc), or fossil fuels. Indirect energy calculations are found in various methodologies used to evaluate energy efficiency. NEV, lifecycle analyses, and emergy analyses all include such calculations.

Assessing Indirect Energy: Input-Output and Process Analysis

Regardless of the type of energy assessment, when accounting for indirect energy, the energy embodied in various inputs should be assessed. This is done mainly through calculations using input-output (IO) tables or process analysis.

Input-Output analyses are done using industry- or economy-wide models of economic data. The Leontief model, developed in the 1930s by Professor Wassily

Leontief describes the movement of goods through the economy using currency flows as the indicator of movement. Using matrix algebra, a system of coefficients are determined that indicate the flow of goods between two sectors or region. The US provides a detailed, 428 sector breakdown of the US economy that can be used to assess the movement of goods. A detailed model, developed by the Green Design Institute at Carnegie Mellon is free and available for use, using recent economic census data (1992-2002). This specific model also evaluates energy flows and greenhouse gas emissions. It does so through the use of pollution and energy coefficients for each industry. The model is linear and based on dollar flows between industries using the North American Industry Classification System (NAICS) code. It uses the producer price of goods and services (Carnegie Mellon University Green Design Institute 2008).

Process analysis requires knowledge of the processes used in the manufacturing of a good or service. By analyzing each process and the energy inputs required, the total energy embodied by a good can be determined. The process analysis approach can become difficult, as the processes for the manufacturing of the inputs are needed to account for the energy embodied by the inputs.

Both input-output and process calculations can be difficult due to the complexity of embodied energy paths, the lack of data, and the inability to divide the energy for each process given co-creation during a coupled process. An analysis of hybrid techniques between IO (and its sensitivity analysis) and process analyses provide the following insights into embodied energy calculations (Treloar 1997):

Input-output analysis is often cumbersome due to the lengthy list of assumptions used in the analysis, including proportionality between inputs and outputs, and the use of price as an indicator of sector outputs, despite output differences in product. Also, information and coefficients about specific small industries are often not available (for example, tractor manufacturing information is not available, while farm machinery equipment manufacturing is available). Process analysis can be difficult because of the specificity of the system requirements and the lack of information. Often process analysis only encompasses a couple of stages upstream and ignores many of the inputs, making the system boundaries largely incomplete. Despite this, process analyses tend to be more accurate for a specific system when analyzed, though the analysis of one system is often irrelevant for other systems. Both IO and process analysis can be difficult when dealing with globalized markets that have production components in various foreign countries.

By creating a hybrid methodology using both input-output analysis and process analysis, the variability is potentially lessened. The most common hybrid analysis, as there can be many, "comprises the application of IO-derived total energy intensities to a material inventory collected using process analysis" (Treloar 1997). By combining the two in this manner, the system boundaries are more complete.

Net Energy Value as a Tool

When analyzing the energy efficiency of a product, there are various system boundaries that can be assessed, sometimes these are specified by the analysis chosen, while other analyses allow boundary specification for each assessment. This paper will focus on a tool used in life-cycle assessment—net energy value (NEV). With respect to ethanol, a life-cycle assessment could include the reduction in global warming, and the increased acidification, eutrophication, or other pollution caused by runoff from agriculture fields, among other side effects (Gonzalez-Garcia et al. 2009). The definition of the system boundaries must be clarified for each NEV.

The calculation of net energy value (NEV) is often used as an analysis for fossil fuel alternatives. In this calculation, the amount of energy of inputs (not counting solar radiation as an input) is subtracted from the final amount of energy derived from the energy source, usually in British thermal units (Btu). A positive NEV denotes a gain of overall energy from the use of the energy source. Though the estimation for NEV seems rather straightforward, calculations for NEV for the same fuel source vary depending on the conversion technologies, assumptions on yields, and the number of energy inputs included in the calculations (Shapouri et al. 1995). The use of renewable forms of energy does not need to have a positive net energy balance to be an improvement on the harmful effects of using fossil fuels; however, renewable energy sources should be utilized most efficiently through careful evaluation of alternatives. There are a number of energy analyses that are variations of this computation. For example, energy balances are often done using a similar logic, however instead of a subtraction, the inputs and outputs are used in a ratio.

NEV of Biofuels

To some extent, calculating the NEV of biofuels is a type of process analysis because the process of making a biofuel is analyzed for energy inputs. In the analysis of this process, the energy used in agricultural tools and machinery, conversion tools and machinery, and transportation can all be considered part of the indirect energy contributing to the NEV of biofuel production, which can be calculated using input-output analyses as a tool. When assessing energy associated with biofuels, many types of analyses have been completed, accounting for a variety of feedstocks.

Net energy value:

Net Energy Value	=	Total energy derived from the biofuel	-	Total energy used in biofuel production

The production function of a biofuel can be separated into two basic parts—feedstock production and conversion, though other aspects of production, like land preparation and pollution abatement, are also involved. In order to quantify the energy in these, the energy associated with the following will be determined:

Total Energy for Biofuel Production:

Total energy for biofuel production	=	Energy for land preparation	+	Energy for feedstock production	+	Energy for conversion	+	Energy for pollution abatement

As mentioned earlier, each of these areas contain direct energy inputs like fuels, electricity, and labor; and indirect energy inputs, like embodied energy in machinery and buildings, the transportation associated with inputs, and energy associated with pollution abatement. For each of the three areas, potential generic energy inputs are listed in Tables 2.1-2.3. The energy associated with pollution abatement depends largely on the boundaries of the system, and can be assessed for each part of biofuel production, and overall, in terms of greenhouse gas reduction.

Table 2.1. Energy for Land Preparation (generic)

	Direct	Indirect
Land Clearing	▪ Fuels ▪ Labor	▪ Energy embodied in machinery and equipment
Land Forming	▪ Fuels ▪ Labor	▪ Energy embodied in machinery and equipment
Planning	▪ Labor	
Pollution Abatement	▪ Labor ▪ Fuels	▪ Energy associated with pollution/erosion abatement techniques, including embodied energy in equipment and machinery

Table 2.2. Energy for Feedstock Production (generic)

	Direct	Indirect
Seed	▪ Fuels ▪ Labor	▪ Energy embodied in machinery ▪ Energy required to make and transport seeds
Crop Maintenance (fertilization, herbicides, insecticides, irrigation)	▪ Fuels ▪ Labor	▪ Energy embodied in machinery/equipment ▪ Energy required to make chemicals ▪ Transportation of inputs
Harvest	▪ Fuels ▪ Labor	▪ Energy embodied in machinery and equipment
Transport to Conversion Facility	▪ Fuels ▪ Labor	▪ Energy embodied in machinery and equipment
Pollution Abatement	▪ Labor ▪ Fuels	▪ Energy embodied in equipment and machinery, and possibly chemicals

Table 2.3. Energy for Conversion (generic)

	Direct	Indirect
Feedstock Preparation	▪ Fuels ▪ Electricity ▪ Labor	▪ Energy embodied in machinery, equipment, and facilities
Chemical Conversion	▪ Fuels ▪ Electricity ▪ Heat ▪ Labor	▪ Energy embodied in machinery, equipment, and facilities ▪ Energy required to make chemicals ▪ Transportation of inputs
Biofuel refining or purifying	▪ Electricity ▪ Labor	▪ Energy embodied in machinery, equipment, and facilities
Waste water reuse or treatment and other pollution abatement mechanisms	▪ Fuels ▪ Labor ▪ Electricity	▪ Energy embodied in machinery, equipment, chemicals and facilities

These energy inputs should be compared to the energy yield of the biofuel and the associated byproducts, including pollution abatement of greenhouse gases (should GHGs be reduced), to calculate the NEV.

The calculation of embodied energy in machinery can be done using the input-output model made by Carnegie Mellon University. By inputting the dollar amount of the farm machinery, the energy associated with the manufacture of that amount of equipment is generated under the industry code: 333111—Farm Machinery and Equipment Manufacturing. As mentioned previously, this assessment would be a gross generalization of the industry, and cannot provide specific information about any further disaggregation of machinery or equipment type. Using statistics from the US Census Bureau (2003) the following breakdown of the industry was determined by size, assuming the ratio of producer cost to consumer cost is the same across all subsections. (Detailed calculations are shown in Appendix A).

Table 2.4. Industry Breakdown of NAICS 333111 – Farm Machinery and Equipment Manufacturing Based on Value of Shipments

Product Code	Product description	%of NAICS
333111C	Parts for each category (total)	12.3
3331111	Wheel tractors (except contractors' off-highway wheel tractors, garden tractors, turf tractors, and motor tillers) and attachments	25.7
3331113	Farm dairy machines, sprayers, dusters, elevators, and farm blowers	5.4
3331117	Planting, seeding, and fertilizing machinery	7.1
3331119	Harvesting machinery	12.6
333111A	Haying machinery	4.6
333111E	Plows, harrows, rollers, pulverizers, cultivators, and weeders	3.1
333111G	All other farm machinery and equipment (except parts)	15.5
333111J	Commercial turf and grounds care equipment, including parts and attachments	13.7

If process analysis was done to identify more energy intensive subsections, the energy allocated to this industry could be redistributed among subsections using a weighted average based on sub-industry distribution within the industry code. For example, a process analysis could be done to assess the energy intensities of wheel tractors versus farm dairy machines, and the manufacturing process that used more energy would have a greater share of the total energy used in that NAICS code given by the input-output table.

A second method used frequently by Pimentel involves assessing the energy embodied in the materials used to make the machinery, the energy used to manufacture that piece of equipment, and the energy associated with the parts that will be used in a piece of machinery over its lifetime (assumed to be 25% of the total of the machine) (Pimentel 2003). An important assumption employed in this method is that each piece of machinery is comprised entirely of steel (thus using only the energy embodied in steel). However, farm tractors contain about 45% steel, 45% cast iron, and 10% rubber on a weight basis and other agricultural machinery is comprised mainly of steel (Borjesson

1996). The data for the energy embodied in machinery used by Pimentel is also outdated (Shapouri et al. 2004). Though Pimentel has updated his numbers since 1976, the analysis dates back to 1976.

Table 2.5. Fabrication Energy for Farm Equipment (data from 1976), adapted from Pimentel (1980)

	Energy (kcal/kg)
Tractors	3,494
Harvesters, combines, cotton pickers, and self-propelled forage harvesters	3108
Primary tillage equipment	2,061
Secondary tillage equipment	2,061
Sprayers and small grain planters	1995

Ultimately, assessing all of the energy associated with inputs and conversion can be used to determine a net energy value, which could be compared between crops and biofuels to determine the best crop (from an efficiency standpoint) to produce. This calculation can also be used to compare biofuels to other forms of energy.

There have been various examples of energy accounting done for energy crops grown around the world. Cassava, sugarcane and energy cane, and corn have all received particular attention as they all represent crops that were previously grown on industrial, commercial scales, thus having ample information about growth, yield, and production techniques, and can now be utilized as feedstock. Because corn is a subsidized commodity crop in the US, and is now used to produce ethanol, questions have arisen regarding the efficiency and economic value of corn as a feedstock for ethanol production. Ethanol from starch and sugar are examples of first generation biofuels that utilize prime agricultural land and crops that can also be used for food. Though second and third generation biofuels may prove to be more efficient users of land and water resources, the lack of information about feedstock yield, scaled conversion techniques, and byproducts make the analysis of energy efficiency and balance difficult and less reliable.

Corn Energy Analyses: An Example of NEV Calculations

There have been various studies evaluating the energy efficiency, NEV, or greenhouse gas emissions of corn ethanol (Shapouri et al. 2004; Shapouri, Duffield, and Wang 2002; Pimentel and Patzek 2005; Pimentel 2003; Lorenz and Morris 1995; Agriculture and Agri-food Canada 1999; Kim and Dale 2005; Marland and Turhollow 1990; Grabowski 2002). Though many of the authors, some of whom repeatedly analyze corn data as new numbers become available, find that corn ethanol uses less energy than it produces, the main dissenter of the group is Dr. David Pimentel. His numbers consistently contradict numbers put forth by Dr. Hosein Shapouri and the USDA. The following section describes the calculations done by Shapouri et al in 2004 and 2002, and Pimentel (2003) and Pimentel and Patzek (2005). It will summarize their sources of data and conversion statistics wherever possible.

Agricultural Inputs and Transportation

Shapouri and his USDA team use statistics taken from the USDA Agricultural Resource Management Survey. To determine yield data, they combine the three top years for the top nine corn producing states. To determine the data associated with inputs, they use a weighted average of the top nine corn producing states. In addition to data from the USDA, they use the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, developed by the Argonne National Laboratory, to assess the energy associated with import hauling. The term “custom work” refers to the costs incurred for contracting out specific farm operations. This would include the cost for using machines and labor, but is referred to as labor in the table below.

Pimentel and Patzek use data from the USDA for some of their sources. However, they also use other research papers, and their data sourcing is sometimes vague. They do not account for some of the forms of fuel inputs, which is partially due to the accounting methods of the USDA. Some of the natural gas inputs are used to power irrigation systems in some states, and the use of liquefied petroleum gas (LPG) in farm machinery is not as common as other fuels. There is very little yield difference between the two studies: Shapouri et al. (2004) use a yield of just over 139 bushels/acre and Pimentel and Patzek (2005) use a yield of just over 137 bushels/acre. For a table of data and sources, please see Appendix B.

When examining the production side of corn for conversion to ethanol, the main differences between the calculations done by Shapouri and Pimentel and Patzek fall in the machinery category (see Table 2.6), indicating that accounting for the energy embodied in machinery can impact the total results when accounting for energy embodied in agricultural production. Shapouri and the USDA criticize Pimentel for using old information in the calculation of embodied energy of machinery. In order to calculate energy embodied by machinery, Pimentel uses a method that assumes machinery is made up of steel (its principal component) and then uses the weight of the equipment and data from input-output tables that assess the energy embodied by that steel to extrapolate the amount of energy embodied by that piece of machinery. The assumed lifespan of the piece of equipment is 10 years.

Table 2.6. Energy Inputs and Energy Conversion Factors for US Corn Production

	Shapouri et al. 2004			Pimentel and Patzek, 2005		
Inputs	Energy per acre (Btu)	Conversion factor	Conversion Units	Energy per acre (Btu)	Conversion factor	Conversion Units
Seeds	84,022	4.7X total Energy	N/A	834,609	44,546	Btu/lb
Labor	220,297	157,821	Btu/hr	741,518	160,727	Btu/hr
Machinery	N/A	N/A	N/A	1,633,909	33,297.44	Btu/lb
Diesel	1,043,796	152,372	Btu/gal	1,609,833	171,094.82	Btu/gal
Gasoline	490,337	144,221	Btu/gal	650,032	151,989.51	Btu/gal
LPG	293,729	85,895	Btu/gal	N/A	N/A	N/A
Electricity	314,630	9,367	Btu/kWh	54,571	10,215.45	Btu/kWh
Natural Gas	257,222	1,046	Btu/cu ft	N/A	N/A	N/A
Nitrogen	3,271,285	24,500	Btu/lb	3,929,085	28,783.64	Btu/lb
Phosphorus	227,264	4,000	Btu/lb	433,355	7,472.68	Btu/lb
Potassium	264,607	3,000	Btu/lb	402,860	5,864.20	Btu/lb
Lime	8,778	559	Btu/lb	505,581	505.96	Btu/lb
Irrigation	18,950	105,279	Btu/dollar	513,606	156,681.48	Btu/cm H_2O
Chemicals: herbicide	409,799	154,000	Btu/lb	995,111	179,897.76	Btu/lb
Chemicals: insecticide				449,405	179,897.76	Btu/lb
Transport: inputs	28,147	N/A	N/A	271,248	1,490.33	Btu/lb
Total	6,932,862			13,024,723		

Table 2.7. Energy Totals of Inputs into Corn Production

	Shapouri 2004		Pimentel and Patzek 2005		Difference (Pimentel and Patzek-USDA)	
Inputs	Energy (BTU/ bushel)	% of Total	Energy (BTU/ bushel)	% of Total	Energy (BTU/ bushel)	% of Total Difference
Seeds	603	1.21%	6076.2	6.41%	5473.16	12.14%
Labor	1581	3.18%	5398.4	5.69%	3817.43	8.47%
Machinery	N/A	N/A	11895.3	12.54%	11895.25	26.39%
Diesel	7491	15.06%	11720.0	12.36%	4228.98	9.38%
Gasoline	3519	7.07%	4732.4	4.99%	1213.39	2.69%
LPG	2108	4.24%	N/A	N/A	-2108.00	4.68%
Electricity	2258	4.54%	397.3	0.42%	-1860.71	4.13%
Natural Gas	1846	3.71%	N/A	N/A	-1846.00	4.10%
Nitrogen	23477	47.19%	28604.7	30.17%	5127.69	11.38%
Phosphorus	1631	3.28%	3154.9	3.33%	1523.93	3.38%
Potassium	1899	3.82%	2932.9	3.09%	1033.92	2.29%
Lime	63	0.13%	3680.8	3.88%	3617.75	8.03%
Irrigation	136	0.27%	3739.2	3.94%	3603.18	7.99%
Chemicals	2941	5.91%	10516.4	11.09%	7575.43	16.81%
Transport	202	0.41%	1974.8	2.08%	1772.75	3.93%
Total	49755		94823.1		45068.14	

Conversion to Ethanol

The data on conversion of corn grain to ethanol comes from a survey done by the Office of Energy Policy and New Uses of the USDA. In the conversion to ethanol, the main components are transportation to the plant, the energy used by the plant to produce ethanol, and, in the case of Pimentel, the energy embodied in various parts of the plant.

The USDA team accounts for corn hauling using the GREET model. They also account for distribution of the ethanol product using the same model. The Shapouri group also analyzes both dry and wet milling operations for conversion. Wet mills produce a variety of corn products in addition to ethanol and consequently use more energy in production processes.

Though it is not explicitly stated in Pimentel's articles, the analysis of corn to ethanol conversion appears to be a dry mill process because the corn is finely ground before water is added (Pimentel 2003). Therefore, the corn NEV comparison will be based on the dry mill process only. Pimentel and Patzek also account for transportation using a conversion factor of 0.83 kcal/kg·km, which appears to be based on the energy intensities of various forms of transportation and their ratios used to transport agricultural goods (Pimentel and Pimentel 2008). Table 2.8 Summarizes the energy intensities of the conversion process as stated in the literature.

Table 2.8. Conversion Energy Inputs for Corn

	Shapouri, 2004			Pimentel and Patzek, 2005		
	Energy per gal EtOH (Btu)	Conversion factor	Conversion Units	Energy per gal EtOH (Btu)	Conversion factor	Conversion Units
Transport: Corn	2120	N/A	N/A	4834	0.83	kcal/kg-km
Electricity	10210	N/A	N/A	15176	0.83	kcal/kg-km
Water	N/A	N/A	N/A	1351	2.25	kcal/L
Steam/Heat	34700	N/A	N/A	38219	N/A	N/A
Stainless Steel	N/A	N/A	N/A	180	4000	kcal/kg
Steel	N/A	N/A	N/A	180	3000	kcal/kg
Cement	N/A	N/A	N/A	120	1000	kcal/kg
95-99.5% distillation	N/A	N/A	N/A	135	N/A	N/A
Sewage effluent	N/A	N/A	N/A	1036	3450	kcal/kg
TOTAL	47030			61231		
Corn input	21 lb corn/gallon ethanol			22 lb corn/gallon ethanol		

NEV Calculation

Shapouri et al. (2004) account for the energy of the byproducts as well as the resulting corn ethanol when assessing the NEV for corn. There are various ways byproducts can be accounted for with respect to energy embodied in them: caloric content, relative market value (between ethanol and the coproduct), relative weight, and replacement value. This group uses the energetic replacement value as a conservative estimate. Both studies use the low heat value for ethanol.

Table 2.9. NEV Without Assessing for Co-products

	Shapouri et al. 2004	Pimentel and Patzek, 2005
Energy Input for 1 acre of corn (Btu)	6,932,862	13,024,720
Energy Input to convert produced corn to ethanol (Btu)	17,495,160	21,430,850
Total Energy Inputs (Btu)	24,428,022	34,455,570
Ethanol produced/acre (gal)	372	350
Energy content of produced ethanol (Btu)	31,248,000	29,400,000
NEV (Btu)	6,819,978	-5,055,570

The USDA team finds that there are almost six million more Btu derived from corn ethanol than the Btu used to produce it, while Pimentel and Patzek's results indicate that five million more Btu is required to produce the ethanol than energy derived from the process. However, there are some interesting calculations used by Pimentel that can reduce the energy calculations. First, Pimentel and Patzek fail to account for the energy of co-products, or the combustion of by-products, which could either increase the energy of the products or decrease the amount of energy required for conversion, respectively. Since ethanol is derived from the starch part of the kernel, which makes up about 66% of the kernel weight, an additional 34% of the kernel can be used for something. Second, the transport of the corn, which accounts for almost 10 percent of the energy required for corn conversion is calculated on a round trip basis, however the empty trucks leaving the facility do not consume as much energy as the trucks hauling the corn to the facility. Though the number used for conversion to transportation is not clearly explained in the Pimentel literature, it appears to be a weighted average of road and rail transport (Pimentel and Pimentel 2008). Because the USDA data are very clearly sourced, there is little flexibility around their numbers, but the NEV does vary with respect to yield data, and the addition of embodied energy of machinery as an input would reduce the positive energy value.

Chapter Three – Literature Review: Biofuels in Hawai‘i

There have been a large variety of publicly and privately funded studies completed for various aspects of biofuels in Hawai‘i, dating back several decades. The use of biomass for biofuels is not new to Hawai‘i, as bagasse from the sugarcane industry was used to create electricity. Currently, the only commercial production of electricity from renewable, biological sources on Oahu is the H-Power plant, which turns refuse to energy. Hawai‘i Island also produces electricity from macadamia nut agricultural waste. Other operations create usable fuels from used oil, on both commercial scales (like Pacific Biodiesel) and smaller, on-farm/in-home operations. There are many questions surrounding the production and use of biofuel in Hawai‘i. These questions can be organized into the categories of land suitability/availability, feedstock/crop selection, production concerns, economics, infrastructure and policy changes, and end use concerns. The following section addresses these questions using relevant studies.

Table 3.1. Studies Relating to Biofuels in Hawai‘i

Study	Year	Author(s)	Prepared for:
The Potential for Biofuels Production in Hawai‘i	2010	Black and Veatch Corporation	State of Hawai‘i Department of Business, Economic Development and Tourism
Hawai‘i Bioenergy Master Plan	2009	Hawaii Natural Energy Institute	Mandated by the Hawai‘i State Legislature in 2007
A Scenario for Accelerated use of Renewable Resources for Transportation Fuels in Hawai‘i	2007	Surles, Terrence et al; (Hawaii Natural Energy Institute)	State of Hawai‘i Department of Business, Economic Development and Tourism
Biofuels Market Overview	2006	Kinoshita et al	Kamehameha Schools Land Assets Division
Hawai‘i Biofuels Summit Briefing Book	2006	Rocky Mountain Institute	State of Hawai‘i Department of Business, Economic Development and Tourism
Biomass and Bioenergy Resource Assessment for the State of Hawai‘i	2002	Turn, Scott, et al. (Hawaii Natural Energy Institute)	State of Hawai‘i Department of Business, Economic Development and Tourism

Table 3.2. Studies Related to Biomass Production or Ethanol Production in Hawai‘i

Study	Year	Author(s)	Prepared for:
Biofuels in Hawai‘i: A Case Study of Hamakua	2009	Coffman, et al.	The Kohala Center
Potential for Ethanol Production in Hawai‘i	2006	Keffer, Vheissu, et al. (Hawaii Natural Energy Institute)	State of Hawai‘i Department of Business, Economic Development and Tourism
Physicochemical Analysis of Selected Biomass Materials in Hawai‘i	2005	Turn, Scott, et al. (Hawaii Natural Energy Institute)	State of Hawai‘i Department of Business, Economic Development and Tourism
Hawai‘i Ethanol Alternatives	2003	Gieskes, Thomas; and Hackett, David (Stillwater Associates)	State of Hawai‘i Department of Business, Economic Development and Tourism
Economic Impact Assessment for Ethanol Production and Use in Hawai‘i	2003	BBI International	State of Hawai‘i Department of Business, Economic Development and Tourism
Siting Evaluation for Biomass-Ethanol Production in Hawai‘i	1999	Kinoshita, Charles, and Zhou, Jiachun	National Renewable Energy Laboratory
Ethanol Production in Hawai‘i	1994	Shleser, Robert	State of Hawai‘i Department of Business, Economic Development and Tourism
Investigation of Biomass-for-Energy Production on Molokai	1993	Hubbard, H.M.; and Kinoshita, Charles	Hawai‘i Natural Energy Institute
Comparative Study of Biomass Yields for Tree and Grass Crops Grown for Conversion to Energy	1993	Osgood, Robert; and Dudley, Nicklos (Hawaiian Sugar Planters’ Association)	State of Hawai‘i Department of Business, Economic Development and Tourism

Though many studies and reports discuss economics, and physical attributes of biofuel/biomass production in Hawaiʻi, there have been no studies specifically addressing the energy efficiency of biomass production in Hawaiʻi.

Land Suitability and Availability

The State of Hawaiʻi has a variety of soils and climate regimes. Using GIS software, various soil, climate, topography, and ownership maps, and other information can be analyzed for suitability and availability for biomass production. In a 2006 study, rain-fed land receiving greater than 78 inches of rain was quantified for production of sugarcane and banagrass. Though water requirements for banagrass and sugarcane are different, the land availability throughout the state for banagrass/sugarcane production (zoned as agriculture) was determined to be almost 360,000 acres, capable of producing 429 million gallons of ethanol from sugarcane, and 524 million gallons of ethanol from banagrass (Keffer, et al. 2006).

In a 2010 (Black and Veatch) survey of agricultural lands of Hawaiʻi for energy crop production, 810,000 acres of land could be considered non-prime and 300,000 acres are prime, irrigated lands. The 810,000 acres consist of land that is zoned for agriculture, but not deemed prime or unique, with a land slope of less than 20 percent (functional), and excluding lava land and rocky lands. Though irrigated lands offer significantly higher yields, they are often more profitably used for food commodity production, and in the case of the 810,000 acres of non-prime agricultural lands, irrigation does not seem feasible due to cost, distances between irrigation ditches, and topography. Over 680,000 acres of the non-prime land are classified as having enough moisture to support plant growth, with 80 percent of this land found on Hawaiʻi Island (Black and Veatch 2010).

In a study by Kinoshita and Zhou (1999), available land was also categorized based on historical use making the lands easily used for crop production without the costs of preparing large tracts of land that have not been farmed in the past. They identified seven sites on four islands that met criteria for ethanol-crop production totaling about 85,500 acres.

According to the 2010 Black and Veatch study produced for DBEDT, Hawaiʻi BioEnergy members, a group of local biofuel production entrepreneurs and researchers currently oversee enough land to produce the fuel necessary to meet the Act 240 goals of

20 percent of transportation fuels by 2020, if ideal production requirements were met, and yields achieved. Because the crops all have different requirements of rainfall and soil requirements, and many of them lack the appropriate data for growth in Hawaiʻi, yields have to be estimated from other sources, with some uncertainty. Despite this uncertainty, it is clear that Hawaiʻi can produce enough biomass to meet the goals of Act 240 with available non-prime agricultural land, though the costs of this production, both financially and environmentally may not be desirable.

Crops/Feedstock

The most current and comprehensive study of biofuel production in Hawaiʻi, a Black and Veatch study commissioned by DBEDT, looked at sugarcane, banagrass, miscanthus, eucalyptus, leucaena, oil palm, and jatropha as the potential biofuel feedstock crops. New or genetically altered biomass sources and technologies could increase the yields that are capable of being produced.

For ethanol production, sugarcane, banagrass, eucalyptus and leucaena are considered likely candidates because of their growth potential in Hawaiʻi, their presence in Hawaiʻi, and the relative amount of information about their production in Hawaiʻi (Keffer, et al. 2006). Tew (1988) compared the biomass of sugarcane and banagrass yields for five sites in Hawaiʻi for biomass fuel potential. The crops had similar dry biomass yields per acre, but the banagrass had a much higher percentage of fiber in the fresh weight (about 9%). All four of these crops have assessments that include fertilizer and weed control in their production (Hubbard and Kinoshita 1993).

Other crops mentioned by Osgood and Dudley (1993) include sweet sorghum and maize though yield data is not studied or estimated for Hawaiʻi in the report. Other tree crops (analyzed for chemical composition) include Moluccan albizia, tropical ash, ironwood, and waiwi, (Turn, et al. 2005). These other crops often lack specific yield data for Hawaiʻi and cannot be further analyzed for economic feasibility. The use of agricultural crop and forestry residues for biofuel or energy production is also a likely scenario in Hawaiʻi, as sugarcane bagasse produced nine percent of the state's energy needs in 1987 (Hubbard and Kinoshita 1993) and macadamia nut shells are used for electricity production (Turn, et al. 2002).

Additional resources (in addition to agricultural and forestry wastes) including animal wastes (hog, cattle, poultry), and urban wastes (landfill gas; fats, oil, and grease; municipal solid waste; sewage) are also potential feedstocks (Turn, et al. 2002). Ethanol from cellulosic wastes and molasses could supply 95 million gallons per year. Waste oil can provide 2,000,000 gallons of biodiesel (Black and Veatch 2010).

Algae represent another future crop type that could provide biomass for biofuel in Hawaiʻi. Because algae do not require agricultural land or fresh water, they are attractive as a biomass source. However, technological advancements are required to improve the profitability of algae, including strain selection for oil production and resistance to contamination, and extraction and processing techniques (Black and Veatch 2010).

Biomass Production Concerns

Water Resources

Rehabilitation costs for irrigation systems could increase the cost of biomass production in Hawaiʻi. In addition to the monetary costs of fixing irrigation systems, the access to water and the energy associated with implementing irrigation systems in agricultural fields could make the biomass production system unfeasible (Rocky Mountain Institute 2006). Crop yield is often directly related to the amount of water a crop receives. Specifically, sugarcane shows a linear relationship between water and yield (Hubbard and Kinoshita 1993). Salinity also affects crop health and is related to ground water sources as overdrawing from aquifers increases the size of the basal lens, which is the area of mixing between fresh and salt water.

Water use for biomass production agriculture must also be balanced against the water needs of higher value crops and growing populations. Selecting a variety of crops that can utilize the available water in the best way possible may help produce the most biomass for a given area. The diversion of water from streams must also ensure that there is enough water left in the stream to not affect the biodiversity and ecosystem health of the stream. The use of water (both surface and subsurface) could also affect the rate of aquifer recharge for the given island (Hawaii Natural Energy Institute 2009).

Invasive species concerns

Invasive species management is another concern relating to biomass production in Hawaiʻi. None of the biomass crops considered for biofuel production are native to Hawaiʻi and most are considered invasive. The traits that make a good feedstock crop are also traits associated with a high risk for invasiveness—tolerance of various climatic conditions, fast growing (Hawaii Natural Energy Institute 2009). Weed risk assessments (WRAs) of various candidate species rank some candidates as high risk and some as low. The assessment score is tabulated using published information on invasiveness in a location, and thus does not measure actual invasiveness (Daehler 2010). Table 3.3 lists the WRA scores as presented in the Hawaiʻi Bioenergy Master Plan Environmental Impact Issue Report (Hawaii Natural Energy Institute 2009).

Table 3.3. Weed Risk Assessment Scores for Various Potential Feedstocks

Feedstock Name	Scientific Name	Weed Risk Assessment Score	Notes
Sugarcane	*Saccharum officinarum*	2 (low risk)	• Grown in Hawai‘i for more than a century • Does not behave as a weed
Banagrass/ Napier grass	*Pennisetum purpureum*	16 (high risk)	• Documented in Hawai‘i since 1922, naturalized • Behaves as a weed in Florida • Concern about riparian zone health
Eucalyptus	*Eucalyptus grandis*	11 (high risk)	• Grown in Hawai‘i since the early 1900s • Behaves as a weed in South Africa
Eucalyptus	*Eucalyptus urophylla*	4 (low risk)	• Grown in Hawai‘i since the early 1900s • Does not behave as a weed
Leucaena	*Leucaena leucocephala*	15 (high risk)	• Found in Hawai‘i for more than 150 years • May have reached its full range of invasion already
Oil Palm (African oil palm)	*Elaeis guineensis*	10 (high risk)	• Found in Hawai‘i in gardens and small-scale research plantings • Naturalization in Hawai‘i may have little negative impact
Miscanthus *	*Miscanthus floridulus*	13 (high risk)	• Has become naturalized where introduced
Jatropha	*Jatropha curcas*	17 (high risk)	• Has been grown in Hawai‘i for more than a century • Considered a noxious weed in Australia

*Information from the Weed Risk Assessments for Hawai‘i and Pacific Islands web page maintained by Curt Daehler: http://www.botany.hawaii.edu/faculty/daehler/wra/default2.htm

In addition to potential invasiveness, many crops are or can be genetically modified to optimize their performance, which brings up some additional concerns, relating to gene transfer to other varieties of plants, potentially creating herbicide resistant weeds. Also, there are long-term concerns with the promotion of genetically modified organisms and the control companies have over food crops (Coffman 2009).

Though the growth of genetically modified organisms is not new to agricultural operations in Hawai‘i, the addition of potentially large-scale operations using genetically modified crops could be a concern.

Pollution

Pollution associated with chemicals used in agricultural production through runoff, leaching, volatilization, and erosion can affect air and water quality, and surrounding ecosystems. These chemicals can have deleterious effects on nearby communities and ecosystems by leaching into the water table or polluting surrounding soil. The potential eutrophication of coastal waters can also destroy the fragile ecosystems (Coffman 2009).

Food-Fuel debate

Roughly 42% of Hawai‘i's land zoned in agriculture is not being used in farm operation. Agricultural land currently in use in Hawai‘i is often used for diversified agriculture, typically for niche market products like flowers, coffee, and macadamia nuts (Coffman 2009). The food consumed in Hawai‘i consists of 90% imported beef, 65% imported fruit, and 70% imported vegetables (Office of the Governor 2008; Coffman 2009). Though the debate between food production and biomass production is an important one for the people of Hawai‘i, the market for locally grown food is only viable for food used in niche markets, or foods that hold up poorly over the long transportation time. It is unclear whether the economics of biomass production would allow it to compete from prime agricultural land due to the scale of production necessary for profitability. However, because food security rivals energy security, and biomass crop selection can utilize non-prime agricultural land, the debate between food or energy production can be easily resolved by relegating biomass production to non-prime agricultural land. Biomass for biofuel production would be a way to use and thus preserve the non-prime agricultural land in Hawai‘i, protecting it from development while providing some income to landowners.

Economics

Competitiveness and profitability

For corn-based ethanol in the U.S. mainland, there is a profit margin suitable for competition with gasoline, even without federal tax credits. Biodiesel can also be profitable nationally, depending on the source. Waste oil is the most profitable, though imported palm oil is also a profitable source (RMI 2006). Profitability in Hawaiʻi is unique to these islands because of the isolated nature of the islands and the limited amount of land.

A variety of grass and tree crops were analyzed by Osgood and Dudley (1993) for electricity production in Hawaiʻi and determined to be unprofitable. However, the data used from 1993 does not accurately reflect current prices, thus reassessing energy costs can change profitability. When comparing feedstock use for electricity generation versus ethanol production, it is more economical to burn ligno-cellulosic biomass because of Hawaiʻi's high cost of electricity (Gieskes and Hackett 2003). However, this does not account for the required need of a liquid fuel replacement for fossil fuels, which would affect the price of electricity given other alternatives for electricity generation. Depending on crop yields and conversion efficiency, breakeven costs can fluctuate, but the Black and Veatch (2010) study for DBEDT reveals that ethanol production is not profitable unless ethanol is well over $2 per gallon. Breakeven costs for sugarcane ethanol is $2.40, banagrass is $2.10, Eucalyptus is $2.63, and Leucaena is $2.03. Biodiesel costs have a breakeven price of over $10 for both oil-crop feedstocks examined (oil palm, jatropha) because of high feedstock production costs (Black and Veatch 2010).

For cellulosic ethanol conversion, ethanol plants in Hawaiʻi cannot experience economy-of-scale benefits that could be seen on the US mainland, due to the plant size and acreage constraints. Biodiesel production does not experience economy-of-scale benefits like cellulosic ethanol conversion and its economics are less affected by Hawaiʻi's limited land and isolation. Much of the economic analysis for oil crops cannot be done because crops like oil palm and jatropha are so new to cultivation in Hawaiʻi that yields are not known and harvest machinery has not been developed. Options to increase profitability include on- or near-farm processing of biomass to a liquid fuel, which can be transported to a refining facility or stored at a lower cost and with less difficulty. At the refining facility, the initial liquid fuel can be turned into a more functional fuel (Black and Veatch 2010).

Though biomass is not currently being produced explicitly for energy in a for-profit situation, byproducts of agricultural production have been used for energy production since the times of the sugar plantations. By using agricultural byproducts as feedstock for energy production, there is an increased value in the production of the crop, and this can improve the economic feasibility of an agricultural operation. However, utilizing only agricultural residue for energy production may not provide the quantity of energy demanded by Hawai‘i’s population.

Algae production is also a potential source of biomass (bio-oil) production through aquaculture (an approved use of agricultural land) that could change the way agriculture utilizes land for energy production. Because algae does not compete directly with agricultural land or resources, and has potentially high yields per acre, algae could be the source of the bio-oil needed to make biodiesel. Algae production for bio-oil is so new that significant research and development is necessary before profitability can be determined, and production mechanisms are still experimental, and funded through investors and grants (Black and Veatch 2010).

Other economic benefits: jobs, energy security, keeping money in local economy

The development of a locally produced biofuel industry in Hawai‘i will provide jobs for the local labor market; however, the number of jobs is unclear, and the ability of these jobs to provide a “livable” wage is questionable. The development of a biofuels market does also increase the energy security of the state and help with greenhouse gas emission reduction, both of which have positive economic effects. The utilization of fallow agricultural land also prevents its conversion to “gentleman estates” which means the land can be more productive for the State (Hawaii Natural Energy Institute 2009). The extent of these economic benefits is not yet known and will be difficult to calculate.

Infrastructure, Policy, and End use concerns

Federal loan guarantees, tax credits, and grants are just some of the ways the national government supports biofuel research and development of biofuel industry. The government subsidizes the production of biomass feedstocks and supports end-use modifications and vehicle credits for biofuel use (Black and Veatch 2010). The selection or preferential treatment of biofuels can be of concern to taxpayers, despite needing to provide some incentive to alternative energy projects because of the subsidization of fossil fuels. In facilitating investment in biofuels, the government could be incentivizing them over other alternative energy options, which could be an issue.

There are some end use concerns because of incompatibility issues between fuel grade ethanol and gasoline, requiring a complete change of some parts of the distribution infrastructure, should higher blends of biofuels become more widespread. The present (2009) value of Hawaiʻi's petroleum infrastructure is about $3.6 billion dollars (Hawaii Natural Energy Institute 2009), thus compatibility with the existing infrastructure would have to play into the selection process of energy alternatives, specifically biofuels, since it is such a large investment. Additionally, a transition period towards biofuel use would be necessary, during which both biofuel and petroleum products would need to be readily available (Hawaii Natural Energy Institute 2009). There are also some concerns associated with pollution from conversion processes, like potential acidification associated with nitrogen oxides (Coffman 2009). From a consumer point of view, the transition to biofuels may cause some concern because of compatibility issues in existing engines.

Though low-level blends of ethanol in gasoline require little change in infrastructure, Hawaiʻi's mandated E10 fuel caused problems in old engines and storage tanks (DBEDT 2007). Higher blends like E85 (which is about 75% ethanol), a standard fuel for commercially produced flex fuel vehicles, require more extensive and costly changes to distribution, storage, and dispensing equipment (EIA 2007). Also, the engines that utilize such fuels must be compatible with the biofuel. As of 2004, only 2% of Hawaiʻi's vehicles were E85 flex-fuel vehicles (Rocky Mountain Institute, 2006) and one station in the State that supplies the fuel by private access only on the Kaneohe Marine Corps Base Hawaiʻi (EERE 2011).

Chapter Four – Methodology

Assumptions

This research derives a net energy value calculation for ethanol production from banagrass. The system boundary encompasses the production of biofuel only, thus end-use modifications will not be accounted for. Energy associated with transportation of inputs, and energy embodied in all inputs will be included wherever possible. However, energy associated with pollution abatement for farming techniques will not be accounted for. This is not a lifecycle analysis or emergy analysis for biofuels; therefore, the energy supplied by nature will not be accounted for. A greenhouse gas inventory for the process will also not be calculated. Other assumptions will be mentioned beneath each subheading.

There is sparse data on embodied energy in banagrass conversion to ethanol. Because of this, conversion numbers will be used from general ligno-cellulosic conversion to ethanol (noting the various fuel sources). Despite the use of this number for NEV calculations, a detailed, process analysis of cellulosic conversion is not the focus of this research.

Farm Production Energy Assessment

Crop selection and Yield

Banagrass, *Pennisetum purpureum* Schumach*,* is a type of Napier grass originating in Africa. It was chosen as crop for this analysis because it meets the minimum requirements for analysis given that there is yield data available, planting and harvesting techniques and machinery are known, and it is able to yield large amounts of biomass on unirrigated, non-prime agricultural land under growing conditions found in Hawai‘i. The crop was originally documented in Hawai‘i in 1922, and is naturalized on the main Hawaiian Islands (Hawaii Natural Energy Institute 2009). It is considered “moderately” invasive, which means it is secondarily important at the present but is not innocuous (Sherley 2000). The WRA (see Table 3.3) lists banagrass as high risk because it behaves as a weed in other states.

Banagrass has some of the highest yields among tropical forage grasses. It is capable of tolerating drought, waterlogging and monsoons, though it can be damaged by frost. It grows in dense clumps. Napier grasses contain 28% hemicellulose and 39% cellulose (similar to energy cane which is 28% and 38% respectively) (El Bassam 1998). Takara and Khanal (2010) found similar results for a banagrass yield grown in Hawaiʻi, with 64% of the total biomass dry weight consisting of sugars. Twenty-one percent of the total dry weight was lignin and 8% ash.

Yield varies with production estimates. Kinoshita and Zhou (1999) report 26.1 dry tons/acre-year for planted crops and 30.1 dry tons/acre-year for ratoon crops, however these yields are from irrigated fields. The yield estimates by Black & Veatch (2010) for non-irrigated banagrass yields are estimated to be (on average in the State of Hawaiʻi) 21.5 dry tons/acre/year with a range of 8.7-38.0 dry tons/acre/year based on an average of six ratoon crops. Tew (1989) indicates that productivity is still high after eight ratoon crops. Data on yields from further ratoon crops is unknown.

Ratooned banagrass crops have a moisture-content of about 64.2% (Kinoshita and Zhou 1999), meaning fresh crop yield is about 60 fresh tons/acre/year. Crops are harvested on an average of 7.7 months (Tew 1989). An optimal harvest interval would need to be established for the conditions of each farm, and may vary slightly with season. For this exercise, it will be assumed to be the same as the irrigated experiment on Molokai, 226 days (Kinoshita, et al 2002).

Farm Information

Size:

Farm acreage is based upon the amount of biomass supply necessary in order to have a viable conversion operation. The state has created tax credits to benefit ethanol production facilities that meet a nameplate capacity of 500,000 to 15,000,000,000 gallons of ethanol per year. The facility must operate at 75% of its nameplate capacity in the least. Five hundred acres should suffice to meet the biomass needs for an ethanol plant that satisfies the State's minimum requirements according to HRS § 235-110.3 while allowing for variability in yield. The 500 acres should produce enough feedstock to produce about 720,000 gallons of ethanol per year, allowing for large variability in yield while still meeting the requirements for tax credits.

Alternately, direct combustion of biomass can be used to create electricity. The profitability and size of such a facility would depend partially on the negotiated power purchase agreement with the utility. Such contract rates are dependent upon the type of power provided (firm or intermittent). Typically, if firm power is negotiated, the conversion facility must provide that specified amount of firm power with penalties for not meeting contract requirements. Intermittent power receives lower rates, however there is more flexibility in the amount of power supplied. Though there is no specified minimum set by utilities in Hawaiʻi of the amount of power a provider must supply, the electricity must be transmitted to the grid system without extensive infrastructure needs. In the case of small energy production operations, proximity and ease of transmission to the grid would be a necessary factor for negotiating a purchase agreement. Because of the variability involved in contract negotiations for providing electricity through combustion, and the importance of an intermediary liquid biofuel for achieving energy self-sufficiency in Hawaiʻi, the ethanol plant scenario is used for farm-size selection.

Conversion Facility Location:

The location of the ethanol plant is assumed to be five miles from the farm. Transportation assessments will use this distance for calculation of energy. An estimation of one mile will be used for farm to road transport distance for in-field equipment

Land:

The land on the farm will be assumed to be contiguous, zoned as agricultural land, non-prime, perhaps formerly used for plantation crop production. Thus land preparation will occur once, and can be allocated over the life of the farm (assumed 30 years). The slope of the land is assumed to be less than 20%.

Production Inputs

Land Preparation

Land preparation, which consists of clearing, land forming, and drainage ditch construction, is necessary for access and management (water, erosion, crop, soil) of cropland (Shih 1992).

Land clearing is dependent upon the condition of the vegetation present. Using an estimate of energy tied to a dollar value, standard energy intensity was estimated to be about 875-2625 MJ/ha to clear sparse to moderate stands of large mesquite (Fisher, et al 1973).

Land forming for the assumed farm will be limited to plowing and ditch clearing. Large modifications to the topography of the land are assumed unnecessary because the land has been previously used as plantation land. Land grading and stockpiling of soil, which is not an issue given the assumptions for the farm-land, is typically the most energy expensive part of land preparation, taking up 80% of the energy associated with land preparation. An additional 1000 MJ/ha is associated with the technical services needed for land preparation (mapping, planning and design) (Shih 1992).

Land preparation will only be done once over the lifetime of the farm, and thus the energy required for land preparation will be divided among the years of operation (assumed to be 30 years).

Seed

Banagrass is seeded from stem-cuttings, therefore, little extra effort is placed in the preparation of banagrass as seed. Additional machinery is required to create cuttings of appropriate size to plant; however, the seed itself requires no special treatment and can be assumed to take the same amount of energy as the crop itself to grow.

Equipment

Land Preparation—The embodied energy association with the equipment involved in land preparation will not be accounted for in this process because land preparation will only be done once over the life of the farm, and can assume to be rented and thus the energy embodied by the machinery will be divided among its total use, reducing it significantly. The energy used by the rest of the farm equipment will be accounted for.

Seed Preparation—Because banagrass seeds, which are actually stem cuttings, are only necessary every five years (or longer, depending on the number of ratoon crops harvested per planting), seed preparation equipment will be a variation of harvest machinery, and thus no new equipment is necessary. Stem cuttings can be made by the harvester selected.

Planting—The yield of ratoon crops has only been studied for six (Kinoshita and Zhou 1999) and eight (Tew 1989) ratoons for banagrass. It is unknown whether further ratooning would be economical or beneficial for the crop yield. Because of this, six ratoon crops are assumed to be harvested. Crops will be harvested at a 6-8 month cycle according to practices by Kinoshita and Zhou, and Tew, or on average, every 226 days.

Requirements for planting include tillage and disc harrowing. In Kinoshita et al (1993) equipment for soil preparation includes three construction-type shanks on a tool bar on a 200-270 hp drawbar-power tractor. The same tractor used for disc harrowing using two gangs of 3-foot diameter blades.

Harvest—The harvesting of banagrass is also similar to sugarcane harvesting. The equipment used: a combine-type cane harvester (Austoft Model 7000). Biomass is harvested into in-field tipper-trailers (CAMECO industries), which self-unload into highway transportation vehicles (Jakeway 1993).

Energy embodied in machinery will be calculated using two methods: cost and weight. The cost basis will use the input-output table, which converts economic activity into energy flows. The total cost for all of the equipment and parts will be amortized over 15 years for the tractor and 10 years for the in-field tipper trailers, and 5 years for the harvester. Repair costs will be assumed to be 25% of the total new machinery cost over the 15 years of the tractor (based on a 400 hour/year use), and similar estimates for in-field trailers (Edwards 2009). Harvesters in general have much higher maintenance costs, especially given that they are used much less per year than a tractor. The lifespan of the harvester is assumed to be 5 years, with the maintenance cost of a self propelled combine harvester at about 40% per 3000 hours of machine life (Edwards 2009)—two harvesters working slightly less than four hours per day (total) give a similar hour usage over five years. Other estimates for machinery life can be used, Lazarus (2009) from the University of Minnesota estimates 12 years for all machinery as an estimate for economic life. The specific methods of calculating the embodied energy from price are explained in the corn example. The Carnegie Mellon IO model uses producer prices as part of the cash flow. To determine the producer price, it will be assumed that dealer markup on new agricultural equipment is about 8% over cost. This number is taken from a 1980s industry assessment on farm machinery industry on the Small Business Advancement National Center based at the University of Central Arkansas. The number was calculated from a database of dealer surveys in the 1980s.

In addition to the assumptions inherent in the use of this analysis method, assumptions for this method include:

- The energy flows of the United States IO table are the same as the energy flows in the country the equipment is manufactured in, thus the IO table for the US can be used
- All equipment falls under the farm machinery NAICS code

The generalized process analysis for equipment will also be looked at (Pimentel method in corn example). For this, the weight of each piece of equipment must be known. A John Deere 8430 Tractor with a PTO horsepower of 250 has a manufactured weight of 11,700 kg (Tractordata.com 2011), and an approximate price tag (new) of $193,000. The Austoft 7000 (sugarcane harvester) weight is 28,000 kg and costs around $195,000 new (Case IH, 2010). The Stronga BL600 Agricultural Tipper Trailer weighs about 5,000 kg when empty (Stronga 2009), and costs about £15,000 or $25,000 new (farmersguardian.com 2009). It requires a tractor that is at least 150 hp. The weight of the Volvo FM 32 ton 8x4 tipper trailer is 11.76 tons when empty (Coyle 2007) and the estimated price new is $135,000 (Coyle 2010). The Stronga trailer will be used for in-field collection and transport, and the Volvo trailers will be used for road transport to the conversion facility. In addition to the assumptions inherent in the use of this analysis method, assumptions for this method include:

- The energy embodied in steel wherever the equipment is manufactured is the same as the energy embodied in steel in the US
- The equipment is made entirely of steel (which is an untrue assumption used for calculation purposes)

Labor

Similar to sugarcane, the direct labor required for land and soil preparation is about three operator-hours/acre. For planting, the requirement is about 10 worker hours/acre (Kinoshita et al 1993). Harvest labor costs are estimated by Jakeway (1993) to be $0.42/ton wet biomass.

Metrics conversion methods for evaluating labor in Fluck (1992) indicate that system boundaries definitions greatly impact the energy requirement of labor. When accounting for all aspects of human labor in agriculture, the boundaries are often so broad that they include the energy embodied in the clothing worn while working, and the energy required to make agricultural labor available, the difference in energy consumed if the laborer was employed elsewhere or unemployed. In addition to this, the system boundaries often include the energy embodied in food production, and the energy required to meet general consumption of all goods and services in the life of a person.

Table 4.1. Summary of Energy Embodied in Labor at various Boundary Levels, modified from Fluck (1992)

Level	Energy range	Description
Muscular Energy	0.5-1.50 MJ/day	Derived from the amount of muscular work that can be done by an adult male per day
Partial Energy of Food Metabolized while working	3-10 MJ/day	Accounts for the energy in the food metabolized while working verses metabolism while sleeping
Total Energy of Food Metabolized while working	4-12 MJ/day	Accounts for the total energy in the food metabolized while working
Total Energy Content of Consumed Food	18.23 MJ/day	Based on the energy in all of the food consumed by a worker (based on a 40 hour workweek)
Energy Sequestered in Food	93.2 MJ/day	Accounts for the food energy required to produce food (excludes other inputs)
Life-style Support Energy	1448 MJ/day (US in 1983)	Accounts for all of the energy in the products and services used by a farm-laborer and his/her family (varies greatly depending on standard of living)

The USDA uses estimates consistent with life-style support energy when attributing labor energy costs in corn accounting in the amount of about 1550 MJ/day (workday) in 2002 and 2004 (see Appendix C for calculation and sources for this number). This analysis will utilize lifestyle support energy of 1550 MJ/day.

Electricity

There is no data on the electricity required for farm production of banagrass. Because there would be very little use for electricity in this type of farm production, it is assumed electricity use is none, which is consistent with unirrigated farm production.

Fuels

Fuel use is calculated using statistics for farm equipment. The only piece of equipment required for planting is a 200-270 hp drawbar-power tractor. Harvest equipment consists of a combine-type cane harvester (Austoft Model 7000). Biomass harvested into in-field tipper-trailers (Volvo 8X4 32 ton tipper trailers), which self-unload (Jakeway 1993).

To analyze fuel consumption of the tractor-trailers, known industry fuel consumption will be used (Downs and Hansen 1998). Fuel requirements for the Austoft 7000 were determined by a study by Yadav et al. (2002). Three different sizes of in-field tipper trailers, 26, 32, and 44 ton were analyzed for fuel consumption at maximum load and empty (Coyne 2007). The fuel consumption results will be used to analyze the fuel needs of this vehicle.

Chemicals

The unirrigated fields of banagrass will be difficult to fertilize (without irrigation to apply the fertilizer). It is estimated that the banagrass will get too dense to apply fertilizer after about 60 days. Therefore fertilizers will be applied at planting and harvest, and once when still able to take machinery through the crop. There is no available yield data for unirrigated banagrass in Hawaiʻi, thus there is no yield data for directly applied chemical fertilizers. Fertilizer requirements on irrigated fields in Molokai to provide maximum yields are 270 pounds per acre of N, 180 pounds/acre P, and 270 pounds/acre K annually, when applied initially at planting then through irrigation monthly (Kinoshita et al. 1993).

Potassium

On unirrigated fields, applying fertilizer for the first two months is likely. A study by Vincente-Chandler et al. (1959) on forage grasses including napier grass in Puerto Rico examined rainfed yields, as a response to varying amounts of applied K. The soil, a moderately well-drained oxisol (Fajardo clay), did show a strong ability to retain exchangeable K, thus applying the entire amount of K fertilizer, 270 pounds/acre, at two intervals is assumed.

Nitrogen

A study by Ferraris (1980) indicates that unirrigated elephant grass (*Pennisetum purpureum*, cultivar Q5083) grown in Australia on mixed alluvial soil with basaltic influence shows that nitrogen amounts greater than 446 pounds/acre annually failed to influence yields. Because the experimental plots were small, fertilizer was side banded into the soil. Fertilizer application was at 3, 6, or 12 month intervals, with harvest at 3, 6, and 12 months. The timing of the fertilizer applications did not significantly affect dry matter yields. Unfortunately, this study had no increments of nitrogen fertilizer application between 0 and 445 pounds/acre, thus a more precise quantity is unavailable. The application rate of 270 pounds/acre annually, as used in Kinoshita et al. (1993) for banagrass in Hawaiʻi, is used.

Phosphorus

There have been no specific studies addressing optimal amounts of phosphorus applications for banagrass yields. In the Ferraris study analyzing nitrogen, P was applied at the rate of 133.8 pounds/acre, annually banded into the soil. For the purposes of the analysis in this study, phosphorus will be assumed to be applied at the rate used in Kinoshita et al. (1993): 180 pounds/acre per year.

Lime

Because of the application of fertilizers, the pH of the soil may eventually decrease, thus requiring the application of lime. Energy used for producing lime is 620 Btu/lb (Shapouri, Duffield, and Wang 2002). In a 1986 study of *Pennisetum purpureum* L. Lam grown in south central Florida on a Spodosol (sandy, siliceous, hyperthermic, haplaquod soil), the soil required 2.2 Mg/ha of dolomitic limestone after a little over a year of growth (Mislevy et al. 1986). The addition of lime also imposes an additional labor cost as lime should not be added at the same time of fertilizer addition in order to be more effective. Because the addition of lime depends on the soil, lime use will be ignored. Generally lime would not be necessary to treat the soil before initial planting for land that is not in agricultural production, and the natural buffering capability of soil may not require any lime use at all. If lime were to be necessary, its use can easily be incorporated into the formula using the methods used in calculating labor, fuel, shipping energy, and embodied energy of lime found in the corn example and in this methodology and data analysis. The amount of lime necessary can be calculated using a formula found in Hue (2008).

Herbicides and insecticides

Weed control must be done in the early stages of the initial planting of banagrass, after which the rapid growth of the banagrass should stop the propagation of weeds. One application should suffice, and can be distributed via tractor using a mounted sprayer (Kinoshita et al. 1993, Karimi et al. 2008). The herbicide used can be similar to that used for sugarcane. Because the application of the herbicide must be done when or before the field is initially planted, it would only occur once every four years or so. The total amount of energy embodied in the herbicides and insecticides used to grow one hectare of sugarcane is 1.92 GJ (Karimi et al. 2008). Because herbicide is typically diluted and in this case applied so infrequently (every few years) the transportation cost of these chemicals will be considered to be negligible.

Transport

In-field Transport

As mentioned previously in the equipment section, in-field transport of the harvested banagrass can be done using in-field tipper trailers. The Stronga BL 600 can be pulled by a tractor alongside the Austoft 7000 harvester and can unload into highway transport vehicles. These trailers can also be used to help transport fertilizers and for other on-farm transportation needs.

Highway Transport

On-road tipper trailers can be used for highway transport to the conversion plant. As mentioned in the equipment section, Volvo 8x4 tipper trailers can be used for this. Coyle (2010) specifically analyzed fuel usage of these trailers for highway transport (both with maximum payload and empty).

Shipping

According to data from 2008, 838 tons of fertilizers arrived from foreign sources (not including Canada) to Hawai'i, and there was no interisland shipping of fertilizers (Waterborne Commerce Statistics Center 2008). The 2008 average energy intensity of freight waterborne commerce is 418 Btu/ton-mile. This calculation is a basic calculation using the amount of fuel purchased by waterborne freight carriers divided by the amount of ton-miles, thus it does not account for the energy embodied in the vessel, or any labor associated with the transport (Davis et al. 2010). The United States imports fertilizers from South and Central America, Asia, the Middle East, and Europe, among others. Since Hawai'i is located in the middle of the Pacific, the general number of 3,000 miles will be used for shipping calculations of chemicals.

Banagrass Conversion to Ethanol Energy Assessment

Assumptions:

There are many possible conversion mechanisms for the conversion of the banagrass produced into usable forms of energy. Because this report is specifically addressing the production of biofuels, and the large demand for ethanol in Hawai'i, banagrass yield will be analyzed for its conversion to pure ethanol. The basic steps for conversion of ligno-cellulosic biomass to ethanol are similar regardless of feedstock. The feedstock must first be treated to free the cellulose and hemicellulose from the lignin and other materials. The cellulose must then be hydrolyzed into individual sugars, which are then fermented. The ethanol is then distilled from the mixture and purified.

The initial treatment of the ligno-cellulosic biomass can be done in various ways, using acids, ammonia, or lime among other chemicals; however, the most economically efficient method is dilute acid pretreatment, which is in the plans for ethanol plants in various states (Takara and Khanal 2010).

From a practical standpoint in construction of ethanol conversion plants in the industry today, Wooley et al. (1999) outlined an industrial process for woodchips that Aden et al. (2002) adjusted for corn stover, which included eight major areas of processing for a cellulosic feedstock conversion plant:

- Feed Handling—where feedstock is stored and made ready for processing (size-reduction)

- Pretreatment and conditioning—feedstock treatment with dilute acid and heat and removal of acid and toxic compounds that would inhibit enzyme activity
- Saccharification (hydrolysis) and co-fermentation
- Distillation and dehydration
- Wastewater treatment—treatment of wastewater from pretreatment and distillation process using anaerobic and aerobic digestion (biogas is created in this step). Water can be reused in the process
- Storage of ethanol product
- Burner/boiler turbogenerator that combusts products from distillation, wastewater, to provide electricity and heat for the processes
- Utilities

In an attempt to evaluate other aspects of the feedstock conversion process with respect to energy, Cardona Alzate and Sanchez Toro (2006) examined various parts of the conversion process to see which configuration of processes had the highest NEV for ethanol production. Simultaneous saccharification and cofermentation reduces the energy required in the process. Recycling water also reduces the energy cost of the process.

This optimized process results in 41.96 MJ energy consumed to convert a lignocellulosic feedstock (woodchips) to one liter of anhydrous ethanol (Cardona Alzate and Sanchez Toro 2006); however, this does not account for the energy embodied in the machinery or buildings in the ethanol plant. The creation of the anhydrous ethanol releases 40.6 MJ/L ethanol through the combustion of waste products from the conversion process, making the total energy required for conversion to be 1.4 MJ/L ethanol when accounting for all byproducts.

Pimentel and Patzek (2005) also assessed the conversion of cellulosic biomass to ethanol using switchgrass as a feedstock. Their calculations do include the energy embodied in the cement, and steel, as well as the electricity, steam production, and water, but do not address the energy embodied in byproducts. Their conversion mechanism also does not seem to recycle water or waste heat, though little is detailed about the conversion mechanisms. They report a value of 6461 kcalx1000 used to create 1000 L of

99.5 % ethanol. Even though they do account for embodied energy, their total amount of energy required for conversion of switchgrass to ethanol is 27 MJ/L ethanol, less than the Cardona Alzate and Sanchez Toro calculation, but about 10 MJ/L more than conversion of corn to ethanol.

Another study by Luo, et al. (2009) calculated that 9.5 MJ/L are required to transform corn stover into ethanol, using the most efficient numbers for a cellulosic biorefinery, though it does not assess the energy embodied in materials to make the refinery. This number does not account for the energy in the co-products, which is 3.5 MJ/L for corn stover. This study also stated that accounting for co-products often changes NEV from negative to positive, even in the two Pimentel studies for corn. A comparison of herbaceous feedstocks done by South Dakota State University states that corn stover and switchgrass are similar in chemical content, at about 38% cellulose, 26% hemicellulose and 19% lignin for corn stover; and 37% cellulose, 29% hemicellulose and 19% for switchgrass, though there is significant variation on chemical content based on the growth environment of the crops (Lee et al. 2007). These numbers are very similar to the numbers given earlier in this section for Napier grasses (39% cellulose, 28% hemicellulose) and for banagrass yields in Hawai‘i (64% of the total biomass dry weight consisting of sugars and 21% lignin).

For banagrass, the conversion rate of 67 gallons of ethanol per ton of biomass (dryweight) (Shleser 1994, Black and Veatch 2010) has been calculated by Shleser using an analysis of the components of banagrass (lignin, cellulose, hemicellulose, etc) and their conversion rates to ethanol.

Chapter Five – Data and Analysis

All energy data will be converted to, analyzed, and reported in Btu/acre/year for comparison purposes.

Assumptions for the Production of Biomass – Banagrass

Table 5.1. Assumptions Used in Calculations*

Assumptions	
Farm size	500 acres
Annualized yield	60 fresh tons/acre/year or 21.5 dry tons/acre/year
Ratoon time	226 days
# Ratoon crops	6 crops
Energy costs of labor	1550 MJ/day
Land prep for planting labor	3 hrs/acre
Planting labor	10 hrs/acre
Crop maintenance labor	1.5 hrs/acre
Harvest labor cost	$0.42/ton biomass
Road transport labor	3 trips/acre/year
Distance to conversion plant	5 miles
Distance to origin of shipped goods	3,000 miles
Lifespan of farm	30 years
Lifespan of tractor	15 years
Lifespan of harvester	5 years
Lifespan of all other farm machinery	10 years
Quantity of equipment	2 of each type
Maintenance Costs	24% over lifetime
Land condition	< 20% slope
	Initially covered with sparse to moderate stands of large mesquite
	No land forming necessary
Conversion Rate	67 gallons ethanol per ton banagrass

*Explanation of assumption substantiated by references or otherwise explained in each section of the methodology

Production Inputs

Land Preparation

Table 5.2. Energy Intensity of Land Preparation from a State of Overgrown Shrubbery and Trees

	Energy Intensity (MJ/ha)	Energy Intensity (Btu/acre)	Annual Energy Intensity (Btu/acre/year)
Land Clearing	2625	6147873	204929
Technical Services/Labor	1000	2342047	78068
		Total:	282997

Equipment Embodied Energy Calculations – By Cost

As stated in the methodology and literature review, the embodied energy of equipment can be calculated using a variety of methods. The first table utilizes the energy flows by industry in the Carnegie-Mellon input-output table.

Table 5.3. Calculation of Embodied Energy of Machinery Using the Total Cost and the Energy Intensity Given in the Input Output Table

Equipment	Cost Equipment ($)	Total Cost with Maintenance ($)	Cost/Year ($)	Embodied Energy/year (Btu)	Embodied Energy/acre /year (Btu)
John Deere 8430 Tractor	177,560	221,950	29,593	260,574,817	521,150
Austoft 7000 Harvester	179,400	251,160	33,488	884,604,250	1,769,208
Stronga BL600 Agricultural Trailer	23,000	28,750	3,833	50,629,822	101,260
Volvo 8x4 Transport Trailer	124,200	155,250	20,700	273,401,039	546,802
				Total:	2,938,420

Equipment Embodied Energy Calculations – By Weight

The embodied energy by weight calculation uses numbers used by Pimentel in his analysis of embodied energy in farm machinery for corn production: 33,300 Btu/lb of machinery.

Table 5.4. Calculation of Embodied Energy of Machinery Using the Total Weight and the Energy Intensity of Steel

Equipment	Weight (lb)	Embodied Energy/year (Btu)	Embodied Energy/acre/year (Btu)
John Deere 8430 Tractor	22,394	99,366,964	198,734
Austoft 7000 Harvester	61,600	820,004,416	1,640,009
Stronga BL 600 Agricultural Trailer	11,000	73,214,680	146,429
Volvo 8x4 Transport Trailer	25,872	172,200,927	344,402
		Total:	2,329,574

Equipment Embodied Energy Calculations – Shipping

Shipping energy is calculated using the energy intensity of shipping from the Waterbourne Commerce and Statistics Center of 418 Btu/ton-mi, the weight of the machinery, and the assumed distance of 3000 miles.

Table 5.5. Calculation of Energy Intensity in Shipping for Machinery

Equipment	Weight (ton)	Shipping Energy (Btu)	Shipping Energy/year (Btu)	Shipping Energy/acre/year (Btu)
John Deere 8430 Tractor	11.197	14,040,913	1,872,122	3,744
Austoft 7000 Harvester	30.8	38,623,200	15,449,280	30,899
Stronga BL 600 Agricultural Trailer	5.5	6,897,000	1,379,400	2,759
Volvo 8x4 Transport Trailer	12.936	16,221,744	3,244,349	6,489
			Total:	43,890

Fuel Use Calculations

Estimated values of tractor fuel consumption under various conditions were taken from Downs and Hansen (1998). Fuel estimates for planting are divided by 3.7 years because ratoon crops will provide most of the biomass. The sprayers to dispense chemicals will be used twice per ratoon crop, or 3.2 times every year.

Total daily harvested acreage is based on a 226-day growth cycle (1.6 harvests/year) on the 500-acre farm: 2.2 acres/day will be harvested. The Austoft 7000 harvests at a rate of 0.6 acres/hour (Yadav et al 2002), consuming diesel fuel at a rate of 7.1 gal/hr. Given the growth estimates from Kinoshita and Zhou (1999), that amounts to about 82 wet tons of banagrass harvested per day. Fuel estimates for the Cameco 8x4 tipper trailer at a max load of 20 tons, are given both full and empty from Coyne (2007) for their five-mile haul to the conversion plant.

Table 5.6. Fuel Usage for Various Banagrass Farm Operations

Process	**Rate from Literature**	**Fuel Usage (gal/acre/year)**	**Energy Intensity (Btu/acre/year)**
Planting			
Tandem disk harrow	0.65 gal/acre	0.18	26,768
Field Cultivator	0.60 gal/acre	0.16	24,709
Planting row cultivator	0.50 gal/acre	0.14	20,591
Maintenance			
Sprayer	0.1 gal/acre	0.32	48,759
Harvest			
Cane Harvester	11.83 gal/acre*	19.10	2,910,305
In-Field Tipper Trailer	0.60 gal/acre	0.97	147,801
Road Transport			
Tipper Trailers-Full	6.4 mi/gallon	2.28	347,042
Tipper Trailer-Empty	12.24 mi/gallon	1.17	177,970
Total		24.31	3,703,946

*(7.1 gal/hour)/(0.6 acres/hour)

Labor Calculations

Table 5.7. Labor Calculations for Various Banagrass Farm Operations

Farm Operation:	Rate from Literature	Converted Rate (hrs/acre/year)	Energy (Btu/acre/year)
Land prep	3hrs/acre	0.8	148,295
Planting	10hrs/acre	2.7	494,317
Maintenance	1.5 hrs/acre*	2.4	440,733
Harvest	$0.42/ton wet biomass	4.8	881,466
Transport	3 trips/acre/year*	3.0	550,917
		Total:	2,515,729

*calculated from literature

Chemical Inputs – Embodied Energy

Table 5.8. Energy Embodied in Various Chemical Inputs Including Shipping

	Amount (lb/acre/yr)	Conversion (Btu/lb)	Embodied Energy (Btu/acre/yr)	Shipping Energy (Btu/acre/yr)	Total Energy (Btu/acre/yr)
Nitrogen	270	24,500	6,615,000	169,290	6,784,290
Potassium	270	3,000	810,000	169,290	979,290
Phosphorus	180	4,000	720,000	112,860	832,860
Herbicides/ Pesticides*			200,000	Negligible	200,000
				Total:	8,796,440

*Total amount: 736,000 Btu/acre per planting from literature (Karimi et al. 2008)

Production Inputs – Totals

The production of banagrass requires a total of about 18.3 million Btu/acre/year. This number was calculated using the embodied energy calculation that used the IO table (rather than by weight) because the cost calculation was higher. The bulk of the energy required for the production of banagrass is found in the chemicals required to grow the crop.

Table 5.9. Energy Intensity of Production Inputs

Production Process	Energy Intensity (Btu/acre/year)	% of Total Energy
Land Preparation	282,997	1.5%
Equipment	2,938,420	16.1%
Fuel	3,703,946	20.3%
Labor	2,515,729	13.8%
Chemicals	8,796,440	48.1%
Shipping-Equipment	43,890	0.2%
Total	**18,281,422**	

Conversion Energy

The total amount of yield is estimated to be 21.5 tons/acre/year of banagrass, yielding about 1440 gallons of ethanol per acre. As mentioned in the methodology section, there are various estimates for calculating the energy involved in the conversion process. In this research, one conversion method uses calculations from the cellulosic conversion of corn stover estimate given by Luo, et al. (2009) of 9.5 MJ/L ethanol, and assuming 3.5 MJ/L generated from the combustion of byproducts. Pimentel and Patzek (2005) calculated the conversion energy for switchgrass of 6461 kcal/L ethanol or 27 MJ/L ethanol. Their conversion method did not account for the combustion of co-products or the recycling of waste and is not assumed to be efficient in terms of utilizing the lowest energy system to break down the plant matter.

The Pimentel and Patzek (2005) calculation does account for the energy embodied in the building and machinery, which Luo's calculations do not address. The amount assessed for a large, modern ethanol plant (245-285 million L/year) for stainless steel, steel, and cement total 32 kcal/L ethanol or about 471 Btu/gal ethanol. Using the yield statistic of 1440.5 gal/acre/year, this amounts to about 680,000 Btu/acre/year, which is a relatively small part of their total energy for conversion. In Pimentel and Patzek's work the highest energy costs in the conversion process are in electricity and steam energy. When accounting for co-products, assuming the same 3.5 MJ/L can be generated from the combustion of co-products under the Pimentel and Patzek conversion conditions, which was not accounted for at all, the following table was derived giving a range 30 million Btu/acre/year to almost 137 million Btu/acre/year.

Table 5.10. Comparison of Conversion Energy Intensities

		Pimentel and Patzek 2005		Luo et al 2009	
		Without Co-products	With Co-products	Without Co-products	With Co-products
Conversion Rate	(MJ/L)	27	23.5	9.5	6
	(Btu/gal)	95,058	82,751	33,406	21,098
Yield (gal/acre/year)		1440.5			
Energy Intensity (Btu/acre/year)		136,931,049	119,202,816	48,121,343	30,391,669

Table 5.11. Comparison of Conversion Energy Intensities in Luo et al (2009) Factoring In the Embodied Energy of Conversion Plant Construction Materials

Data from Luo et al 2009		With Co-products		Without Co-products	
		With Plant Embodied Energy*	Without Embodied Energy	With Plant Embodied Energy*	Without Embodied Energy
Conversion Rate	(Btu/gal)	21569	21098	33877	33406
Yeild (gal/acre/year)		1440.5			
Energy Intensity (Btu/acre/year)		31,070,145	30,391,669	48,799,819	48,121,343

*From Pimentel and Patzek 2005 assessment of embodied energy in stainless steel, steel, and cement for ethanol conversion plant

Total Energy Yield

Given that the yield of banagrass assumed (from literature) is 21.5 tons/acre/year, and 67 gallons of ethanol can be made from each ton of biomass, the farm has an annual ethanol production amount of just over 720,000 gallons of ethanol/year. The low heat value of ethanol is 75,700 Btu/gal (the high is 83,961 Btu/gal), so using the low heat value of ethanol, a total of over 109,000,000 Btu is produced per acre every year.

NEV

The calculation of the NEV of ethanol production from banagrass grown in Hawai‘i is largely dependent upon the energy consumed by the conversion process. The energy used in the production process, or about 18,280,000 Btu is far less than the 109,000,000 Btu produced by each acre of land. Because the combustion of co-products from the conversion process is optional, the conversion energy has been assessed with and without co-products, similar to Table 5.10. Also, because the conversion numbers from Luo et al (2009) did not include the embodied energy of materials used for conversion plant construction, these numbers have been added, see Table 5.11.

Table 5.12. NEV Calculations for Ethanol from Banagrass in Hawai‘i

<table>
<tr><td>Energy Derived from Ethanol (Btu/acre/year)</td><td colspan="6">109,045,850</td></tr>
<tr><td>Agricultural Production Energy (Btu/acre/year)</td><td colspan="6">18,281,422</td></tr>
<tr><td rowspan="4">Conversion Energy (Btu/acre/year)</td><td colspan="2">Pimentel and Patzek 2005</td><td colspan="4">Luo et al 2009</td></tr>
<tr><td rowspan="2">Without Co-products</td><td rowspan="2">With Co-products</td><td colspan="2">Without Co-products</td><td colspan="2">With Co-products</td></tr>
<tr><td>Without Embodied Energy</td><td>With Embodied Energy</td><td>Without Embodied Energy</td><td>With Embodied Energy</td></tr>
<tr><td>136,931,049</td><td>119,202,816</td><td>48,121,343</td><td>48,799,819</td><td>30,391,669</td><td>31,070,145</td></tr>
<tr><td>NEV</td><td>-46,166,621</td><td>-28,438,387</td><td>42,643,085</td><td>41,964,610</td><td>60,372,759</td><td>59,694,284</td></tr>
</table>

Chapter Six – Conclusions

The Amount of Energy Used in Agricultural Production of Banagrass is Comparatively Small

The energy used for banagrass production is relatively low compared to the total output of energy derived from the ethanol it produces (16% of the total derived energy). The bulk of the energy used in production is embodied in the chemicals necessary for high yields (48%) though fuel-consumption, equipment and labor are also significant factors at 20%, 16%, and 14% respectively. The energy in the chemicals used for this analysis comes to about 8% of the total energy derived from the ethanol produced, and thus still represents a fairly good energy return on investment. Because the chemical needs of banagrass have not been specifically calculated for Hawai‘i, there is some need for more information in order to accurately assess this component. Once yield-optimizing amounts have been determined, chemicals can also be assessed using more specific embodied energy numbers.

Additionally, all inputs will likely be determined based on cost efficiency in meeting the specific needs of the farm with the highest profitability. For example, farm equipment choice will likely be made based solely on cost and reliability. Once optimal amounts of all inputs are determined, a true calculation can be made; however, the calculations in this work were meant to serve as a framework for future calculations that allowed another comparison mechanism for biomass for biofuel production scenarios and show that when accounting for all production aspects, energy intensity of agricultural production is a small compared to the total energy derived from the biomass.

Total Net Energy is Dependent on Conversion Efficiency

There range of conversion energy associated with banagrass conversion to ethanol is 30-137 million Btu/acre/year. It is this large range of energy that governs the outcome of the NEV calculation. Because there is very little information regarding the energy used in commercial-scale cellulosic conversion plants, and much of the technology is experimental and not yet commercialized, calculating the NEV for ethanol from banagrass is dependent upon further analysis of specific conversion mechanisms. Similar to the assumptions necessary for the agricultural production of biomass, many assumptions would be necessary to account for all of the energy of a given conversion plant. Even if there were commercially available large-scale cellulosic conversion plants, a detailed energy calculation would still be riddled with assumptions, though the range of possible energy intensities would most likely narrow significantly.

The NEV for Banagrass Production for Conversion to Ethanol is Most Likely Positive

The energy intensity numbers for banagrass show that it is probably (dependent on conversion, as listed above) a positive energy investment for Hawai‘i because it is unlikely that a conversion plant will not utilize by-products for energy or recycle water, and conversion efficiencies are constantly being improved upon with new techniques (and have been improved upon since the 2005 publication date of the Pimentel and Patzek paper, which uses even older data for its calculation). It is likely that commercial-size plants can have conversion energy costs that result in a positive NEV of banagrass for ethanol production in Hawai‘i, if they are able to capitalize on advancements in the conversion process. A 2006 analysis by Cardona Alzate and Sanchez Toro used a computer model to indicate that there is almost a 20% energy savings for ethanol conversion of woodchips if simultaneous saccharification and cofermentation are used in the processing. Though these numbers are based on a model, they do indicate that the conversion process does have room for additional energy savings. Because the huge range of conversion energy (30 million Btu/acre/year to almost 137 million Btu/acre/year) currently governs the outcome of the NEV calculation, a 20% savings on the upper end of the scale could make NEV positive, as 20% of 137 million Btu is about 27 million Btu, and assessing that savings on the Pimentel and Patzek 2005 numbers with co-products amounts to a negative NEV of -1,000,000 Btu/acre/year. With further energy efficiencies anywhere in the production, it is entirely possible that NEV is zero or positive. It should also be noted here that when using the Pimentel and Patzek (2005) figures for the embodied energy in the steel, stainless steel and cement for plant construction, which amounted to almost 700,000 Btu/acre/year, the NEV for banagrass production including conversion came out positive using the Luo, et al (2009) conversion rate with the energy embodied in the plant accounted for.

Net Energy Value Does Not Necessarily Correlate to Economic Viability

The majority of energy in banagrass production lies in the energy embodied in the chemicals used in production; however, equipment cost is often the greatest expense for most farmers (Massey 1998). Because the cost of goods and services are not often correlated to their energy intensities, and there are many subsidies given to both fossil fuels and ethanol, the true costs of goods and services are unknown and energy costs are not properly factored into any service or product price.

Though a net energy value calculation is a valuable tool in comparing the long-term sustainability, and potentially even the long-term economic viability of a specific renewable energy technology, countless other factors involving end uses, political palatability, social and employment factors, and game-changing technology advancements affect the selection of and investment in renewable energy technologies. However, though NEV calculations do not necessarily predict economic success, poor NEVs can indicate long-term dysfunction of a system.

There are other additional benefits and costs associated with biofuel production. Local production of biomass for fuel would help to reduce Hawai‘i’s energy dependency, and help to keep local money within the economy. In addition to the local investment in energy security, banagrass production on non-prime agricultural land would help to secure the land as agricultural land, lowering its risk for development. By converting the biomass to a liquid fuel, the demand for liquid fuels will be addressed. However, depending on the use of chemicals and land management systems, costs associated with pollution from agricultural production and conversion to biofuels could also factor into the economic equation.

Further Research

Production Details

As mentioned in earlier conclusions, further research can be done in all aspects of banagrass production in Hawai‘i. To better calculate the NEV for banagrass production in Hawai‘i, specific yield information and optimization of yields would help assess the total energy that can be produced.

Conversion Details

Additionally, research should focus on cellulosic conversion processes, particularly the scaling-up of proven laboratory processes. Many aspects of cellulosic conversion are theoretical. A practical assessment would provide interesting information on actual energy needs for conversion; however investment in a large-scale plant to assess the information would be extremely difficult. To aid in the actual production of a large-scale cellulosic conversion plant, there could also be the need for some financial analyses to bring the financing of such an renewable energy venture into fruition.

End-Use Optimizations

Research is necessary to understand and optimize the end-use modifications for biofuel use in Hawai‘i. Though this analysis did not account for end-use modifications, a cradle-to-grave assessment of biofuels in Hawai‘i includes an understanding of this component of biofuel use. Because Hawai‘i is relatively small, its biofuel must meet the standards of engines, generators, transportation and storage equipment produced elsewhere. To understand the true cost of biofuel use in Hawai‘i, these changes should also be accounted for.

Other Types of Energy Assessments

There are a variety of other types of energy assessments that could be done to aid in an analysis of energy use in biomass for biofuel production, or in renewable energy creation in general. Sourcing the energy that is used in the calculation for NEV could also be helpful in determining the renewable energy technologies for Hawai‘i. Similar to emergy calculations, identifying the origin of the energy used in each aspect of production could add some depth to the energy analysis. As mentioned previously, a lifecycle assessment that accounts for end-use modifications could also be a valuable assessment tool. Also, a ratio of input energy to output energy could be another way of evaluating the energy used.

Final Thoughts

Other Crops

Other agricultural crops can also be assessed that will utilize the non-prime land for their ability to meet the energy needs of Hawaiʻi. Other types of biomass, for example, oil crops, tree crops, other grasses, grains, and algae, can all be compared from an energetic standpoint to determine which has a maximum NEV, for either use as a biofuel feedstock or direct combustion for electricity production. Also, a hybrid model of crop use, where part of the crop goes to higher-value products and remaining biomass is left for biofuel production can also be examined for a variety of crops.

Biofuel vs. Direct Combustion

Assessing the best use of any biomass to energy includes assessing whether the biomass is best used as a feedstock for fuel production or as a combustible fuel for electricity production. Though electricity can be created from other sources, there is a need for renewable energy sources that can provide firm, on-demand power, which can be met by the burning of biomass. The burning of ethanol could also be used to create energy, however there is a significant amount of energy lost in the processing of biomass for fuel then burning that fuel for electricity. Understanding the electricity, biomass and biofuel markets as they develop would help to assist in the best use of the biomass produced for energy purposes.

Energy Research in Hawaiʻi

Any research towards renewable energy can help address Hawaiʻi's energy needs and ultimately could factor into the feasibility of production and use of biofuels in Hawaiʻi. Because Hawaiʻi's renewable energy portfolio is so diverse, there are a variety of uses of each renewable energy source, and there is a lot of variability in the potential mix of resources used. Any advancement in fuels, energy storage, energy conversion mechanisms, and end-use technological advancements can change the composition of the renewable energy portfolio. Because of this, in addition to understanding the efficiency of biomass for biofuels, any information about renewable energy advancements helps to figure out a functional energy portfolio for Hawai‘i.

Appendix A – Breakdown of 333111 by Subsector Calculated from the US Census Bureau Current Industrial Reports: Manufacturer's Shipments of Farm Machinery and Lawn and Garden Equipment

Product Code	Product Description	Quantity	Value^	% Parts Given	Estimated Value^*	%of NAICS
333111	Farm machinery and equipment, including parts and attachments	(X)	12,217,607			
	Total Parts (both provided and estimated, Method 1)		1,495,464			12
3331111	**Wheel tractors (except contractors' off-highway wheel tractors, garden tractors, turf tractors, and motor tillers) and attachments ....**	**(X)**	**(D)**		**3,141,539**	**25.71**
	Wheel tractors, farm-type (PTO hp)	(X)	(D)			
3331111101	2-wheel drive, including front wheel assist types	(D)	(D)			
3331111106	4-wheel drive, including tractors with, equal size tires, front and rear	(D)	(D)			
3331111111	Attachments for wheel tractors, farm-type........	(X)	74,421			
333111C116	Parts for wheel tractors, farm-type	(X)	(D)		615,836	
3331113	**Farm dairy machines, sprayers, dusters, elevators,**					

	and farm blowers	**(X)**	**655,633**	**13**	**5.37**
3331113 pt.	Farm dairy machines and equipment …………………	(X)	112,744		
	Parts for farm dairy machines and equipment, replacement units only...	(X)	58,172	**51.60**	
3331113 pt.	Sprayers and dusters	(X)	508,674		
	Power sprayers, field and row crop types only:				
3331113116	Self-propelled	2,614	301,445		
3331113121	Tractor mounted	8,984	19,321		
	Other than tractor mounted:				
3331113124	Power take-off driven, piston pump type...........	709	2,965		
3331113128	Nonpiston pump type	881	4,292		
3331113132	Other power sprayers, over 4 g.p.m.	(X)	(D)		
	Power sprayers, other than row crop and field types, over 4 g.p.m.:				
3331113136	Power take-off driven	263	2,458		
3331113141	Engine-driven...	872	2,962		
3331113144	Air carried type power sprayers (field, row crop, and orchard types)	533	3,870		

3331113148	Foggers and mist sprayers portable..........................	(D)	(D)	
3331113152	Hand-pulled and garden-type,4 g.p.m. and under	(D)	(D)	
	Sprayers, agricultural hand:			
3331113156	Under 1 gallon...	774,597	3,835	
	1 gallon and over:			
3331113161	Compressed air or gas	7,529,525	104,456	
3331113164	Other, including knapsack, hose end and flame sprayers and sprayer pumps.............	(X)	19,167	
3331113168	Dusters, power, hand, all types	81,038	782	
3331113172	All other sprayers	(X)	783	
3331113176	Attachments for sprayers and dusters	(X)	12,229	
333111C223	Parts for sprayers and dusters, replacement units only...	(X)	25,253	4.96
3331113 pt.	Farm elevators and blowers	(X)	34,215	
	Farm elevators, portable:			
3331113181	Single and double chain	3,658	6,935	
3331113188	Auger type	5,216	10,920	

	Other farm portable and stationary augers and elevators	(X)	13,303		
3331113192	Other farm blowers, including forage blowers, combination grain and forage blowers	(X)	2,055		
	Attachments for farm elevators and blowers..........	(X)	1,002		
	Parts for farm elevators and for grain and forage blowers, replacement units only..........	(X)	1,595	4.66	
3331117	**Planting, seeding, and fertilizing machinery ....**	**(X)**	**863,562**	**11.55**	**7.07**
3331117101	Corn planters, corn and cotton planters, and lister plant pull-type and mounted (total rows mounted)..........	(D)	(D)		
3331117108	Grain drills (fixed frame), all types	6,271	89,311		
3331117111	Transplanters (pull-type or mounted) and broadcast seeders (end-gate, mounted and drawn)	7,646	4,942		
	Fertilizer distributors (pull-type or mounted):				

3331117118	Dry, including lime spreaders..................................	9,094	39,590		
3331117121	Liquid and anhydrous ammonia................................	5,407	18,317		
3331117128	Manure spreaders, rear discharge.................................	6,397	38,117		
3331117131	Manure spreaders, side discharge................................	2,238	29,093		
3331117138	Manure pumps, liquid..	976	5,059		
3331117141	Front and rear tractor mounted loaders (farm-type), manure and general utility (except beet and sugar cane loaders)	51,149	116,520		
3331117148	Row crop unit planters (quantity in rows)	39,104	107,030		
3331117151	Other planting, seeding, and fertilizing machinery...	(X)	(D)		
3331117158	Attachments for planting, seeding, and fertilizing machinery	(X)	51,682		
333111C229	Parts for planting, seeding, and fertilizing machinery, replacement units only	(X)	99,750		
3331119	**Harvesting machinery...**	**(X)**	**1,539,440**	**11.73**	**12.60**
3331119101	Combines (harvester-threshers), grain-types only (self-propelled and pull-type)	(D)	(D)		

3331119111	Small grain header for combines, all sizes	9,921	138,291
3331119121	Corn heads, all sizes	2,442	70,659
3331119131	Other grain-type combines	(X)	(D)
	Field forage harvesters:		
3331119141	Shear bar, self-propelled type and pull-type (basic machines)	1,198	30,461
3331119151	Attachments for shear bar type forage harvester	(X)	(D)
3331119161	Flail-type (horizontal knives or vertical free-swinging knives or hammers), including discharge spouts	76	751
3331119171	Other harvesting machinery, including potato diggers, cane harvesting equipment, and picker-shellers	(X)	283,881
3331119181	Attachments for harvesting machinery, including platform and seeder, reel, straw spreaders, load levelers, weed stripper, grate unit, knife grinders, and stalk walkers..	(X)	83,305

333111C22A	Parts for harvesting machinery, replacement units only	(X)	180,546		
333111A	**Haying machinery**	**(X)**	**560,415**	**22.77**	**4.59**
333111A101	Mowers, cutter bar type, including drum and disk	2,799	14,609		
333111A111	Mower-conditioners and windrowers with conditioner auger and draper-type (pull-type and self-propelled)	14,595	227,252		
333111A121	Rakes, side delivery, cylinder type, and finger wheel type	9,812	31,593		
333111A131	Hay balers, hay stackers, (field type), hay bale loaders, bale throwing attachments	(D)	(D)		
333111A141	Other haying machinery	(X)	33,389		
333111A151	Other attachments for haying machinery (stripper, bale chute and knife attachments)	(X)	(D)		
333111C22C	Parts for haying machinery, replacement units only	(X)	127,626		
333111E	**Plows, harrows, rollers, pulverizers, cultivators, and**				

	weeders	**(X)**	**376,922**	**31.61**	**3.09**
333111E pt.	Plows (primary tillage equipment)	(X)	96,230		
333111E101	Subsoilers, deep tillage	4,264	35,782		
333111E109	Terracing and ditching plows	456	1,297		
	Chisel plows, deep tillage (chisel or sweep type):				
333111E111	Pull-type	1,038	17,822		
333111E119	Mounted	799	2,197		
333111E121	Other plows (except snow plows)	(X)	11,595		
333111E159	Middlebusters and disc bedders	2,709	2,893		
333111E131	Attachments for plows (coulters, jointers, root cutters subsoilers, fertilizer distributors, etc.), excluding lister planting attachments	(X)	19,971		
333111E139	Plowshares (quantity in thousands of pounds)	3,790,807	4,673		
333111C22E	Parts for plows (except plowshares, replacement units only)	(X)	44,881	46.64	
333111E pt.	Harrows, rollers, pulverizers and similar equipment (secondary tillage)	(X)	180,274		

333111E141	Spike-tooth harrow sections and spring-tooth and tine-tooth harrow sections	16,946	8,241	
333111E149	Disc harrows, single, tandem, and offset	12,834	75,733	
333111E151	Combination tillage equipment, roller/ harrows, disc or coulter/field cultivators, disc or coulter/spring tooth	5,481	27,332	
333111E158	Blade terracers or scrapers (farm-size)	34,725	19,303	
333111E161	Land levelers	3,485	9,178	
333111E169	Other harrows, rollers, pulverizers, and similar equipment	(X)	28,255	
333111E171	Attachments for harrows, rollers, pulverizers, and similar equipment	(X)	12,232	
333111C22G	Parts for harrows, rollers, pulverizers, and similar equipment, replacement units only............	(X)	41,749	23.16
333111E pt.	Cultivators and weeders	(X)	100,418	
333111E179	Corn and cotton type cultivators, shank and sweep type (front and rear mounted).....................	1,127	6,471	
333111E181	Rotary cultivators, ground and power driven...........	2,682	5,855	

333111E189	Field cultivators	4,835	53,297		
333111E191	Other cultivators and weeders, including tool bars (basic units)	(X)	7,088		
333111E199	Attachments for cultivators and weeders (front mounting frame, disc weeders, rear section, and drawbars)	(X)	27,707		
333111C22J	Parts for cultivators and weeders, replacement units only	(X)	32,510	32.37	
333111G	**All other farm machinery and equipment (except parts)**	**(X)**	**1,889,795**		**15.47**
333111G pt.	Stalk shredders and cutters or rotary mowers (PTO)	(X)	237,603		
333111G102	Flail type (without spout)	2,188	15,063		
	Horizontal blade type:				
333111G104	66 inches cutting width and under	79,016	45,159		
333111G106	Over 66 inches up to 100 inches cutting width	50,821	66,690		
333111G108	Over 100 inches cutting width	14,480	110,691		

333111C22L	Parts for stalk shredders, and cutters or rotary mowers (PTO), replacement units only..................	(X)	32,814	13.81
333111G pt.	Machines for preparing crops for market or for use	(X)	201,181	
333111G112	Feed grinders and crushers, power	(D)	(D)	
333111G114	Feed mixers, farm-size, stationary and portable	2,777	57,222	
333111G116	Combination grinder-mixers	(D)	(D)	
333111G117	Cotton ginning machinery......................................	-	-	
	Dryers (grain, hay, and seed):			
333111G118	Heated air crop dryers	3,905	22,649	
333111G122	Crop drying fans (over 15,000 c.f.m. at approximately 1-inch pressure)	7,164	6,803	
333111G124	Other machines for preparing crops for market or for use	(X)	64,128	
333111G126	Attachments for machines for preparing crops for market or for use	(X)	6,453	
333111C22N	Parts for machines for preparing crops for			

	market or for use, replacement units only................	(X)	37,878	18.83	
333111G pt.	Farm poultry equipment	(X)	308,872		
333111C22P	Parts for farm poultry equipment, replacement units only...	(X)	16,980	5.50	
333111G pt.	Hog equipment	(X)	122,171		
333111C22T	Parts for hog equipment, replacement units only	(X)	(D)		23,949
333111G pt.	Other barn and barnyard equipment	(X)	218,966		
333111C22U	Parts for barn and barnyard equipment, replacement units only	(X)	15,884	7.25	
333111G pt.	Farm wagons, and other farm transportation equipment	(X)	123,370		
333111G172	Wagons (chassis only) and trailer gears, excluding motor trucks, 4-wheel................	16,927	35,808		
	Boxes and racks for mounting on wagons and trailer gears:				
333111G174	Manual unloading or dump	1,035	3,688		
333111G176	Gravity unloading, grain-type only......................	5,270	6,590		

333111G178	Power unloading	2,483	24,655		
333111G182	Boxes with integral running gear, grain- and forage-types	2,761	20,867		
333111G184	Other farm transportation equipment	(X)	30,007		
333111G186	Attachments for farm transportation equipment	(X)	(D)		
333111C232	Parts for farm transportation equipment, including operator cabs for farm tractors..............	(X)	(D)	24,184	
333111G pt.	Irrigation systems	(X)	677,632		
333111C22V	Parts for irrigation systems, replacement units only..	(X)	(D)	132,836	
333111J	Commercial turf and grounds care equipment, including parts and attachments	(X)	1,677,857		13.73

(D) Withheld to avoid disclosing data for individual companies.

(X) Not applicable.

^ Value in thousands of dollars

* Average parts calculated using the average percentage parts that were given. Average: 19.6% parts. Used to estimate withheld data.
Wheeled tractors estimated using total amount given for 333111 and parts numbers including estimates.

Appendix B – Sources for Data Used in Corn NEV Analyses

Inputs	Study	Quantity per acre	Source
Seeds	1	18.7 lbs	Pimentel and Pimentel 1996
	2	18.7 lbs	Pimentel and Pimentel 1996
	3	28739 kernels	USDA 2001 Agricultural Resource Management Survey
	4	25502 kernels	USDA. 1996 Agricultural Resource Management Survey
Labor or Custom Work	1	4.6 hours	National Agricultural Statistics Service 1999
	2	2.5 hours	National Agricultural Statistics Service 1999
	3	$10.12	USDA 2001 Agricultural Resource Management Survey
	4	$6.68	USDA. 1996 Agricultural Resource Management Survey
Machinery	1	49.1 lbs	Pimentel and Pimentel 1996
	2	49.1 lbs	Pimentel and Pimentel 1996
	3	N/A	
	4	N/A	
Diesel	1	9.4 gallons	Wilke and Chaplin, 2000
	2	9.6 gallons	1991 Corn-State, Costs of Production: US Department of Agriculture, Economic Research Service 133 p
	3	6.85 gallons	USDA 2001 Agricultural Resource Management Survey
	4	6.85 gallons	USDA. 1996 Agricultural Resource Management Survey
Gasoline	1	4.3 gallons	Estimated
	2	6.0 gallons	1991 Corn-State, Costs of Production: US Department of Agriculture, Economic Research Service 133 p
	3	3.4 gallons	USDA 2001 Agricultural Resource Management Survey
	4	3.4 gallons	USDA. Agricultural Resource Management Survey
LPG	1	N/A	
	2	N/A	
	3	3.42 gallons	USDA 2001 Agricultural Resource Management Survey

	4	3.42 gallons	USDA. 1996 Agricultural Resource Management Survey
Electricity	1	5.3 kWh	1991 Corn-State, Costs of Production: US Department of Agriculture, Economic Research Service 133 p
	2	5.3 kWh	1991 Corn-State, Costs of Production: US Department of Agriculture, Economic Research Service 133 p
	3	33.59 kWh	USDA 2001 Agricultural Resource Management Survey
	4	33.59 kWh	USDA. 1996 Agricultural Resource Management Survey
Natural Gas	1	N/A	
	2	N/A	
	3	245.97 cu ft	USDA 2001 Agricultural Resource Management Survey
	4	245.97 cu ft	USDA. 1996 Agricultural Resource Management Survey
Nitrogen	1	136.5 lbs	USDA 2002 Agricultural Statistics
	2	132 lbs	1997 Census of agriculture
	3	133.52 lbs	USDA 2001 Agricultural Resource Management Survey
	4	124.5 lbs	USDA. 1996 Agricultural Resource Management Survey
Phosphorus	1	58 lbs	USDA 2002 Agricultural Statistics
	2	53 lbs	1997 Census of Agriculture
	3	56.81 lbs	USDA 2001 Agricultural Resource Management Survey
	4	58.17 lbs	USDA. 1996 Agricultural Resource Management Survey
Potassium	1	68.7 lbs	USDA 2002 Agricultural Statistics
	2	50.9 lbs	1997 Census of Agriculture
	3	88.2 lbs	USDA 2001 Agricultural Resource Management Survey
	4	52.77 lbs	USDA. 1996 Agricultural Resource Management Survey
Lime	1	999.2 lbs	Brees, 2004
	2	623.6 lbs	1997 Census of Agriculture
	3	15.67 lbs	USDA 2001 Agricultural Resource Management Survey
	4	242.18 lbs	USDA. 1996 Agricultural Resource Management Survey

Irrigation	1	3.3 cm	Farm and Ranch Irrigation Survey, 1998: 1997 Census of Agriculture v. 3 Special Studis part 1 280 p
	2	3.3 cm	Farm and Ranch Irrigation Survey, 1998: 1997 Census of Agriculture v. 3 Special Studis part 1 280 p
	3	$0.18	USDA 2001 Economic Research Service and Office of Energy Policy and New Uses
	4	N/A	
Chemicals	1	8.0 lbs	Larsen and Cardwell 1999, and USDA 2002
	2	2.0 lbs	1997 Census of agriculture
	3	2.66 lbs	USDA 2001 Agricultural Resource Management Survey
	4	23 lbs	USDA. 1996 Agricultural Resource Management Survey
Transport	1	271248 Btu	Machinery, fuels and seeds shipped an estimated 1000 km at .83 kcal/km
	2	433832 Btu	Machinery, fuels and seeds shipped an estimated 1000 km at .83 kcal/km
	3	28167 Btu	GREET Model
	4	80819 Btu	GREET Model
Yield	1	137.4 bushels	USDA 2003 Agricultural Statistics
	2	136.3 bushels	USDA 2001 Agricultural Statistics
	3	139.3 bushels	USDA 2001 Agricultural Resource Management Survey
	4	121.9 Bushels	USDA. 1996 Agricultural Resource Management Survey

Study #	Reference
1	Pimentel and Patzek 2005
2	Pimentel 2003
3	Shapouri et al. 2004
4	Shapouri et al. 2002

Appendix C – Calculating Labor Energy from Shapouri et al. 2004

Known information from Shapouri et al. 2004, using data from 2001:

Labor expenditure: 1581 Btu/bushel

Yield: 139.34 bushels/acre

Labor costs: $10.12/acre

From NASS Quick Stats for farm labor (accessed online at http://quickstats.nass.usda.gov/results/6CDE440B-D412-3A03-A7B5-C02B979FD19E?pivot=short_desc):

Average hourly wage for farm labor in 2001: $8.45/hr

Calculation:

(1581 Btu/bushel)*(139.34 bushels/acre)/($10.12/acre)*($8.45/hour)*(8 hours/day) =

1471546 Btu/day

1471546 Btu/day)*(.00105506 MJ/Btu) = 1553 MJ/day

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