THREE ESSAYS ON LIGNOCELLULOSIC ETHANOL DEVELOPMENT IN HAWAIʻI: CROSS-DISCIPLINARY ANALYSES BASED ON GEOSPATIAL, LIFE-CYCLE AND GENERAL EQUILIBRIUM MODELING

A DISSERTATION SUBMITTED TO THE GRADUATE DIVISION OF THE
UNIVERSITY OF HAWAIʻI AT MĀNOA IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY
IN

NATURAL RESOURCES AND ENVIRONMENTAL MANAGEMENT

AUGUST 2013

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Acknowledgement

I would like to acknowledge everyone who has helped make this thesis possible.

First and foremost, I would like to express my deepest appreciation to my primary advisor Dr. John F. Yanagida for his continuous encouragement and patience and allowing me to undertake this interdisciplinary work. Through his guidance, I have learned to grow as an applied researcher by synthesizing new ideas and approaches and learning through trial and error. Like so many students who came before me, I was inspired by his academic dedication, and I am deeply indebted to his academic support and friendship.

Furthermore, I would like to acknowledge my appreciation for my committee members who have generously devoted their time and effort to guide me through my research: Dr. Makena Coffman for her invaluable insights regarding renewable energy development, economic theory, and empirical modeling; Dr. PinSung Leung for his expertise and guidance on mathematical programming and economic/policy assessment; Dr. Tomoaki Miura for his knowledge of geographical information management and analysis; and Dr. Richard M. Ogoshi for his expertise in tropical agronomy and banagrass in particular. Working on an interdisciplinary project was an exciting process due to their intellectual curiosity, camaraderie and readiness to guide.

I was also blessed to work with colleagues who have given me invaluable support, and I would like to acknowledge their contributions: Dr. Ganti S. Murthy and Mr. Kumar Murthy of Oregon State University for their support pertaining to technoeconomic analysis and life-cycle assessment; Drs. Samir Khanal and Devin Takara of MBBM for providing me with field and laboratory data. Through their work, I have been inspired to learn about the ingenuity of bioengineering and the opportunities for a more sustainable economy.

My sincere appreciation is also extended to the East-West Center community, including Ms. Mary Hammond, Ms. Mendl Djunaidy and Ms. Valerie Wong for their continued support which has made my PhD study possible. Also, special thanks go out to my peers at the EWC who, with their high spirits and inexhaustible energy, continued to cheer me on throughout the four years of my academic endeavors.

Abstract

This dissertation examines lignocellulosic bioethanol development in the State of Hawai‘i using banagrass (*Pennisetum purpureum Schum*), as a candidate species. The dissertation is comprised of three essays which examine spatial, environmental, and economics aspects of bioethanol production respectively.

In essay one, geographical information system (GIS) and mixed integer linear programming are combined to identify economically optimal supply chain configuration on the island of Hawai‘i to meet 20% of the island’s gasoline demand and 20% of the state’s demand respectively. In essay two, an attributional life-cycle energy and GHG emissions model is built to compare the biochemical conversion of lignocellulosic ethanol based on the conventional pathway of Simultaneous Saccharification and Co-fermentation (SSCoF) based on dilute acid pretreatment and a novel option of green-processing, which uses freshly harvested banagrass and yields an additional revenue stream of protein-rich fungal biomass *(Rhizopus microsporus var. oligosporus*) as a co-product. In essay three, an agricultural and energy sector-focused computable general equilibrium (CGE) model of Hawai‘i is built to estimate the market, welfare, land-use and GHG emissions impacts of the banagrass-derived bioethanol industry. Together, these cross-disciplinary essays examine the technological and economic feasibility of this emerging bioethanol option in Hawai‘i.

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1. INTRODUCTION

Concerns regarding rising oil prices, rural development and anthropogenic climate change has led to a rapid development of biofuels industry in recent years. Global biofuels market is currently dominated by the so-called ‘first-generation’ technologies derived from food crops such as corn and sugarcane; however, it is increasingly recognized that more advanced conversion options using non-edible biomass is needed to expand biofuel use while reducing adverse impacts on global food prices and the natural environment. The development of these so-called ‘second’ and ‘third’ generation biofuels hence received considerable governmental support including consumption mandates, research development and demonstration (R&DD) grants and subsidies and tax credits in recent years (Rajagopal et al. 2009; UNEP 2009).

This dissertation, through a series of three essays attempts to evaluate one such option of advanced biofuels —lignocellulosic bioethanol in the State of Hawai‘i. This dissertation focuses on a tropical fodder crop Banagrass (Pennisetum purpureum), which is converted to bioethanol using a biochemical conversion pathway based on Simultaneous Saccharification and Co-fermentation (SSCoF) with dilute acid pretreatment. This particular conversion platform is chosen for analysis because this technology is at a fairly advanced stage of RD&D and that banagrass has been evaluated as a potential bioenergy source in Hawai‘i over past decades, offering rich sources of primary data that may be gathered for this interdisciplinary study.

Three essays presented here are cross-disciplinary in nature. Reflecting the applied focus of the natural resources and environmental management (NREM) discipline, this dissertation synthesizes existing knowledge across traditionally separate academic subjects that form the foundation of advanced biofuels development. Also demonstrated are quantitative methodological focuses of NREM doctoral program, which afforded an opportunity to apply analytical tools to tangible policy questions of alternative fuels development.

In essay one, a geospatial optimization model of banagrass-derived lignocellulosic ethanol option combines geographical information system (GIS) and mathematical programming techniques to answer the questions of “how feasible is it to produce banagrass-derived lignocellulosic ethanol in the State of Hawai‘i, in particular to meet the States’ Alternative Fuels Standard (AFS) of 20% of transport fuel demand?” And, “what would an economically optimal supply chain configuration look like, given resources constraints and technological level?” Using the island of Hawai‘i as a case study, the essay integrates a range of agro-environmental and economic indicators and evaluates land suitability, while identifying least-cost configuration of feedstock production and processing site combinations.

The major findings of the essay one echoes results from existing studies. It confirms that the State mandate of 20% transport fuel consumption is technically feasible given land availability. Furthermore, it highlights the interconnectedness of land characteristics, logistical configuration and scale economy of this advanced biofuels option, and provides important insights as to how a small island-based production system such as Hawai‘i may leap benefit through the identification of a least-cost biofuels supply chain configuration. Further, the essay also offers an effective analytical framework which may be expanded for an assessment of inter-island supply chain optimization.

In essay two, life-cycle assessment offers another important aspect of advanced biofuels development—i.e. fossil fuel needed to produce lignocellulosic bioethanol and its overall green-house gas (GHG) emissions. Within the larger discussion of ‘net-energy balance’ and GHG mitigation potential, essay two builds a detailed attributional life-cycle assessment model combining a bottom-up engineering model of ethanol conversion via simultaneous saccharification and co-fermentation with dilute acid pretreatment and publically available transport fuel life-cycle assessment model (GREET), to quantify the energy and GHG impacts of banagrass-derived bioethanol option. In doing so, this essay compares the so-called green processing (an innovative front-end operation using freshly harvested feedstock) and conventional processing based on the use of dried feedstock. Green processing is combined with the production of a high value protein-rich fungal co-product to create an additional revenue stream.

The major findings of essay two offers an important insight into further research and development needs of banagrass-derived bioethanol, and green-processing option in particular. From the well-to-pump and well-to-wheel life-cycle GHG emissions perspectives, biochemical conversion of lignocellulosic ethanol yields limited reduction as compared to gasoline in both conventional and green-processing options. The essay conducts sensitivity analysis and finds that the range of variability in GHG emission estimate is high due to varied assumptions that may be taken regarding the level of technology, unit emissions factor for key inputs and processing configurations.

In essay three, land-use, market and welfare implications of in-state production of lignocellulosic ethanol are evaluated using a general equilibrium framework. The burgeoning ethanol industry creates competition for scarce resources, though policy interventions such as consumption mandates and tax credits are known to have considerable impact on economic welfare (Kretschmer et al. 2009; Ando et al. 2010; McCullough et al. 2011; Taheripouri and Tyner 2012). The essay three conducts numerical simulations based on a static single region 25 sector computable general equilibrium (CGE) model of Hawai‘i calibrated for the year 2007, and estimates the economy-wide impacts of in-state production to meet 10% and 20% of states’ gasoline demand respectively.

The modeling results indicate that the overall economic and GHG impacts at state-level is found to be small: the use of banagrass-derived local ethanol to meet 10% and 20% of mandate will lead Gross State Product to change from -$62.5 million to +$48.6 million. In all scenarios, the use of costlier local ethanol leads to a decline in welfare: resident welfare declines 0.14% to 0.24 % under the 10% mandate and 0.10 % to 0.32 % under the 20% mandate. Assuming that agricultural land endowment is fixed, an increase of 0.1 % and 0.9 % (cropland) 44.0 % and 152.9 % (pasture land), 0.8% and 2.4 % (forest land) and 1.5% and 4.4 % (miscellaneous land) will occur under the 10% and 20% mandate respectively. The cost-effectivness of lignocelluloisc bioethanol also comes under question: the cost of subsidy per tonne of GHG displaced ranges widely from \$226.7/toones of CO2e to \$2,116.4/tonnes of CO2e under the 10% mandate and \$130.1/tonnes of CO2e to \$217.1 tonnes/CO2e under the 20% mandate.

To further explain the policy context and motivation behind this dissertation. The following sections briefly describe biofuels policy in the United States in general and Hawai‘i in particular.

1.2. Biofuels Policy Background

1.2.1. State Biofuels Policy

Public opinion is perceived to be in constant flux, oscillating across three themes of energy security, environment and local jobs.[1] When energy price increases, the public demands an alternative source, while in other occasions they also demand more local jobs. The environment is also perceived to be important, but whether or not it becomes their priority, at any point in time, depends on a number of other variables including prevalent economic and political situations. Within such constraints, the State of Hawai‘i promotes one of the most aggressive alternative fuels mandate within the United States, calling for 20% of transport fuel to be supplied through renewable fuels by 2020 and 30% by 2030. This transport sector initiative echoes the larger across-the-board call for renewable fuels deployment, known as the Hawai‘i Clean Energy Initiative (HCEI) which mandates the use of 70% clean energy use, consisting of 40% renewable energy and 30% improved efficiency (EPA 2012). With crude oil price hovering around \$ 90/barrels since then, this has kept momentum to promote alternatives to crude oil imports which supplies 85% of state’s primary energy demand, costing approximately \$2.6 billion in fuel imports (DBEDT 2011). Furthermore, recent federal-level initiatives, including greening of military fuel consumption have also prompted new interest in advanced biofuels development.

The State of Hawai‘i currently has a number of regulations in support of local biofuels production and ethanol in particular. Both first and second generation ethanol based on a number of potential feedstocks including sugarcane (*Saccarum officinarum*), banagrass, eucalyptus (*Eucalyptus grandis)*, and leucaena (*Leucaena leucocephala*) have been evaluated (Keffer et al. 2009); however, no domestic ethanol production exists at the moment. The barriers to local production stem from a number of factors including: i) lack of a viable production scale, which results in high product costs and persistent barriers, which were not present with former plantation agriculture which used large contiguous tracts of land under its vertical integrated production system; ii) existing infrastructure including irrigation is now dilapidated, and identifying and attracting skilled labor poses new challenges; and iii) recent land fragmentation due to patchy urban development has made these areas more prone to nuisance caused by extensive agricultural production.[2] Whether domestic ethanol production can become feasible remains to be seen, in-state bioethanol consumption is nonetheless expected to increase in the future. The HCEI mid-term roadmap, for example,

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[1] A personal communication with M. Tome September 27 2012.

[2] Personal interview with C. Kioshita August 28 2012.

foresees the continuation of E10 standard to 2015 and 50 million gallons per year of renewable fuel use in the transport sector by 2020, in which [i]deally, as much of the local demand as possible should be met through local sources. (HCEI 2011, pp. 17) These milestones hence beg the questions of whether, and how, local bioethanol production could be made possible, and whether the associated benefits and costs can be estimated.

Table 1-1: A List of Recent Regulations Related to Biofuels Development in Hawai‘i

STATUES	DETAILS
HRS 486J-10 and HAR Title 15, CH35	• Required 10% ethanol use in at least 85% of motor fuel gasoline soil in Hawai‘i
HRS 196-42	• Established an Alternative Fuel Standard (AFS), requiring 10%, 15%, 20% and 30% of highway fuels be supplied by renewable fuels by 2010, 2020, and 2030 respectively.[3]
HRS 269-61-95	• Spelled out biofuel use as part of the Renewable Portfolio Standard (PRS).
HRS 304 A-C, A-D, A-E	• Established a special fund for energy systems development, and called for a comprehensive assessment of biofuels options known as the Bioenergy Master Plan.
HRS 141-9	• Set up an energy feed stock program within Hawai‘i’s Department of Agriculture
HRS 103D-1012	• Specified biofuels procurement preference for State and County agency contacts.
HRS 243-4	• Stipulated alternative fuel tax rates (ethanol: 0.145 times the rate for diesel)
HRS 245-110.3	• Established ethanol production incentive in a form of income tax credit (30% of annual nameplate capacity from 500,000 to 15 million gallons. Available for first 40 million gallons per year)
HRS 201N-14, 205-2, 205-4.5	• Permitted biofuel production and distribution on lands originally classified as agricultural zone districts (must have a capacity above 100,000 gallons).

Source: USDOE AFDC State Incentives and Law Database [4]

Although Hawai‘i faces constraints for small-scale production systems, technical feasibility is repeatedly demonstrated in the existing studies, which provides an important motivation for essay one. The Hawai‘i Bioenergy Master Plan (2008), for example, demonstrates that the state “does have the potential to meet the production scenario goal of 20% displacement of 2007 Hawai‘i fuel consumption (p.1), ” whereas Keffer et al. (2009) concludes that all but two of the 16 feedstock and land use combinations examined in their study “exceeded the State of Hawai‘i alternate fuels target of 20% of motor gasoline consumption by volume” In fact, one of their scenarios “exceed[ed] the State of Hawai‘i’s motor gasoline consumption on an energy

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[3] As of this writing, Hawai’i is among twelve states which stipulate a mandatory blending target of renewable fuels.

[4] http://www.afdc.energy.gov/afdc/laws/ (Accessed October 22, 2011).

equivalent basis (p. 253)". This is further confirmed by the recent study by Black and Veatch (2010) which suggested that "[i]t should be quite achievable for biofuels produced from in-state resources to displace 20 percent of the gasoline and diesel fuel needed for vehicle transportation in Hawai‘i. This could be accomplished using about 10 percent of available agricultural land for energy crop production to supply the required biomass feedstock (p.15)." Hence, it is evident that additional constraints including economical, institutional and social factors increase the difficulties for local bioethanol productions.[5] This dissertation examines and identifies optimal land-use allocation that primarily stem from Hawai‘i's unique agro-environmental advantages offered by its tropical climate and fertile soils.

1.2.2. Federal Biofuels Policy

At the federal level, one of the important drivers for advanced biofuels development is the concern for environmental and social sustainability, in particular the need to mitigate greenhouse gas (GHG) emissions while averting negative impacts on the global food market. The US federal biofuels policy has thus gradually shifted away from corn-based ethanol production, dominant in the current market, to a more sustainable option such as lignocellulosic bioethanol. As of 2007, the revised US Renewable Fuels Standard (RFS) established GHG emissions thresholds for the following four categories of biofuels, and established new consumption mandate accordingly.[6] RFS now foresees biofuels use to reach 36 billion gallons by 2022 with advanced biofuels expected to supply 21 billion gallons, and cellulosic biofuels 16 billion gallons by 2022 (Fig1).[7]

i) **Conventional biofuels** which are derived from corn and achieve at least 20% GHG reduction;
ii) **Biomass-based diesel** derived from vegetable oils, fats or cellulosic materials which achieves at least 50% GHG reduction;
iii) **Advanced biofuels** other than corn-based ethanol which achieve at least 50% GHG reduction, including cellulosic biofuels and biodiesel;
iv) **Cellulosic biofuels** which are derived from lignocellulosic biomass and achieve at least 60% GHG reduction, placing particular emphasis on the use of non-corn based ethanol.

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[5] In promoting local biofuel production at the state level, the inter-state commerce clause of the U.S. constitution has proven to be a significant obstacle. Though a detailed discussion is beyond the scope of this dissertation, the inter-state commerce clause stipulates that state legislatures may not discriminate against in-state vs. out-of-state biofuel production using instruments such as a preferential tax credit or mandates (except when the state government is a buyer, and the mandate applies to the state purchase of biofuels) (Farrell 1997). This leaves state legislatures few options to promote in-state production of biofuels. Some of the common instruments used at present include production subsidies and mandates, which only take effect when local production reaches a certain threshold.

[6] Originally, the Energy Policy Act of 2005 established for the first time a RFS requiring ethanol use of 4 billion gallons by 2006 and 7.5 billion gallons by 2012.

[7] This is further supported by the Food, Conservation and Energy Act of 2008 which supports cellulosic ethanol development through the introduction of a tax credit of $1.01 per gallon for cellulosic ethanol (Schnepf 2012).

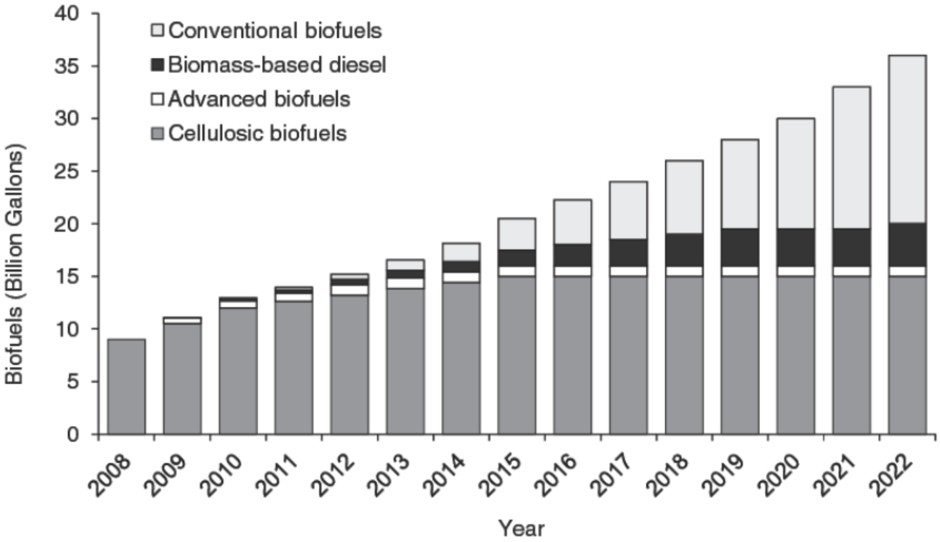

Figure 1-1: Renewable Fuels Mandate According to RFS 2
Source: National Research Council (2011)

Furthermore, the revised RFS also stipulates that feedstocks grown must be grown on agricultural land "cleared or cultivated at any time prior to [December 19, 2007]" to be classified as renewable fuels (EPA 2010). This makes active cropland, pastureland and Conservation Research Program (CPR) land eligible, but tree biomass and residues collected from federal lands are ineligible[8] (Schnepf and Yacobucci 2012).

The call for sustainable biofuels therefore provides an important motivation behind the second essay in particular. The kind of questions relevant to larger discussion of sustainability within current Federal biofuels policy include: i) how will banagrass-derived bioethanol fair in terms of fossil energy use and GHG emissions as compared to gasoline, convention ethanol and other advanced ethanol options derived from common feed stocks currently evaluated including corn-stover, switchgrass, miscanthus and forest residue? ii) how will co-product generation and innovative green-processing option impact GHG emissions, and iii) what are emissions 'hot-spots' where further research and development should be taken to mitigate its life-cycle GHG emissions. The essay two addresses these questions.

1.2.3. Biofuels Economics

The U.S. biofuels industry has received governmental support as early as 1978 when a tax credit of $0.40 per gallon was introduced for both imported and domestically produced ethanol. Since then, domestic policies have continued to favor the use of domestic corn. In 1980, the first duty was introduced on imported ethanol, followed by an increase in the tax credit to $ 0.60 per gallon by the Deficit Reduction Act of 1984 (Schnepf 2012). In recent years, the ethanol industry received further support including: i) the Commodity

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[8] These restrictions also apply to imported biofuels

Credit Corporation (CCC) Bioenergy program provided biofuel producers cash payments of up to $150 million per year from 2003-2006; ii) the Energy Policy Act of 2005 established the Cellulosic Biomass Program, which provides up to $250 million in loan guarantees per facility for bioefuels production, $650 million as research grant, and $550 million to establish DOE's Advanced Biofuels Technologies Program; and iii) the Energy Independence and Security Act of 2007 established the revised renewable fuels standard, favoring advanced fuels production including cellulosic bioethanol; and iv) the Food, Conservation and Energy Act of 2008 supports cellulosic ethanol development through the introduction of a tax credit of $1.01 per gallon for cellulosic ethanol (Duffield et al. 2008. Schnepf 2012). Until the corn-based ethanol subsidy expired at the end of 2011, the US government extended subsidies totaling about $20 billion over the past 30 years.

Such rigorous official support in the form of subsidies, tax credit and mandate has prompted questions regarding its market as well as welfare impacts. While benefits of biofuels development including rural job creation, GHG emissions reduction and energy security are often cited as the rationale behind policy support, it remains debatable as to whether a chosen set of policies may achieve purported objectives and the likely cost of intervention may be justified (Moschini et al. 2010). Such economic and welfare concerns provide rationale for this dissertation work and essay three in particular.

While these are important policy context, the following section briefly discusses –lignocellulosic bioethanol— the technological option chosen for this study.

1.3. Lignocellulosic Bioethanol

1.3.1.Technology Overview

Lignocellulosic biomass generally refers to any biomass composed of i) cellulose, ii) hemicelluloses and iii) lignin, including agricultural residue, forestry waste, wood process residue, and dedicated energy crops. The availability of advanced conversion technologies enables their use as liquid fuels, which is perceived as a preferred alternative to conventional bioethanol for a number of reasons. First, the common second generation feedstocks including agricultural and forest residues are abundant and readily available (IEA 2011; Slade et al. 2011). In the United State as a whole, for example, forest and agricultural land could supply over 1.3 billion dry tons of biomass, enough to meet the goal of replacing 30% of petroleum consumption by 2030 (USDOE/USDA 2005). Second, lignocellulosic biofuels brings a number of environmental and social benefits including prevention of soil erosion, improving soil carbon stocks, water quality and wild habitat, and avoiding direct competition with food production (Tilman et al. 2009). It also brings GHG benefits since second generation biofuels generally require less fossil energy input, as compared to the conventional technology. Second generation feedstocks also require less agrochemical input in general, and have a higher energy yield per land area than conventional food crops (IEA 2008).[9]

Currently, two major pathways—biochemical and thermochemical conversion technologies— are under research and development. In addition, algal biofuel technologies, or the so-called 'third generation' technologies have emerged as an important non-lignocellulosic alternative in recent years. These three technologies combined account for all of the existing efforts that are near commercialization (National Research Council 2011). [10]

Table 1-2: **Corn vs. Lignocellulosic Ethanol Production Cost in 2007 Price**

	Corn Ethanol (Dry Mill)	Lignocellulosic Ethanol (Biochemical)	Lignocellulosic Ethanol (Theormochemical)
Yield	2.66 gal/bu	79.0 gal/dry ton feedstock	83.8 gal/dry ton of feedstock
Feedstock cost ($/gal)	0.78	0.74	0.74
Electricity ($/gal)	0.03	-0.11	0.0
Enzymes ($/gal)	0.05	0.19*	n.a.
Other Cost	-	-	$1.31/gal
By Product ($/gal)	DDGS(-0.29)	Electricity (- 0.11)	Higher Alcohol (-0.24)
Total Cost ($/gal)	1.04	2.15	2.05

Note:* the cost of gluclose for enzyme production

Source: Kwiatkowski et al. (2006); Humbird et al. (2011); Dutta et al. (2011)

The biochemical pathway, adopted for this study, uses chemicals and enzymes to break down lignocellulosic materials and covert them to biofuels.[11] This technology is suitable for the conversion of herbaceous feedstocks such as banagrass which has a lower lignin fraction than wood-based feedstocks (Foust et al. 2009; Khanal et al. 2010). Biochemical conversion of bioethanol consists of four major operations including : i) pretreatment using chemicals (acid or alkali) and/or high pressure and temperature to break down the rigid structure of cellulose, hemicellose and lignin; ii) hydrolysis in which polymers of cellulose and

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[9] Despite these benefits however, the second generation technology also have some drawbacks. In addition to the production cost which remains prohibitive due to complex process requirements, the use of dedicated energy crops may cause adverse direct and indirect land use impacts if it is not managed properly. Furthermore excessive removal of biomass (e.g., corn stover) could harm the environment, while the invasiveness of some feedstocks may threaten native species (Buddenhagen et al.2009). These are the factors that demand close attention when considering second generation biofuel development.

[10] Of those companies planning demonstration facilities, 46% employ biochemical conversion, 28% thermochemical conversion and 26% algal biofuel technology

[11] As a relatively young technology, it is perceived to have further cost reduction potential through research and development (IEA 2008; Foust 2009). Options such as process integration, genetic modification of enzymes, and breeding of better feedstock species are under ongoing investigation (Science Daily 2011).

hemicelluloses are separated as monometric sugars of glucose and xylose and iii) fermentation, which then converts these sugars to ethanol using a yeast fermentation process (Taherzadeh and Karimi 2007; Kumar and Murthy 2011) and iv) distillation which purifies output into anhydrous ethanol. Essay two and appendix 5.1 will provide further details of this conversion process.[12]

As illustrated in table 2, the production cost of biochemical conversion is still prohibitive compared with the conventional corn-based ethanol option. Especially, the high capital cost and high cost of catalysts (enzymes) are the major bottle-necks for commercialization. While an average-size corn-ethanol plant may be constructed at a cost of $2 per annual gallon of ethanol, biochemical conversion requires $4-7 per annual gallon of capital, due to more complex production technology. Therefore, identification of potential synergies including co-product generation is perceived as an important contributor to potential net revenue increases.

1.3.2. Banagrass as candidate species

This dissertation focuses on Banagrass as a candidate feedstock for lignocellulosic ethanol conversion.

Table 1-3: Banagrass Characteristics (Source: Skerman and Riveros 1990)

	DESCRIPTION
Scientific Name	*Pennisetum purpureum Schum*
Natural Habitat	Damp grassland, forest edges or by cultivation
Latitude/ Altitude Range	Typically between 10N and 20S/ sea level to 2,000m
Characteristics	Robust growth with a vigorous root system
Seasonal of Growth	Summer
Optimal Temperature	Typically 25-40 with mean 21.1 +or-2.8°C
Min Temp for Growth	15°C
Frost Susceptibility	Susceptible
Drought/Flood/Salinity Tolerance	Drought tolerance due to the deep root system/flood intolerant/ salinity tolerance not recorded
Natural Ability to Spread	Spreads slowly, thus is typically planted
Natural Ability for Weed Competition	Able to surpass weeds once established
Natural Response in Fire	Will burn in very dry conditions, followed by new growth. However, natural conditions are usually not dry enough for it to burn
Invasiveness	Listed invasive in the Pacific islands

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[12] For pretreatment, a range of options including dilute acid, steam explosion, hot liquid water, AFEX and ARP achieve a varying degrees of sugar release at different levels of variable costs and energy intensity. For hydrolysis and fermentation, options such as Separate Hydrolysis and Fermentation (SHF), Simultaneous Saccharification and Fermentation (SSF), Simultaneous Saccharification and Co-fermentation (SSCF) and Consolidated Biomass Processing (CBP) are at varying stages of research and development (Menon and Rao 2012). Using different process configurations, biochemical conversion also produces drop-in fuels including biobutanol and aviation fuel (Rajagopal et al. 2009; Menon and Rao 2012).

Banagrass, also known as Napier and Elephant grass, is one of the highest yielding C4 grass, native to subtropical Zimbabwe. Morphologically, banagrass resembles sugarcane with broad leaves with thick stems and is known for its robust growth and drought tolerance. These attributes make banagrass one of the most economically valuable forage species, widely grown in wet tropics (Skerman and Riveros 1990). Banagrass was first introduced to Hawai‘i from Australia in the mid-1970s, followed by a number of field trials to examine its potential as an energy crop, administered by the Hawai‘i Agriculture Research Center (HARC) and other state and federal institutions. Field trials conducted in Hawai‘i have demonstrated its rapid growth and high yields.

1.3.3. Organization

The following chapters provide three essays. Chapter 2 examines optimal biofuel plant site selection for banagrass-derived bioethanol and considers transportation costs and other important factors necessary for strategic industry development. Chapter 3 analyzes the life-cycle energy and GHG footprints of banagrass-to-bioethanol conversion. Chapter 4 builds a CGE model of the Hawai‘ian economy and estimates potential economy-wide impacts of the biofuels industry, which consists of feedstock production and processing. Lastly, Chapter 5 synthesizes important observations made in the preceding chapters and draws major conclusions.

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2. COMBINED GIS AND MIXED INTEGER LINEAR PROGRAMMING (MILP) OF BANAGRASS-BASED BIOETHANOL PRODUCTION IN HAWAI‘I

2.1. Introduction

In recent years, there has been considerable interest in the development of alternative energy sources including biofuels. While world production of biofuels is currently concentrated in a handful of countries, including the United States, Brazil and Europe, as much as 72 countries, provinces and states are now adopting mandates, and its use is expected to increase in the near future (REN21, 2012). As the debate over ‘food versus fuel’ illustrates, future increases in energy demand must be met with the use of non-food based biofuels that may mitigate adverse impacts on the environment including global Greenhouse gas (GHG) emissions and global food prices. The State of Hawai‘i, in its effort to achieve clean energy goals, also adopted one of the most aggressive targets for state-level alternative fuels standard; the Hawai‘i Revised Statues 196-42 calls for 15% of highway fuels to come from renewable sources by 2015, 20% by 2020, and 30% by 2030 (State of Hawai‘i, 2010). With no ethanol production currently taking place locally, this has raised questions as to whether local bioethanol production is possible (Hao, 2007; Arakawa, 2008; Yonan, 2010; Borreca, 2011).

In a small production system like Hawai‘i, the optimal siting of bioethanol facilities is one of the key criteria in order to achieve economic and sustainable local biofuels production. For biofuels production to be environmentally and socially sound, production activities must be strategically located in suitable areas and such locations must enable economically rational logistic operations. Criteria that would underpin the optimal locations include land characteristics, accessibility to key infrastructures such as major roads and ports; in addition, environmental constraints such as water availability is of particular importance, since lignocelluloses conversion is a relatively water-intensive process (Aden, 2007). The sizing of a plant is also important, since trade-off between economies of scale in plant size and diseconomies of scale in feedstock transportation cost is a key factor affecting ethanol production cost (Kocoloski, Griffin, and Matthews, 2011; Leboreiro and Hilaly, 2011; Rosburg and Miranowski, 2011).

The importance of supply chain components is well illustrated. In the case of dedicated energy crops, harvest and transportation generally accounts for a large portion of production costs. For Banagrass, it estimated to account for approximately 38% of its production cost (Black and Veatch, 2010). This makes geospatial analysis one of the most important first steps in sound bioethanol development planning, and an ideal modeling framework should be flexible enough to allow for evaluation of multiple feedstock options, conversion technologies, and inter-island supply chain optimization in the case of island economy such as Hawai‘i. The present study proposes a combined Geographical Information System (GIS) and mixed integer linear programming (MILP) based approach to find optimal siting of feedstock production and bioethanol processing facilities and applies it to the island of Hawai‘i, using Banagrass as a candidate species. In particular, this study aims to: 1) identify whether the island of Hawai‘i has enough land to produce lignocellulosic ethanol to meet the State's alternative fuels standards; 2) find optimal configuration of biomass production and processing sites; and 3) estimate total cost of feedstock and ethanol production for selected sites. Given the anticipated growth in renewable fuels use in Hawai‘i, this study considers the following scenarios: 1) to meet 20% of island's current gasoline demand; and 2) 20% of State's gasoline demand.

2.2. Literature Review

GIS, as an analytical tool, has a particular advantage in this type of analysis, because of its ability to integrate a wide array of spatial and non-spatial information. It performs analyses at varying geographical scales, produces outputs that are visual and accessible to a wide array of stakeholders, and has thus played an important role in biomass-based energy planning (An, Wilhelm, and Searcy, 2011). Thus far, GIS analyses have primarily focused on two important aspects of biomass-energy planning: 1) biomass resource assessment and 2) optimal logistic planning.

In the field of resource assessment, Ranta (2005) used a GIS-based model to estimate logging residue availability in Finland. Beccali et al. (2009) integrated environmental and economic data using GIS to estimate biomass potential and production cost in Italy. Lovett et al. (2009) performed GIS-based suitability and yield modeling to estimate land potential for Miscanthus in England. Fiorese and Guariso (2010) used a GIS-based suitability model and optimization technique to estimate land availability and optimal allocation of woody and herbaceous crops in Italy. Zhuang et al. (2011) used GIS to estimate the area of marginal land and potential yield of bioenergy crop in China. In the context of Hawai‘i, a number of studies, including Liu, Phillips, and Singh (1992), Liang, Khan, and Meng (1996), and Keffer et al. (2009), have incorporated GIS and estimated technical potential of biomass production. For most of these studies, information on land availability and environmental characteristics (e.g., soil characteristics, topography and climate), yield potential and land use patterns were important factors determining the biomass resources availability in the region.

For optimal logistic planning, a number of GIS-based modeling studies were developed: Noon, Zhan, and Graham (2002) demonstrated the usefulness of a GIS-based marginal price surface approach in optimizing switch grass-to-bioethanol plant selection in Alabama. Ma et al. (2005) integrated GIS and Analytical Hierarchy Process (AHP) for animal waste anaerobic digester site selection in New York. Panichelli and Gnansounou (2008) proposed a GIS-based algorithm to solve a location-allocation problem in the presence of ranging farmgate price and resource competition and performed multiple site selection of biomass-to-power plants in Spain. Perpiñá et al. (2009) used a two-stage GIS method incorporating suitability modeling and network analysis for forest and agricultural residue-based bioenergy plant selection in Spain. Wu, Wang, and Strager (2011) used two-stage GIS modeling based on fuzzy logic prediction and compromise-programming to identify the best woody biomass plant site in West Virginia. Zhang et al. (2011) proposed another two-stage GIS method using suitability and transport cost model to choose the best wood-biomass plant location in Michigan.

Building on these studies, this study employs a GIS-based methodology to determine optimal biofuels production logistics, including locations, sizes and capacities. This method consists of three main stages, namely 1) suitability and yield modeling; 2) origin-destination (OD) cost matrix based network analysis and 3) cost-minimization model using mixed integer programming. The following section explains the study site and frameworks adopted for this study.

2.3. Methodology

2.3.1 Study Site

The study site, the island of Hawaiʻi, is the largest island in the state of Hawaiʻi with a total land area of 10,104 km^2 (2,573,400 acre), comprising roughly two thirds of the state's land. It has a population of 185,079, and serves as the hub of agricultural production: of the total land area, 47% is classified as agricultural land, 51% conservation and 2 % urban according to the State Land Use Districts categorization) (State of Hawaiʻi, 2010b; State of Hawaiʻi, 2013d).[13]

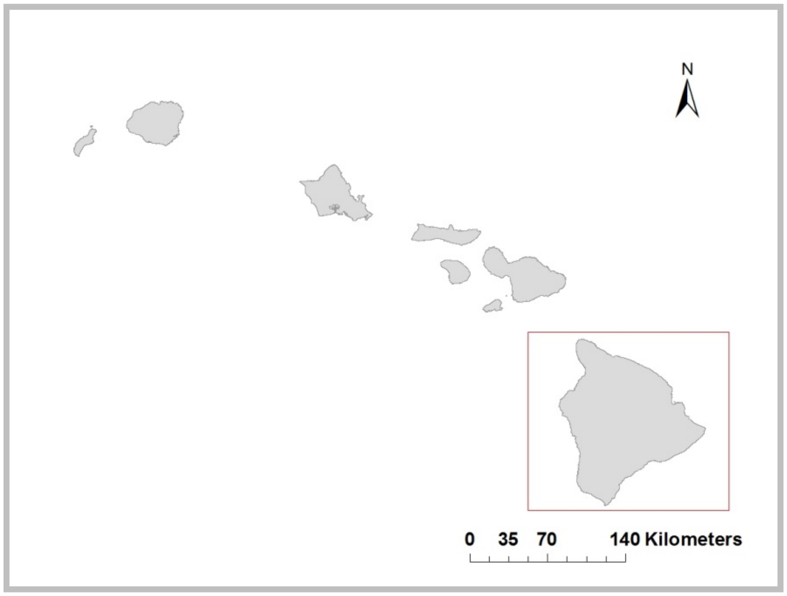

Figure 2-1: **The study site-the island of Hawai ʻ i**
Source: Authors based on State GIS program

As pointed out by a recent report by Melrose and Delparte (2012), however, land currently under active agricultural use is much smaller than official classification. Of those areas classified as agricultural land, "just 4% is in active crop production, 2% is in commercial forestry, 40% is in pasture use" and "[t]he remaining 54% of State designated land is un-used" (p. 32). Furthermore, agricultural land area in Hawaiʻi is

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[13] Under the State Land Use Law, the Hawai'i State Legislature adopted this particular method of land categorization as a way to preserve and manage land in 1961.

also classified according to the Agricultural Land of Importance to the State of Hawaiʻi (ALISH), which has three land categories: Prime, Unique and Other. To illustrate the extent of overlap of these two classifications, of the land classified as Agricultural Land based on the State Land Use District, some 47% are also given the ALISH classification: Prime 463 km^2 (114,501 acres), Unique 6.8 km^2 (1,686 acres) and Other 1764 km^2 (436,000 acres).[14]

The food vs. fuel debate carries much relevance to a small island like Hawaiʻi, where the majority of food produce is imported (State of Hawaiʻi, 2008). Recent years have hence seen a growing awareness among local communities as to the need for locally sourced food. To avoid direct competition between food and energy crop production, this study incorporates up-to-date information on cropland usage on the island based on Melrose and Delparte (2012) and excludes those areas that are currently in active crop production.[15] To further ensure that the most productive land will be available for food crop production, this model only uses those land areas classified as 'non-prime' and 'non-unique' based on the Agricultural Land of Importance to the State of Hawaiʻi (ALISH) classification.

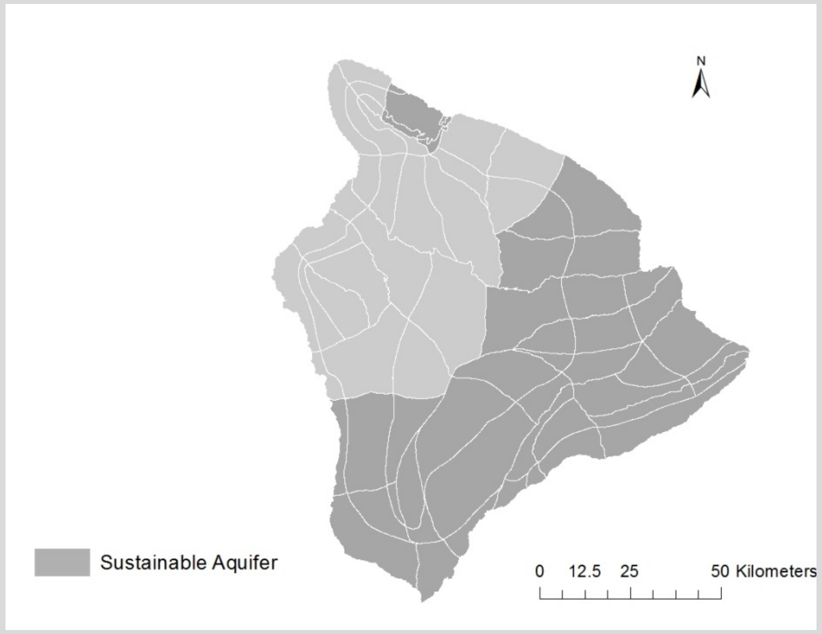

Figure 2-2: **Aquifers deemed sustainable**
Source: Author based on Fukunaga and Associates 2010 and State GIS program.

Water is another important and often contested resource in Hawaiʻi. This is because the island's climate is categorized by uneven rainfall which renders some areas less suitable for crop production and water demand is expected to increase due to future population growth and economic activities on the island. The

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[14] The ALISH classification is based primarily on the suitability of land to grow high value crops in Hawaiʻi: Prime land generally follows the pattern of former sugarcane plantations, whereas unique land is mainly used for coffee and taro production. Finally, other land is generally used for pasture or no agricultural production is taking place at the moment (Melrose et al., 2012).

[15] The area under active pasture use is included for this analysis.

island has year-around warm temperature—suitable for perennial crop production. Annual mean rainfall of 204 mm/year on the leeward side is insufficient to grow Banagrass without irrigation, while 7,600 mm/year observed on the windward side is more than sufficient (Giambelluca et al., 2011).[16]

Because of this highly uneven rainfall, some aquifer systems within the island are deemed unsustainable in the longer term: of the 24 aquifer system on the island of Hawaiʻi, water demand in 9 areas on the leeward side are expected to surpass their sustainable yields by 2025 (Fukunaga and Associates, 2010). To avoid unnecessary competition for water, this study selects candidate sites among those areas where expected demand in 2025 is below sustainable yield.

2.3.2. Candidate Species

Banagrass, also known as Napier or Elephant grass[17], is a high yielding perennial crop, native to subtropical Africa. It was originally introduced in Hawaiʻi in the mid-1970s from Australia, and has been used locally as windbreaks and more recently as a potential bioethanol feedstock. Banagrass is known for its robust growth and high biomass yield potential.

Table 2-1: **Irrigated Banagrass yield from past field trials in Hawaiʻi.**

Location	Plant (dry t/acre/yr)	Ratoon (dry t/acre/yr)	References
Mauna Kea Agribusiness Co	19	48	Kinoshita et al. 1995
HC&S Co.	17	41	Kinoshita et al. 1995
McBryde Sugar Co.	15	32	Kinoshita et al. 1995
The Lihue Plantation Co.	17	42	Kinoshita et al. 1995
Waialua Sugar Co.	24	47	Kinoshita et al. 1995
HARC Breeding Station	26	30	Osgood et al. 1996
Hoolehua	59	67	Kinoshita et al. n.d.

Past field trials in Hawaiʻi demonstrated high yields ranging from 15 to 59 dry tons/acre/yr for plant crops and 30 to 67 dry tons/acre/yr for ratoon crops (Table 1). These field trial demonstrated that: i) banagrass achieves high yield under sufficient irrigation and fertilization, ii) ratoon crops in general achieved higher yield than planted crops, and iii) crops grown during summer months achieved higher yield than those grown during winter months (Kinoshita et al., n.d.) .With the tropical climate of Hawaiʻi allowing for year-round harvests, Banagrass has been identified as one of the most economically viable energy feedstock option in Hawaiʻi (Tran et al., 2011). Furthermore, an innovative green-processing of banagrass—which eliminates

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[16] Banagrass is relatively drought tolerant, and may grow under annual rainfall as little as 350mm/year (Van Den Burg et al., 2001). Of course the use of annual rainfall as the sole criterion may not be sufficient in some cases, in which monthly and seasonal variability may be a mismatch with the water demand needed at various growth stages for banagrass. Due to data limitations, however, this study makes a simple assumption that non-irrigated banagrass production is infeasible in those areas with annual rainfall less than 350 mm/year.

[17] Other common names of this forage grass include gigante (in Costa Rica), mfufu (in Africa) (Skerman and Riveros, 1990).

extensive drying and storage process— is also demonstrated to be feasible at lab scales Takara and Khanal, 2011). Banagrass may be harvested mature (around 8 month) or younger depending on the needs, and it is carried out using sugarcane harvesters with minor modifications and in-field tipper trailers. This is followed by trucks for delivery to processing sites (Kinoshita et al., 1995).

2.3.3. Modeling Framework

Fig. 2.3 explains the overall modeling flow adopted in this study. The models adopted for this study includes: i) suitability modeling, which identifies candidate biomass production and processing sites, ii) yield estimation for rain-fed banagrass production; iii) GIS network analysis based on the existing road network and geocoding of blending sites which allows for the calculation of biomass hauling costs, and iii) data analysis using a mixed integer linear programming approach to identify the least-cost supply chain configuration. The following section explains the details of each module.

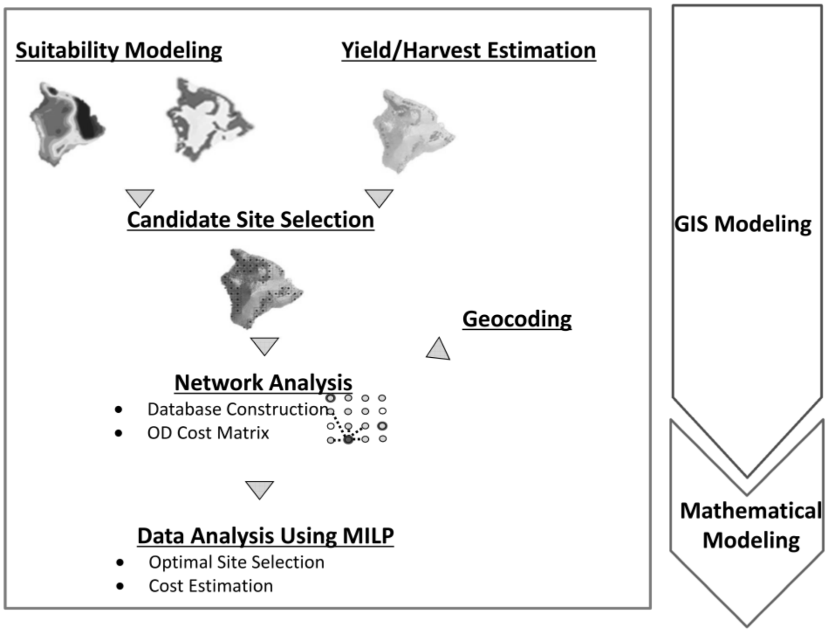

Figure 2-3: **Modeling Frameowork Adapted for Chapter 2**
Source: Author

2.3.3.1. Suitability Modeling

Land-use suitability analysis is one of the widely applied methods in GIS based land use planning, in which lands are selected based on characteristics which meet the specific requirements, restrictions and preferences of specific land uses (Malczewski, 2004). This study adopts a number of criteria that are deemed important for the production of banagrass and processing of bioethanol (Table 2). Most of the criteria are based on the literature, while others are added to reflect the locally specific constraints on the island.

Table 2-2: **Suitability criteria selected for this study**

Criteria	Description	Resources
Banagrass Production Sites		
Land Classification	• Land is classified as Agricultural Land under State LUD • Land that is not classified as Prime nor unique Agricultural Land • currently not in active crop production, nor classified as reserve land • Slope above 20%, rocky areas excluded	• Criteria: Primarily based on [11], adjustments are made to reflect the outputs of recent land-use survey [29]. • Data: Black and Veatch, 2010 and Melrose and Delparte, 2012.
Water Resource Availability	• Annual Rainfall of at least 350mm/year	• Criteria: Van Den Burg et al., 2001. • Data: Giambelluca et al., 2011.
Ethanol Processing Candidate Sites		
Proximity to Major Roads	• Within 3200m of major highways	• Criteria: Wu et al., 2011. • Data: State of Hawaiʻi, 2013c.
Proximity to Blending Areas	• Within 50km of blending sites	• Criteria: locally specific criteria added for this study. • Data: Phone interviews with local fuel distributors.
Land Area	• Must have at least 40 acres of land	• Criteria: Clean Fuels Development Coalition et al., 2006. • Data: Black and Veatch, 2010.
Land Classification	• Land is classified as Agricultural Land under State LUC • Land that is not classified as Prime nor unique Agricultural Land • currently not in active crop production, nor classified as reserve land • Slope above 20%, rocky areas excluded	• Criteria: Primarily based on Black and Veatch, 2010, adjustments are made to reflect the outputs of recent land-use survey Melrose and Delparte, 2012. • Data: Black and Veatch, 2010 and Melrose and Delparte, 2012.
Water Resource Availability	• Within those aquifer systems , whose water demands in 2025 are below their sustainable yields	• Criteria: Locally specific criteria adopted for this study. • Data: Fukunafa and Associates, 2010 and State of Hawaiʻi, 2013a.
County Zoning	• Exclude mixed Ag/Residential Area (500 meter buffer zones)	• Criteria: locally specific criteria added for this study. • Data: State of Hawaiʻi, 2013e
Natural Hazards	• Areas that are not prone to volcanic hazards	• Criteria: locally specific criteria added for this study. • Data: State of Hawaiʻi, 2013b

First, land classification is an important constraint in biomass production. For this study, land that is classified Agricultural land under the State Land Use District categorization and as non-prime and non-unique based on the ALISH categorization was used. In addition, the areas under active crop production and under forest reserves were excluded from the analysis. Since Banagrass production will likely require the use of agricultural machinery, the areas of slope above 20% with rocky surface was also excluded (Black and Veatch, 2010). Second, the areas with rainfall below 350mm/yr were also excluded from the analysis, since rained production of banagrass will not be feasible under the extremely dry weather condition (Van Den Burg et al., 2001).

For bioethanol processing candidate sites, this study further selected the areas based on logistical, social and environmental concerns. First, the study selected those lands that are close to major highways, so as to facilitate the hauling of biomass to and from the field. Single ring buffers of 3,200 m was created based on the cut-off criteria (Wu et al., 2011) Second, the distances to existing blending sites were also taken into account, since processed ethanol must be transported to blending sites for distribution within the island, or for further shipment to neighboring islands. For this, the study selected the cut off criteria of 50 km from existing blending sites. Other criteria including aquifer sustainability, lava hazards, and presence of mixed agricultural and residential zoning areas were also taken into account, as water availability, volcanic hazard risks and proximity to residential areas are locally specific conditions that affect the suitability of land for biofuels processing.

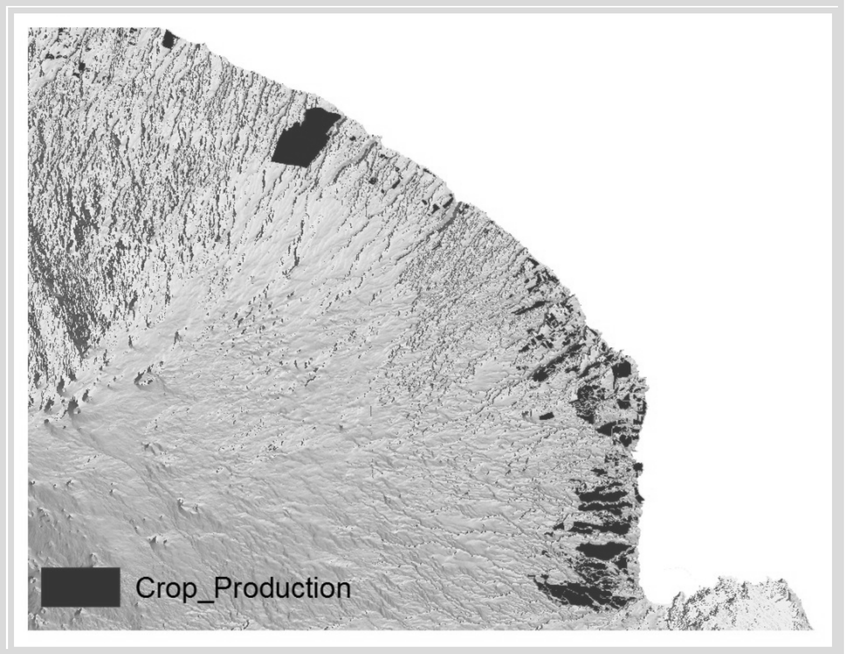

Figure 2-4: **Areas of Active Crop Production**

Source: Author based on Melrose and Delparte (2012)

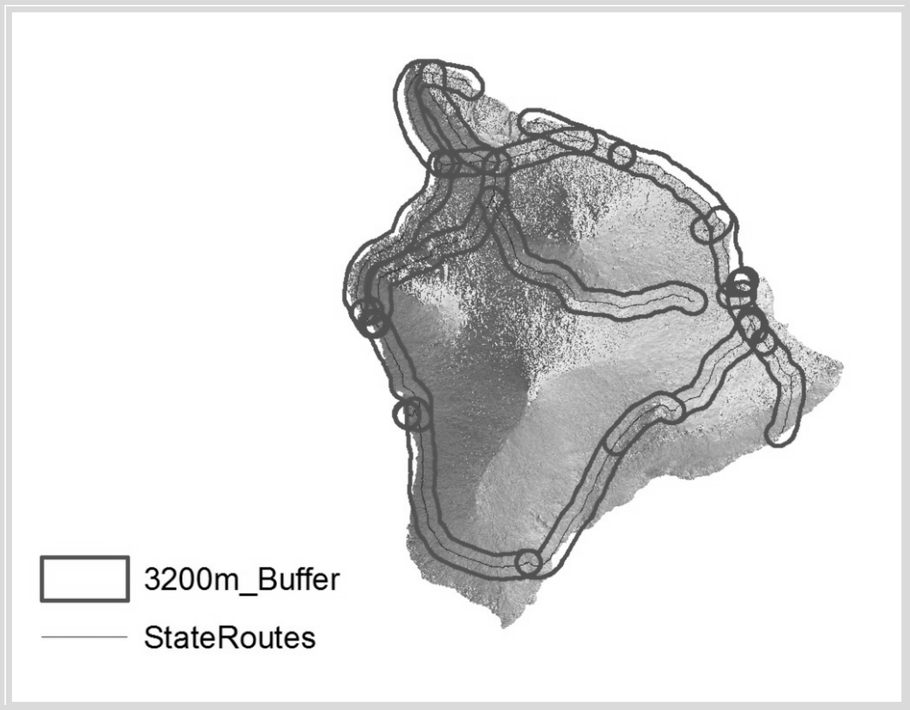

Figure 2-5: **Road Buffer Areas**
Source: Author based on State GIS program

For site selection, agricultural zoned land (non-prime and non-unique agricultural land currently neither under active crop use nor classified as reserve land) was divided into 3 km-by-3 km square grids using a grid index feature tool available from Arc GIS. These potential sites were then filtered based on the criteria listed in Table 2, which yielded 587 sites that were regarded as “potential biomass production sites” (Fig. 2) and 9 sites that were classified as “potential ethanol processing sites.”

2.3.3.2. Yield and Harvest Estimation

This study estimates rain-fed banagrass yield based on land characteristics, namely soil moisture and temperature. Hawai‘i, despite its small land mass, hosts a remarkably diverse set of soils: 10 out of 12 soil orders in the world are found in Hawai‘i with 190 soil series offering diverse properties and behaviors (Hue et al., 2007). These diverse soils provide an important foundation for our yield estimation.[18] For isohyperthermic soils, rainfed yields were assumed as 21.5 ton/acre (ustic)[19], 26.8 ton/acre (udic) and 14.1 ton/acre (aquic). For isothermic soils, these were assumed as 7.5 (ustic), 7.5 (udic), and 6 (aquic)[20]. Finally, for isomesic soils, these were assumed as 7 ton/acre (ustic) and 8.2 ton/acre (udic) respectively. Since

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[18] Because yield information from rain-fed banagrass trials is limited, assumptions are introduced based on irrigated yield observations when necessary. Otherwise noted, rain-fed yields are as recorded in Black and Veatch, 2010).

[19] Assumed that yield is 1/2 that based on irrigated trials as recorded in Black and Veatch, 2010 .

[20] For isothermic soils, it is assumed that yield is ¾ that based on irrigated trials as recorded in Black and Veatch, 2010 .

banagrass cannot be grown under low rainfall conditions, those areas with less than 350 mm of rainfall/year were omitted for this study and all aridic soils are given an assumed yield of zero. Also, this study assumes harvesting efficiency of 73%, so that 27% of yield will be left in the field (Osgood, Dudley, and Jakeway, 1996).

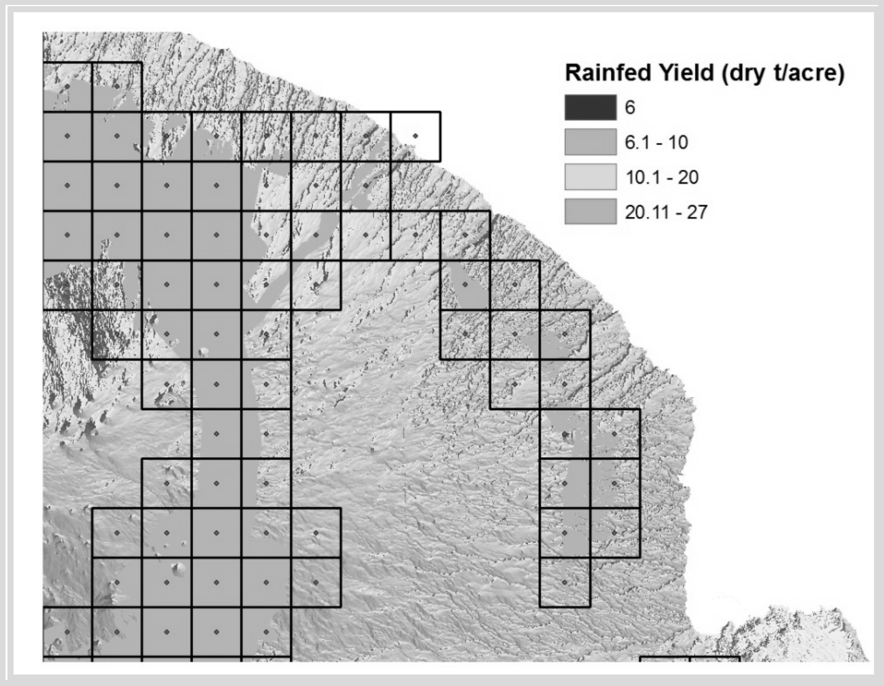

Figure 2-6: **Yield Estimation Based on Rainfed Banagrass Production**
Source: Author based yield calculation

2.3.4. Banagrass to Ethanol Cost Minimization Model

The cost minimization model is built using GIS Network Analyst available from ArcGIS 10 (Esri, Redlands, California, USA) and mixed integer programming. To perform cost minimization, this study first builds the network analysis dataset based on existing road networks, geocodes for existing ethanol blending facilities, and incorporates this information to the OD cost matrix tool. Outputs calculated using the GIS interface are then modeled using the mixed integer programing framework.

2.3.4.1. Network Analysis—OD Cost Matrix

Network datasets represent key attributes of the existing road network, thereby enabling realistic modeling of transportation logistic optimization problems. The concept of ‘network’ is synonymous to a ‘graph’ used in the graph theory, in which relationship between objects or nodes are expressed in relations to links which connect them. More specifically, a network is valued in that links contain attributes regarding its lengths and other information. In the Arc GIS environment, a network consists of three elements of i) edges which represent streets in a form of line features, ii) junctions which represent crossing or connecting of edges as point features; and iii) turns which define how traffic may flow between connected edges (Fig 2.7). Edges, junctions and turns combined represent the geographic connectivity of locations, and how one may travel from one location to

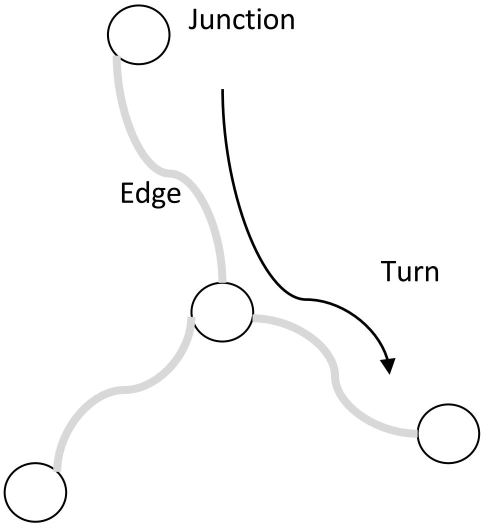

Figure 2-7: **A graph representation of street network**
Source: Author's adaptation[21]

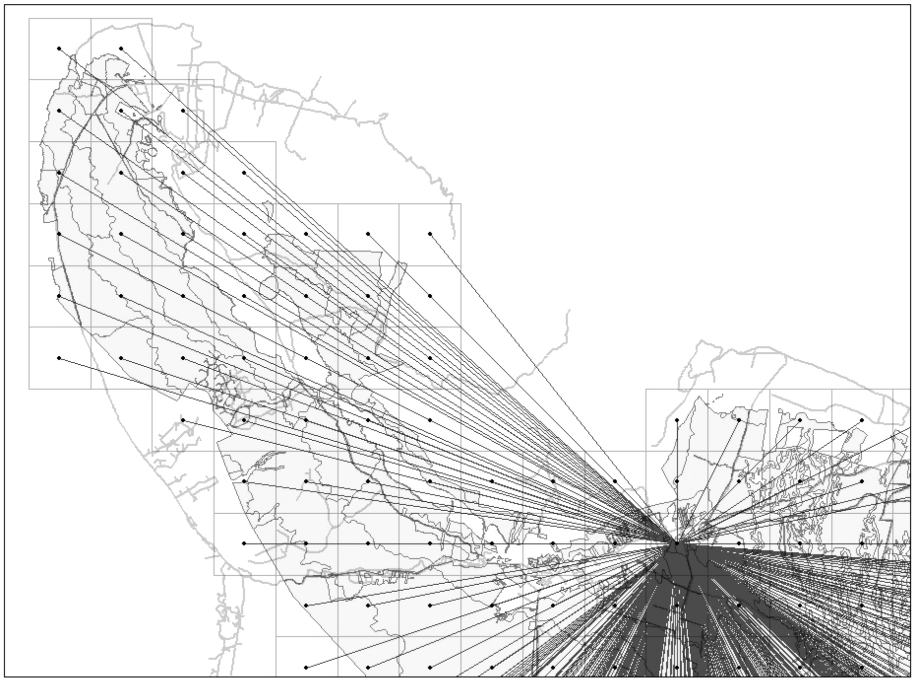

Figure 2-8: **OD Cost Matrix Implementation**
Source: Author based on modeling results

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[21] http://resources.esri.com/help/9.3/arcgisengine/dotnet/e084da94-d4f7-4da7-86ed-7df684ff2144.htm

another. Attribute information such as such as elevation, slope and traffic restrictions (one-way streets, etc.) of existing road networks are taken into account to allow for a realistic modeling of transportation. To represent existing road networks, the network dataset is generated using the North America Detailed Street Map available from ArcGIS online (Esri, 2007). Based on phone inquiries with local blenders, the addresses of three blending sites on the island were obtained. This information is then incorporated into a GIS layer using the Address Geocoding function.

Distances needed for biomass collection and ethanol distribution for each candidate site are calculated using the 'OD Cost Matrix' function available in the GIS Network Analysis tool. In ArcGIS 10, the OD cost matrix identifies and calculates least-cost paths from a specified number of origins to various destinations. This study calculates OD cost matrixes from origins (i.e. potential candidate processing sites) to destinations (i.e. potential banagrass production sites). For this step, distance is measured as meters traveled on existing roads rather than straight-line distance. In a similar manner, the OD Cost Matrix tool calculates driving distance from each candidate processing site to the three blending sites on the island. These data are then exported as comma-separated values (CSV) files and will be used for the subsequent analysis.

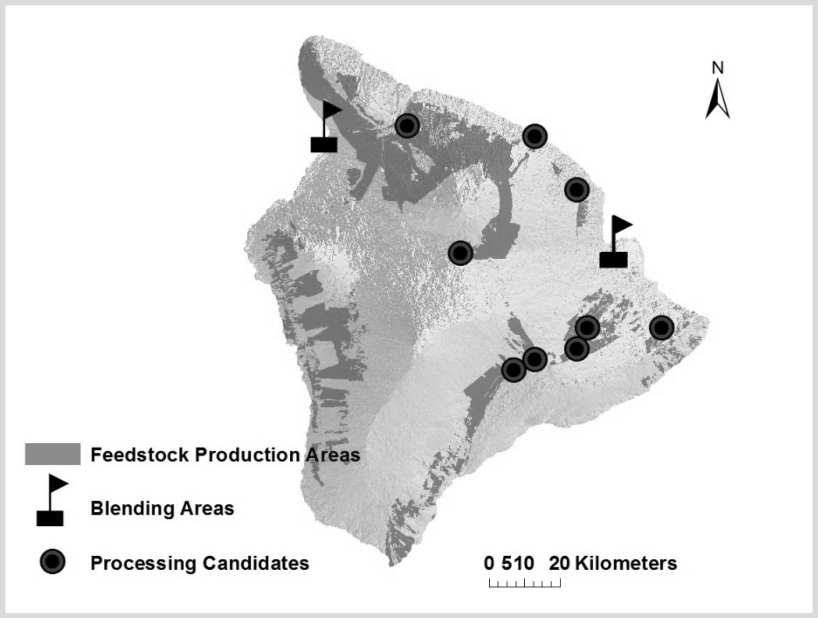

Figure 2-9: **Map of Candidate Sites**
Source: Author based on modeling results

2.3.4.2. Data Analysis Using Mixed Integer Linear Programming

This study builds the following mixed integer programming model using Risk Solver Platform to estimate the optimal numbers, sites and sizes of bioethanol plants. As shown below, a biofuels producer's cost minimization problem can be expressed as eq (1).

$$\min \quad C = C_{ag} + C_{pv} + C_{pf} + C_{tv} + C_{tf} + C_{ds} \qquad \ldots(1)$$

Here, the total cost of lignocellulosic ethanol production consists of agricultural production cost C_{ag}, processing variable cost C_{pv} , processing fixed cost C_{pf}, transportation variable cost C_{tv}, transportation fixed cost C_{tf}, ethanol distribution cost $C_{ds.}$ These are annualized cost figures for the project life of 27 years.[22] Furthermore, each cost component is calculated as follows.

First, feedstock production cost C_{ag} is calculated as a function of land area under cultivation, where φ denotes the unit feedstock production cost (in \$/km^2) in eq (2). The term θ_{ij} is the land area (km^2) assigned for biomass production in grid (i) to be used in plant (j). Subscript i denotes biomass production sites ($1 \leq i \leq N$) and j denotes candidate processing sites ($1 \leq j \leq M$).

$$\text{Cag} = \sum_i \sum_j \theta_{ij} \times \varphi \qquad \ldots(2)$$

Next, ethanol processing costs include variable and fixed cost components. In this model, ethanol processing variable costs are a function of ethanol produced, where α is the biomass yield (dry ton/km^2), ω is the biomass to ethanol conversion factor (gallons per ton), ρ is the unit variable cost of processing (\$/gallon) in eq (3).

$$\text{Cpv} = \sum_i \sum_j \theta_{ij} \times \alpha_i \times \omega \times \rho \qquad \ldots(3)$$

The processing fixed cost is estimated using piecewise linear functions represented by slopes (β), breakpoints (BK) and nonnegative decision variables (Z) (see eq 11-16 for additional constraints). These equations approximate an exponential scaling expression with a factor of 0.7, used in Humbird et al., 2011.

$$\text{Cpf} = \sum_j \beta_1 * \text{BK}_1 * \text{Z}_{j1} + \beta_2 * \text{BK}_2 * \text{Z}_{j2} + \cdots + \beta_{r-1} * \text{BK}_{r-1} * \text{Z}_{jr-1} + \beta_r * \text{BK}_r * \text{Z}_{jr} \qquad \ldots(4)$$

Next, the transportation cost of biomass feedstock consists of variable and fixed cost components (Mahmudi and Flynn, 2006). Transportation variable cost C_{tv} is calculated as a function of tonnage of biomass produced and distance hauled eq. (5). Transportation fixed cost C_{tf} is a function of the tonnage of biomass produced eq (6). The term γ_{ij} represents the distance between grid (i) and plant (j) (km), α_i is the unit yield of a grid (i) (dry tons/km^2), μ is the unit transport variable cost (UDS/ton-km), and δ is unit transport fixed cost (\$/ton).

$$\text{Ctv} = \sum_i \sum_j \theta_{ij} \times \alpha_i \times \gamma_{ij} \times \mu \qquad \ldots(5)$$

$$\text{Ctf} = \sum_i \sum_j \theta_{ij} \times \alpha_i \times \delta \qquad \ldots(6)$$

Finally, ethanol distribution cost is calculated as a function of ethanol produced and distance transported, where d_{jk} is the amount of ethanol transported from plant (j) to blending site (k), σ_{jk} the distance from plant (j) to blending facility (k) (km), and τ the unit cost of ethanol distribution (\$/gallon-km) eq (7).

$$\text{Cds} = \sum_j \sum_k d_{jk} \times \sigma_{jk} \times \tau \qquad \ldots(7)$$

In addition, the following constraints must hold for this optimization model.

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[22] This study assumes the plant construction period of two years. Therefore, both banagrass and ethanol production begins from year 3.

$$\sum_j \theta_{ij} \leq \overline{X_i} \quad \text{…(8)}$$

where $\overline{X_i}$ is the maximum available land in grid (i), which can be used for feedstock production (km^2). This ensures that the land area allocated in each grid does not exceed the available land area in each grid.

$$\sum_i \sum_j \theta_{ij} \times \alpha_i \geq B_t \quad \text{…(9)}$$

where B_t is the minimum biomass required to meet the ethanol production target (ton). This constraint ensures that the total ethanol produced from sites combined will be enough to supply the exogenously set target.

$$\theta_{ij} \geq 0 \quad \text{…(10)}$$

This ensures that land areas chosen in all grids are non-negative numbers.

Based on Winston and Venkataramanan, 2003, the following constraints are also used for the piecewise linear functions, where Y denotes a binary decision variable determining which of the possible piecewise linear segments will be selected as the solution. Depending on the piecewise segments selected, decision variable Z then determines the appropriate point along the line to be selected as an optimal solution.

$$\sum_i \theta_{ij} \times \alpha_i = BK_1 * Z_{j1} + BK_2 * Z_{j2} + \cdots + BK_{r-1} * Z_{jr-1} + BK_r * Z_{jr} \quad \text{…(11)}$$

$$Y_{js} = 0 \; or \; 1 \; (s = 1, 2, \ldots, r-1) \quad \text{…(12)}$$

$$Y_{j1} + Y_{j2} + \cdots + Y_{jr-1} = 1 \quad \text{…(13)}$$

$$Z_{j1} \leq Y_{j1}, Z_{j2} \leq Y_{j1,} + Y_{j2,} \ldots, Z_{jr-1} \leq Y_{jr-2} + Y_{jr-1,} Z_{jr} \leq Y_{jr-1} \quad \text{…(14)}$$

$$Z_{j1} + Z_{j2} + \cdots + Z_{jr} = 1 \quad \text{…(15)}$$

$$Z_{jr} \geq 0 \; (r = 1, 2, \ldots, r) \quad \text{…(16)}$$

Finally, the following constraints ensure that for each plant (j), the sum of all the ethanol shipped to each blending site (k) equals the amount of ethanol produced in plant j and that each blending site (k) accepts 1/3 of ethanol produced denoted as $\overline{d_k}$ in both scenarios.

$$\sum_k d_{jk} = \sum_i \theta_{ij} \times \alpha_i \times \omega \quad \text{…(17)}$$

$$\sum_j d_{jk} = \overline{d_k} \quad \text{…(18)}$$

In this model, all data are adjusted for 2011 prices using the average increase of consumer price indexes over applicable periods (U.S. Bureau of Labor Statistics, 2012). The data are taken from a range of published sources, including: i) banagrass production cost of \$290,000/km^2 as estimated based on Kinoshita and Zhou 1999), ii) biomass transportation cost of \$5.52/ton (fixed cost) and \$0.15/ton-km (variable cost) as estimated by Mahmudi and Flynn, 2006, iii) ethanol processing cost of \$568,129(fixed annual cost of a 1MGY facility) and \$1.13/gallon (variable cost) estimated based on the technoeconomic model in Kumar and Murthy, 2011; and (iv) ethanol shipping cost of \$0.17/ton-km taken from Kocoloski et al., 2011.

2.3.4.3. Model Implementation

The optimization model is applied to the following two scenarios that are relevant to the policy context of Hawai‘i. For Scenario 1, the optimal siting and land allocation are performed for an ethanol production target of 13.86 MGY or 20 percent of the gasoline demand of the Big Island of Hawai‘i in 2010. To meet this target, 173,318 dry tons of biomass must be collected, assuming the conversion rate of 80 gallons per dry ton. For Scenario 2, the model finds the optimal configuration for a larger production capacity, which will meet the target of 83.23 MGY or 20% of the gasoline demand of the State of Hawai‘i. To do so, 1,040,325 dry tons of biomass must be collected, assuming that the conversion rate remains the same. In both scenarios, the model will identify those configurations which minimize the total cost of ethanol production.

2.4. Results

The modeling results indicate that both targets may be achieved using a relatively small portion of suitable land identified in this study (Table 2). In Scenario 1, 36.7 km^2 selected along the most productive soils on the island produces the target yield of 173,318 dry tons. The identified single plant produces 13.86 MGY of ethanol at the cost of \$3.37/gallon. Equal proportions of ethanol produced are then transported to each blending site. In Scenario 2, 279.3 km^2 of selected land produces 1,040,325 dry tons of biomass. In this scenario, it is also optimal to have a single processing plant; while feedstock and transportation costs per gallon are higher in Scenario 2, the total production cost is lower in Scenario 1 at \$3.32/gallon.

Feedstock production and processing are large contributors to the cost structure in both scenarios. In Scenario 1, feedstock production and processing account for 22.8 % and 71.8%, respectively; in Scenario 2, these two account for 29.2% and 56.9 %, respectively. Transport and distribution showed relatively small contributions at 5.3 % and 13.8 % for Scenarios 1 and 2, respectively. These results indicate that processing efficiency is an important factor affecting the economy of ethanol production. In terms of site selection, biomass yield appears to be the key factor affecting whether or not particular biomass production sites are selected. For Scenario 1, the average yield of selected sites is 26.22 dry tons/acre as opposed to the non-

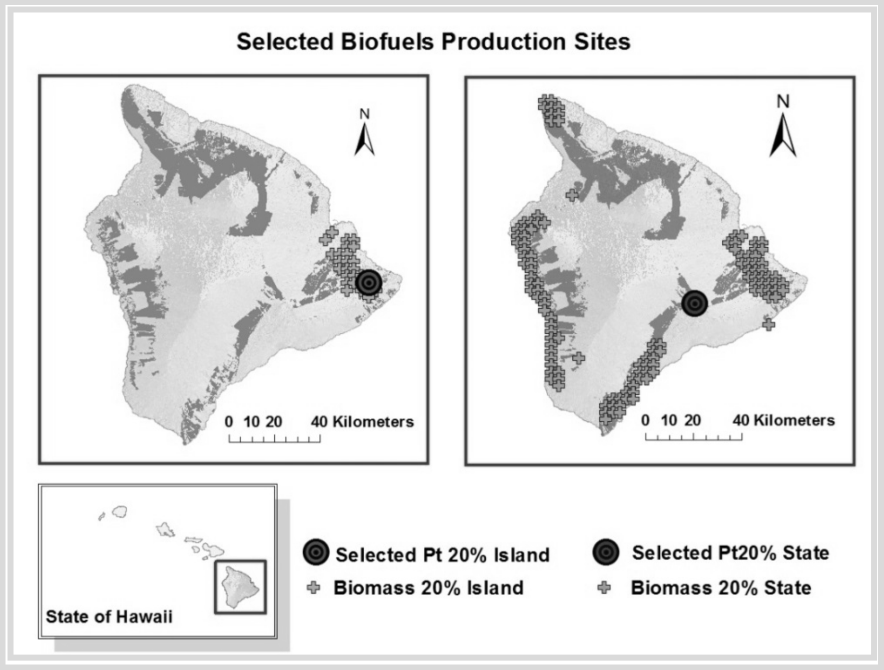

Figure 2-10: **Maps of selected sites**

Table 2-3: **Results of MILP model**

	Scenario 1 (20% of Island Demand)	**Scenario 2 (20% of State Demand)**
Ethanol Production (MGY)	13.86	83.23
Biomass Production (dry tons/yr)	173,318	1,040,325
Plant Selected	Single site	Single Sites
Cultivated Land Area (km^2)	36.7	279.3
Average Yield (dry tons/km^2 (dry ons/acre))	6,461.34 (26.22)	5,103.00 (20.66)
Ethanol Production Cost ($/gallon)	3.37	3.32
Feedstock Production ($/gallon)	0.77	0.97
Ethanol Processing ($/gallon)	2.42	1.89
Transport/Distribution ($/gallon)	0.18	0.46

selected grids with an average yield of 8.80 dry tons/acre. In Scenario 2, the average yield of selected grids is 20.66 dry tons/acre as opposed to 7.37 dry tons/acre for non-selected sites.

2.5. Sensitivity Analysis

It is commonly regarded that the biofuels industry, which primarily depends on the output of the agricultural sector, faces different types of business risks than other energy sectors (English, Menard, and Jensen, 2008). As the severe drought of 2012 illustrated, an acute production shortfall could severely impact the feasibility of production, while potential risk in fuel and other commodity prices may also hamper its profitability.

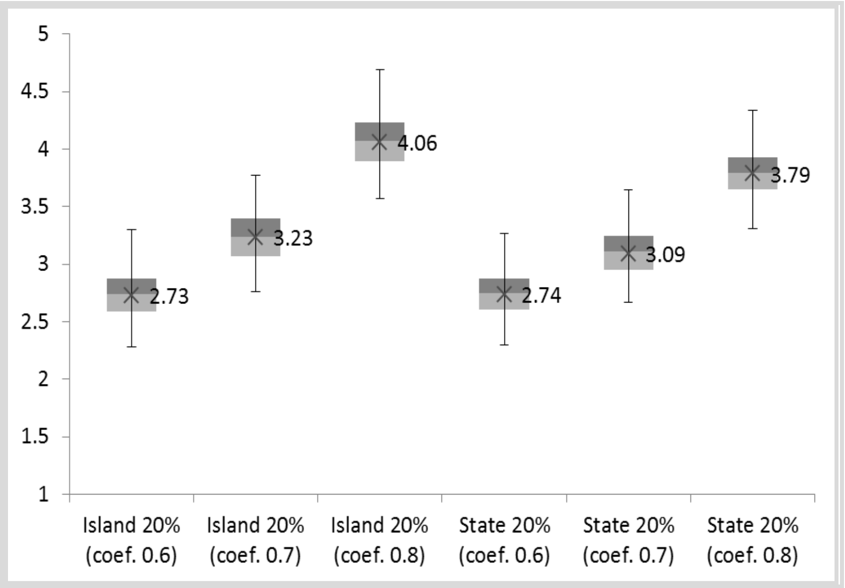

Figure 2-11: **Estimated Ethanol Price Ranges and Means by Monte Carlo Simulation (in 2011$)**

Among the five major categories of risks/uncertainties in agriculture—i.e. 1) production, 2) market/price, 3) technological, 4) social/legal and 5) human source (English et al., 2008; Sonka and Patrick, 1984), this study focuses on the first three and conducts Monte Carlo simulations. The major assumptions adopted in the simulation are described in Table 3. Based on these assumptions, the simulation was evaluated using three different values for exponent for the processing fixed cost scaling factor: a lower estimate (coefficient of 0.6), a medium estimate (coefficient of 0.7), and a higher estimate (coefficient of 0.8).

Table 2-4: **Assumptions for Monte Carlo Simulation**[*1]

		Low Estimate	**Med Estimate**	**High Estimate**	**Unit**	**Source**
Yield[*2]	**Isohyperthermic**					
	Ustic	8.7	21.5	38.0	dry ton/yr	Black and Veatch, 2010
	Udic	15.2	26.8	38.3	dry ton/yr	Black and Veatch, 2010
	Aquic	6.4	14.1	21.8	dry ton/yr	Estimated based on Black and Veatch, 2010
	Isothermic					
	Ustic	3.6	7.5	11.9	dry ton/yr	Estimated based on Black and Veatch, 2010
	Udic	3.6	7.5	11.9	dry ton/yr	Estimated based on Black and Veatch, 2010

Aquic	2.9	6.0	9.5	dry ton/yr	Estimated based on Black and Veatch, 2010
Isomesic					
Ustic	3.3	7.0	11.1	dry ton/yr	Estimated based on Black and Veatch, 2010
Udic	3.9	8.2	13.0	dry ton/yr	Estimated based on Black and Veatch, 2010
Ethanol Conversion Rate	70.0	80.0	90.0	gallons/dry ton	English et al. 2008
Ethanol Conversion Variable Cost[*3]	0.52	1.13	1.35	$/gallons	Estimated based on U.S. Energy Information Admin., 2012 and Bracmort et al. 2010
Transport Variable Cost[*4]	0.09	0.15	0.20	$/ton-km	Estimated based on U.S. Energy Information Admin., 2012
Distribution Cost[*4]	0.10	0.17	0.22	$/ton-km	Estimated based on U.S. Energy Information Admin., 2012
Feedstock Production Cost[*5]	250.0	290.0	320.0	Thousand $/km2	Estimated based on U.S. Energy Information Admin., 2012

Note: [1] For all inputs, triangular distribution was used. [2] Estimated based on the average yield variation of non-irrigated banagrass yield .[3] The figure is estimated based on low and high residual oil based electricity scenarios in 2025 (U.S. Energy Information Admin., 2012).[4] Estimated based on low and high diesel fuel price scenarios in 2025 (U.S. Energy Information Admin., 2012).[5] Estimated based on low and high diesel fuel price scenarios in 2025 and low and high natural gas price scenario in 2025 (as a proxy for fertilizer cost) (U.S. Energy Information Admin., 2012).

The results of the Monte Carlo Simulation show that production costs for banagrass-based ethanol may range between $2.13/gallon to $4.69/gallon for Scenario 1 and $2.15/gallon to $4.34/gallon for Scenario 2. The relatively wide range of cost estimates illustrates the magnitude of uncertainty observed in lignocellulosic ethanol production. Due to variation in yields, biomass production may fall to 84.0% of the target in Scenario 1 and 94.1% of the target in Scenario 2 in case of lower estimates.

2.6. Discussion

Modeling and sensitivity analysis provide important insights into the optimal siting in the case of Hawaiʻi. First, given the natural variation in soil, water and climatic conditions, simple logistic decision-making based on transport cost minimization might not provide the optimal configuration of biofuels production in Hawaiʻi. The analysis showed that the most productive land is scattered around the edge of the island, making consolidated feedstock production difficult. In Scenario 2, relatively contiguous and adjacent land areas from processing plants are found to be sub-optimal, due to their lower productivity. Hence, to meet the State's renewable fuels standard, commercial scale operation of banagrass-to-ethanol production faces challenges of scale economies in feedstock production, transportation/distribution and processing. To counter this issue, a producer may choose to enhance productivity of adjacent land with improved management by including an increased use of fertilizer, or to consider expanding potential processing plants further away from existing blending sites, where ethanol produced may be consumed within its locality, avoiding extensive hauling of fuels across the island. For either of these options, there appears to be trade-offs between factors such as potential land productivity, agrochemical use, land contiguity, transport distance, plant scales, and the appropriate configuration to minimize total production cost. An integrated approach of geospatial analysis and mathematical programming such as the one provided by this study will allow a more flexible geospatial modeling framework than one afforded by conventional GIS-based modeling such as a p-median problem and other geospatial optimization algorithms[23]. By integrating spatial attributes with a range of cost components, this type of modeling serves as a useful tool in providing much needed insights into optimal land allocation and cost-minimizing strategies.

Second, the scale of production affects the cost of ethanol production to some degree, but the difference between production based on the island demand and state demand appear to be relatively small. This is because even though the larger-scale production benefits from gains made in processing, the improvement is offset by the increased per unit cost of feedstock production and transportation. While detailed assessment regarding optimal configuration and cost of inter-island shipment is beyond the scope of the present analysis, barge shipments of ethanol from the island of Hawaiʻi to the island of Oahu is estimated to cost around $0.07/gallon.[24] Therefore, the cost of production based on the state demand will likely be similar to that of smaller production based on island demand.

Finally, given the uncertainty regarding production, market and technological aspects of banagrass-to-ethanol production, and highly volatile price of ethanol in general, governmental support in the form of long-term commitment such as consumption mandates and production subsidies is helpful in providing long term stability. The overall costs of production, together with the likely range of uncertainty, appear relatively high as compared to conventional ethanol (estimated as $0.88/gallons using Brazilian Sugar-cane and $1.44/gallon using US dry-mill corn Hettinga et al., 2009), though they fall within the range of existing lignocellulosic ethanol cost estimates.[25] The common range of lignocellulosic estimates spans widely from lower estimates of $0.81 to $1.10/gallon using Corn Stover (Sendich et al., 2008), $2.35/gallon using Eucalyptus (Gnansounou and Dauriat, 2010), $2.39/gallon using Corn-Stover (Humbird et al., 2011), $3.24/gallon using switch grass (Gnansounou and Dauriat, 2010) , $3.26/gallons using Tall Fescue (Kumar and Murthy, 2011) to a high estimate of $ 4.85/gallon using Corn-Stover (Klein-Marcuschamer et al., 2010). The present estimates hence fall within the range of estimates available from the prior studies.[26]

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[23] For discussions of various heuristics and methods for facility locations see for example Marianov and Serra, 2009.

[24] The estimate is based on unit ethanol barge shipment costs reported in National Academy of Sciences et al., 2009.

[25] All exiting cost estimates are expressed in 2011 price for ease of comparison.

[26] While the technoeconomic model used in the study does not take the potential revenue from lignin-rich waste stream into account, a separate calculation may be performed outside of the model to estimate such potential using appropriate heating values and generation efficiency (Kumar and Murthy, 2011)..Based on values of process steam and water cooling requirements and other parameters as explained in Kumar and Murthy, 2011, it is estimated that banagrass-based plant has the potential to produce 72.05% of plant's power need. Given Hawaiʻi's relatively high cost of power, this could reduce the unit cost of ethanol production by 33 cents, making per gallon cost of banagrass-based ethanol down to $3.04/gallon (20% of state's demand) and $2.99/gallon (20% of island's demand.)

Further improvements in terms of feedstock production and ethanol conversion efficiencies are crucial in making locally produced ethanol competitive with imports. While government support in these aspects will also be helpful, the cost of doing so must be weighed against the potential benefits of local ethanol production and alternative policies. Policies such as vehicular efficiency improvement, modal shift to encourage the use of public transportation, and the use of emerging technologies such as electric vehicles must also be considered to provide a holistic and robust set of policies to reduce imported oil dependencies in the transportation sector.

2.7. Conclusion

This study develops a combined Geographical Information System (GIS) and mixed-integer linear programming approach to identify optimal siting of feedstock production and lignocellulosic bioethanol processing facilities. The modeling results indicate that Hawai‘i’s renewable fuels targets are achievable with a relatively small portion of available land on the island of Hawai‘i. Due to likely variation in banagrass yield, it is economically optimal to choose more productive land, which can minimize the cost of overall feedstock production. In the case of Hawai‘i, distance between biomass production sites and processing plants per se does not appear to dictate the optimal site selection, illustrating the importance of other factors such as feedstock production and conversion efficiencies in the overall production cost structure. Based on this model, the optimal number of plants is identified as one for both Scenario 1 and 2. Per gallon ethanol production costs are estimated as \$3.37/gallon, and \$3.32/gallon to meet 20% of the islands’ and state’s demand respectively. . Further exploration into economies-of-scale in feedstock production and factors affecting land contiguity and other factors can enhance the viability of lignocellulosic ethanol production.

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APPENDIX 2.1: GIS MODULE FLOWCHART

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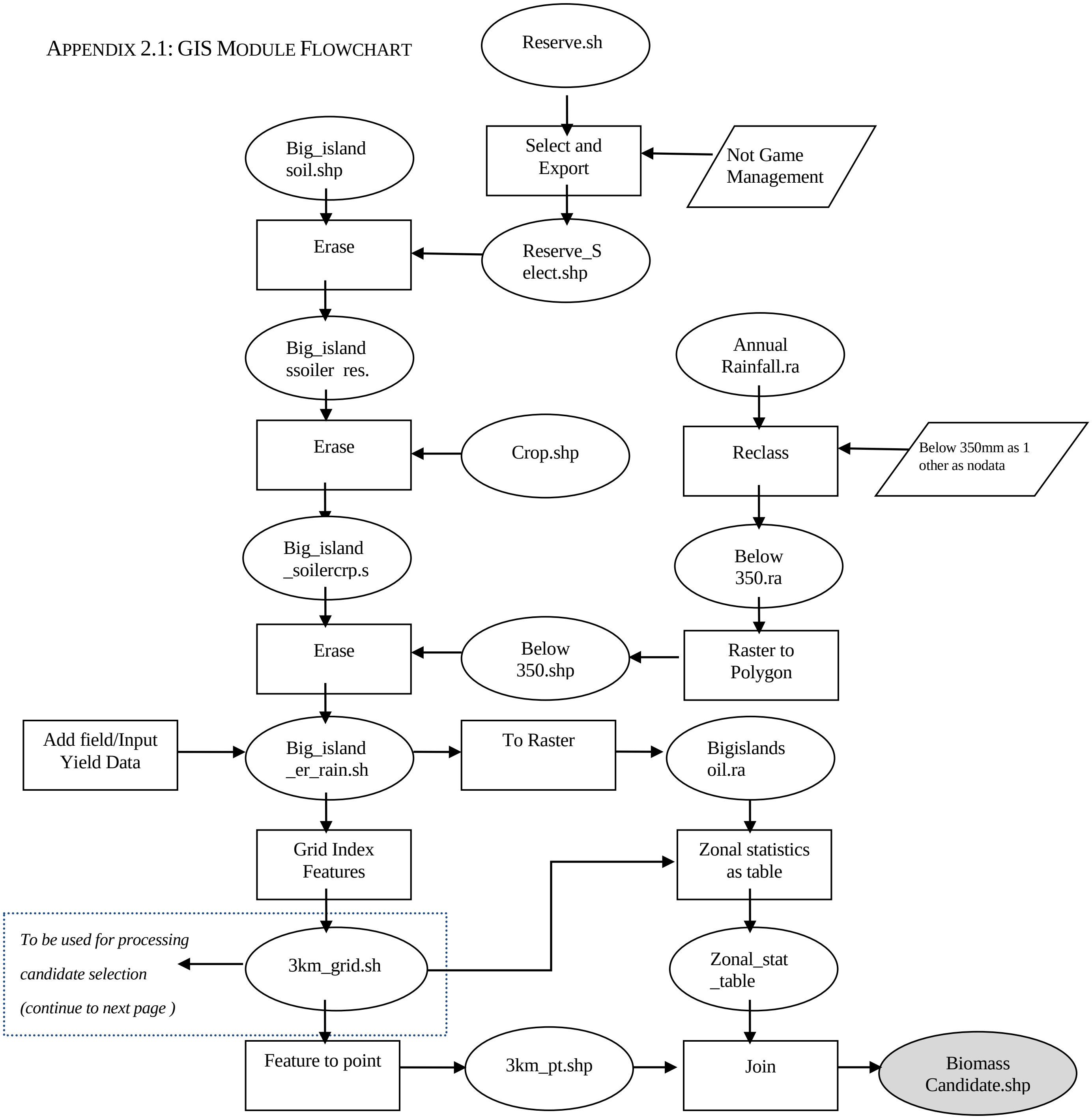

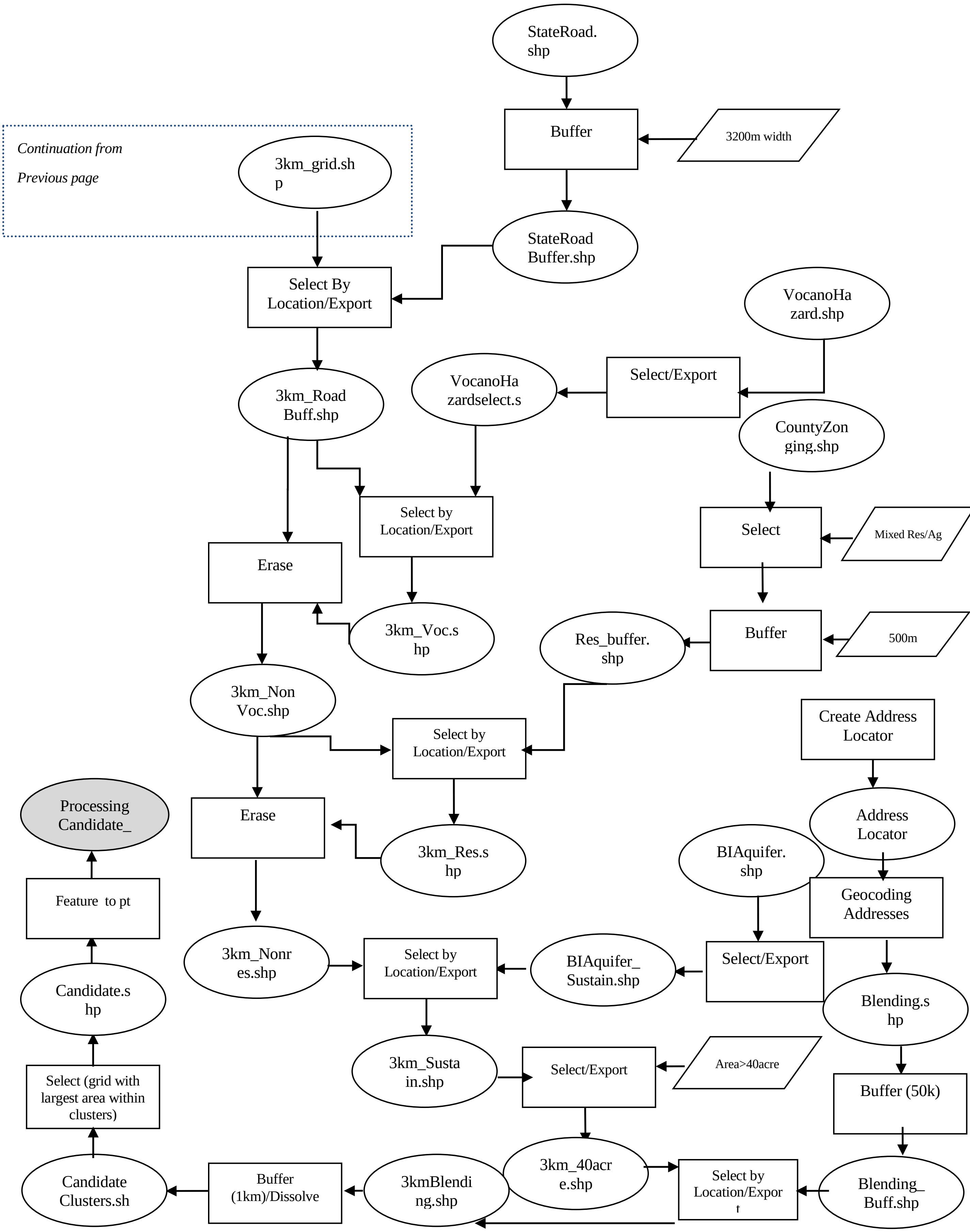
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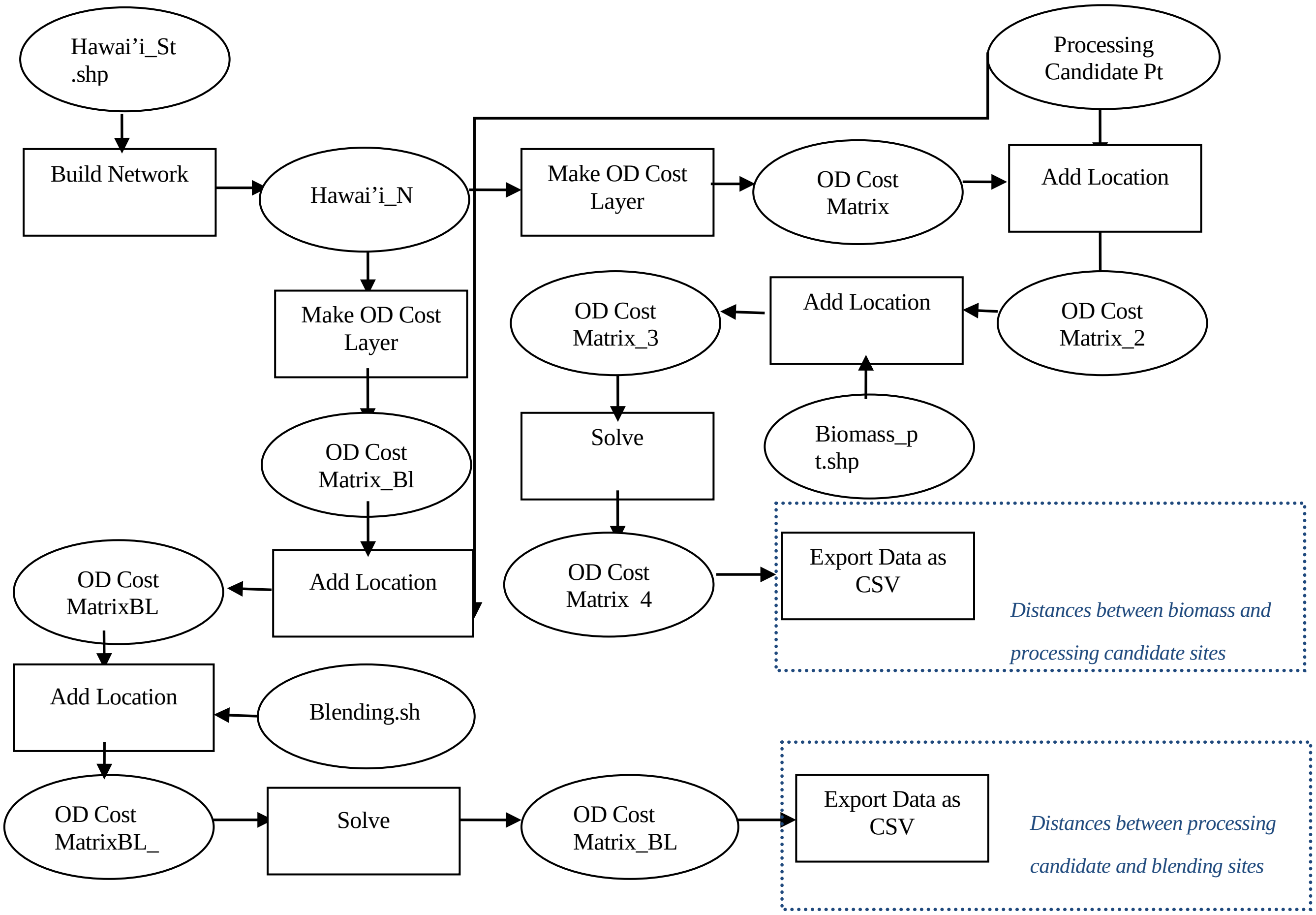
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3. LIFE CYCLE ASSESSMENT OF ETHANOL PRODUCTION FROM TROPICAL BANAGRASS (PENNISETUM PURPUREUM) USING GREEN AND NON-GREEN PROCESSING TECHNOLOGIES IN HAWAIʻI

3.1 Introduction

A rapid rise in oil prices and an increased awareness concerning anthropogenic climate change have led to concerted efforts to curtail fossil fuel consumption through the use of alternative energy including biofuels. While the world's bioethanol production has almost quadrupled over the past decade; the use of food crops—primarily corn in the United States, sugar in Brazil—has raised heated concerns over a food versus fuel debate (REN 21 2010). Against this backdrop, lignocellulose-derived biofuels have captured growing attention as a more sustainable alternative to conventional corn/sugar-based biofuels (McMillan 1997; Zaldivar et al., 2001; Cardona and Sanchez 2007; Laser et al. 2009; Gnansounou 2010; Klein-Marcuschamer et al. 2010). Lignocellulosic feedstocks are abundant and readily available, (IEA 2011; Slade et al. 2011) and dedicated energy crops such as switchgrass, miscanthus and banagrass can be grown in marginal lands, reducing direct competition for agricultural and food crop resources . Cultivation of lignocellulosic crops are also known to bring a plethora of benefits including soil erosion mitigation, carbon sequestration, and local water quality and wild habitat improvements (Sims et al. 2008; Tilman et al. 2009).

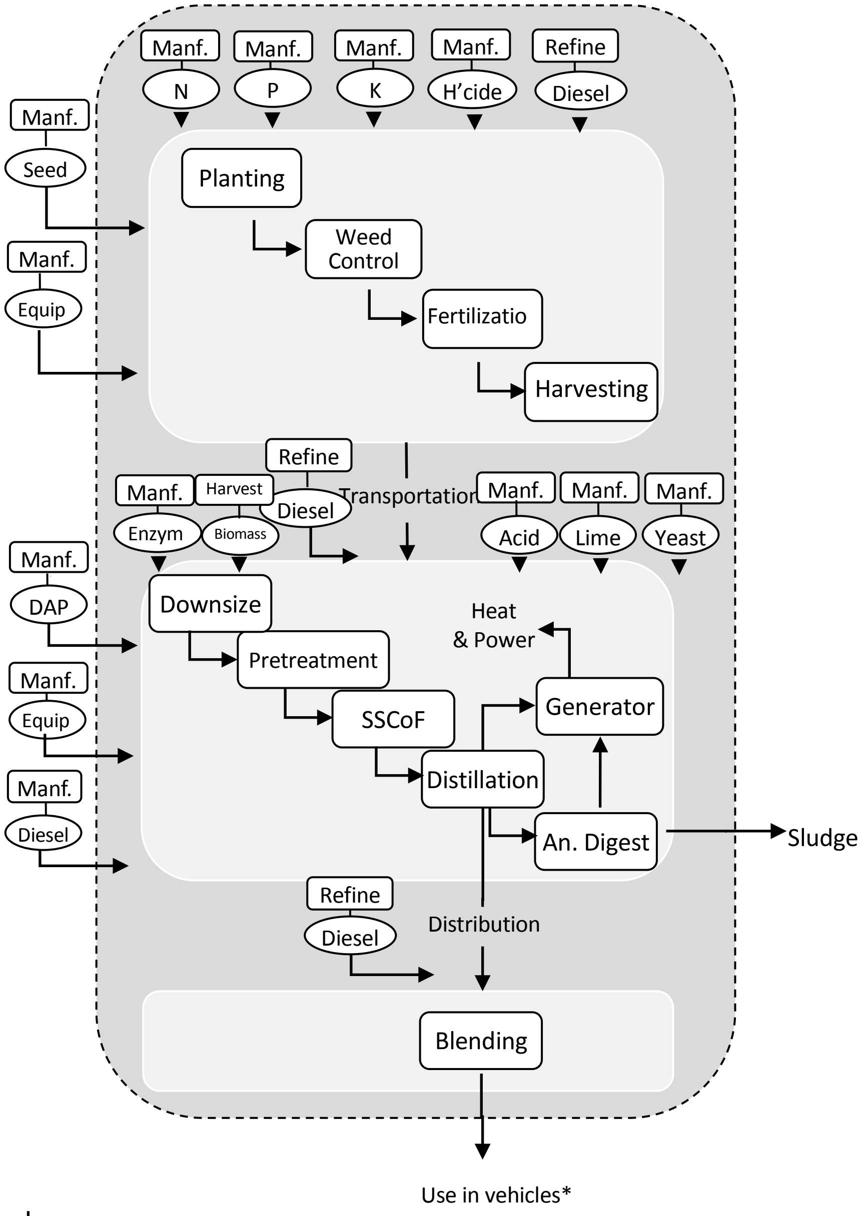
In the context of Hawaiʻi, a perennial fodder crop known as banagrass (*Pennisetum purpureum*) has been identified as a promising feedstock owing its robust growth (Tran et al. 2011) and carbohydrate content, consisting of approximately 37% cellulose and 22% hemicellulose (Takara 2012 a). Because Hawaiʻi is highly dependent on imported oil (over 85% of primary energy demand is met through the use of imported petroleum products) and serves as a military hub in the Pacific region (DBEDT 2011), the use of tropical fodder crops as a domestic energy resource has been perceived to be of local and regional importance in recent years. Furthermore, a novel processing strategy known as 'green-processing,' which directly converts freshly harvested biomass into biofuels, has been identified to offer benefits in tropical climates: the green-processing of banagrass eliminates the need for biomass drying and storage, which can pose an operational challenge due to frequent rain and humidity, while simultaneously enabling the harvesting of plant juice which can be used to produce a high value protein-rich co-products for local fish/animal production (Takara and Khanal 2011). The feasibility of this processing option has been demonstrated in laboratory scale studies (Takara 2012a); however a detailed life-cycle assessment (LCA) has not been conducted. Therefore, this study seeks to fill this knowledge gap by providing a life-cycle assessment of this biofuel option.

3.2 Literature Review

LCA is a systematic accounting approach designed to estimate energy requirements and environmental impacts of commercial products. Originally developed for industrial process assessment in the late 1960s, the use of LCA has expanded to other sectors of the economy including agriculture and services (Baumann and Tillmann 2004). Today, LCA is widely regarded as an appropriate methodology to account for potential environmental impacts of biofuel and biobased products (Luo et al, 2009; Papong and Malakul 2010). The holistic approaches typically employed in LCA are commonly referred to as ‘cradle-to-grave’ or ‘cradle-to-gate’ depending on the chosen system boundaries, or ‘well-to-wheel’ or ‘well-to-tank’ in the case of biofuels.

Existing literature suggests wide-ranging estimates of environmental impacts, which demonstrate the complexity and inherent challenges of biofuel LCA studies (Gnansounou et al. 2008; Cherubini et al. 2009; and Singh et al. 2010). In the field of second generation bioethanol production, factors such as the choice of system boundaries, feedstock options, conversion technologies and efficiencies, coupled with allocation methods, translate to a range of life-cycle environmental impacts. Reviewing 53 scientific articles on lignocellulosic bioethanol life-cycle assessment, Borrion et al. (2012) reports that the use of lignocellulosic bioethanol, in general, leads to sizable energy and GHG savings, estimated to range from 56% to almost 100% and from 46% to 90%, respectively, as compared to conventional gasoline in the case of E100, and from 45% to 76% and 12% to 96% , respectively in the case of E85. In terms of emission sources, existing studies disagree as to the contribution of each production operation: Nitrogen fertilizer emissions are reported to contribute the most GHGs, according to Wang et al. (2011), while Gonzalez-Garcia et al. (2012) has reported that ethanol conversion contributes to almost all of the life-cycle emissions. Still others, including Bai et al. (2010), reported a large contribution of fossil fuel extraction, while Maclean and Spatari (2009) and Kumar and Murthy (2012) emphasize the sizable contribution of enzyme production in overall life-cycle emissions of bioethanol. The perceived difference in the footprint of each production process is attributable to the heterogeneity in environmental and technological assumptions. For example, the relative importance of nitrous oxide, which has 298 times more potent global warming potential, depends on agro-environmental, technological and management factors including soil moisture, the rate of fertilizer application, the use of irrigation and the choice of annual versus perennial crops (Cherubini and Stromman 2011). The GHG emissions related to the production and use of pre-treatment chemicals and enzymes depends on specific parameters adopted for conversion processes. Whether the facility becomes a net producer or consumer of electricity under varying assumptions also affects overall energy and GHG footprints.

In terms of geography and feedstocks, the existing literature draws largely on European and North American cases, investigating key biomass options including agricultural waste such as corn and wheat straws, forest residues, and dedicated energy crops such as switchgrass and miscanthus (Cherubini et al. 2009; Borrion et al. 2012). There has been a gradual increase in the number of LCA studies that have been conducted in other regions around the world in recent years; however, feedstock options relevant to tropical climates remains limited. Given such paucity, the present study makes a contribution to literature by examining the environmental impacts of advanced bioethanol options using a tropical fodder crop, banagrass. In particular, this study examines a novel green-processing technology and compares it with conventional ethanol processing which implements dried feedstock with no fungal co-product.



---- System Boundary

* included in well-to wheel

Figure 3-1: System Boundary for Banagrass to Ethanol Production.

3.3 Goals and Scoping

The goal of this study is to quantify the well-to-pump and well-to-wheel life-cycle energy and GHG emissions of banagrass-derived bioethanol and to analyze this vis-à-vis conventional gasoline and existing first and second generation bioethanol options. The following two ethanol production technologies are considered for analysis:

1. Green-processing, which utilizes moisture-rich immature harvests of banagrass for the co-production of high value fungal protein; and
2. Non-green processing, which utilizes mature harvest of banagrass-to-ethanol conversion with no co-product output.

The functional unit used in this study is 10,000 MJ of ethanol produced for well-to-pump study. The fuel economy of a flex fuel vehicle (FFV) is assumed to be 24 miles per gasoline equivalent gallon (GREET 2012).

3.4 System Boundaries

The system boundaries include all material inputs used during ethanol production life-cycle: feedstock production, biomass transportation, ethanol production and distribution. Relative mass energy and economics (RMEE) method with a cut-off value of 0.01 was used to draw system boundaries (Reynolds et al 2000). RMEE assesses the contribution of each process input in terms of mass, energy and economic value (relative to the functional unit), and ensures that those production processes found to be above this cut-off will be included in the analysis. The economic values of inputs are based on published materials and vendor quotes including USDA (2012) for fertilizers, Grube et al. (2011) for pesticides and Kumar and Murthy (2011) for processing chemicals. Fuel prices are based on USDOE (2012). The heating values of fuels are based on GREET (2012). A few production stages, for example, fuel use during distribution and planting, were found to be outside the system, these are included in the analysis.[27] The emissions related to direct and indirect land use changes, as well as any production of capital goods including machinery are excluded in this study.

3.5. Life Cycle Inventory

Inventory data are drawn from publically available sources including scientific journal articles and a transportation energy focused life-cycle assessment tool, the Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET 1-2012) model. Table 3.1 summarizes sources used to extract data in this study.

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[27] Inclusion of these processes will make this study's boundary more comparable to existing studies, and similar approaches are taken in studies such as Kumar and Murthy (2012).

Table 3-1: Life-Cycle Inventory Sources

Processes	Items	Sources
Feedstock production	Agricultural machinery operation and fuel demand	Downs and Hansen (1998)
	Fertilizers and chemical application rates	Osgood et al. (1996)
	Emissions related to fertilizers and chemical production; emissions factor for agricultural machinery fuel use	GREET (2012)
Ethanol Production	Electricity generation.	DBEDT (2010); HCEI (2011)*
	Chemicals and yeast ($Ca(OH)2$, Sulfuric Acid), yeast) production	GREET (2012); EuLA (2007)
	Cellulase production	GREET (2012)*; MacLean and Spatari (2009); Novozymes (2012)*
	Emissions related to co-product generation	GREET (2012)
Biomass Transport & Ethanol Distribution	Heavy-duty truck fuel economy; emissions related to fuel combustion, refinery and crude oil production	GREET (2012)

Note. * used for sensitivity analysis.

3.5.1 Feedstock production

Banagrass, also known as Napier or Elephant grass, is one of the highest yielding C4 plants, native to the subtropical African country of Zimbabwe (Skerman and Riveros 1990). It is a perennial crop which matures within seven to eight months and yields multiple ratoon harvests.[28] Because of its robust growth, it is considered one of the most valuable forages and is grown widely across the wet tropics (Skerman and Riveros, 1990), and has been considered as a potential bioenergy crop in a number of countries including Thailand, the Philippines, China, Australia and the United States (Holm 2010; Manila Times 2011; BMWi and Giz, 2012). Since its original introduction from Australia to Hawai‘i in the mid-1970s, banagrass has been used locally as windbreaks and more recently has been studied as a bioethanol feedstock option (Keffer et al. 2009; Black and Veatch 2010; Tran et al. 2011). The potential yield of banagrass depends on many factors including environmental conditions such as climate and soil, together with management choices including irrigation and fertilization. This study assumed rain-fed production of banagrass in Hawai‘i. Table 3.2 summarizes major assumptions used for feedstock production

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[28] Ratooning refers to “a practice of growing full crop of sugarcane [or other similar crops] from sprouts of underground stubble left in the field after harvest of the plant (main) crop” (Shukla et al. 2013, P. 50).

Table 3-2: Major Assumptions Regarding Feedstock Production

Categories	Values	Sources
Biomass production scale	256,278dry tons/year	250,000 metric ton/day based on Kumar and Murthy (2011)
Banagrass yield	21.5 dry tons/acre/year	Tran et al. (2011)
Harvesting efficiency	73%	Osgood et al. (1996)
N fertilizer use	203 lb/acre/year (planting) 180 lb/acre/year (ratoon)	Osgood et al. (1996)
P_2O_5 fertilizer use	111.5 lb/acre/year (planting) 180 lb/acre/yr (ratoon)	Osgood et al. (1996)
K2O fertilizer use	185.5 lb/acre/year (planting) 0 lb/acre/year (ratoon)	Osgood et al. (1996)
Lime application	None	Sakuda (2011)
Irrigation requirement	None	Tran et al. (2011)
Lifetime of farm	20 years	Based on the project life-span of an ethanol plant Kumar and Murthy (2011).
Zoning	Non-prime non-unique agricultural land	Black and Veatch (2010)

The cultivation process of banagrass is similar to that of sugarcane because of similar morphology. The cultivation process include: i) soil preparation; ii) cuttings production; iii) planting; iv) fertilization; v) weed control; vi) irrigation (if applicable); and vii) harvesting and transportation. Although no commercial scale banagrass production has taken place in Hawaiʻi, a number of field trials have demonstrated that conventional sugarcane machinery may be used with minor modifications and these provide important insights regarding the likely banagrass production at a commercial scale (Kinoshita and Zhou 1999). Due to data limitations, herbicide application in banagrass production was estimated based on the sugarcane figures available in GREET (2012), assuming that herbicide use is the same as for sugarcane in planting years and is minimal during ratoon years (Hubbard et al. 1993). For the current study, the fertilizer application rate was taken from a previous field trial (Osgood et al. 1996).

3.5.2. Farm to plant feedstock transportation

In this study, it is assumed that a bioethanol plant will have a production capacity of 704.5 dry tonnes of feedstock a day. Existing studies of resource availability have shown that Hawaiʻi has 814,500 acres of non-prime and non-unique land under the Agricultural Lands of Importance to the State of Hawai ʻi (ALISH) categorization, which can be used for dedicated energy crop cultivation (Black and Veatch 2011). Assuming a rain-fed yield of 21.5 dry tons per acre of banagrass, the land area required to produce 704.5 dry tonnes of feedstock per day is estimated at approximately 11,900 acres per year. Hence, the existing non-prime, non-unique agricultural land is sufficient to support this production scale. Upon harvest, biomass is assumed to be transported to a bioethanol processing plant via ground transportation. Feedstock is hauled using heavy-duty trucks, which can transport up to 17 wet tons of biomass per trip (GREET, 2012). Required transportation distance was calculated using the following equation (Aden et al., 2002; Kumar and Murthy, 2012):

$$\alpha = \frac{\delta\ banagrass}{\beta\ banagrass * \gamma\ cropland * \gamma\ availability * \gamma\ collect} \qquad \ldots(1)$$

Where α is the total area served by feedstock transportation, δ *banagrass* is the total biomass needed for bioethanol production, β *banagrass* is annual yield, assumed as 21.5 dry ton/acre/year based on Tran et al. (2011), and γ *cropland* is the ratio of farmland to the overall area including roads and non-farm lands. The γ *cropland* is assumed to be 0.6 based on Kumar and Murthy (2012). The γ *availability* is the fraction of farmland which may grow banagrass, as opposed to other crops. The γ *availability* is assumed to be 1 based on the fact that production of banagrass takes place on non-prime non-unique agricultural lands as opposed to prime-agricultural land currently used for other agricultural crop production. While sizable fallow land area exists within non-prime, non-unique agricultural land on the island of Hawaiʻi (Melrose and Delparte 2012), it is assumed that all agricultural land within the vicinity could be used for banagrass production purposes. The γ *collect* is the ratio of banagrass actually harvested as opposed to yield, which is assumed as 0.73 based on the harvesting efficiency recorded in Osgood et al. (1996). Based on these values, the distance needed to collect banagrass (i.e. the radius of a circle, assuming that a bioethanol plant would be sited at the center of the area) is estimated as 5.9 km (or approximately 12 km per around trip). The life-cycle energy requirements and emission factors of a heavy-duty transportation truck operation were also taken from GREET (2012).

3.5.3. Banagrass-to-ethanol conversion

Lignocellulosic biomass may be converted into biofuel by a variety of technologies including biochemical, thermochemical and combined pathways. This study examines a biochemical pathway based on Simultaneous Saccharifiction and Co-Fermentation (SSCoF) with dilute acid pretreatment, comparing two options of green and non-green processing of banagrass to ethanol conversion. In green-processing, freshly harvested banagrass is the feedstock of choice, while dried banagrass is used in non-green processing operations. For the non-green processing option, it is assumed that banagrass is dried using a biomass-fired rotary drying system which requires a minimal consumption of fossil fuel (i.e. 5% of energy needed) to sustain flame for safety based on personal communication with a vendor.This type of process is necessary in tropical regions like Hawai ʻi, which maintain an average relative humidity of 60%. The fossil fuel consumption for the dryer was below the RMEE threshold, and was thus excluded in the following analysis; however the life-cycle energy and emissions associated with growing, harvesting and transportation of biomass materials are above the RMEE threshold and are thus included in the analysis. In both cases banagrass is converted using dilute sulfuric acid pretreatment and saccharification, and co-fermentation (SSCoF). The basic process model follows that of Kumar and Murthy (2011) with a modification produced by introducing the green-processing option. The composition of mature banagrass used in this analysis contains 37 % cellulose, 22% hemicellulose, 21% lignin, 8.3% ash, and 13 % extractives on a dry weight basis (Takara, 2012a).

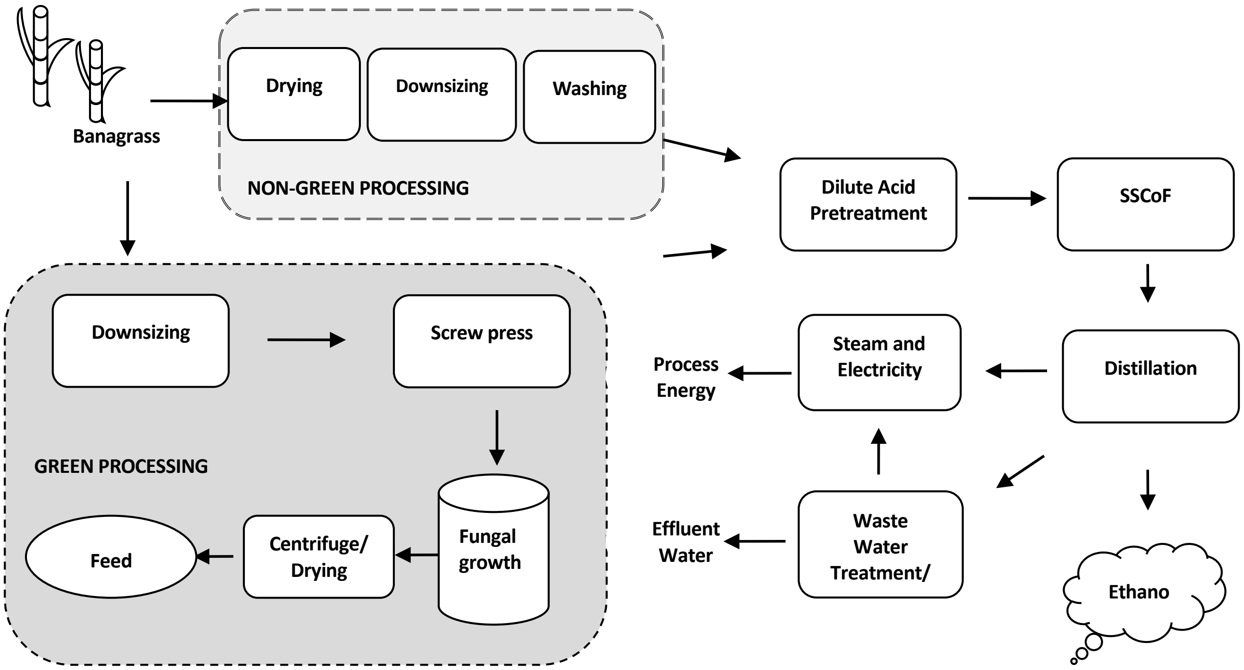

Figure 3-2: Process Design of Green and Non-Green Processing of Banagrass to Ethanol

The innovative concept of green or wet processing is based on the use of fresh crops with high moisture contents. In this front end operation, feedstocks with a moisture content of about 60 % - 70 % is chopped and juiced for co-product generation. Banagrass juice is known to contain dissolved nutrients (i.e. organic compounds glucose, and nitrogen), which act as a suitable substrate for microbial feed production through fungal fermentation (Takara and Khanal 2011).

Co-product generation is based on the cultivation of *Rhizopus microsporus var. oligosporus*, a commonly used ingredient of the fermented Indonesian soy product tempeh. Fungal cultivation of *R. oligosporus* has been studied extensively in the context of co-product generation and waste water treatment (Jasti et al. 2008; Sankaran et al. 2008; Nitayavardhana and Khanal 2010 ; Takara and Khanal 2011; van Leeuwen et al. 2012). This study assumes that *R. oligosporus* will be grown in a stirred tank reactor with operating conditions including energy needed for agitation and aeration, equivalent to that of cellulase production (Humbird et al. 2011). Once produced, the edible fungal biomass will be dewatered using a decanter centrifuge and dried in a biomass-fired rotary drying system. Given the lack of data on fungi biomass drying, it is assumed that the energy requirement is equivalent to that of the DDGS drying system reported in

Kwiatkowski et al. (2006), assuming biomass as the source of energy with 5% diesel use to sustain flame for safety. Based on these assumptions, the diesel use for this process is also found to be below the RMEE cut-off, and thus was excluded from the analysis. Based on laboratory scale data available from Takara (2012a), it is estimated that 6.8 g of fungi may be produced per liter of banagrass juice. Based on the assumed production scale, it is estimated that the plant will produce 1,380 tonnes of fungal co-product with a moisture content of 11%. Assuming the feed may be sold at an equivalent price with soybean meal, this new product stream will generate a revenue of $309/dry ton of fungi biomass (Nitayavardhana and Khanal 2010).

Table 3-3: Pretreatment conditions adopted for this study

	Green Processing	Non-Green Processing
Acid concentration (% Sulfuric Acid)	5	5
Temperature (°C)	120	120
Pressure (kPa)	199	199
Residence time (min)	45	30
Solid loading (%)	20	20
Cellulose +0.111 H_2O= 1.111 Glucose (%)	11	5
Hemicellulose + 0.136 H_2O=1.136 Xylose (%)	99	55
Lignin -> Soluble lignin (%)	5	5
Xylose->0.64 furfural + 0.36 H_2O (%)	5	5
Glucose -> 0.7 HMF+0.3 H_2O (%)	5	5

Kumar and Murthy (2011); Takara (2012a)

Once the juice is extracted, the remaining biomass goes through biochemical conversions based on the dilute acid pretreatment of lignocellulosic feedstocks followed by SSCoF, as described in Kumar and Murthy (2011). Dilute acid pretreatment using sulfuric acid is one of the commonly used methods of solubilizing and hydrolyzing hemicellulose, at the same time reducing the crystallinity of cellulose; although the degradation of carbohydrates and the formation of inhibitors (i.e. furfural, HMF, and acetic acid) are possible and require additional procedures such as over-liming and conditioning. In the process mode, banagrass was heated to an optimal temperature based on lab scale trials (i.e. 120 °C for 30 minutes in the case of non-green processing, and 120 °C for 45 minutes in the case of green processing) in acid concentration of 5% at a pressure of about 199kPa during dilute acid pretreatment. During the pretreatment process, 5% of cellulose, 55% of hemicellulose (non-green processing), 11% of cellulose, and 99% of hemicellulose (green processing) were hydrolyzed (Takara 2012a). Both furfural and HMF formation rates were assumed to be 5%

as reported by Kumar and Murthy (2011). Upon dilute acid pretreatment, banagrass will go through over-liming at a pH of 10 to reduce inhibitor activities, thereby increasing subsequent fermentation efficiency.

After pretreatment, biomass was detoxified (or conditioned) using the over liming process to remove toxic compounds (e.g. furans from sugar degradation) formed during the pretreatment process. The conditioned biomass was saccharified and fermented using the SSCoF process, in which biomass is hydrolyzed using a commercially obtained enzyme mixture, and simultaneously, sugars were fermented to ethanol. The process conditions for SSCoF are the same for both green and non-green processing options (a stirred reactor is kept at the temperature of 35°C with a residence time of 5 days), which achieve varying levels of sugar release as suggested by laboratory measurements (i.e. hydrolysis efficiencies were assumed as 81% for cellulose and 99% for hemicellulose in the case of non-green processing, and 83% for cellulose and 99% for hemicellulose in the case of green-processing) (Takara 2012a). The enzyme loading was assumed as 15 FPU/g of cellulose with an activity level of 600 FPU/g of protein (with 10% protein content in slurry) (Kumar and Murthy 2011). Finally, glucose and xylose fermentation efficiencies were assumed to be 95% and 70% respectively.

Table 3-4: SSCoF Condition Adopted for this Study

	Green Processing	Non-Green Processing
Temperature (°C)	35	35
Enzyme Loading (FPU/g of cellulose)	15	15
Residence Time (days)	5	5
Cellulose +0.111 H_2O = 1.111 Glucose (%)	83	81
Hemicellulose + 0.136 H_2O = 1.136 Xylose (%)	99	99
Glucose->0.489 CO_2 + 0.511 Ethanol (%)	95	95
Xylose->0.489 CO_2 + 0.511Ethanol (%)	70	70

Kumar and Murthy (2011); Takara (2012 a)

Pure ethanol is recovered after fermentation using a combination of distillation columns and molecular sieves. About 1% gasoline is added to pure ethanol for denaturation. The co-product stream contains lignin-rich residues together with effluent water. These residues may be recycled as a source of heat, power and process water, which may be reclaimed and recycled into other unit operations. The bottom stream from the distillation column contains lignin, unhydrolyzed cellulose and hemicellulose, unfermented sugars and other soluble compounds; these lignin-rich energy sources are used to produce steam and electricity in the plant. Waste water is treated using a series of anaerobic and aerobic digesters. During anaerobic digestion, methane is produced from a wastewater stream at a rate of 0.24 kg /kg of COD removal (Barta et al. 2010). The gas and remaining sludge are then fed to a fluidized bed reactor for power generation. The amount of power generated is calculated based on the heating value of waste stream components, assuming 30% efficiency in power generation (Kumar and Murthy 2011).

3.5.4. Ethanol distribution

From a production plant, ethanol is transported to blending facilities via ground transportation using heavy duty trucks. On the island of Hawaiʻi, ethanol-to-gasoline blending takes place at three locations—all of which may be accessed within roughly 45 km of linear distance from anywhere on the island. Therefore this study assumes that ethanol is transported 45 km using trucks fueled by diesel. The emission factors for ethanol distribution are based on GREET (2012) using 100% truck transport. This study assumes no inter-island shipment of bioethanol within Hawaiʻi.

3.5.5. Co-product accounting

Co-product accounting is an important factor affecting the life-cycle impact of a product. Lignin energy is co-produced along with ethanol during both green and non-green processing technologies, whereas fungal protein is also produced as a co-product during green processing of biomass. To account for emissions associated with co-product generation, this study uses the system expansion method. For the protein-rich fungal biomass co-product, it is assumed that the fungi-derived feed will replace soybean meal used commonly as a conventional feed ingredient. Since soybean meal is also a co-product of soy oil production, this complicates the accounting procedure. For soybean meal life-cycle assessment, it has been pointed out that system expansion is not a viable choice because "[n]o data on an alternative soymeal process were available" (US Soybean Board 2010, p.40). Therefore, this study allocates material and energy use of soy oil and soy bean meal based on mass available from GREET (2012). For excess electricity produced by lignin, it is assumed that the excess electricity will replace the current electricity generation mix on the island of Hawaiʻi, composed of 69% petroleum, 14% geothermal, 12% wind, 5% hydro and 1% solar uses (DBEDT 2010).

3. 5.6. Results and discussion

3.5.6.1. Life-cycle energy use

Model results indicate that process energy and chemical input requirements differ between green and non-green processing options. While the differences are found to be small for all input uses during feedstock production, and transport and distribution phases, sizable differences exist in ethanol conversion (Table 3.5). The difference is particularly notable in power consumption and production, with green-processing consuming 60 kWh more power on a gross basis than the non-green processing option. The higher gross power consumption in green-processing is primarily due to the additional power need stemming from aeration and agitation requirements for fungal co-product generation, while lower power production is caused by the higher process steam requirement. Green processing needs additional heat agents due to an increased use of an evaporator to handle the additional waste-water stream. As a result, more lignin-rich waste is diverted for steam generation, and less remains for electricity production. Other inputs, including cellulase, yeast, lime and gasoline, are found to be similar for both options. As for feedstock production, transportation, and distribution phases, the differences are found to be small for all input uses.

Table 3-5: Resources and Energy Use in Green and Non-Green Ethanol Processing Options (per10,000 MJ)

	Green Processing	Non-Green Processing
Feedstock requirement (dry tonnes)	1.8	1.6
Sulfuric acid (kg)	330	330
Cellulase (kg)	120	130
Yeast (kg)	1.4	1.3
Ca(OH)2 (kg)	200	200
Gasoline (kg)	3.7	3.7
Heat/cooling requirement		
Steam (kg)	3,300	2,800
Cooling water (kg)	197,000	196,000
Chilling water (kg)	330	360
Gross power consumption (kWh)	390	330
Power produced from lignin energy (kWh)	88	250
Net power consumption (kWh)	302	80

Investigation of the energy balance of these two options involves evaluating common measures including net energy value (NEV) and net energy ratios (NER) (Schmer et al. 2008). The concept of net energy balance has been used widely to measure the potential energy gains and losses that can be made by the use of biofuels (Schmer et al. 2008; Khatiwada and Silveira 2009; Bureau et al. 2010), though NER or NEV alone cannot be used to compare alternative fuel options without considering the quality of fuel (Kumar and Murthy, 2012). As shown in equation (2), NEV is calculated as the difference between the energy content of ethanol denoted E_{output} (i.e., the functional unit) and the amount of fossil fuel used in production E_{input}, taking into account fossil energy allocated for co-product generation noted $E_{coproduct}$ (Farrell et al. 2006). NER is calculated as the ratio of the two, while taking account of co-product energy needs. A positive NEV indicates relative gains whereas negative NEV indicates that more fossil fuel energy is needed to be produced than the energy contained in the final product. Similarly, NER of >1 indicates energy gains.

$$\text{NEV} = \text{Eoutput} + \text{Ecoproduct} - \text{Einput} \qquad \ldots(2)$$

$$\text{NER} = \frac{E_{output} + Ecoproduct}{E_{input}} \qquad \ldots(3)$$

The results indicate that both green and non-green processing require less fossil energy to produce than the amount of energy the ethanol is able to deliver. For green processing, the net energy value is found to be lower at 1,800 MJ/functional unit (3.8MJ/liter) , while that of non-green processing is higher at

3,020MJ/functional unit (6.4 MJ/liter) (see table 3.6). Both of these estimates are relatively lower as compared to the existing NEV calculation of lignocellulosic ethanol, including Schmer et al. (2008) whose switchgrass-based ethanol was found to have 21.5 MJ/liter across all regions, and Kumar and Murthy (2011) whose tall-fescue-based ethanol had a NEV of 12.89 MJ/ liter.[29] This is due to many factors including the different feedstock production processes required for banagrass production as compared to switchgrass and tall fescue, and varying levels of chemicals and energy needed for ethanol conversions. The total life-cycle fossil fuel related to agricultural machinery use per functional unit were 370 MJ, and agrochemical use was 810 MJ, while for non-green processing, figures were 340 MJ and 760 MJ respectively. Life-cycle fossil fuel use related to ethanol processing per functional unit are 2,700 MJ (net process power), 2,900 MJ (enzyme), 880 MJ (calcium hydroxide Ca(OH)2), 200 MJ (sulfuric acid (H2SO4)), 55 MJ (yeast), 37 MJ (gasoline) for green processing, and 730 MJ (net process power), 3,200 MJ (enzyme), 880 MJ (Ca(OH)2), 201 MJ (H2SO4), 51 MJ (yeast), 37 MJ (gasoline) for non-green processing respectively. Those related to biomass transportation and ethanol distribution per functional unit were 150 MJ and 64 MJ for green-processing and 140 MJ and 64 MJ for non-green processing.

Table 3-6: Net Energy Balance of Banagrass-based Ethanol Production and Gasoline

	Green-processing	Non-green processing	Gasoline (Greet 2012)
Total life-cycle energy Consumption (per 10,000 MJ)	8,400MJ	7,400MJ	12,000 MJ
Total life-cycle fossil energy consumption (per 10,000 MJ)	8,200MJ	7,000MJ	12,000 MJ
NEV (per 10,000 MJ)	1,800 MJ	3,020MJ	-2,100MJ
NEV (per liter)	3.8MJ	6.4 MJ	-6.6 MJ
NER	1.2	1.4	0.8

3.5.6.2. Well-to-pump analysis

The well-to-pump analysis measures the life-cycle environmental impact of a fuel throughout its production chain except those associated with final combustion due to vehicular operation.[30] The well-to-pump GHG emissions related to ethanol production via green and non-green processing is shown in Table 3.7. Both green and non-green processing options are found to be a net emitter of GHGs, with their well-to-pump emissions more than the amount of CO2 sequestered in 10,000 MJ of ethanol.

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[29] NEV based on dilute acid pretreatment.

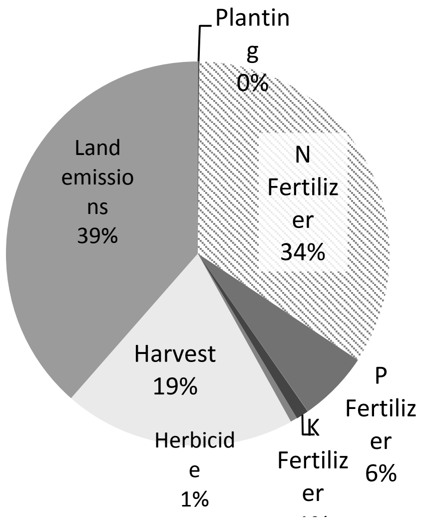
[30] It is generally recognized that well-to-pump analysis is "sufficient only for comparing various production technologies for ethanol production from lignocellulosic biomass, while well to wheel (cradle to grave) is the best approach for comparing ethanol utilization with different biofuels or fossil fuels" (Singh et al. 2010 p.5006).

Table 3-7: Well to Pump Life-Cycle GHG Emission: a Green Processing and Non-Green Processing per 10,000 MJ

	Green processing	Non-green processing
Feedstock production (gCO2)	144,000	134,000
Transportation(gCO2)	11,600	10,900
Ethanol processing(gCO2)	695,000	552,00
Distribution(gCO2)	5,990	4,990
Co-product credit for fungal biomass (gCO2)	3,350	n.a.
CO2 sequestered in fuel(gCO2)	709,800	709,800
Total life-cycle GHG emissions(gCO2)*	143,000	59,900

Note * may not add up due to rounding

On a net basis after taking the CO2 sequestrated in fuel, green-processed ethanol is found to emit 143,000 g of CO2e (carbon dioxide equivalent)/10,000MJ of ethanol, while non-green processed ethanol is estimated to emit 59,900g of CO2e/10,000MJ of ethanol. These figures are smaller than the well-to-pump GHG emissions of gasoline, estimated at 185,000 g of CO2e per 10,000 MJ of gasoline, though such comparison merits caution given the difference in energy content of two fuels. Some of the emission 'hot-spots' identified are presented below.



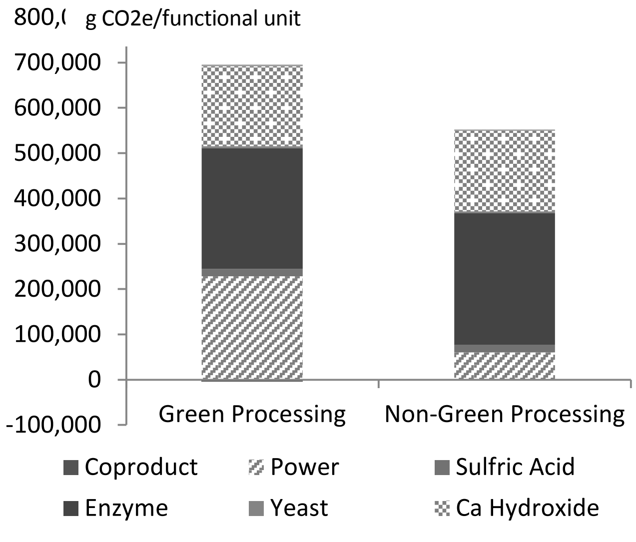


Figure 3-3:GHG emissions breakdown of banagrass production Figure 3-4: GHG from Ethanol Processing

For the banagrass production stage, direct nitrous oxide emissions from land application of fertilizer account for the largest portion, followed by emissions related to production and transport of agrochemicals including nitrogen fertilizer (Fig. 3.3). The significant contribution of nitrous oxide emissions observed during banagrass production resembles that of sugarcane production (Renouf and Wegener 2007). With a global warming potential approximately 300 times the potency of carbon dioxide, and with more than a 100 year life-span in the atmosphere (Klemendtsson and Smith 2011), nitrogen fertilizer application appears as an important hot-spot requiring efficient management to reduce feedstock related emissions.

During ethanol conversions, enzyme production contributes to the highest portion of green-house gas emission for both green and non-green processing. The contribution of enzyme use to the overall GHG emission was 27g CO2e/MJ of ethanol for green processing and 29 g CO2e/MJ of ethanol for non-green processing. These figures are higher than in previous studies such as that done by MacLean and Spatari (2009) which reported figures between 3.3 g and 3.6 g of CO2e/MJ and that of Dunn et al. (2012) which estimated 4.6 g of CO2e per MJ of ethanol, but similar with that of Kumar and Murthy (2011) which reported 27.8 g to 34 g of CO2e per MJ of ethanol. This is due to the fact that the former studies assumed the lower enzyme dosage of 9.2 g to 9.6 g per kg of biomass reported by MacLean and Spatari (2009), and 10 g per kg of biomass reported by Dunn et al. (2012), whereas the latter assumed a higher enzyme dosage of 62.4 to 71.8 g per dry kg of biomass based on laboratory measurement of purchased enzyme cocktail. The enzymes used in this study were estimated at 67 g and 78 g per kg of biomass in green and non-green process respectively. Since enzyme dosage and emissions during its production process is complex and variable (Dunn et al. 2012), sensitivity analysis was conducted and is reported on in a later section of this report.

Greenhouse gas emission related to calcium hydroxide production is also an important contributor during ethanol processing, estimated at 25% and 32% of processing related GHG emissions in green and non-green processing. Calcium hydroxide is used as the over-liming agent to remove the toxicity of inhibitors formed during pretreatment. The relatively high contribution estimated in this study stems primarily from the higher sulfuric acid concentration (5%) adopted for this study, as compared to existing technoeconomic studies based on alternative feedstock options including Aden et al. (2002) which adopted the concentration of 1% acid for corn stover and Kumar and Murthy (2011) which adopted the concentration of 1 % acid for tall fescue. Further optimization of pretreatment conditions could lower GHG emissions during these steps.

The green-processing option is found to produce protein-rich fungal product at a rate of 9.4 kg/functional unit. Assuming that this co-product will replace soybean meal, with the life-cycle GHG emissions of 356g of CO2e/kg of meal, it yields an equivalent of 3,350 g of CO2e/functional units of GHG emissions replacement (GREET 2012), though further optimization of fungal biomass yield and process integration will likely improve the GHG emissions impact of the green-processing option. The LCA results suggest that the fungal biomass co-product is more energy intensive than the product it is meant to replace. The differences in power and steam use, for example, is estimated to add 168,300g of CO2e per kg of functional unit for green-processing owing to higher steam requirements and power needs during fungal cultivation. Green processing with fungal biomass co-product, therefore, appears less favorable than non-green processing and stand-alone green processing without a fungal biomass co-product stream. Finally, given the relatively small biomass collection radius and ethanol distribution distance, both transportation and distribution related GHG emissions were found to be small in both options.

3.5.6.2. Well-to-wheel analysis

To further examine our results in comparison with existing studies, this section conducts well-to-wheel assessment, assuming that banagrass-derived ethanol will be used in a Flex-Fuel Vehicle as E85. Tail-pipe emissions related to E85 and fuel economy are based on GREET 2012. The results of well-to-wheel analysis show that green-processed and non-green processed banagrass-derived ethanol E85 emits 280 g CO2e and 260 g CO2e per km driven respectively. As Figure 3.5 shows, these results are relatively high compared to the existing estimates of lignocellulosic ethanol options including miscanthus (22g of CO2e/km), corn stover (75g to 120 of CO2e/km), switchgrass (82 g of CO2e/km), poplar (140 g of CO2e/km) and flax (180 g of CO2e/km). This is primarily because many of the feedstock and conversion options have emissions allocated to co-products during feedstock production (e.g. alfalfa, flax, hemp and corn-stover) and excess electricity produced from the lignin-rich co-product stream. Other factors such as the difference in enzyme loading discussed previously, have resulted in varying well-to-wheel emission estimates. Both green and non-green processing options had lower life-cycle GHG emissions than gasoline (290g of CO2e/km), but had higher GHG emissions than corn-derived ethanol (220 g of CO2e/km).

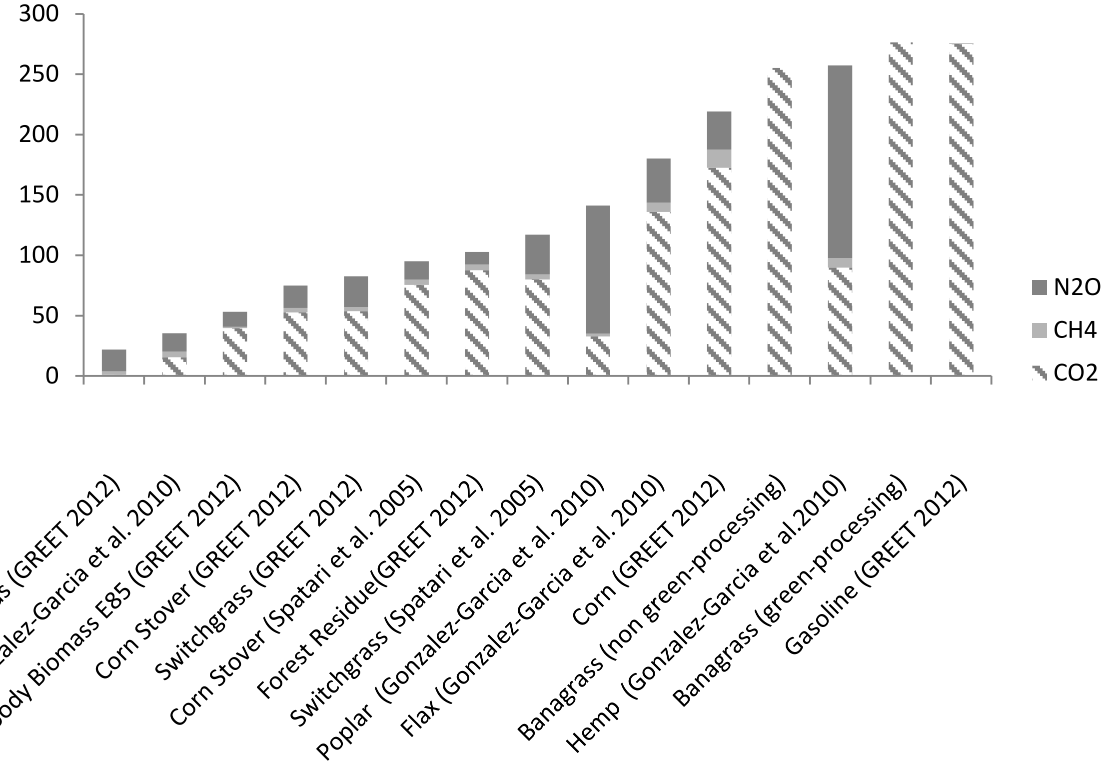


Figure 3-5: Comparison of Well-to-Wheel GHG Emissions with Existing Studies (in g of CO2e/km driven)

Note. The detailed GHG gas breakdown is not shown for green and non-green processing due to the lack of such data from the original reference used. To make studies more comparable, emissions figures are adjusted based on the fuel economy of GREET (2012).

3.6. Sensitivity Analysis

Uncertainty is inherent in elements of LCA, which requires cautious examination (McKone et al. 2011). A range of inputs, scenarios and modeling relationships adopted significantly affect the modeling outputs—which are also subject to discrepancy due to a number of factors including measurement errors and statistical variation, temporal, geographical and technological variation and the extent of simplifications and approximations adopted in each study (Lloyd and Ries 2007). For LCA in general, and biofuels LCA in particular, the choices of system boundary, co-product accounting methods, fuel-economy assumptions, etc. are found to impact analysis outcomes (Luo et al. 2009; Singh et al. 2010). Furthermore, continued research and development and commercialization efforts of lignocellulosic bioethanol means that technology is hardly static and uniform, and that temporal and technological variations will likely be a major contributor to the uncertainty of its life-cycle environmental impacts.

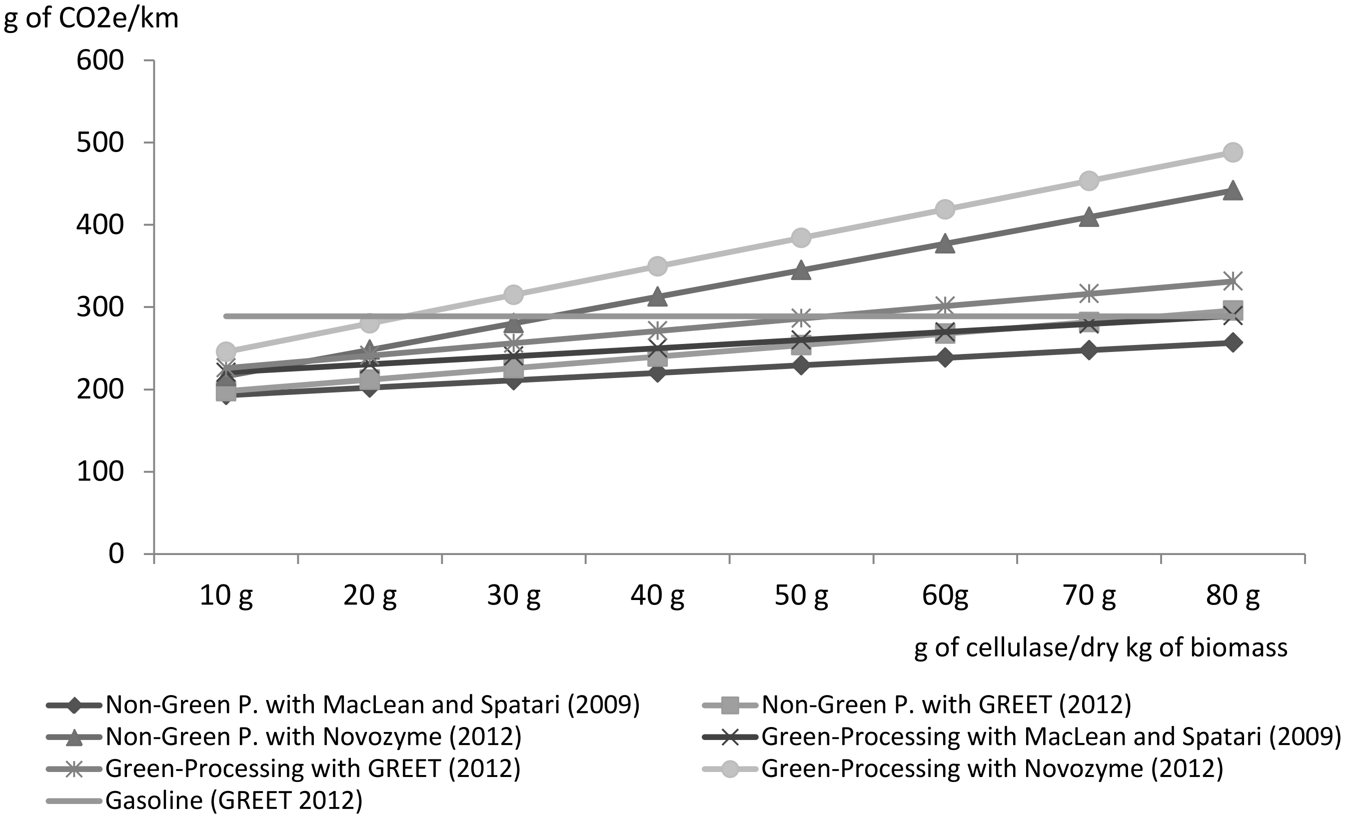


Figure 3-6: Sensitivity analysis with different enzyme loading (g of cellulase/dry kg of biomass) and emissions factors

Given the inherent uncertainty in bioethanol LCA, sensitivity analysis offers an important insight regarding the likely variation of GHG emissions and energy demand. By analyzing a range of key parameters, sensitivity analysis helps to avoid drawing false conclusions regarding life-cycle impacts solely based on default values (Cherubini et al 2009). This study conducts sensitivity analysis with regards to enzyme technology (with different loading and emissions factors), and power generation and usage (i.e., varying amounts of water diverted to anaerobic digestion and multiple effect evaporators, and different power mix that may occur on the island of Hawai‘i.)

Figure 3.6 shows the results from sensitivity analyses of enzyme-related parameters. As illustrated, well-to-wheel GHG emissions of both green and non-green processing options declined as enzyme load (g per dry kg of biomass) declined. Also, a range of emission factors assumed by each source— 2,260 g of CO2e per kg of enzyme by MacLean and Spatari (2009), 3,480 g of CO2e by GREET (2012), and 8,000 g of CO2e by Novozyme (2012) resulted in a wide range of global warming impacts.

First, when one adopts the higher emission factor suggested by Novozyme (2012), both green and non-green processing emit higher amounts of GHG than gasoline fueled options, emissions increased from 230g of CO2e/km (10g of enzyme/kg biomass) to 330g of CO2e/km (80g enzyme/kg of biomass) for green processing, and 220 g of CO2e/km (10g of enzyme/kg of biomass) to 440g of CO2e/km (80g of enzyme/kg of biomass) for non-green processing. Adopting GREET’s (2012) figure, emissions increased from 230 g of CO2e/km (10g of enzyme per kg of biomass) to 330 g of CO2e/km (80g of enzyme/kg of biomass) for green processing, and 200 g of CO2e/km (10g of enzyme/kg of biomass) and 300g of CO2e/km (80g of enzyme/kg of biomass) for non-green processing. Based on McLean and Spatari (2009), emissions were estimated at 220 g of CO2e/km (10g of enzyme/kg of biomass) to 290g for green processing and 190 g of CO2e/km (10g of enzyme/kg of biomass) and 260 g of CO2e/km (80g of enzyme/kg of biomass). The wide range of variation observed in this study confirms the general experts’ view that enzyme loading and emissions related to its production are highly uncertain (Dunn et al. 2012; McLean and Spatari 2009). Further optimization of enzyme production process, together with improvements in enzyme activity and saccharification efficiency will likely improve these emission impacts, and it is generally difficult to draw precise conclusions given the likely range of enzyme related life-cycle GHG emissions.

Second, the amount of water diverted to anaerobic digestion (as opposed to multiple effect evaporators) is an important parameter affecting the process power use and generation (Kumar and Murthy 2011). In the base case, 25% of water is diverted to anaerobic digestion, which resulted in production of 88 kWh and 250 kWh of power per 10,000MJ of ethanol in green and non-green processing. In this sensitivity analysis, the proportion of wastewater stream sent for anaerobic digestion was gradually increased from 5% to 45%, which resulted in a varied rate of power generation and total life-cycle emissions. As shown, the total GHG emissions decreased steadily as the ratio of wastewater diverted to anaerobic digestion increased. An increase in biogas generated from anaerobic digestion, together with a decrease in the moisture content of the lignin-rich waste stream, increased power generation. For green processing, power generated from the lignin-rich waste stream increased from -48kWh/functional unit (5% split) to 220 kWh/functional unit (45% split). For non-green processing, the power generation increased from 98 kWh/functional unit (5% split) to 380 kWh/functional unit (45% split). While the state of Hawaiʻi currently envisions the use of 40% renewable energy in its power generation mix by the year 2030, this sensitivity also increased the base power generation mix (69% petroleum) to a 40% renewable case (60% petroleum), but the differences in life-cycle emissions across these two cases are found to be relatively small, ranging from 10 g of CO2e/km (5% split) to 4.5 g of CO2e/km (45% split) for green processing and 5.0 g of CO2e/km(5% split) to -0.8 g of CO2e/km (45% split).

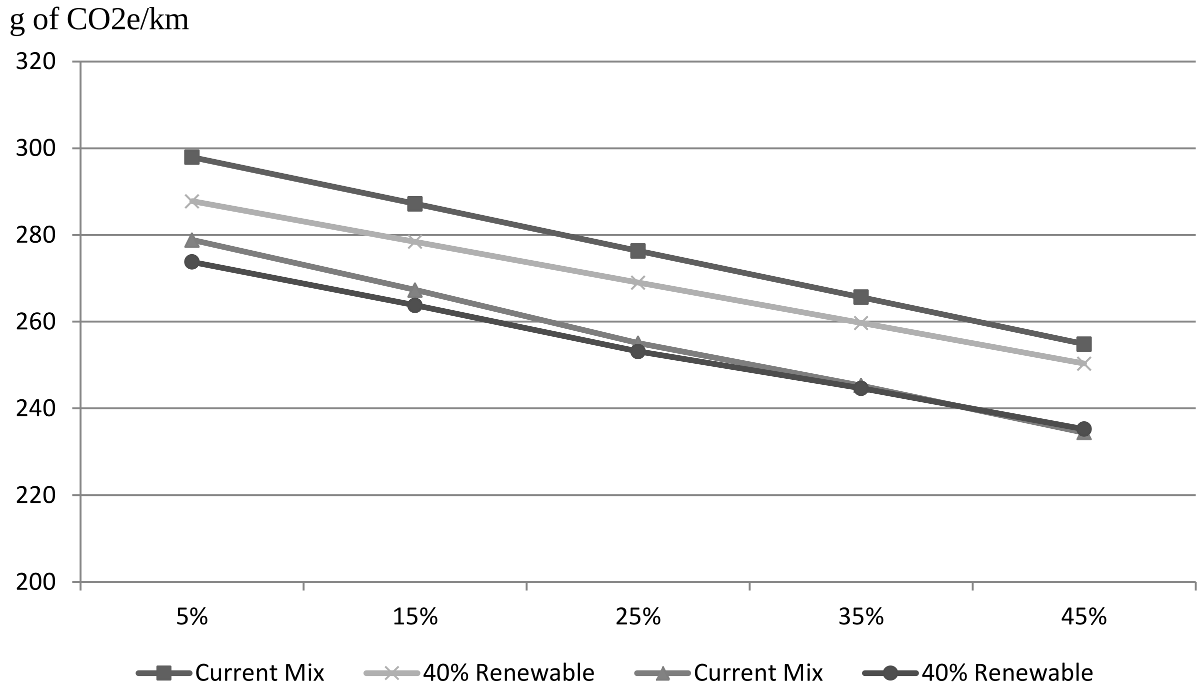


Figure 3-7: Sensitivity analysis with a different split between water recycling and waste-to-power generation

3.7. Discussion

Life-cycle assessment of green and non-green processing of banagrass-derived ethanol highlights important insights regarding the global warming implications for the tropical grass-to-ethanol option. It has identified some of the key 'hot-spots' of energy use and emissions, while also suggesting how energy and GHG impacts may be mitigated with improved technological development. Some of the important insights gained are discussed in the following sections.

First, green-processing, while determined to be a promising option for co-production generation, requires considerable technological improvement before it can achieve significant GHG reduction benefits. This is largely due to fungal cultivation being a relatively energy-intensive process when compared to conventional animal/fish feed sources such as soybean meal. Fungal cultivation is a continuous process requiring sufficient aeration, agitation and temperature—all of which requires additional energy use. On the other hand, current animal/fish feed ingredients such as soybean meal themselves are often co-products generated from existing food manufacturing processes (e.g. soybean oil processing), and agro-chemical and fuel use during crop production are generally less energy intensive than those used during biochemical manufacturing. Therefore, in order for green-processed co-products to bring about greenhouse gas benefits, further research is needed to increase efficiency by improving fungal yield and energy use, and by exploring possibilities to integrate more renewable energy options into processing, such as solar hot-water and industrial steam generation (Takara 2012 b). This will likely involve a trade-off between higher capital investment required for these renewable options vs. gains made in reducing costs and life-cycle emissions, which merits further examination from a life-cycle perspective. Furthermore, while life-cycle water-use is not fully investigated in this study, differences in water footprints between green and non-green processing will also be informative in highlighting their varied environmental impacts.

Second, both green and non-green processing of banagrass to ethanol lead to small gains, (10 g and 30g of CO2e/km driven) according to the well-to-wheel analysis, though continued improvement in technological options and life-cycle GHG footprints of inputs used in the process will lead to further reduction potential. For example, the island of Hawai‘i currently supplies around 69% of electricity needs by petroleum-based generation facilities, leading to both a high GHG emission footprint and operational cost of power consumption. The high emissions intensity of power generation reflects unfavorably when a plant is a net consumer of power (as is the case based on parameters chosen in this study); however, the same condition could work favorably when a plant becomes a net producer of energy and additional co-product credit maybe given, in addition to a further stream of revenue generated by electricity sale. Therefore, reconfiguration of process designs and improved utilization of anaerobic digesters (e.g. taking locally available animal manures) etc, may significantly improve the GHG emissions profile of these alternative fuel option.

In addition, continued improvements in yield, crop management techniques, and harvesting efficiency will likely improve their life-cycle greenhouse gas emissions. In particular, nitrogen fertilizer use was found to be a large contributor to life-cycle emissions during its production and as part of direct land emissions. Therefore, efficient use of fertilizers based on varying soil properties and timing of application and rate of nutrient requirements at different stages of plant growth will likely improve its productivity. Also, though soil carbon is not included in this analysis, a perennial crop such as banagrass has the potential to contribute to soil carbon sequestration and, an LCA ideally should also look at carbon sequestration to give a complete balance of net CO2 emitted versus CO2 sequestered (Sumiyoshi 2012). The potential impact of carbon sequestration should be analyzed together with other impacts that may arise from direct and indirect effects of land-use changes.

Third, the range of uncertainty regarding GHG emissions appears high due to varying parametric assumptions regarding emission factors, enzyme loading and process power generation. While further optimization of processing conditions will likely reduce chemical and energy usage, technological choices and process designs should take into account the current range of energy use and emissions associated with input use. Given these uncertainties, it is difficult to draw robust conclusions regarding GHG benefits of banagrass-based bioethanol production in Hawai‘i; however, this study does provide some indicative patterns. While reduced energy and chemical use typically lead to reduced cost, and hence increased competiveness, of the final product, further efficiency improvements in these regards will be beneficial for both emissions and economic perspective. The analysis should be updated as and when new information becomes available—such as optimal processing conditions particular to banagrass and emissions factors for key inputs used in the process.

Finally, the use of biomass as a source of drying heat, assumed in this study, should be evaluated with caution as biomass drying needs are high especially for non-green processing option. To produce10,000MJ of ethanol under non-green processing, it is estimated that 1.6 dry tonnes of biomass will be needed for processing. Assuming that biomass has an initial moisture content of around 67%, it is estimated that around 0.55 dry tonnes of biomass would be needed to bring down the moisture content to 7% assuming biomass boiler efficiency of 75%. If it is technically and economically unfeasible to harvest additional biomass for drying usages, the use of fossil fuel alternative will cause a sharp rise in emissions. Assuming the use of diesel for biomass drying under the same boiler efficiency, it will require approximately 270 liters of diesel to dry biomass sufficiently to produce 10,000MJ of ethanol under non-green processing, which is likely be unacceptably high on the grounds of both environmental and economic costs. Therefore, if collection of sufficient biomass seems unfeasible due to local resources availability, the adoption of green-processing technology, which eliminates excessive feedstock drying process, could become more favorable, especially in the tropical regions. In this study, the amount of biomass needed to dry fungal co-product was estimated at around 8.5kg per functional unit of ethanol produced.

3.8. Conclusions

This study conducted well-to-pump and well-to-wheel life-cycle GHG assessments of banagrass-to-ethanol options, comparing the innovative concept of green-processing and conventional non-green processing. The results indicate that green and non-green processed ethanol consume 8,200 MJ and 7,000 MJ of fossil fuel energy per 10,000 MJ of ethanol produced. Process power, enzyme and chemical production were some of the hot-spots of life-cycle fossil energy demand. Based on a well-to-pump analysis, green and non-processing of banagrass-derived ethanol were estimated to emit approximately143,000g of $CO2e$ and 59,900 g of $CO2e$ per 10,000MJ of ethanol produced, while well-to-wheel analysis have shown that life-cycle GHG emissions per km of FFV driven were 280g of $CO2e$ for green processing and 260 g of $CO2e$ for non-green processing. Considering the wide range of assumptions that may be adopted regarding the production process designs, input usage including enzyme and chemical loading, and processing conditions, including pretreatment parameters, etc., it is generally difficult to draw robust conclusions regarding GHG emissions impact of these lignocellulosic ethanol options, though the sensitivity analyses have highlighted the likely range of emissions impacts. Given the current level of technologies determined mostly by lab scale observations, GHG emissions reduction potential of green and non-green processing options as compared with conventional gasoline appears limited. To draw a more comprehensive judgment regarding environmental sustainability of this alternative fuel option, continued investigations reflecting further optimization of processing conditions and further analysis on a range of other environmental impacts including eutrophication potential, acidification potential, human toxicity potential, water footprint and potential invasiveness, would be useful.

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4. CHAPTER FOUR: MARKET, WELFARE AND LAND USE IMPLICATIONS OF BANAGRASS-DERIVED BIOETHANOL IN HAWAI‘I

4.1 Introduction

Government interventions in the form of mandates, subsidies and tariffs have served as major drivers behind rapid growth in the global biofuels industry. The U.S. biofuels industry, the largest producer of ethanol in the world, has grown from producing 175 million gallons in 1980 to nearly 13 billion gallons in 2010 (Cardno Entrix 2010). Rigorous research and development efforts are now being taken to develop more sustainable next generation biofuels that do not compete directly with food production. The so-called second-generation or lignocellulose bioethanol derived from a range of plant materials is one such alternative nearing commercialization. Depending on the feedstocks and conversion technologies chosen, second-generation bioethanol could offer a myriad of benefits such as reduced greenhouse gas emissions, reduced competition with food production, soil conservation, carbon sequestration, water quality improvement and habitat improvement (Tilman et al. 2009). The US Renewable Fuels Standard (RFS) now foresees that the use of biofuels can reach 36 billion gallons by 2022 with cellulosic biofuels expected to supply 16 billion gallons (National Research Counil 2011). In the context of Hawai‘i, a host of incentives including tax credits for producers, state and county government procurement preference, and alternative fuels standards (AFS)[31] are now in place to encourage bioethanol production (State of Hawai‘i 2010).

The effects of biofuels policy are felt widely across a range of economic sectors including energy and agricultural markets, making the general equilibrium (GE) framework a preferred policy analysis tool. Unlike the partial equilibrium (PE) framework which analyzes the supply and demand interaction of a particular market while holding other things constant—*ceteris paribus*, the GE framework is able to capture the entire flow of payments and goods in an economy, thereby highlighting the ripple effects of biofuels policy across a wide range of sectors. In addition, the richness of social accounting matrices (SAM) allows for detailed evaluation of policy impacts on a variety of aspects including government spending, consumer welfare, private investment and savings, and balance of trade (Rajagopal and Ziberman 2007; Golub et al. 2010). Compared to the PE framework, the GE models better illustrates growth as well as contraction in individual sector outputs and final demand, thereby identifying potential “winners and losers” from a particular policy within the economy. The ex-ante analyses based on the GE modeling thus offers an invaluable framework for both positive and normative analysis of biofuels policy, enabling policy-makers to identifying the optimal policy mix that can achieve desired outcome. The existing studies have shown that since bioethanol is both a substitute for, and a compliment to, transport gasoline fuel, the exact impact of chosen policy hinges on many factors including existing market structures (Saitone, Sexton, Sexton 2007), prevalent gasoline prices, supply

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[31] ARF calls for 10%, 20% and 30% of highway fuels to be supplied by alternative fuels in 2010, 2020 and 2030 respectively.

elasticity of gasoline (Ando et al. 2010) and interaction with closely-related policy variables such as agricultural subsidies (Taheripour and Tyner 2012).

While multiple-country or global CGE modeling has been widely studied to examine a number of salient impacts including land-use changes, and welfare implications, CGE assessment of advanced biofuels in regional economies are still limited. Given that biofuels are often promoted as a way of simulating regional agricultural activities, it is important to understand the detailed assessment of economy wide impact in the regional context. Therefore, this fills the gap by offering an assessment using the State of Hawaiʻi as an example. In particular, this study builds an agricultural and energy-focused model, which evaluates how a second-generation bioethanol industry will affect the state economy, land-use, and resident welfare.

4.2. Literature Review

CGE models have been one of the dominant methods for assessing biofuels policy impacts especially at the global level.[32] The market, welfare and land use implications are frequently examined aspects of biofuels policy where CGE framework has commonly been adopted. In a pioneering work examining biofuels policy impact on global land use changes, Hertel et al. (2008a) evaluated the combined effects of U.S. and European mid-term biofuels mandates up to 2015 on global agricultural commodity output, land-cover, and welfare changes. The authors conclude that crop cover will rise substantially in Latin America, Oceania and Africa and replace pastureland and commercial forest land. Evaluating a longer term trend up to year 2100, Gurgel et al. (2008) estimate global land use impacts of lignocelluloisc biofuels and highlight the importance of land conversion assumptions. Their study concludes that when unrestricted land conversion is allowed (taking into account the conversion costs), an expansion of biofuels production leads to a substantial conversion of natural forests. When land cover conversion is modeled to follow observed land supply response, however, biofuels expansion leads to a sizable decline in pasture land. In both cases, the majority of biomass production takes place in the regions of Latin America and Africa. Other studies such as Timilsina et al. (2010) Beckman et al. (2011) and Timilsina and Mevel (2011) also concluded that notable land cover conversion is likely, particularly under aggressive promotion of biofuels consumption.

Welfare implications of biofuels policy differ considerably across regions based on assumptions such as existing market distortions (Gitiaux et al. 2009), policy interactions (Kretschmer et al. 2009; Taheripour and Tyner 2012), and the presence or absence of tariff barriers (Gitiaux et al. 2009). In general, the promotion of biofuels tends to reduce welfare since it is a costlier alternative to fossil fuels (Kretschmer et al. 2009; McCullough et al. 2011; Satyakti et al. 2012; Taheripoyr and Tyner 2012); however, differing assumptions could lead to overall welfare gains (Painter et al. 2009; Gunatilake et al.2011; McCullough et al. 2011; Huang

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[32] There are number of reasons why CGE has become dominant in the field of biofuels policy analysis: i) biofuels industry will likely have economy-wide impacts through its forward and backward linkages; ii) the rise in biofuels production affects a number of key variables including direct and indirect land-uses and energy market compositions; and iii) the lack of time series data on biofuels production makes an alternative of econometric analysis difficult.

et al. 2012). For example, evaluating the alternative policy scenarios to promote bioethanol and biodiesel production in Washington State, Painter et al. (2009) concludes that consumer welfare, as measured as the average value of equivalent variation across all income categories, increased under the feedstock subsidies and volumetric and carbon-based renewable fuel subsidies, and decreased under the mandate only, volumetric fossil fuel tax and carbon tax scenarios. The existing studies demonstrate that biofuels mandates tend to increase market prices of agricultural commodities, because these commodities compete for factor inputs (Gurgel et al. 2008; Kretschmer et al. 2009; Arndt et al. 2012). Biofuels policy impacts on fuel prices, on the other hand, are mixed and generally thought to be small. For example, estimates from Taheripor and Tyner (2012) suggest that the US 2015 mandate of 15 billion gallons of ethanol consumption leads to a decline of 1.6 % and an increase of 4.3% in the price of gasoline depending on assumed policy scenario.

Generally, these CGE models incorporate activities of the nascent biofuels industry based on three approaches. First, an implicit modeling approach (Dixon et al 2007 and Banse et al. 2008) treats biofuels as a replacement or intermediate input within a nesting structure of energy goods. Second, a latent technology approach (Boeters et al. 2008) models biofuels production as an activity that is technologically possible, but is not economically profitable (hence inactive) in the base year. Third, a more explicit approach (Birur et al. 2008 and Painter et al. 2009) which estimates the level of the biofuels industry's activity by splitting the base year Social Accounting Matrix (SAM) (Kretschmer and Peterson 2009).

4. 3. Lignocellulosic Bioethanol Development in Hawaiʻi

As a remote chain of islands with limited indigenous sources of conventional energy, the State of Hawaiʻi remains the most fossil fuel dependent state within the United States. Imported fossil fuels (predominantly petroleum products) supply over 85% of the state's primary energy (DBEDT 2011 a). In 2007, the State of Hawaiʻi spent $4.67 billion on petroleum products, of which gasoline consumption accounts for some $1.37 billion.[33]

The volatile international price of oil, growing concerns over adverse impacts of anthropogenic climate change, and the desire to revive a waning agricultural industry have led to a renewed interest in the development of alternative biofuels. The State of Hawaiʻi adopted one of the most aggressive renewable energy deployment goals in the United States: Hawaiʻi's Clean Energy Initiative of 2008 calls for 70% of the state's primary energy to be supplied by clean sources by 2030, consisting of 40% renewables and 30% efficiency gains. In the transportation sector, Hawaiʻi's AFS calls for 20% and 30% of transport fuel to come from renewable sources by 2020 and 2030 respectively. In the area of bioethanol use, Hawai ʻi also has a 10% ethanol blending mandate in 85% of gasoline, and an ethanol facility tax credit worth 30% of annual nameplate capacity for local plants. These incentives, along with a highway gasoline tax rate that is one of the highest in the U.S., provide an impetus for bioethanol development in Hawai ʻi (DBEDT 2012).

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[33] Estimated based on EIA statistics (EIA 2012) and 2007 input-output data (DBEDT 2011b). Please see appendix 4.2 for details.

In the area of lignocellulosic bioethanol, research and development (R&D) efforts are ongoing to convert herbaceous and woody crops through a range of conversion technologies. As of this writing, however, no production is taking place, and bioethanol is being imported from a number of out-of-state sources. In 2007, the State of Hawaiʻi consumed 40,853,720 gallons of ethanol,[34] and approximately 74% of this is imported from foreign countries (e.g. El Salvador and Jamaica) while the rest is imported from other states within the United States (EIA 2007). To encourage local ethanol production, a number of potential feedstock options including sugarcane, banagrass, eucalyptus, and leucaena have been evaluated for their technical and economic feasibility, and a plethora of incentives are in place (DBEDT 2009). Among these options, biochemical conversion of banagrass (*Pennisetum purpureum*) has been identified in Hawaiʻi as an economically viable bioethanol option due to its high yield and agroclimatic advantages (Black and Veatch 2010; Tran et al. 2011).Thus, this study examines the economic impacts of this technology.

4.4. Data and Methodology

4.4.1. Modeling Structure

The modeling structure and parameters are primarily based on the Hawaiʻi General Equilibrium Model (H-GEM) (Coffman forthcoming) and Applied Dynamic Analysis of the Global Economy (ADAGE) model (Ross 2008). The model adopted for this study consists of 25 production sectors, a representative resident and visitor consumption sector, and federal and state government sector. It includes labor, capital and energy as sectorally mobile factors of production and agricultural and forest land is explicitly modeled as a sector-specific factor with a fixed level of initial endowment.[35]

4.4.1.1. Production Block

The production sector is divided into i) Non-Energy (agriculture, industrial commercial), ii) Petroleum (gasoline and non-gasoline), and iii) Electricity in the base model. In the benchmark year, the State of Hawaiʻi mandates 10% of ethanol for use in at least 85% of gasoline consumption. Currently, this ethanol is imported from outside of the state. In the counter-factual scenario, local production of lignocellulosic ethanol will replace this import under the 10% mandate. In the case of a 20% mandate, local ethanol will further replace a portion of gasoline demand to achieve 20% of alternative fuel use.[36] Appendix 4.3 shows the use table employed in this study.

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[34] Author's own calculation based on the fact that the State of Hawai'i met its mandate of 10% ethanol blend for 85% of motor gasoline fuel in 2007 (DBEDT 2013). Though this figure does not match with a more top-down estimate of ethanol consumption available from the EIA database (EIA 2012), the former estimate is deemed more accurate given the existence of the mandate.

[35] Factor mobility is "the speed in which factors can move between sectors in response to changes in relative returns". (Shutes et al. 2012)

[36] What constitutes a 'baseline' scenario in the 20 percent mandate for Hawai'i is open to debate. For example, it is possible to assume that Hawai'i may import 20% of its bioethanol in the baseline year and locally produced bioethanol will replace these imports in the counterfactual scenario. While this interpretation is possible, this study assumes an alternative baseline, which

Each production sector includes a representative producer who maximizes profit subject to a given technological constraint that has constant returns to scale. The production function takes the form of a nested Constant Elasticity of Substitution (CES) function, in which domestically produced intermediate inputs, factors of production, and imports enter as production inputs. Domestically produced goods are then allocated for domestic and export consumption through a constant elasticity of transformation (CET) function.

Figure 4-1: **Nested Structure of Agricultural Commodity Production**

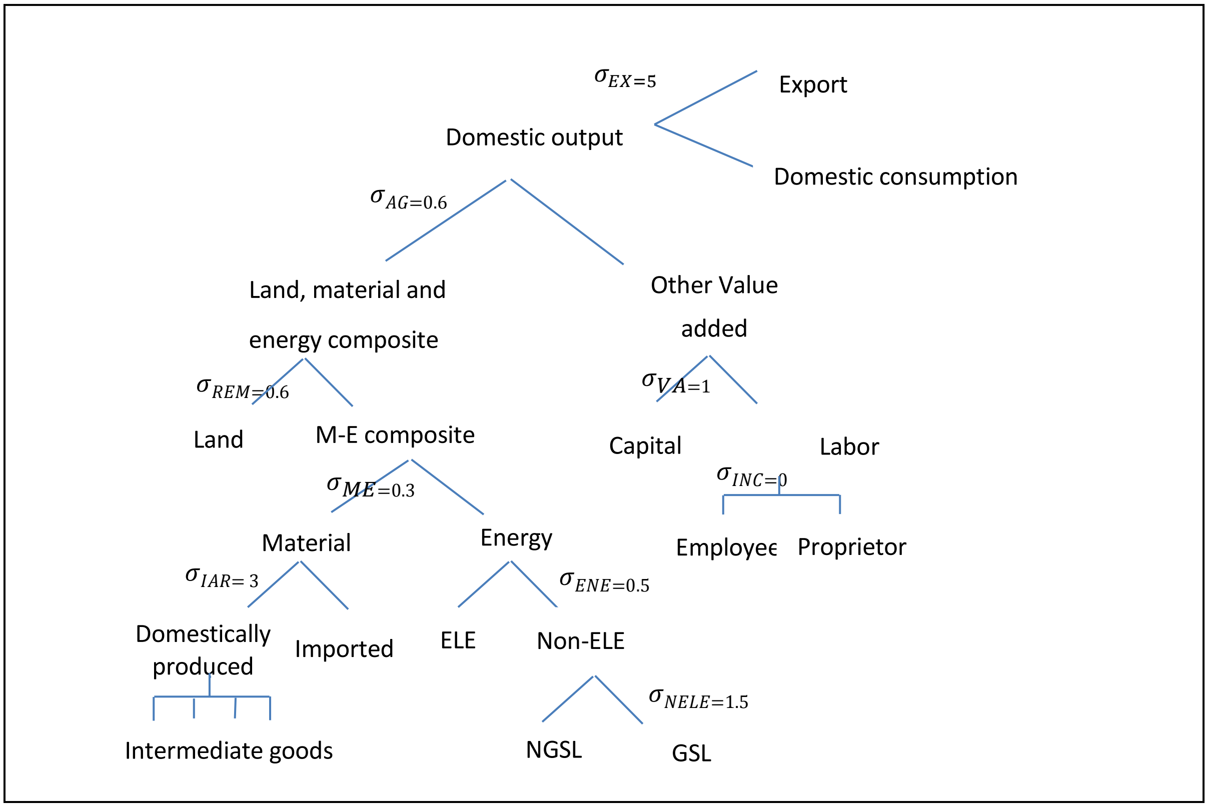

Figure 4.1 shows the nested production structure of the agricultural commodity. The agricultural production functions make a distinction between land, material and energy inputs on the one hand and capital and labor inputs on the other. Given the lack of data on detailed agricultural land use by sector within the state, this study uses individual agricultural sector payments to the real estate sector as a proxy for land inputs in the benchmark year.[37] This distinction allows the producer to increase agricultural output either by expanding land areas (expansive production), adding materials and energy such as fertilizer and fuel and/or by adding labor and capital (intensive production). Though studies such as Bouet et al. (2010) assume the substitutability of land and fertilizer inputs to be as low as 0.05 in the case of developing countries, it is

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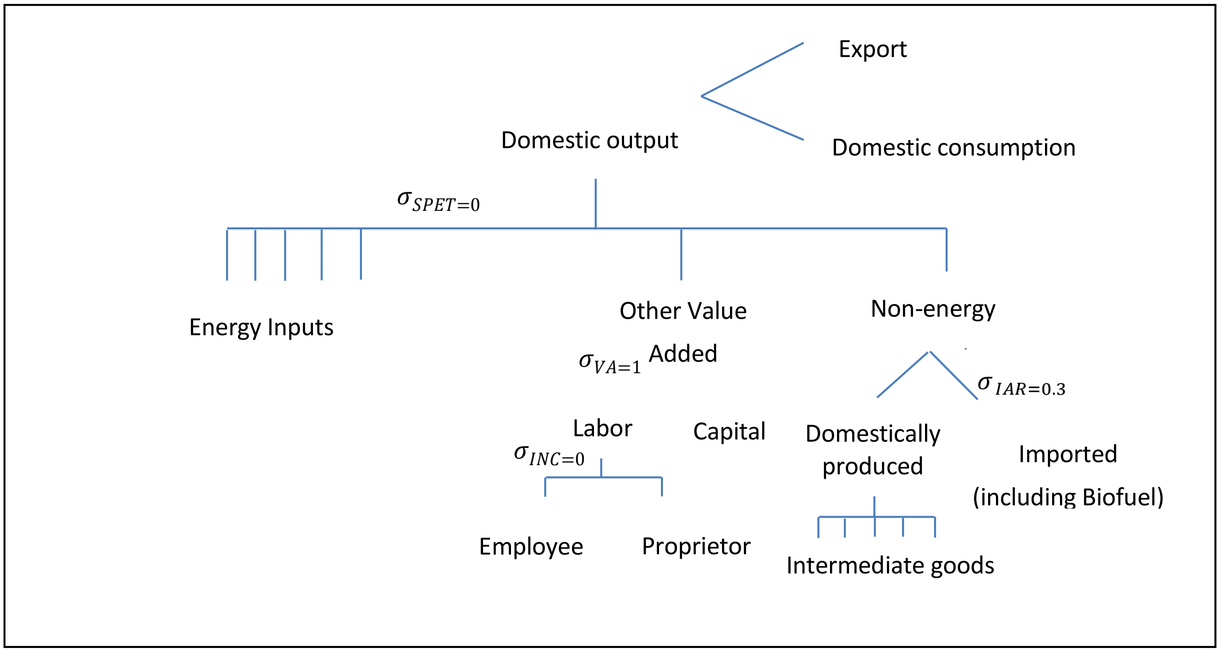
corresponds to the existing 10% mandate being met through bioethanol imports, corresponding to the actual consumption and importation data in the base year dataset.

[37] Since this study treats agricultural land as an endowment, other capital payments into the real estate sector are reduced by the equivalent value of this newly created land endowment to balance the I.O. table. This is of course a crude assumption and detailed estimation of agricultural rent based on unit rent values and existing acreage of crop production within the state will allow for a more accurate modeling of land use impacts.

assumed that Hawai ʻi’s soil condition is more favorable and that land and other material (e.g. fertilizer) and energy may be substituted based on an elasticity parameter of 0.6, and this composite may also be substituted with value added based on an elasticity parameter of 0.6 (Ross 2008). Substitutability of these inputs depends on many factors including agro-climatic conditions, and will likely affect the magnitude of policy impacts; therefore, sensitivity analyses will be conducted regarding these parameters.

Figure 4-2: **Nested Structure of Gasoline Production**

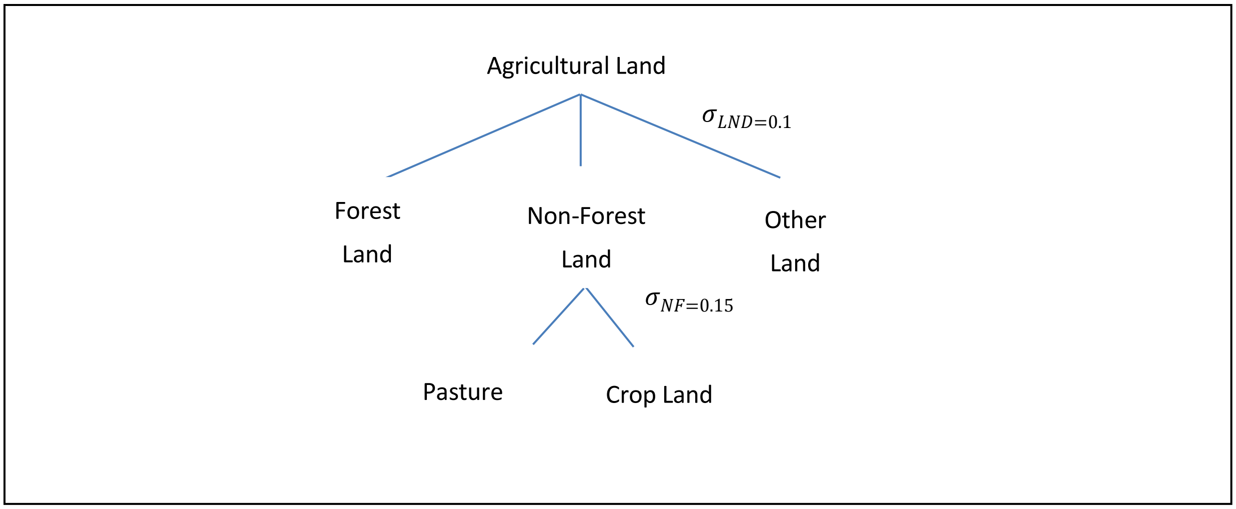


The gasoline production sector has a relatively rigid production technology in which both material and energy must be used in fixed proportion while substitution of capital and labor is allowed. In the base case scenario, imported ethanol enters as an intermediate input as shown in figure 4.2. In the 10% mandate scenario, the gasoline industry will buy locally produced bioethanol instead of imported bioethanol, while in the 20% scenario, the industry will further replace a portion of its gasoline consumption. Because local bioethanol is entered as an input into gasoline production, bioethanol is treated as a complimentary good of gasoline. Non-gasoline petroleum commodity production takes an identical production structure without intermediate consumption of bioethanol. The details of the electricity sector production function are described in the appendix 4.1.

4.4.1.2. Land-Use

Agricultural and forest lands are explicitly modeled as factors of production with a fixed level of initial endowment. Referring to Hertel et al. (2008b), land is allocated to each sector based on a CET function. Land uses adopted for this study include crop land, pasture land, forest land and other uses (e.g., agricultural services and aquaculture). Banagrass production is likely to occur in non-prime, non-unique land based on the Agricultural Land of Importance to the State of Hawai‘i (ALISH) categorization. Prime and unique land will likely be too costly for biofuels production and will compete with local food production (Black and Veach 2010). In Hawai ʻi, prime agricultural land is considered to be most suited for high value crops, including irrigated sugarcane, pineapple, and other orchards, while the unique agricultural land are areas that are primarily suited other crops including coffee, taro, and non-irrigated pineapple (State of Hawai ʻi 1977). While non-prime non-unique category of land is currently dominated by pasture use (Melrose and Delparte 2012), this study assumes that Banagrass production requires an input of pasture land in the base case.

Figure 4-3: **Nested Structure of Agricultural Land Transformation**



The remaining agricultural sectors use non-pasture land for production: crop land is used by the sugarcane, pineapple, orchard, and flower sectors. Forest land is used by the forestry sector, while other land is used by the agricultural service and aquaculture sectors respectively. For sensitivity analysis, this study also evaluates an alternative case in which new arable land becomes available. The limitation of this approach is that the model only constrains the rent weighted sum of land areas as an endowment instead of actual land areas in production (Hertel et al. 2008c). Also, important attributes of land which determine yield, such as soil characteristics and water availability, are not taking into account, and the cross island mobility of land is unconstrained. More explicit modeling which incorporates physical land areas, and geographic and environmental heterogeneity would be desirable.[38]

4.4.1.3. Consumption Block

The consumption block includes five agents consisting of a resident consumer, a visitor consumer, the state government, the federal government and an investment agent. A resident consumer is assumed to

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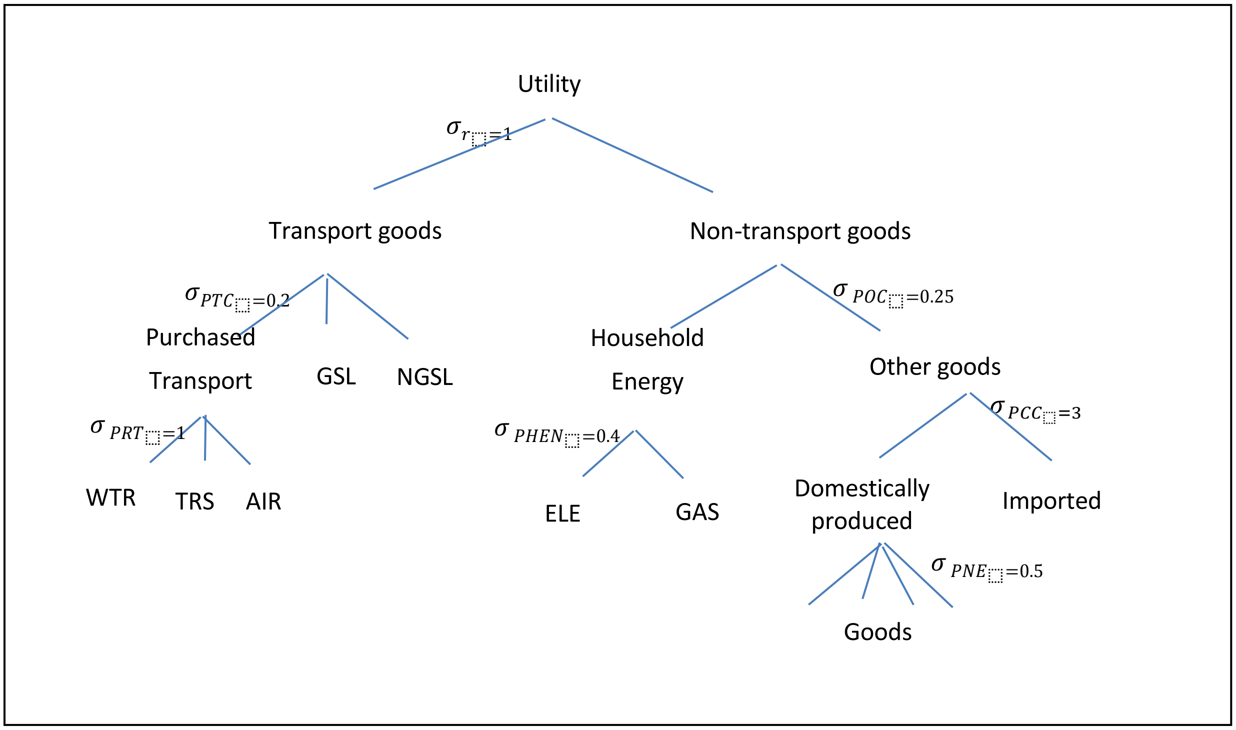
[38] In the context of Hawai’i where the diverse set of soils (190 soil series in 10 out of 12 soil orders in the world are found locally) offers a wide range of properties and behaviors (Hue et al. 2007), and rainfall variability ranges widely within islands, the aggregated treatment of land adopted in this study should be treated with caution.

maximize his/her utility based on a nested utility function consisting of transport and non-transport goods that are subject to a budget constraint.

Figure 4-4: **Nested Structure of Consumer Utility**



The transport goods are further divided into purchased transport (i.e. water, air and ground transportation commodities) and private transport demand, a demand consisting primarily of gasoline and ethanol consumption. A representative agent has a budget constraint equal to his/her income based on labor, capital and land endowment as well as foreign exchange earnings from the balance of payment and lump-sum tax or transfer. The visitor consumer and federal government demands are treated as exogenous while the state government maintains a minimal level of public goods and services provision based on a Leontief utility function. The state government's budget constraint equals its general exercise tax revenue plus lump-sum tax/transfer and fuel tax in applicable scenarios.

4.4.1.4. Market Clearing Conditions and Closure

Under perfect competition with constant returns to scale, equilibrium is achieved when marginal cost of production equals its producer price. Market clearing conditions ensures that all goods produced in a market are consumed. Therefore, the sum of intermediate demand, final demand by a resident, visitor, state, federal, investment, and export equals the sum of domestic supply and import of goods in each sector. All factor markets also clear so that the sum of labor, capital and land employed equals its respective initial endowment. Finally, the model adopts the following closure: Hawai‘i is a small economy and does not affect world commodity prices. The level of state government goods and services provision is assumed fixed, and the model must adjust its revenue through the use of endogenous taxation.

4.4.2. Data

The model is calibrated using the 2007 Hawai‘i State Input Output Study (DBEDT 2011b). All price information is therefore converted into 2007 prices using the U.S. Bureau of Labor Statistics' consumer price index of Hawai‘i (U.S. Bureau of Labor Statistics 2013). Fuel and ethanol use and production are important pieces of data utilized in this study. First, a detailed breakdown of fuel demand is estimated based on a number of sources including the State Energy Data System (EIA 2012) , agricultural fuel use (Schnepf 2004) and military fuel use (Defense Logistics Agency 2010), since consumption by sector is not available for Hawai‘i. Second, bioethanol imports in the base year is estimated using the State of Hawai‘i Databook (DBEDT 2007) and an average rack price of US ethanol in 2007 (Bloomberg Finance L.P. 2013). Third, production of ethanol includes feedstock production and processing costs. Production costs of banagrass are estimated using sugarcane industry data available from an input-output table based on an earlier year (Sharma et al. 1997), acreage in production available from (USDA 2013), and the average difference between per acre sugarcane and banagrass production cost as estimated by Kinoshita et al. (1995) (table 4.1). At present, sugarcane production takes place on a limited scale at two firms in Hawai‘i as of 2007. The existing economic feasibility studies of banagrass production are based commercial and experimental scale operation took place in the early to mid 1990s when the local sugarcane industry had a sizable production capacity. Given the paucity of detailed bottom-up cost estimates conducted in recent years, it was deemed appropriate to use an earlier IO table reported in the early to mid 1990s, which corresponds to the years in which these economic studies were conducted, taking into account factors such as inflation rates and changes in real prices of crude oil and electricity (DBEDT 2011a). The value of each input used in sugarcane production is first divided by the acreage in production to yield per acre input requirements. These are then multiplied by a factor of 0.51, (the estimated average costs of labor, material and services used in banagrass production relative to sugarcane production). This study assumes that banagrass yields 1 plant crop followed by 5 ratoon crops which are harvested every 8 months (Kinoshita et al. 1995), while that of sugarcane yields 1 ratoon crop. Banagrass yield was assumed as 21.5 dry ton/acre/year (Tran et al. 2011).

The production cost of lignocellulosic bioethanol is estimated using the bottom-up technoeconomic model of Kumar and Murthy (2011) using SuperPro Designer (Intelligen, Inc., Scotch Plains, NJ). This model adopts a biochemical conversion of lignocellulosic materials using dilute acid pretreatment and simultaneous scarification and co-fermentation (SSCoF). Kumar and Murthy (2011) was modified to reflect local costs and feedstock choice in Hawai‘i: First, electricity price was adjusted from the original value of \$0.07/kWh to \$0.29/kWh based on the large power user rate on the island of Hawai ‘i (HECO 2012). Second, water price was adjusted from the original value of \$0.30/tonne to \$1.60/tonne according to Hawai‘i Department of Water Supply (2012). Third, waste water treatment cost was adjusted from the original value of \$0.00/1,000 gallons to \$21.9/1,000 gallons according to Hawai‘i County (2012). Fourth, the base rate for operator wage was adjusted from the original value of \$30.0/hr to18.89/hr based U.S. Bureau of Labor Statistics (2011). Finally

Table 4-1: **Estimated Banagrass Production Cost Per Acre (in 2007 $)**

	Sugarcane[*]	Banagrass
Agricultural services	222.7	114.4
Other manufacturing	90.0	43.9
Non-gasoline petroleum products	238.5	122.5
Ground transportation	4.5	2.3
Water transportation	2.2	1.2
Electricity	322.4	165.6
Rental service	29.2	15.03
Real estate[**]	215.9	111.0
Other services	40.5	20.8
Total intermediate	1166.0	596.8
Value added	2339.4	1202.0
Labor income	1691.6	869.2
Capital payment	647.8	332.9
Imports	202.5	104.0
Total input	3707.9	1902.8

Note:[*] Sector inputs based on Sharma et al. (1997) was divided by the acreage in production based on USDA (2013). Prices of electricity and petroleum products are adjusted based on DBEDT (2011a).
[**] Used as a proxy for agricultural land rent.

Table 4-2: **Estimated Ethanol Processing Industry Inputs to Meet 10% and 20% Mandates (in Million 2007$)**

	10% mandate	20% mandate
Banagrass production	45.7	107.6
Other manufacturing	21.5	50.6
Gasoline manufacturing	0.9	2.1
Electricity	8.8	20.7
Sewage and waste management services*	0.1	0.3
Water provision*	1.1	2.6
Water transportation	0.7	1.8
Ground transportation	1.1	2.7
Real estate	1.5	3.4
Other services	1.0	2.3
Total intermediate demand	82.5	194.1
Value added	44.3	104.3
Labor income	6.9	16.3
Capital payment	37.4	88.1
Imports	-	-
Total input	126.8	298.4

Source: Authors estimate based on Kumar and Murthy (2011) with modification and DBEDT (2011b).Note: *reported as ‘other utilities’ sector according to the 2007 IO table.

the composition of banagrass was taken from Takara (2012), with the carbohydrate content consisting of approximately 37% of cellulose and 22% hemicellulose. These inputs are used in the technoeconomic calculation.[39] For the lignocellulosic industry, the additional cost of running the businesses (rent, insurance and other administrative costs) were estimated utilizing other manufacturing production sectors present in the 2007 IO table (Table 4.2). Finally, life-cycle emission factors for individual fuel types are taken from Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model 1 2012 version (Argonne National Laboratory 2012). It is assumed that the fuel mixes within sectoral energy demand (i.e., power generation fuel mix and non-gasoline fuel demand breakdown) remain unchanged and a blend of 26% US corn-derived ethanol and 74% Brazilian sugarcane-derived ethanol are used as a proxy for imported biofuel emissions intensity.

4.4.3. Policy Scenarios

The simulation estimates the land-use, market and welfare implications of banagrass-based bioethanol for the scenarios listed in Table 4.3. Scenarios 1A and 1B, also termed “federal credit-10%” and federal credit-20%” cases, assume that federal government tax credit of $1.01/gallon is extended to blenders of banagrass-derived bioethanol. These scenarios are developed based on the fact that the federal government currently offers a cellulosic bioethanol tax credit of $1.01/gallon effective until December 31, 2013 at the time of writing (Renewable Fuels Association 2012). Scenarios 2A and 2B, also termed “mandate only-10%” and “mandate only-20%” cases, assume that there is neither federal mandate nor state-level subsidies for bioethanol production, and that local bioethanol must be bought based on long-term contracts between ethanol producers and blenders. These scenarios are developed based on the fact that the State of Hawaiʻi recommends the use of long-term contracts as a way to reduce future financing costs and the risks of a local biofuels industry (DBEDT 2012). Scenarios 3A and 3B, also termed “lump-sum-10%” and “lump-sum-20%” cases, assume that the state government extends a production subsidy to cover 30% of ethanol production cost, and that this subsidy is financed through a lump-sum tax on consumers. These scenarios are adopted because the technoeconomic analysis based on Kumar and Murthy (2011) has indicated that the minimum selling price of banagrass-derived ethanol is higher than the average price of corn ethanol used in the base year by approximately 30%, and that this difference must be supported locally to make the former economically competitive in the absence of federal tax credit. Finally, scenarios 4A and 4B, also termed “fuel tax-10%” and “fuel tax-20%” cases, assume that the state government extends production subsidies of 30%, financed through a ad valorem tax on gasoline consumption. While revenue neutral subsidies based on fuel tax may be politically difficult to implement, these scenarios are evaluated since fuel tax as a revenue source for alternative energy development has been discussed in recent years in Hawaiʻi (Yonan 2013).

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[39] Regarding the detailed cost estimation methodology used in SuperPro Designer, see for example Petrides (2012).

Table 4-3: **Policy Scenarios**

Scenario 1A (Federal credit-10%) **1B** (Federal credit-20%)	• Local bioethanol production replaces imported sources currently used to meet 10% of ethanol use in 85% of gasoline demand. The federal government subsidizes lignocellulosic biofuel through a tax credit of $1.01 per gallon. • Local bioethanol production replaces imported sources currently used to meet 20% of all gasoline demand. All other assumptions remain the same as scenario 1A.
Scenario 2A (Mandate only -10%) **2B** (mandate only-10%)	• Local bioethanol production replaces imported sources currently used to meet 10% of ethanol use in 85% of gasoline demand. A blender adopts a long-term contract with a local ethanol producer, which drives the consumption of local ethanol. It is assumed that neither federal nor state-level subsidies are extended for an ethanol blender, ethanol producer, or banagrass producer. • Local bioethanol production replaces imported sources currently used to meet 20% of all gasoline demand. All other assumptions remain the same as scenario 2A.
Scenario3A: (Lump-sum 10%) **3B** (Lump-sum 20%)	• Local bioethanol production replaces imported sources currently used to meet 10% of ethanol use in 85% of gasoline demand. There is no federal tax credit. Instead, the state government subsidizes 30% of ethanol production cost. This subsidy is financed through a lump-sum tax on a representative household. • Local bioethanol production replaces imported sources currently used to meet 20% of all gasoline demand. All other assumptions remain the same as scenario 3A.
Scenario 4A (Fuel tax-10%) **4B** (Fuel tax-20%)	• Local bioethanol production replaces imported sources currently used to meet 10% of ethanol use in 85% of gasoline demand. There is no federal tax credit. Instead, the state government subsidizes 30% of ethanol production cost. This subsidy is financed through an endogenously determined ad-valorem tax on gasoline consumption. • Local bioethanol production replaces imported sources currently used to meet 20% of all gasoline demand. All other assumptions remain the same as scenario 4A.

4.5. Results

4.5.1. Market Impacts

To replace bioethanol imports of 40.8 million gallons (10%) and further gasoline inputs of 96.1 million gallons (20%) respectively in the benchmark year, it is estimated that 510,672 and 1,201,580 tons of banagrass must be produced based on the conversion rate of 80 gallons/dry-ton of biomass (Black and Veatch 2010). Locally sourced lignocellulosic ethanol will require a range of inputs throughout its supply chain: feedstock production requires seedling, agrochemicals, fuels, other support activities for agriculture and transportation as well as factor inputs of land, labor and capital. Ethanol processing requires inputs of feedstock, enzyme, yeast, acid, lime, gasoline with electricity, land, labor, and capital. While the lignin-rich waste product can be recycled as a source of heat and power through technologies such as anaerobic digestion for biogas generation and rankine cycle for power generation, whether or not a particular lignocellulosic ethanol plant becomes a net consumer or exporter of power depends on factors such as a feedstock composition, plant's power demand and proposed operation design (Kumar and Murthy 2011). Our preliminary results indicate that lignocellulosic ethanol production based on SSCoF technology with dilute acid pretreatment of banagrass will supply around 80% of a plant's power needs while the remaining power needs must be purchased from outside sources. Thus, the emergence of a local ethanol industry will increase demands for these commodities, and combined with other general equilibrium effects, this industry will stimulate the local economy.

In the benchmark year, the cost of banagrass feedstock production is estimated at \$88.5/ton while the cost of processing based on biochemical conversion is estimated at \$3.04/gallon. Local bioethanol production will thus be worth \$124 million (10%) and \$292.1 (20%). The level of economic activity will be sizable as compared to the existing in-state agricultural production. Sugarcane production in Hawai'i, for example, was worth \$47.6 million in 2007 and while generating a total of 465 and 523 wage and proprietor jobs (DBEDT 2011 b).

Table 4-4: **Summary of Economic Impacts**

	Federal		Mandate only		Lump-sum		Fuel tax	
	10%	20%	10%	20%	10%	20%	10%	20%
Nominal GSP change (in million \$)	74.5	237.2	72.7	224.5	43.2	165.7	56.4	183.5
%Δ	0.1	0.4	0.1	0.3	0.1	0.3	0.1	0.3
Real GSP change (in million \$)	13.4	48.6	-10.0	-5.0	-1.4	15.4	-35.5	-62.5
%Δ	0.0	0.1	0.0	0.0	0.0	0.0	-0.1	-0.1
Ethanol Job**	746	1636	730	1558	741	1609	727	1609
Real Effective Ethanol Price (\$/gallon)	2.17	2.18	3.18	3.19	2.44	2.45	2.44	2.46
Real Motor Fuel Price* (%Δ)	0.02	0.13	3.21	7.12	0.98	2.23	1.03	1.90
CPI (%Δ)	0.10	0.29	0.13	0.36	0.07	0.23	0.14	0.38

Note: * the price of gasoline and ethanol blend.

**includes jobs in the banagrass production and ethanol processing sectors. To estimate these figures, it was assumed that labor wage in the banarass sector was equivalent to an endogenously determined wage in the sugarcane sector, while that of ethanol processing is assumed be the same as the other manufacturing sector.

The emergence of a local bioethanol industry has various impacts on macroeconomic indicators (Table 4.4). Through a reduction in ethanol imports and increased value added by the local ethanol industry along with a general decline in consumption and exports, the state's economic outputs as measured in real Gross State Product (GSP) changes from the lowest of -\$62.5 million to the highest of +\$48.6 million depending on blending targets and other supporting policies chosen. While commodity prices in general increase primarily due to a higher domestic price of ethanol as compared to imports and additional demand for

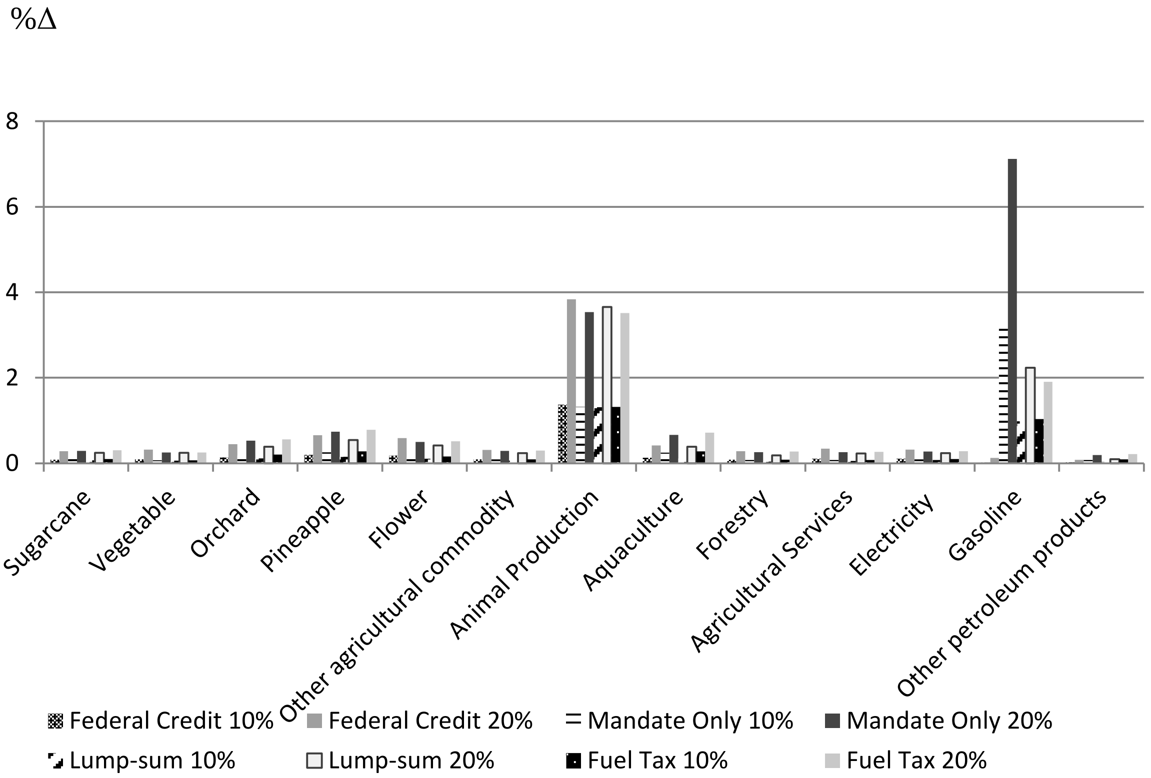

Figure 4-5: **Percentage change in real prices for selected commodities**

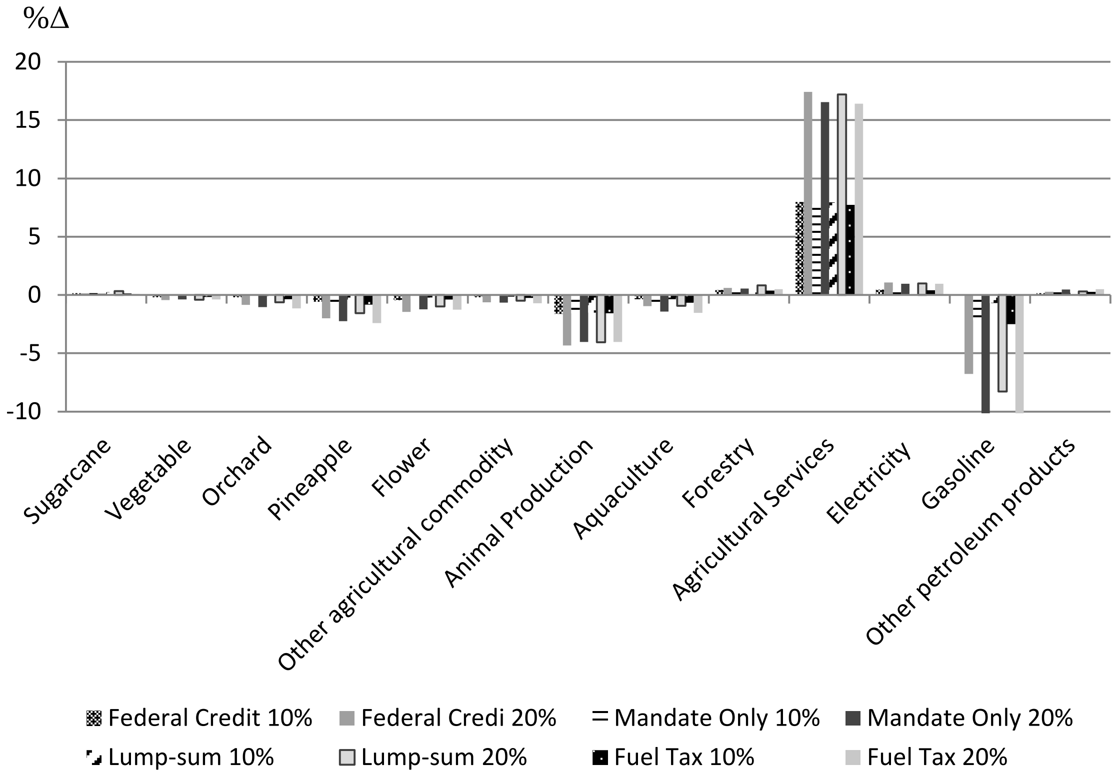

Figure 4-6: **Percentage change in quantity of production for selected commodities**

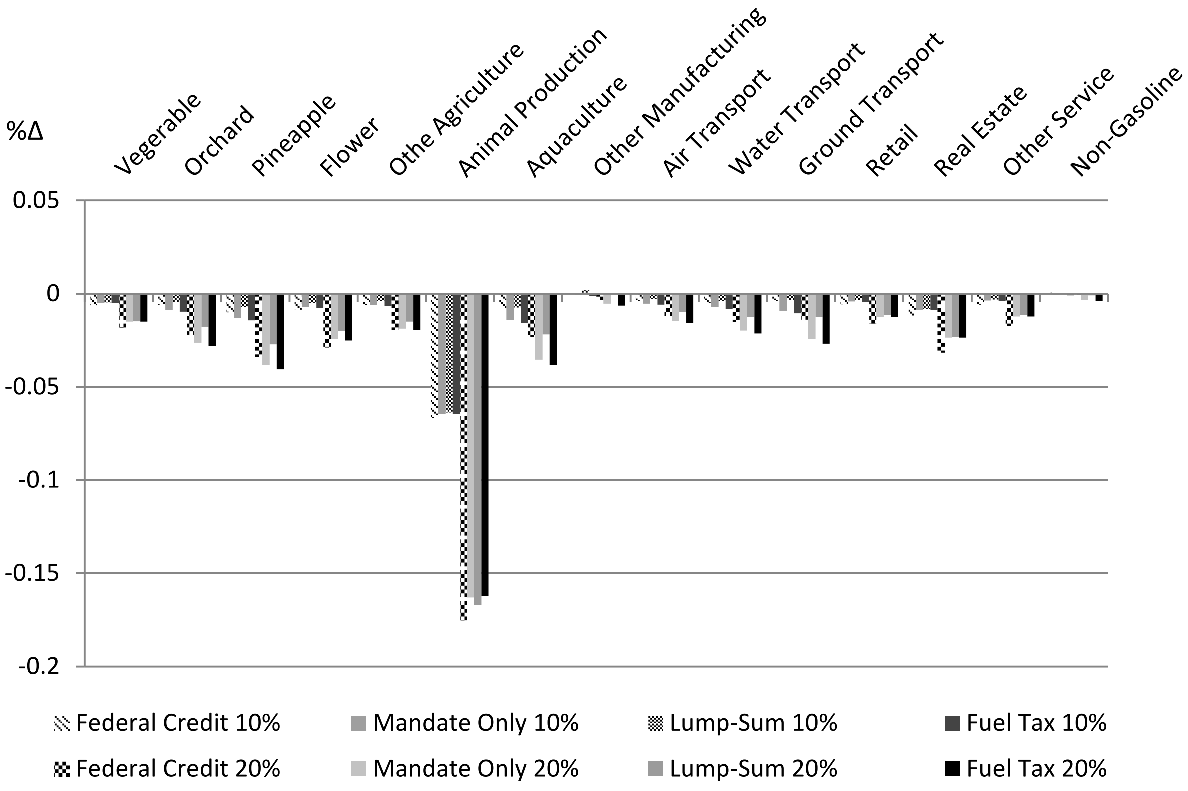

Figure 4-7: **Percentage change in quantity of export**

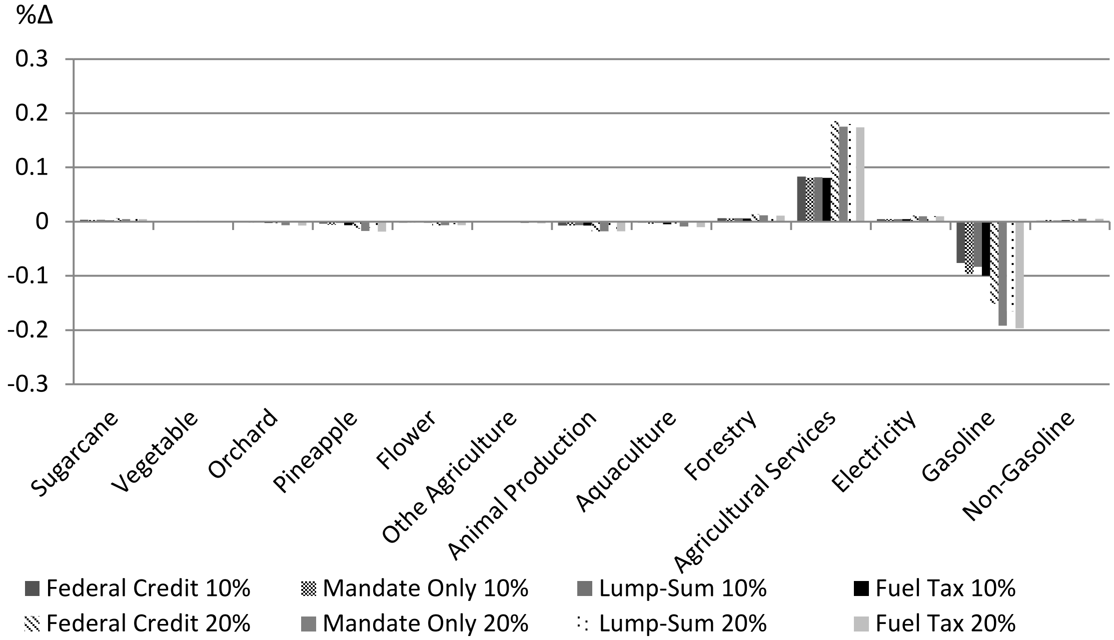

Figure 4-8: **Percentage change in quantity of import for selected commodities**

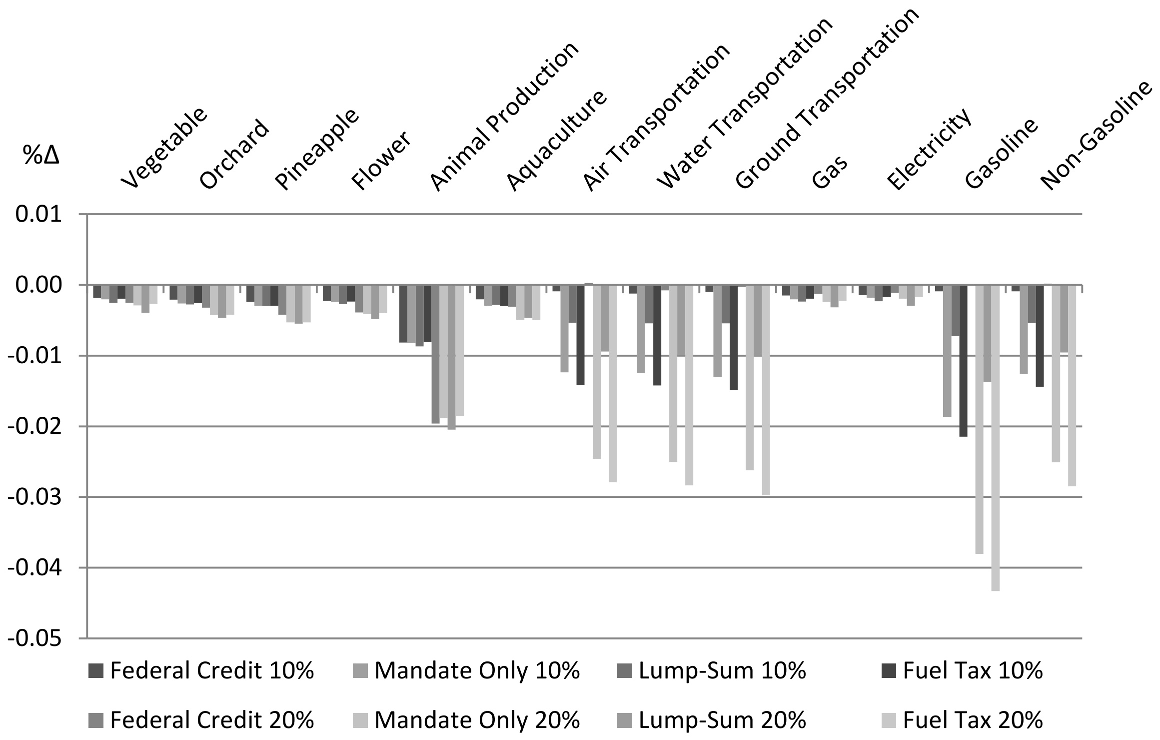

Figure 4-9: **Percentage change in quantity of household consumption for selected commodities**

ethanol inputs, the Consumer Price Index (CPI) also rises from 0.07 to 0.38%. The GSP impact is fairly small and diffused, confirming an observation made in the earlier study on sugarcane-derived ethanol and its impact on Hawai‘i's economy (DBEDT 2009). The local ethanol industry will create a total of 727 to 1636 jobs with around 18% in the processing and 82% in the feedstock production sector, while other sectors will experience contraction in labor use.

Individual sector impacts vary depending on the assumed policy scenario. Commodity prices in all sectors are expected to increase, and impacts are particularly notable in sectors such as gasoline production. In this sector, costlier domestic bioethanol must be purchased as an intermediate input. The price of gasoline is expected to increase from 0.02% (federal credit-10%) to 7.12% (mandate only-20%). The extent of changes in gasoline price primarily reflects the level of subsidies available and the level of blend mandate. The animal production sector is also expected to rise in price due mainly to an increase in pasture land prices as elaborated in section 5.4.

The remaining sectors experience a small increase in prices of less than 1%; this reflects the relatively diffused overall impact to the economy. In terms of quantity, output for the agricultural services sector is expected to rise notably in support of local banagrass production. Electricity output is also expected to increase slightly in order to supply power for feedstock production and ethanol processing. Given the general increase in commodity and input prices, output in other agricultural sectors will decrease slightly, and output in the gasoline sector will contract due mainly to higher gasoline prices (in the 10% scenarios) and further bioethanol substitution (in the 20% scenarios).

In response to rising prices of domestically produced goods and a general decline in output, export quantities decline in most sectors. The extent of decline is most notable in the animal production sector, which experiences a 0.06 to 0.07% decline under the 10% mandate and 0.16 to 0.18% under the 20% mandate. Other sectors experience still smaller declines, equivalent to less than 0.05% in most cases (Figure 4.7). Likewise, changes in prices and output quantities affect the quantity of imports in each sector. The impacts are notable in sectors that experience larger changes in the quantity of production, including the agricultural services sector, whose import increases by 0.81 to 0.83 % under the 10% mandate and 0.17 to 0.18% under the 20% mandate to support local banagrass production. The gasoline sector imports, on the other hand, are expected decline by 0.08 to 0.10 % under the 10% mandate and 0.15 to 0.20 % under the 20% mandate due to sector contraction and replacement of bioethanol imports.

As a result of a general increase in commodity prices, household demand for transport and non-transport goods declines in most cases. The extent of the impacts on household consumption is generally very small, estimated to be less than 0.05% in terms of quantity demanded in most cases (Fig 4.9). Reflecting the general rise in fuel prices, consumption of transport goods including personal transport fuels (i.e. gasoline and non-gasoline petroleum goods) and purchased transport (water, air and ground) is expected to decline the most under the fuel tax scenario followed by the mandate only scenario.

4.5.3. Welfare Implications

Welfare impacts are measured in terms of the Hicksian equivalent variation. While locally produced lignocellulosic ethanol is a costlier alternative to imported bioethanol at present, an increased demand for intermediate goods created by an emerging local ethanol industry will drive up the cost of local goods and factors. As a result, the consumption of locally produced ethanol leads to a decline in the overall welfare measure.

Table 4-5: **Welfare Impacts of Lignocellulosic Bioethanol Production**

	Federal		Mandate only		Lump-sum		Fuel Tax	
	10%	20%	10%	20%	10%	20%	10%	20%
RESIDENT (%)	-0.14	-0.10	-0.23	-0.31	-0.24	-0.32	-0.23	-0.31

Table 4.5 shows that welfare decline is evident in all scenarios. Note that the welfare effects differ slightly due to the alternative policy assumed. In the case where the federal blender credit is extended for lignocellulosic ethanol blending, in-state resident welfare loss is estimated to be minimal. The use of long-term contracts and a locally financed subsidy based on fuel taxes on the other hand leads to a larger decline in welfare measures. This is mainly because the use of long-term contracts and fuel tax will increase the cost of

gasoline, and the magnitudes of welfare loss in both cases are found to be the same. In the case where production subsidies are financed through a lump-sum tax, the representative agent's welfare declines the most.

4.5.4. Land Use Impacts

The land requirement for banagrass is estimated to be 23,752 acres (10%) and 55,887 acres (20%) respectively based on banagrass yield of 21.5 dry tons/acre/year (Tran et al. 2011). Under the assumption that no new agricultural areas will be cultivated within the state, this acreage will lead to increased direct competition for scarce land resources. Since banagrass production will likely occur on non-prime non-unique agricultural land without irrigation, the price of pasture land will likely increase (Table 4.6). With a sluggish rate of transformation between different agricultural land uses, local banagrass production will have a sizable impact on land rental values and output levels in the agricultural sector. Price effects on crop land is estimated to range from an increase of 0.1 to 0.9%, forest land from 0.8% to 2.4%, pasture land of 44.0% to 152.9%, and miscellaneous land from 1.5% to 4.4%. The quantity of land demanded remains relatively stable, with crop land use decreasing by up to 0.01%, forest land decreasing by up to 0.44 %, pasture land (by the livestock production sector) decreasing by up to 0.01% and miscellaneous land by up to 0.003%. While non-irrigated pasture rent is estimated to be $17.40/acre in 2010, expanded feedstock production will make this rent increase to about $25.10/acre and $44.00/acre. However it will still be less expensive than irrigated land rent, which was estimated to be $ 230.00/acre in the base year.

Table 4-6: **Impact on agricultural land prices (% change in real prices).**

	Federal		Mandate only		Lump-sum		Fuel tax	
	10%	20%	10%	20%	10%	20%	10%	20%
Crop (%)	0.2	0.6	0.2	0.4	0.4	0.9	0.1	0.3
Forest (%)	0.8	2.2	1.0	1.9	1.0	2.4	0.9	1.8
Pasture (%)	45.5	152.9	44.3	139.4.4	45.3	149.0	44.0	137.6
Miscellaneous (%)	1.9	4.4	1.6	3.6	1.9	4.4	1.5	3.5

A trend of increasing land prices correlates with recent observations made in other U.S. states where a burgeoning corn ethanol industry raised local land prices and farm income (informa economics 2010). An increase in land price will likely benefit agricultural land owners while users of land will face increased cost, though further studies would be needed to estimate the exact magnitude of these impacts across different segments of population. The State of Hawaiʻi, and the island of Hawaiʻi in particular, still has sizable land currently under no active use. It is estimated that around a half of agricultural land based on the State Land Use District is unused (Melrose and Delparte 2012), and the use of this land will reduce pressure on available agricultural land. Whether fallow land will be brought into cultivation depends on a number of factors including land preparation cost, expected yield, and logistical ease, etc. Further studies incorporating these disaggregated geographical conditions will also be useful.

4.5.5. GHG Emissions Impact

With the differences in life-cycle GHG emissions for conventional and alternative fuels and the likely change in individual sector outputs and fuel substitution, the introduction of mandates will lead to overall changes in the state's GHG emissions. The extent of such changes vary depending on factors such as fuel prices, fossil fuel use intensity in each sector and a fuel's unit life-cycle GHG emissions. Though a complete evaluation of consequential life-cycle environmental impacts of the biofuel mandate is beyond the scope of this research, macro-level life-cycle GHG emissions may be calculated based on a quantity change in fossil fuel use by sector and GHG emissions intensity (see Appendix 4.3). This section estimates the changes in i) gasoline sector emissions and ii) economy-wide emissions, using the life-cycle GHG emissions intensity of switchgrass based on the GREET model 2012 version as a proxy for banagrass-derived bioethanol.

In the gasoline sector, it is estimated that the 10% and 20% mandates will lead to a decline in GHG due both to the gasoline sector's contraction and fuel substitution by locally produced bioethanol. The extent of reduction parallels the expected changes in gasoline prices (Fig 4.10). Under the 10% scenario, the fuel tax scenario yields the largest GHG emissions reduction, estimated at 209,085 tonnes/yr (-3.65%), in which 65.9% is attributed to the decline in gasoline sector output and 34.1% to the difference in bioethanol emissions intensity. The majority of the reduction stems from the former since the additional tax placed on gasoline consumption depresses the demand in this sector. Likewise, the mandate only scenario offers the second largest GHG emissions reduction potential worth 191,148 tonnes/yr (-3.34%), in which 62.6% is attributed to the gasoline sector decline and 37.4% to bioethanol replacement.

The remaining scenarios lead to smaller GHG reduction, since the expected gasoline price increase is also smaller and the change in gasoline sector output is limited. In the case of a lump-sum tax, GHG emissions decline by 119,694 tonnes/yr (-1.93%) in which the gasoline sector output decline contributes 34.4% and bioethanol substitution contributes 65.6%. Under the federal tax credit scenario, the gasoline sector demand is expected to increase slightly (by 0.07% of quantity demanded), leading to an estimated reduction of 69,557 tonnes/yr (-1.22%), comprising a decline of 73,158 tonnes/yr due to bioethanol replacement, and an increase of 3,601 tonnes/yr due to the gasoline sector growth. Under the 20% scenario, the fuel tax scenario yields the largest GHG emissions reduction, estimated at 799,117 tonnes/yr (-14.0%), in which 81.0% is attributed to the gasoline sector's contraction and 19.0% to bioethanol replacement.

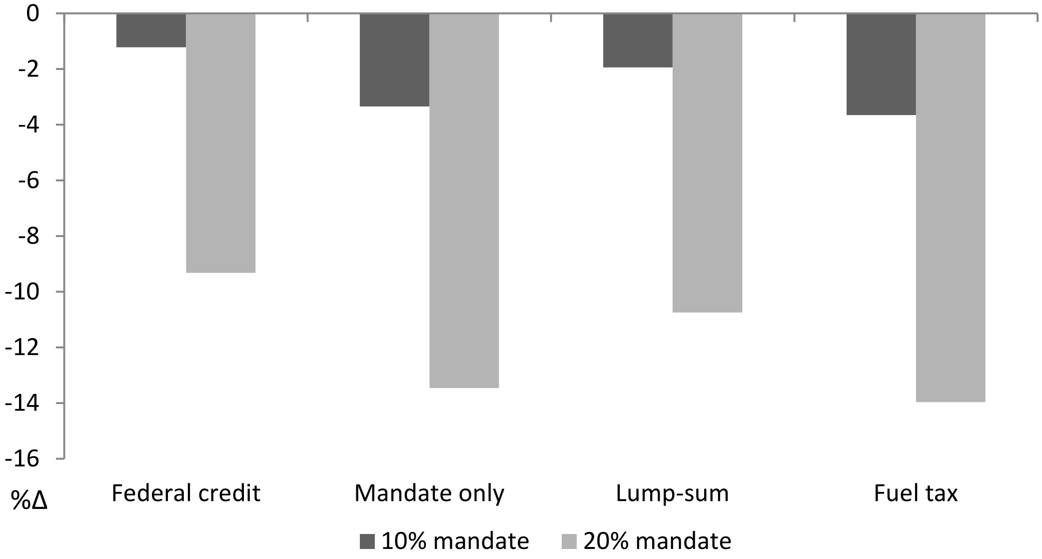

Figure 4-10: GHG emission reduction in the petroleum sector

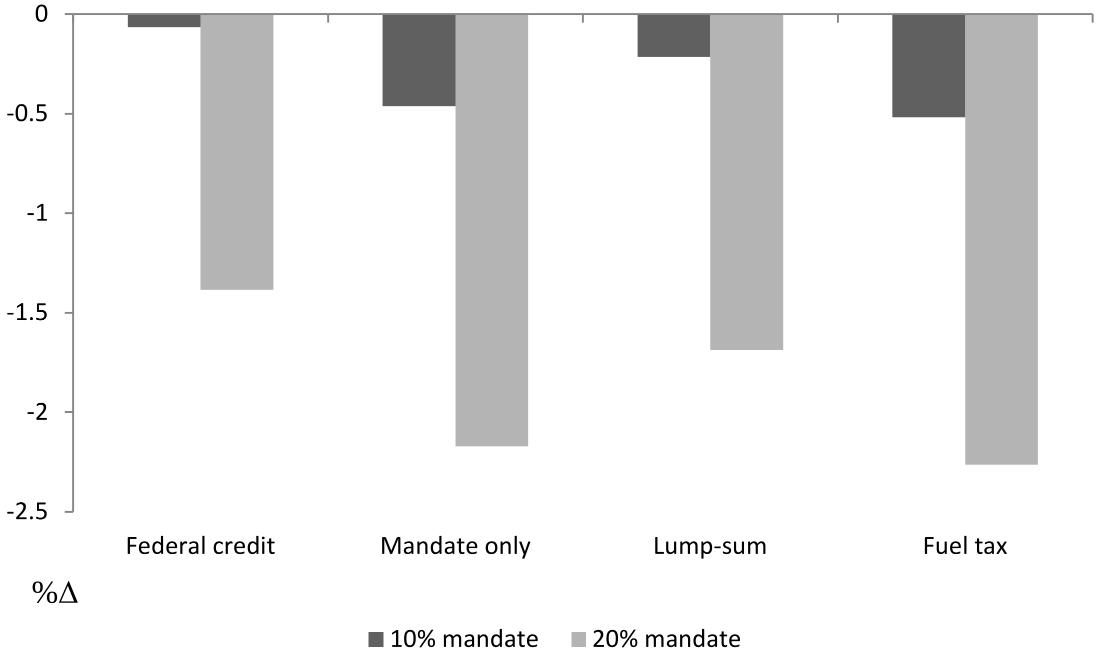

Figure 4-11: Changes in Overall GHG emissions (switchgrass)

The federal tax credit scenario, on the other hand, achieves the lowest GHG emissions reduction, estimated at 533,118 tonnes/yr (-9.88%) with 30.0% due bioethanol replacement and 70.0% due to the gasoline sector's contraction.

Table 4-7: **unit GHG abatement costs**

	Federal credit		Mandate only		Lump-sum		Fuel tax	
Cost of CO2 mitigation ($/ton)	10%	20%	10%	20%	10%	20%	10%	20%
Gasoline sector only								
subsidy cost per ton	593.6	169.8	n.a.	n.a.	383.4	151.1	199.2	112.2
real expenditure decline per ton	846.2	81.6	518.3	171.5	914.8	222.2	585.7	231.6
Economy-Wide Emissions								
subsidy cost per ton	2116.4	217.1	n.a.	n.a.	657.8	181.4	266.7	130.1
real expenditure decline per ton	3017.1	104.3	710.0	201.8	1569.6	268.7	784.2	271.5

Table 4-8: **Subsidy per tonne of CO2e displaced based on existing literature**

Cost of CO2 mitigation ($/ton)	Low	High
United States conventional ethanol*	295	-585
United States cellulosic*	110	195
European union conventional ethanol	590	4520
Australia conventional ethanol	244	1679
EU allowance (EUA)	4.15**	
California C&T, price floor	10.71	

Source: Koplow (2007), Doornbosch and Steenlik (2007), Point Carbon (2013) and California Air Resources Board (2013)

Note: *average costs from 2006-2012. **exchange rate of €1= $1. 24 based on annual average in 2012 (IRS 2013)

The economy-wide emissions reduction is estimated to be smaller than that of the gasoline sector, since an increase in motor fuel prices encourage the use of non-gasoline fuel options (Fig 4.11). Under the 10% mandate, the fuel tax scenario achieves the largest emissions reduction, estimated at 156,170 tonnes of CO2e/yr (-0.52% of total GHG emissions); while emissions due to gasoline and aviation fuel use decline (by 137,801 tonnes of CO2e/yr and 23,249 tonnes of CO2e/yr respectively), and emissions related to electricity, non-gasoline petroleum products, coal and gas increase (by 45,362 tonnes of CO2e/yr, 30, 266 tonnes of CO2e/yr, 495 tonnes of CO2e/yr,,and 44 tonnes of CO2e/yr respectively). The federal tax credit scenario achieves the smallest emissions reduction, estimated at 19,509 tonnes of CO2e/yr (-0.06 %). Under the 20% mandate, the fuel tax scenario achieves the largest reduction estimated at 681,841 tonnes of CO2e/yr (-2.3%), followed by the mandate only scenario estimated at 654,518 tonnes of CO2e/yr (-2.2%), the lump-sum scenario estimated at 508,374 tonnes of CO2/yr (-1.7%), and the federal tax credit scenario estimated at 417,051 tonnes of CO2e/yr (-1.4%). Relatively small changes in GHG emissions confirm observations made by existing studies regarding the biofuel mandate and its impact on GHG emissions (Painter et al. 2009).

Table 4.7 provides the unit costs of GHG emissions as measured in subsidy expenditure and the decline in consumer spending. In general, the cost-effectiveness of GHG abatement options depends on the expected policy impacts on gasoline prices as well as final demand. In the gasoline sector alone, it is estimated that $199.2/tonne to $593.6/tonne of subsidies will be needed under the 10% mandate and $112.2/tonnes to $169.8/tonnes will be needed under the 20% mandate. The use of locally sourced ethanol will cost a decline in consumer expenditure of $518.3/tonnes to $846.2/tonnes under the 10% mandate and $81.6/tonnes and $518.3/tonnes under the 20% mandate. Since the 10% mandate replaces the imported bioethanol that primarily use sugarcane as a feedstock, GHG displacement potential is limited and per unit cost is higher than those under the 20% mandate. Among the alternative scenarios, the use of fuel tax is the most cost-effective policy in terms of subsidy cost, while the mandate only and federal tax credit options were found to be the most cost-effective in terms of the expected decline in consumer spending under the 10% and 20% mandates respectively.

In general, the economy-wide unit abatement costs are found to be higher than in the gasoline sector, suggesting that exclusion of general equilibrium effects will likely underestimate the GHG abatement cost of biofuels policy. In terms of economy-wide emissions, it will cost $266.7/tonne to $2,116.4/tonne of subsidies under the 10% mandate and $130.1/tonnes to $217.1/tonnes under the 20% mandate. The use of locally sourced ethanol will cost $710.0/tonnes to $3017.1/tonnes in terms of consumer expenditure decline under the 10% mandate and $104.3/tonnes to $268.7/tonnes under the 20% mandate. The unit subsidy costs estimated for this study appear to fall within the range of those estimated in recent literature (see table 4.8 and literature cited in the footnote), confirming that the costs of GHG reduction using lignocellulosic ethanol are more than an order of magnitude higher than the price of carbon traded in existing carbon markets.

4.6. Sensitivity Analysis

Determining the robustness of modeling results is a common concern in the CGE approach, because simulation results depend largely on the choice of key assumptions such as elasticity parameters. This section employs three sensitivity analyses to examine how a particular set of assumptions regarding substitutability between i) land and material and energy inputs, ii) energy and other value added inputs, and iii) labor and capital inputs in deriving simulation outputs.

First, the impact of local feedstock production on land prices depends on factors including whether or not new land becomes available and how substitutable are land, capital, material (e.g. fertilizers) and energy in agricultural sector production. To examine the effects of these assumptions, this study implemented

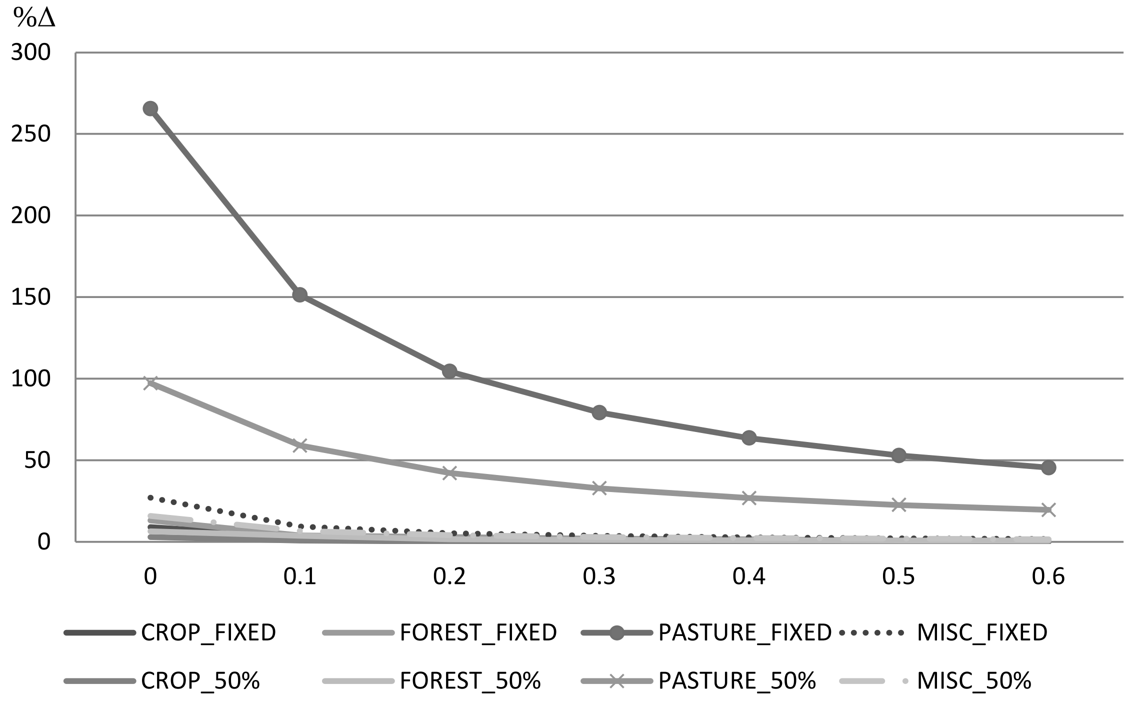

Figure 4-12: **Percentage change in real prices of rent (Federal Credit 10%)**
Note: '_Fixed' denotes fixed land endowments whereas '_50%' denotes 50% of new areas become avaialble.

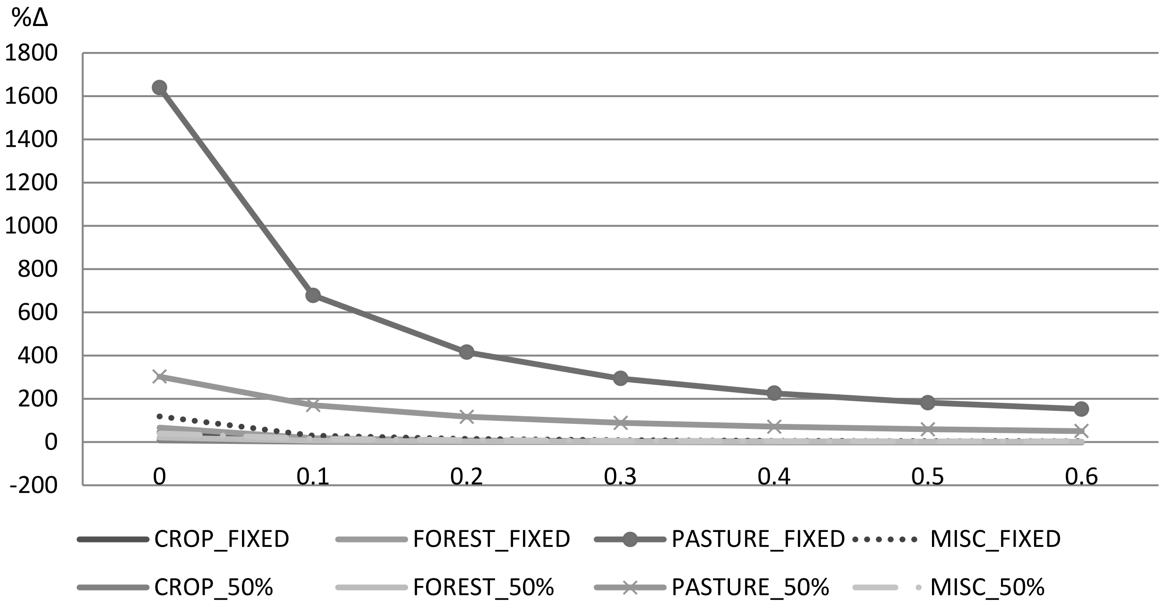

Figure 4-13: **Percentage change in real prices of rent (Federal Credit 20%)**
Note: '_Fixed' denotes fixed land endowments whereas '_50%' denotes 50% of new areas become avaialble.

simulations based on varied parameters and land availability. The substitution parameter between land-material-energy composite and value added composite (originally set as 0.6) and that between land and material-energy composite (originally set as 0.6) are gradually decreased to 0, and the following two cases were evaluated: i) land endowment is fixed; and ii) 50% of land needed for banagrass production comes from new cultivation of fallow land.

As Fig 4.12 and 4.13 show, both elasticity parameters and land endowment assumptions have a large impact on land prices, especially for pasture land. Taking the federal credit scenario as an example, under the original assumption that land may be partially substituted by other material and energy inputs with substitution elasticity of 0.6, the price of pasture land increases by 45.5% (land is fixed) and 19.7% (50% of new land becomes available) based on the 10% mandate and by 152.9% (land is fixed) and 51.1% (50% of new land) based on the 20% mandate. When this model assumes more rigid production technologies however, land price increases sharply: 265.5% (land is fixed) and 97.3% (50% of new land) under the 10% mandate and 1639.6% (land is fixed) and 303.0% (50% of new land) under the 20% mandate. While sizable fallow land exists in the State of Hawaiʻi, it is unlikely that these areas will immediately become available for expanded use for biofuels production. Therefore, some form of competition may arise among alternative land uses, particularly in the short-run. This tension may gradually decrease as more land becomes available for biomass production and/or land productivity improves with the use of fertilizer and other material inputs.

Next, sensitivity analyses were conducted regarding the substitutability of energy and other value added inputs. Simulations were implemented by changing the substitution parameters(σ_{ENE_i},σ_{NENE_i}) from the original values to zero. Results indicate that changes in the energy substitution parameters had a negligible impact on energy prices and quantity demanded have changed slightly (table 4.9).

Table 4-9: **The effect of energy substitution parameters on the quantity of energy commodity demanded**

	Federal Credit		Mandate only		Lump-sum		Fuel tax	
	fixed	flexible	fixed	flexible	fixed	flexible	fixed	flexible
Electricity	0.48	0.47	0.34	0.43	0.40	0.43	0.32	0.43
Gasoline	0.06	0.07	-1.25	-2.17	-0.41	-0.69	-1.43	-2.50
Non-gasoline	0.15	0.17	-0.16	0.27	0.05	0.19	-0.22	0.28
Real GSP ($ mil)	13.5	13.4	-9.97	-10.0	-1.46	-1.44	-35.6	-35.5
CPI (%)	0.10	0.10	0.13	0.13	0.07	0.07	0.14	0.14
Electricity	1.11	1.08	0.79	0.96	0.94	0.98	0.75	0.96
Gasoline	-6.76	-6.76	-9.38	-11.19	-7.70	-8.29	-9.68	-11.74
Non-gasoline	0.21	0.27	-0.47	0.47	-0.02	0.31	-0.57	0.50
Real GSP ($ mil)	48.6	48.6	-3.73	-4.96	15.6	15.4	-61.1	-62.5
CPI (%)	0.30	0.29	0.36	0.36	0.24	0.23	0.39	0.38

Note: top: 10% mandate; bottom 20% mandate

Assuming that it is possible to substitute electricity and non-electric sources of energy such as gasoline and other petroleum productions, this assumption has led to an increased use of electricity in most cases.

Table 4-10: **The effect of labor-capital elasticity of substitution on factor prices**

	Federal Credit		Mandate Only		Lump-Sum		Fuel Tax	
	fixed	flexible	fixed	flexible	fixed	flexible	fixed	flexible
Labor (%)	-0.25	0.03	-0.29	-0.03	-0.29	-0.03	-0.29	-0.03
Capital (%)	0.78	0.27	0.67	0.20	0.66	0.19	0.67	0.20
Real GSP (mil $)	-18.8	13.4	-40.2	-10.0	-31.1	-1.44	-60.2	-35.5
CPI (%)	0.12	0.10	0.16	0.13	0.10	0.07	0.16	0.14
Labor (%)	-0.44	0.18	-0.52	0.04	-0.52	0.18	-0.52	0.04
Capital (%)	1.84	0.71	1.55	0.52	1.55	0.53	1.55	0.52
Real GSP (mil $)	-22.9	48.6	-70.2	-4.96	-49.9	15.4	-114	-62.5
CPI (%)	0.36	0.29	0.42	0.36	0.29	0.23	0.42	0.38

Note: top: 10% mandate; bottom 20% mandate

Finally, sensitivity analyses were conducted regarding substitutability of labor and capital inputs (table 4.10). For these cases, simulations were implemented by varying the elasticity of substitution parameters between capital and labor composites, originally assumed as 1 to 0. Since lignocellulosic ethanol processing is a capital-intensive production activity, prices of capital inputs increase in all scenarios. Allowing for the substitution of capital and labor, an increase in capital cost is estimated to range from 0.19% to 0.27% under the 10% mandate and 0.52% to 0.71% under the 20% mandate. Assuming that capital and labor are not substitutable, the price of capital goods could increase from 0.66 to 0.78% under the 10% mandate and 1.55% to 1.84% under the 20% mandate. Labor prices are expected to decline further under the no-substitution cases. This result is partly due to a decline in labor demand caused by a contraction in economic outputs. The growth of a capital intensive lignocellulosic bioethanol industry leads to larger increases in general price levels as well as capital costs under the no-substitution assumptions, which leads to further decline in real GSP as compared to the substitution cases.

4.7. Discussion

Simulation results highlighted some important insights regarding lignocellulosic ethanol development in Hawai‘i. First, price estimates of locally produced ethanol suggest that it could be competitive with a conventional ethanol option given that a federal tax credit for cellulosic ethanol of $1.01 per gallon continues or if locally funded subsidies are extended for advanced ethanol production. While this is an encouraging result, it is important to note that technoeconomic analyses of advanced fuels typically assume that those technologies adopted are mature. A bottom up model such as one used in this study assumes that production incurs no additional cost as a pioneering plant. However, biochemical conversion technologies of lignocellulosic material are still at a state of research development and demonstration (RD&D). Therefore, the adoption of such technologies at a commercial scale will likely incur additional costs initially until an accumulation of industrial experience allows for improved productivity. Once this experience is established, the substitution of imported ethanol with a locally produced alternative will cause little additional cost locally, especially when subsidies are extended by the federal government.

Second, given the existing level of alternative fuels mandate, economy wide impacts will likely be small. The Gross State Product is estimated to change from -$62.5 million to +$48.6 million, while sectors such as livestock, agricultural services, electricity generation, and gasoline production will be impacted notably. These observations confirm those from existing literature; however, the location specific impacts of ethanol production are less clear. In particular, it is unclear, i) how competition for factor inputs such as land and labor will play out within specific locations chosen as feedstock or ethanol production sites, and ii) how environmental nuisances created by increased traffic volume and other ethanol industrial operations may impact local communities. Existing studies have demonstrated that factors such as air, water and noise pollution may in fact affect the local economy through property values, etc. Though these factors are not taken into account in the current modeling framework, location specific externalities may have important local consequences, and thus deserve a more detailed assessment at the community level.

Third, given the relatively large land use impacts estimated by this study, further study should be conducted to evaluate potential ways in which the local bioethanol industry may be integrated with the local livestock production. Possible avenues for integration include: i) feedstock production: since banagrass is a common cattle feed in other parts of the world, it may be possible to use it as both bioethanol feedstock and fodder depending on their profitability; ii) waste management: the bioethanol plant design adopted for this study includes a anaerobic digestion system, which may process animal manure for biogas production. The use of animal manure for biogas production may reduce the cost of livestock waste management and will mitigate local environmental nuisance associated with poor waste management; and iii) co-product generation: an alternative production design for protein rich animal feed co-product generation from banagrass-derived bioethanol production is currently being evaluated (Takara and Khanal 2011). Such a process could prove to be a viable option, which integrates the bioethanol and livestock industry. The integration of these two industries through these avenues may alleviate direct competition for limited resources.

Fourth, because locally produced ethanol is a costlier alternative to an imported source, both resident and visitor welfare declined in all cases. While welfare effects may be measured using a number of matrices, including its impact on environmental externalities and energy security, this study demonstrates that consumers were worse off as a result of prices changes in all cases according to the equivalent variation method. Moreover, this welfare loss occurred in spite of GSP growth in three out of eight scenarios, and newly created employment opportunities in the ethanol industry in all scenarios. This asymmetry illustrates how a policy to promote local bioethanol creates both winners and losers. Generally, consumers bear the additional burden of costlier local production, making them worse off, regardless of whether local ethanol leads to an increase in overall economic production.

Fifth, the potential GHG reduction resulting from the use of locally produced ethanol will likely be small. Assuming that banagrass-derived lignocellulosic ethanol achieves emissions reduction equivalent to switchgrass, the 10% mandate achieves up to 0.5% of economy-wide emissions reduction while the 20% mandate can achieve a further reduction of around 2.3%. This is because mandated levels are generally small as compared to the overall fossil fuel use in the economy, and a higher price of gasoline encourages the use of non-gasoline fuel. The cost-effectiveness is also limited as the subsidy cost per tonne of economy-wide greenhouse gas displaced ranges from \$130.1 tonnes CO2e to \$2116.4/tonnes CO2e. These figures are well above the price of carbon currently being traded, raising serious doubt as to whether lignocellulosic bioethanol should be promoted as a desirable GHG emissions abatement option on economic grounds.

Sixth, lignocellulosic ethanol derived from banagrass will likely produce a sizable employment opportunity for this new local industry, though further studies are needed to evaluate its full impact on the local labor market. In the case of a 20% mandate, ethanol processing and feedstock production will require over 1,500 workers in all scenarios, though this is also accompanied by a contraction of labor demand in other sectors. The exact impacts of bioethanol policy are difficult to evaluate since this study adopts a simple assumption that labor supply is uniform and fixed and that market-clearing wage adjusts the supply and demand of labor. The possibly of in-and-out migration, as well as the distinction between skilled and un-skilled labor with the sufficient knowledge of agriculture and biochemical engineering, is not taken into account. This poses a major limitation to this study and further studies evaluating detailed labor market impacts will be desirable.

Finally, while this study assumes that locally produced bioethanol will replace an additional portion of domestically produced gasoline in the 20% mandate case, the use of an alternative baseline – i.e. the replacement of additional bioethanol imports required to meet the 20% mandate – will have different impacts on macroeconomic indicators, commodity prices and GHG emissions. These will depend on a number of factors including the likely prices of locally produced ethanol, imported bioethanol and gasoline under such a baseline. The extent of GHG abatement potential will likely be smaller, since the difference in life-cycle GHG emissions between locally produced and imported bioethanol is markedly smaller than the difference between the same emissions of locally produced bioethanol and gasoline. The unit cost of GHG abatement will therefore be higher in this case.

4.8. Conclusions

This essay developed a computable general equilibrium (CGE) model for the State of Hawaiʻi, examining the impacts of lignocellulosic ethanol production on the local economy. Simulation results indicate that the use of banagrass-derived local ethanol to meet the 10% and 20% mandates will lead to changes in

Gross State Product from -$62.5 million to +$48.6 million. In all scenarios, the use of costlier local ethanol leads to a decline in welfare: resident welfare declines 0.14% to 0.24 % under the 10% mandate and 0.10 % to 0.32 % under the 20% mandate. Assuming that agricultural land endowment is fixed, an increase of 0.1 % and 0.9 % (cropland) 44.0 % and 152.9 % (pasture land), 0.8% and 2.4 % (forest land) and 1.5% and 4.4 % (miscellaneous land) will occur under the 10% and 20% mandate respectively. Overall, lignocellulosic bioethanol is found to be a costly GHG abatement option as compared to the prices of carbon currently traded: to reduce 1 tonne of economy-wide GHG emissions, it will cost $266.7/tonne to $2,116.4/ tonne of subsidies under the 10% mandate depending on alternative scenarios and $130.1/tonnes to $217.1/tonnes under the 20% mandate. While the overall economic and GHG impacts at the state-level are estimated to be small, it is likely that location specific impacts will be larger. Hence, further studies evaluating more location specific cases will be helpful to examine the potential opportunities and risks associated with an advanced bioethanol option in Hawai‘i.

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Appendix 4.1: CGE Model Description

Appendix 4.2: Estimating Gasoline and Non-Gasoline consumption by I.O. sectors.

Appendix 4.3: Life-Cycle GHG Emissions Calculation

Appendix 4.4: Use Table based on 2007 Input-Output Table (million $)

Appendix 4.5: MSPGE modeling syntax

Appendix 4.1: CGE MODEL DESCRITPION

Subscripts and Sets

Subscript	Description
i	(1,…,n) sectors with an alias j
Set	**Description**
SNE	Non Energy Sectors
SNE_NA(⊆ SNE)	Non-Energy Non-Agricultural Sectors
SE	Energy Sectors
AG (⊆ SNE)	Agricultural Sectors
NAG	Non-Agricultural Sectors
SEL (⊆ SE)	Electricity Producing Sectors
PET (⊆ SE)	Petroleum Producing Sectors

I.I Agricultural Sectors (AG)

Agricultural production is assumed to have a nested structure. At the top of the nest, a production function is based on a constant elasticity of substitution (CES). This function represents the final output (Y_i^{AG}) in sector i ϵ AG as an aggregate of the land-material-energy composite (Q_i^{REM}) and the value added composite(Q_i^{VA}). The substitution parameter (σ_{AG_i}) represents the substitutability of the land-material-energy composite and the value added composite, while (α_i^{AG}) and $(1-\alpha_i^{AG})$ represent share parameters.

$$Y_i^{AG} = f_i^{AG}(Q_i^{REM}, Q_i^{VA}) = \left[\alpha_i^{AG}(Q_i^{REM})^{\sigma_{AG_i}-1 / \sigma_{AG_i}} + (1-\alpha_i^{AG})\,(Q_i^{VA})^{\sigma_{AG_i}-1 / \sigma_{AG_i}}\right]^{\sigma_{AG_i} / \sigma_{AG_i}-1}$$

At the next level, land-material-energy composite (Q_i^{REM}) is an aggregate of land input LND_i^{AG} and energy-material composite(Q_i^{EM}). The substitution parameter (σ_{REM_i}) represents the substitutability of land and energy-material composite, while (α_i^{REM}) and $(1-\alpha_i^{REM})$ represent share parameters.

$$Q_i^{REM} = f_i^{REM}(LND_i^{AG}, Q_i^{EM})$$

$$= \left[\alpha_i^{REM}(LND_i^{AG})^{\sigma_{REM_i}-1 / \sigma_{REM_i}} + (1-\alpha_i^{REM})\,(Q_i^{EM})^{\sigma_{REM_i}-1 / \sigma_{REM}}\right]^{\sigma_{REM_i} / \sigma_{REM_i}-1}$$

Further, the energy-material composite (Q_i^{EM}) is an aggregate of the energy composite(Q_i^{ENE}) and the intermediate goods composite(Q_i^{IAR}) with a substitution parameter (σ_{EM_i}) and share parameters (α_i^{EM}) and $(1-\alpha_i^{EM})$.

$$Q_i^{EM} = f_i^{EM}(Q_i^{ENE}, Q_i^{IAR}) = \left[\alpha_i^{EM}(Q_i^{EM})^{\sigma_{EM_i}-1 / \sigma_{EM_i}} + (1-\alpha_i^{EM})\,(Q_i^{IAR})^{\sigma_{EM_i}-1 / \sigma_{EM}}\right]^{\sigma_{EM_i} / \sigma_{EM_i}-1}$$

The energy composite(Q_i^{ENE}) combines electricity consumption $\left(ELE_i\ \right)$ and the non-electric energy composite (Q_i^{NELE}) in a similar fashion with a substitution parameter $\left(\sigma_{ENE_i}\right)$ and share parameters (α_i^{ENE}) and $(1-\alpha_i^{ENE})$.

$$Q_i^{ENE} = f_i^{ENE}\left(ELE_i\ , Q_i^{NEL}\right)$$

$$= \left[\alpha_i^{ENE}\left(ELE_i\ \right)^{\sigma_{ENE_i}-1 / \sigma_{ENE_i}} + (1-\alpha_i^{ENE})\,(Q_i^{NELE})^{\sigma_{ENE_i}-1 / \sigma_{ENE}}\right]^{\sigma_{ENE_i} / \sigma_{ENE_i}-1}$$

The non-electric energy composite (Q_i^{NELE}) is an aggregate of gasoline(GSL_i) and other petroleum products($NGSL_i$) with a substitution parameter $\left(\sigma_{NENE_i}\right)$ and share parameters(α_i^{NENE}) and $(1-\alpha_i^{NENE})$.

$$Q_i^{NELE} = f_i^{NELE}\left(GSL_i\ , NGSL_i\ \right)$$

$$= \left[\alpha_i^{NELE}\left(GSL_i\ \right)^{\sigma_{ENEL_i}-1 / \sigma_{ENEL_i}} + (1-\alpha_i^{ENEL})\,(NGSL_i\ )^{\sigma_{ENEL_i}-1 / \sigma_{ENEL}}\right]^{\sigma_{ENEL_i} / \sigma_{ENEL}-1}$$

The intermediate non-energy composite (Q_i^{IAR}) consists of both domestically produced intermediate goods (D_i^{IO}) and imported goods (M_i^{IO}), aggregated through a CES function based on the Armington assumption. The substitution parameter $\left(\sigma_{IAR_i}\right)$ represents the substitutability of domestic versus imported goods, while (α_i^{IAR}) and $(1-\alpha_i^{IAR})$ represent share parameters.

$$Q_i^{IAR} = f_i^{IAR}(D_i^{IO}, M_i^{IO}) = \left[\alpha_i^{IAR}(D_i^{IO})^{\sigma_{IAR_i}-1 / \sigma_{IAR_i}} + (1-\alpha_i^{IAR})\,(M_i^{IO})^{\sigma_{IAR_i}-1 / \sigma_{IAR_i}}\right]^{\sigma_{IAR_i} / \sigma_{IAR_i}-1}$$

Domestically produced non-intermediate goods (D_i^{IO}) consist of intermediate goods (Q_{ji}) aggregated through a Leontief function.

$$D_i^{IO} = f_i^{IO}\left(\{Q_{ji}\}_{j\in NE}\right) = \left[\left\{\frac{Q_{ji}}{\alpha_{ji}}\right\}\right]$$

Within the value added composite (Q_i^{VA}), a further CES nested structure combines the income composite (Q_i^{INC}) and capital input (K_i) in a Cobb-Douglas function with function exponents (α_i^{VA}) and $(1-\alpha_i^{VA})$.

$$Q_i^{VA} = f_i^{VA}(Q_i^{INC}, K_i) = (Q_i^{INC})^{\alpha_i^{VA}}\,(K_i\ )^{1-\alpha_i^{VA}}$$

Here, the income composite (Q_i^{INC}) is an aggregate of labor (L_i) and proprietors' income (PR_i) combined through a Leontief function.

$$Q_i^{INC} = f_i^{INC}(L_i, PR_i) = \left[\frac{L_i}{\alpha_i^{L}}, \frac{PR_i}{\alpha_i^{PR}}\right]$$

Finally, sector output (Y_i^{AG}) is allocated as domestic goods (D_i) and export goods (X_i) based on a constant elasticity of transformation (CET) function with a substitution parameter (σ_{EX_i}) and share parameters (α_i^{EX}) and $(1-\alpha_i^{EX})$.

$$Y_i^{AG} = f_i^{EX}(D_i, X_i) =$$

$$\left[\alpha_i^{EX}(D_i)^{1+\sigma_{EX_i}/\sigma_{EX_i}} + (1-\alpha_i^{EX})(X_i)^{1+\sigma_{EX_i}/\sigma_{EX_i}}\right]^{\sigma_{EX_i}/1+\sigma_{EX_i}}$$

I.2 Non-Agriculture Non Energy Sector (SNE_NA)

Non-Energy sector production is assumed to have a nested structure. At the top of the nest, a Leontief production function represents the final output ($Y_i^{SNE\_NA}$) in sector i ϵ SNE_NA, as an aggregate of the intermediate non-energy composite (Q_i^{IAR}) and the energy and value added composite (Q_i^{EVA}). Here, parameters $\alpha_i^{IAR} and\ \alpha_i^{EVA}$ are unit input coefficients, representing the fixed production technologies used in the base year.

$$Y_i^{SNE\_NA} = f_i^{SNE\_NA}(Q_i^{IAR}, Q_i^{EVA}) = \left[\frac{Q_i^{IAR}}{\alpha_i^{IAR}}, \frac{Q_i^{EVA}}{\alpha_i^{EVA}}\right]$$

The intermediate non-energy composite (Q_i^{IAR}) consists of both domestically produced intermediate goods (D_i^{IO}) and imported goods (M_i^{IO}), aggregated through a CES function based on the Armington assumption. The substitution parameter (σ_{IAR_i}) represents the substitutability of domestic versus imported goods, while (α_i^{IAR}) and $(1-\alpha_i^{IAR})$ represent share parameters.

$$Q_i^{IAR} = f_i^{IAR}(D_i^{IO}, M_i^{IO}) = \left[\alpha_i^{IAR}(D_i^{IO})^{\sigma_{IAR_i}-1/\sigma_{IAR_i}} + (1-\alpha_i^{IAR})(M_i^{IO})^{\sigma_{IAR_i}-1/\sigma_{IAR_i}}\right]^{\sigma_{IAR_i}/\sigma_{IAR_i}-1}$$

Domestically produced non- intermediate goods (D_i^{IO}) consist of intermediate goods (Q_{ji}) aggregated through a Leontief function.

$$D_i^{IO} = f_i^{IO}\left(\{Q_{ji}\}_{j\in NE}\right) = \left[\left\{\frac{Q_{ji}}{\alpha_{ji}}\right\}\right]$$

Likewise, the energy and value added composite (Q_i^{EVA}) is an aggregate of the value added composite (Q_i^{VA}), and the energy composite (Q_i^{ENE}) . σ_{EVA_i}represents the substitutability between each input and $\alpha_i^{EVA}, 1-\alpha_i^{EVA}$ are share parameters.

$Q_i^{EVA} = f_i^{EVA}(Q_i^{VA}, Q_i^{ENE}) =$

$$\left[\alpha_i^{EVA}(Q_i^{VA})^{\sigma_{EVA_i}-1 / \sigma_{EVA_i}} + 1 - \alpha_i^{EVA}\,(Q_i^{ENE})^{\sigma_{EVA_i}-1 / \sigma_{EVA_i}}\right]^{\sigma_{EVA_i} / \sigma_{EVA_i}-1}$$

Within the value added composite (Q_i^{VA}), a further CES nested structure combines the income composite (Q_i^{INC}) and capital input (K_i) in a Cobb-Douglas function with share parameters (α_i^{VA}) and $(1-\alpha_i^{VA})$.

$$Q_i^{VA} = f_i^{VA}(Q_i^{INC}, K_i) = (Q_i^{INC})^{\alpha_i^{VA}}\,(K_i)^{1-\alpha_i^{VA}}$$

Here, the income composite (Q_i^{INC}) is an aggregate of labor (L_i) and proprietors' income (PR_i) combined through a Leontief function.

$$Q_i^{INC} = f_i^{INC}\left(L_i, PR_i\right) = \left[\frac{L_i}{\alpha_i^{L}}, \frac{PR_i}{\alpha_i^{PR}}\right]$$

The energy composite(Q_i^{ENE}) combines electricity consumption $\left(ELE_i\right)$ and the non-electric energy composite (Q_i^{NELE}) in a similar fashion with a substitution parameter $\left(\sigma_{ENE_i}\right)$ and share parameters(α_i^{ENE}) and $(1-\alpha_i^{ENE})$.

$$Q_i^{ENE} = f_i^{ENE}\left(ELE_i, Q_i^{NEL}\right)$$

$$= \left[\alpha_i^{ENE}\left(ELE_i\right)^{\sigma_{ENE_i}-1 / \sigma_{ENE_i}} + (1-\alpha_i^{ENE})\,(Q_i^{NELE})^{\sigma_{ENE_i}-1 / \sigma_{ENE}}\right]^{\sigma_{ENE_i} / \sigma_{ENE_i}-1}$$

The non-electric energy composite (Q_i^{NELE}) is an aggregate of gasoline(GSL_i) and other petroleum products($NGSL_i$) with a substitution parameter $\left(\sigma_{NENE_i}\right)$ and share parameters(α_i^{NENE}) and $(1-\alpha_i^{NENE})$.

$$Q_i^{NELE} = f_i^{NELE}\left(GSL_i, NGSL_i\right)$$

$$= \left[\alpha_i^{NELE}\left(GSL_i\right)^{\sigma_{ENEL_i}-1 / \sigma_{ENEL_i}} + (1-\alpha_i^{ENEL})\,(NGSL_i)^{\sigma_{ENEL_i}-1 / \sigma_{ENEL}}\right]^{\sigma_{ENEL_i} / \sigma_{ENEL-1}}$$

Finally, sector output (Y_i^{SNE}) is allocated as domestic goods (D_i) and export goods (X_i) based on a constant elasticity of transformation (CET) function with a substitution parameter (σ_{EX_i}) and share parameters (α_i^{EX}) and $(1-\alpha_i^{EX})$.

$Y_i^{SNE} = f_i^{EX}\left(D_i, X_i\right) =$

$$\left[\alpha_i^{EX}\left(D_i\right)^{1+\sigma_{EX_i} / \sigma_{EX_i}} + (1-\alpha_i^{EX})\,(X_i)^{1+\sigma_{EX_i} / \sigma_{EX_i}}\right]^{\sigma_{EX_i} / 1+\sigma_{EX_i}}$$

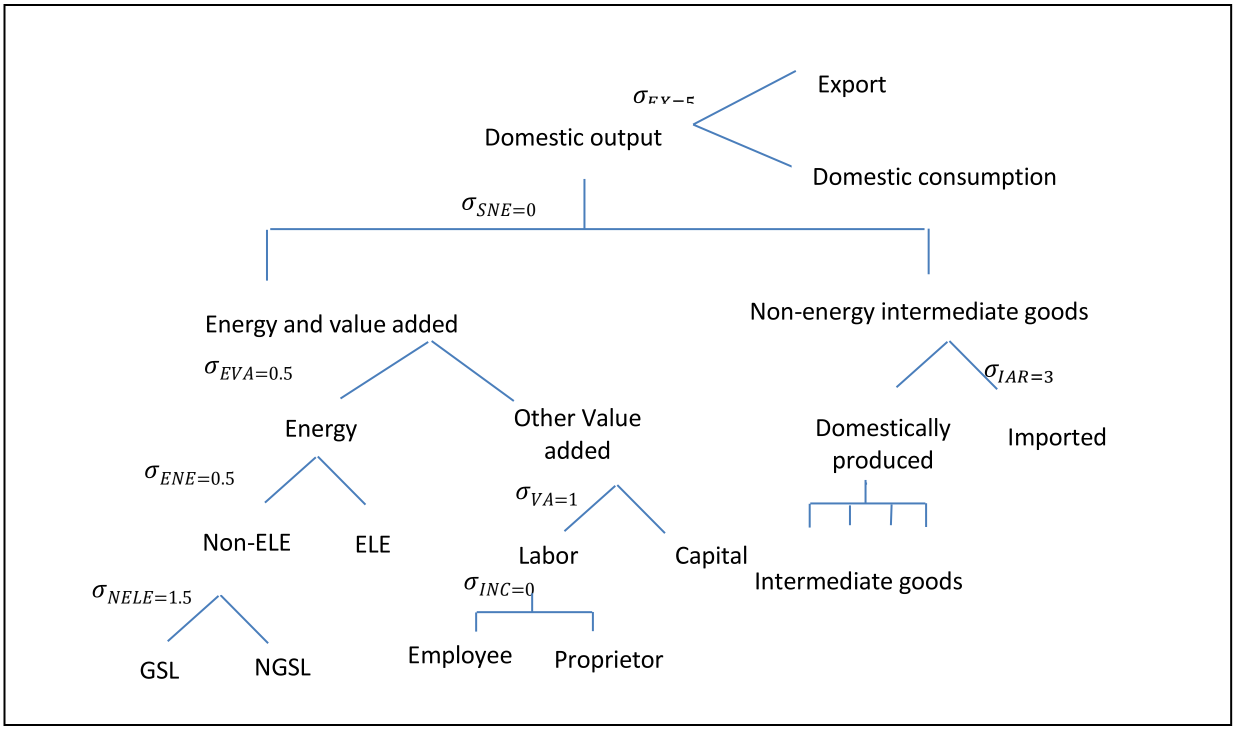

Figure 4-14: Non-Energy Sector Production Nest

I.2 Energy Sector

The energy sector consists of electricity and petroleum sectors. In addition, the petroleum sector is divided into gasoline and non-gasoline sectors to allow for the explicit modeling of gasoline-based transportation. The following sections illustrate the detailed production functions used in each energy producing sector.

I.2.I Electricity Sector (SEL)

At the top of the production nest, the electricity sector output (Y_{SEL}) is represented as a Leontief aggregate consisting of the intermediate composite (Q_{SEL}^{IAR}), the income composite (Q_{SEL}^{INC}), the capital and energy composite (Q_{SEL}^{KP}) and electricity consumption (ELE_{SEL}) . (α_{SEL}^{IAR}), (α_{SEL}^{INC}), (α_{SEL}^{KP}), (α_{SEL}^{ELE}) are input coefficients.

$$Y_{SEL} = f_{SEL}\left(Q_{SEL}^{IAR}, Q_{SEL}^{INC}, Q_{SEL}^{KP}, ELE_{SEL}\right) = \left[\frac{Q_{SEL}^{IAR}}{\alpha_{SEL}^{IAR}}, \frac{Q_{SEL}^{INC}}{\alpha_{SEL}^{INC}}, \frac{Q_{SEL}^{KP}}{\alpha_{SEL}^{KP}}, \frac{ELE_{SEL}}{\alpha_{SEL}^{ELE}}\right]$$

Similar to non-energy producing sectors, the intermediate composite (Q_{SEL}^{IAR}) of the electricity sector consists of both domestically produced intermediate goods (D_{SEL}^{IO}) and imported intermediate goods (M_{SEL}^{IO}), aggregated through an Armington CES function with a substitution parameter $\left(\sigma_{IAR_{SEL}}\right)$ and share parameters(α_{SEL}^{IAR}) and $(1-\alpha_{SEL}^{IAR})$.

$$Q_{SEL}^{IAR} = f_{SEL}^{IAR}(D_{SEL}^{IO}, M_{SEL}^{IO}) =$$

$$\left[\alpha_{SEL}^{IAR}(D_{SEL,}^{IO})^{\sigma_{IAR_{SEL}}-1/\sigma_{AR_{SEL}}} + (1-\alpha_{SEL}^{IAR})\,(M_{SEL}^{IO})^{\sigma_{IAR_{SEL}}-1/\sigma_{IAR_{SEL}}}\right]^{\sigma_{IAR_{SEL}}/\sigma_{IAR_{SEL}}-1}$$

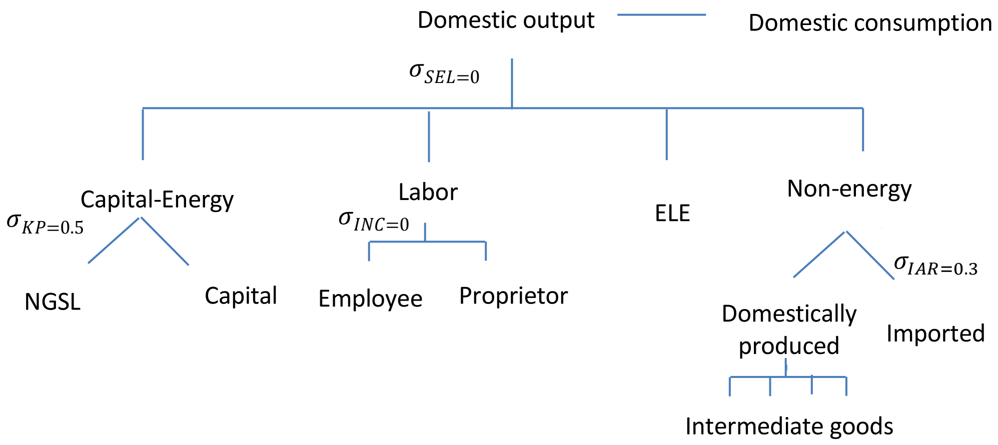

Figure 4-15: Electricity Sector Production Nest

Here, domestic produced non- intermediate goods (D_{SEL}^{IO}) consist of intermediate goods (Q_{ji}) aggregated through a Leontief function.

$$D_{SEL}^{IO} = f_{SEL}^{IO}\left(\{Q_{jSEL}\}_{j\in NE}\right) = \left[\left\{\frac{Q_{jSEL}}{\alpha_{jSEL}}\right\}\right]$$

Also, the income composite (Q_{SEL}^{INC}) is an aggregate of labor (L_{SEL}) and proprietors' income (PR_{SEL}) combined through a Leontief function.

$$Q_{SEL}^{INC} = f_{SEL}^{INC}\left(L_{SEL}, PR_{SEL}\right) = \left[\frac{L_{SEL}}{\alpha_{SEL}^{L}}, \frac{PR_{SEL}}{\alpha_{SEL}^{PR}}\right]$$

Further, the capital-energy-land composite (Q_{SEL}^{KP}) combines capital input (K_{SEL}) non-gasoline petroleum input ($NGSL_{SEL}$). Since electricity production is primarily based on residual oil consumption in Hawai‘i, it is assumed that no gasoline is consumed in the electricity sector.

$Q_{SEL}^{KP} = f_{SEL}^{KP}\left(K_{SEL}, NGSL_{SEL}\right) =$

$$\left[\alpha_{SEL}^{KP}\left(K_{SEL}\right)^{\sigma_{KP_{SEL}}-1 / \sigma_{KP_{SEL}}} + (1 - \alpha_{SEL}^{KP}\ (NGSL_{SEL})^{\sigma_{KP_{SEL}}-1 / \sigma_{KP_{SEL}}}\right]^{\sigma_{KP_{SEL}} / \sigma_{KP_{SEL}}-1}$$

Finally, sector output (Y_i^{SEL}) is supplied as domestic goods (D_{SEL}) and no electricity is exported.

$$Y_{SEL} = f_i^{EX}(D_i\ ) = D_i$$

I.2.2. Petroleum Sector

The petroleum sector (SPET) is divided into gasoline (GSL) and non-gasoline (NGSL) production. The nested structure of these two sectors is largely identical, except that the former consumes either imported or domestically produced bioethanol. In the base year, the gasoline sector consumes imported bioethanol as part of the imported intermediate goods(M_{GSL}^{IO}) . In the counter factual scenario of a 10% mandate, it is assumed that domestic production of ethanol (D_{bio}) occurs, replacing a portion of (M_{GSL}^{IO}). In the 20% mandate scenario, bioethanol produced locally will additionally replace a portion of gasoline input.

At the top of the nest, the petroleum sector output (Y_i^{SPET}) combines the intermediate composite (Q_i^{IAR}), the value added composite (Q_i^{VA}) and the energy consumption (Q_{ji}^{ENE}) using a Leontief function.

$$Y_i^{SPET} = f_i^{SPET}\left(Q_i^{IAR}, Q_i^{VA}, \{Q_i^{EN}\}_{j \in SE}, LN_i \right) = \left[\frac{Q_i^{IAR}}{\alpha_i^{IAR}} \frac{Q_i^{VA}}{\alpha_i^{VA}}, \left\{\frac{Q_{ji}^{ENE}}{\alpha_{ji}^{ENE}}\right\}\right]$$

The intermediate composite (Q_i^{IAR}) is an aggregate of both domestically produced (D_i^{IO}) and imported intermediate goods (M_i^{IO}), combined through an Armington CES function with a substitution parameter (σ_{IAR_i})and a share parameter(α_i^{IAR}).

$$Q_i^{IAR} = f_i^{IAR}(D_i^{IO}, M_i^{IO}) = \left[\alpha_i^{IAR} (D_i^{IO})^{\sigma_{IAR_i}-1 / \sigma_{AR_i}} + (1-\alpha_i^{IAR})\, (M_i^{IO})^{\sigma_{IAR_i}-1 / \sigma_{IAR_i}}\right]^{\sigma_{IAR_i} / \sigma_{IAR_i}-1}$$

Domestically produced non- intermediate goods (D^{IO}) consist of intermediate goods (Q_{ji}) aggregated through a Leontief function.

$$D_i^{IO} = f_i^{IO}\left(\{Q_{ji}\}_{j \in NE}\right) = \left[\left\{\frac{Q_{ji}}{\alpha_{ji}}\right\}\right]$$

The value added composite (Q_i^{VA}) combines the income composite (Q_i^{INC}) and capital input (K_i) in a Leontief function.

$$Q_i^{VA} = f_i^{VA}(Q_i^{INC}, K_i) = \left[\frac{Q_i^{INC}}{\alpha_i^{INC}}, \frac{K_i}{\alpha_i^{k}}\right]$$

The income composite (Q_i^{INC}) aggregates labor (L_i) and proprietors' income (PR_i) in a Leontief function.

$$Q_i^{INC} = f_i^{INC}\left(L_i , PR_i\right) = \left[\frac{L_i^{INC}}{\alpha_i^{L}}, \frac{PR_i^{INC}}{\alpha_i^{PR}}\right]$$

Finally, sector output (Y_i^{PET}) is allocated as domestic goods (D_i) and export goods (X_i) based on a constant elastic city of transformation (CET) function with a substitution parameter (σ_{EX_i}) and share parameters (α_i^{EX}) and ($1-\alpha_i^{EX}$).

$$Y_i^{PET} = f_i^{EX}\left(D_i , X_i \right) =$$

$$\left[\alpha_i^{EX}\left(D_i \right)^{1+\sigma_{EX_i} / \sigma_{EX_i}} + (1-\alpha_i^{EX})\, (X_i)^{1+\sigma_{EX_i} / \sigma_{EX_i}}\right]^{\sigma_{EX_i} / 1+\sigma_{EX_i}}$$

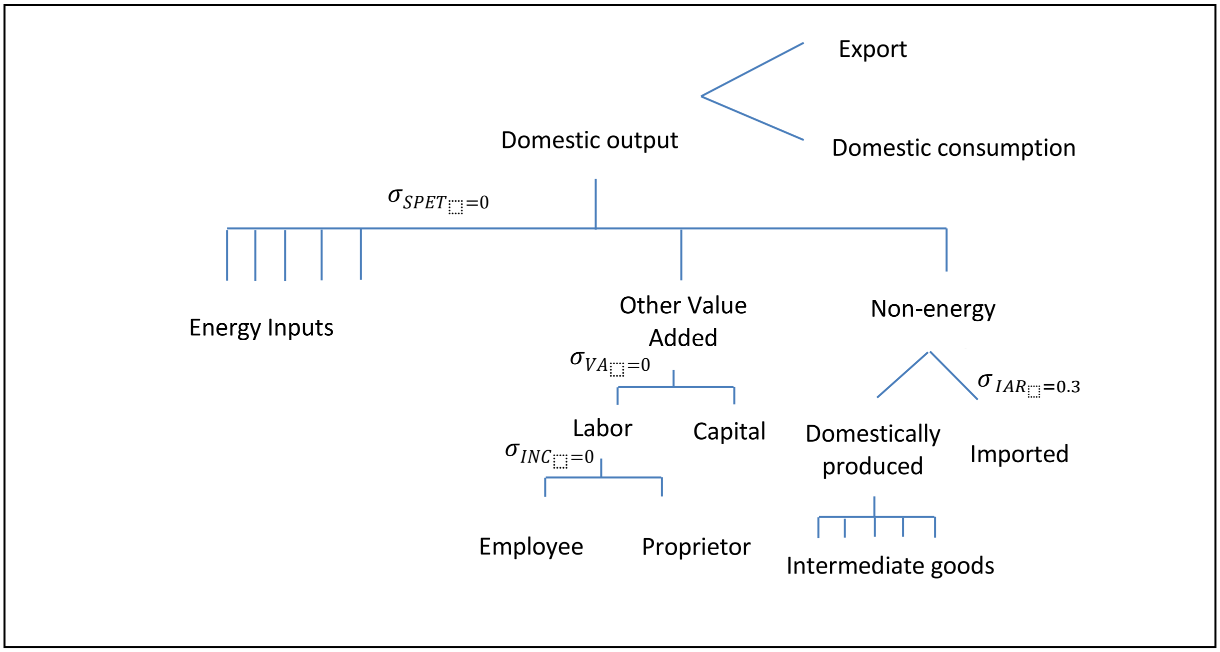

Figure 4-16: Petroleum Sector Production Nest

1.3. Land Allocation

The representative agent is endowed with a fixed initial level of agricultural land. This land is allocated to a range of uses based on a nested CET function.

At the top level of the nest, total agricultural land (LND^{AG}) is separated into forest (LND^{FR}), non-forest(LND^{NF}) and miscellaneous land (LND^{MISC}) with a substitution parameter (σ_{AG}) and share parameters (α^{AG}), (β^{AG}) and γ^{AG}.

$$LND^{AG} = f^{AG}\left(LND^{FR}, LND^{NF}, LND^{MISC}\right) =$$

$$\left[\alpha^{AG}\left(LND^{FR}\right)^{1+\sigma_{AG}/\sigma_{AG}} + \beta^{AG}\left(LND^{NF}\right)^{1+\sigma_{AG}/\sigma_{AG}} + \gamma^{AG}\left(LND^{MISC}\right)^{1+\sigma_{AG}/\sigma_{AG}}\right]^{\sigma_{AG}/1+\sigma_{AG}}$$

Within the lower nest, non-forest land is separated into crop (LND^{CR}) and pasture land (LND^{PSTR}) with a substitution parameter (σ_{NF}) and share parameters (α^{NF}) and ($1-\alpha^{NF}$).

$$LND^{NF} = f^{NF}\left(LND^{CR}, LND^{PSTR}\right) =$$

$$\left[\alpha^{NF}\left(LND^{CR}\right)^{1+\sigma_{NF}/\sigma_{PTC_r}} + \left(1-\alpha^{NF}\right)\left(LND^{PSTR}\right)^{1+\sigma_{NF}/\sigma_{NF}}\right]^{\sigma_{NF}/1+\sigma_{NF}}$$

2. Consumption

The final consumption sectors include in-state household consumption, visitor consumption, and state and federal government consumption.

2.1. Household Consumption (CE)

A representative resident household (r) is assumed to maximize utility (U_r) based on the consumption of the transport composite (C_i^{PTC}) and the non-transport composite (C_i^{POC}) combined using a Cobb-Douglas function. Household consumption is subject to budget constrains determined by the level of factor endowment.

$$U_r \ = \ f_r \ (C_r^{PTC}, C_r^{POC}) = (C_r^{PTC})^{\alpha_r} \ (C_r^{POC})^{1-\alpha_r}$$

On the next level, the transport composite (C_i^{PTC}) aggregates purchased transport C_r^{PRT}), and non-gasoline ($NGSL_r$) and gasoline $\left(NGSL_r\right)$ based transport fuels with share parameters $\alpha_r^{PTC}, \beta_r^{PTC}\gamma_r^{PTC}$ and a substitution parameter, σ_{PTC_r}.

$C_r^{PTC} = \ f_r^{PTC}\left(C_r^{PRT}, NGSL_{r,}GSL_{r,}\right) =$

$$\left[\alpha_r^{PTC}(C_r^{PRT})^{\sigma_{PTC_r}-1/\sigma_{PTC_r}} + \beta_r^{PTC} \ (NGSL_r\ )^{\sigma_{PTC_r}-1/\sigma_{PTC_r}} + \gamma_r^{PTC} \ (GSL_r)^{\sigma_{PTC_r}-1/\sigma_{PTC_r}}\right]^{\sigma_{PTC_r}/\sigma_{PTC_r}-1}$$

C_r^{PRT} is an aggregate of personal transport sector demand, combined using a Cobb-Douglas function.

$$C_r^{PRT} = f_r \ (C_{ri})_{i\in PRT} = \prod_{i\in PRT} (C_{ri})^{\alpha_{ri}}$$

C_r^{POC} is an aggregate of the non-energy commodity composite (C_r^{PCC}) and the non-transport energy composite (C_r^{PHEN}) with share parameters $\alpha_r^{POC}$and $1 - \alpha_r^{POC}$ and a substitution parameter σ_{POC_r}.

$C_r^{POC} = \ f_r^{POC}(C_r^{PCC}, C_r^{PHEN}) =$

$$\left[\alpha_r^{POC}(C_r^{PCC})^{\sigma_{POC_r}-1/\sigma_{POC_r}} + (1-\alpha_r^{POC}) \ (C_r^{PHEN} \ \ )^{\sigma_{POC_r}-1/\sigma_{POCr}}\right]^{\sigma_{POC_r}/\sigma_{POCr}-1}$$

On the third level of this nesting structure, the non-energy commodity composite (C_r^{PCC}) aggregates domestically produced non-energy goods (CD_r^{NE}) and imported final goods (M_r) with share parameters α_r^{PCC} and 1-α_r^{PCC}

$$C_r^{PCC} = \ f_r^{PCC}\left(\ CD_r^{NE}, M_r \ \right) = (CD_r^{NE})^{\alpha_r^{PCC}} \ (M_r \ )^{1-\alpha_r^{PCC}}$$

where $CD_r^{NE}$is an aggregate of domestically produced non-energy goods (CD_{ri}) for i ∈ SNE combined through a CES function with share parameters (ρ_i) and a substitution parameter(α_{ri}^{NE}).

$$CD_r^{NE} = f_r^{NE}(C_{ri})_{i\in SNE} = \sum \left[\rho_i {C_{ri}}^{\alpha_{ri}^{NE}-1/\alpha_{ri}^{NE}}\right]^{\alpha_{ri}^{NE}/\alpha_{ri}^{NE}-1}$$

Likewise, the non-transport energy composite (C_r^{PHEN}) aggregates household electricity consumption $\left(ELE_r\ \right)$ and natural gas consumption (GAS_r) through a CES function with share parameters (α_r^{PHEN}) and ($1 - \alpha_r^{PHEN}$) and a substitution parameter (σ_{PHEN_r}).

$C_r^{PHEN} = \ f_r^{PHEN}\left(ELE_r \ , GAS_r \ \right) =$

$$\left[\alpha_r^{PHEN}\left(ELE_r\ \right)^{\sigma_{PHEN_r}-1/\sigma_{PHEN_r}} + (1-\alpha_r^{PHEN}) \ (GAS_r \quad)^{\sigma_{PHEN_r}-1/\sigma_{PHENr}}\right]^{\sigma_{PHEN_r}/\sigma_{PHENr}-1}$$

The budget constraint of a representative resident household is as follows. The total sum of goods consumed times the price of goods must equal the sum of labor income $(P_L * L)$, proprietors income $(P_{PR} * PR)$, capital income $(P_k * K)$ and rent from agricultural land $(P_{LNA} * LN_A)$, foreign exchange earnings $(\overline{P_{fx}} \quad * BOP_L)$ minus lump-sum tax (T_r) and investment.

$$INC_r = \sum_i P_i \quad (CD_{ri}\ ) + \overline{p_m}(M_r)$$

$$= P_L(L \quad) + P_{PR}(PR \quad) + P_k(K \quad) + P_{LNA}(LN_A) + \overline{P_{fx}} \quad (BOP \quad) - T_r - INVTOT$$

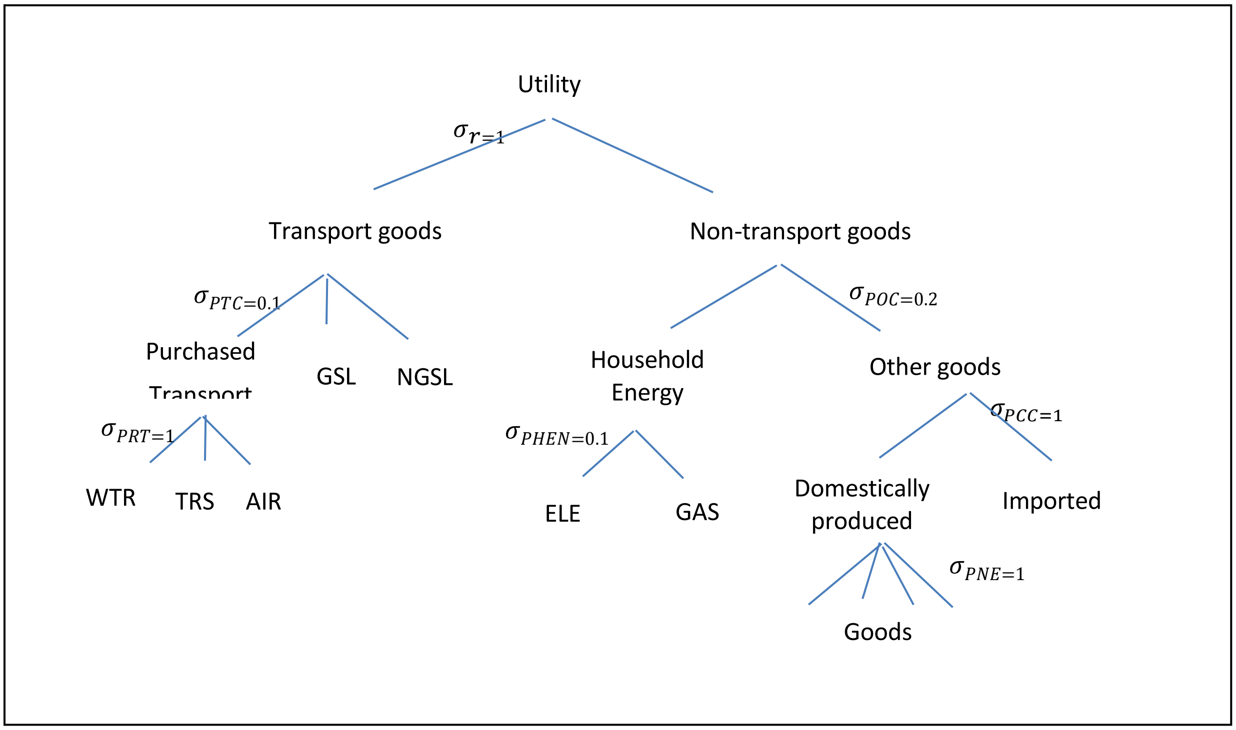

Figure 4-17: Household Utility Maximization

2.2. Visitor Consumption (VE)

A representative visitor is assumed to maximize his/her utility $(U_v\ )$ based on the consumption of domestically produced non-energy goods (CD_v^{NE}) , energy goods (CD_v^E) and imported commodities(M_v), subject to a budget constraint

$$U_v \ = \ f_v \ \left(CD_v^{NE}, CD_v^E, M_v \ \right) = (CD_v^{NE})^{\alpha_v} \ (CD_v^E)^{\beta_v} \ (M_r \ )^{\gamma_v}$$

where CD_v^{NE} is an aggregate of domestically produced non-energy goods (CD_{vi}) for i $\in SNE$ combined through a Cobb-Douglas function.

$$CD_v^{NE} = f_v^{NE}(C_{vi})_{i \in SNE} = \prod_{i \in SNE} (C_{vi})^{\alpha_{ri}^{NE}}$$

A representative visitor is assumed to have an exogenous income.

$$\overline{INC_v} \equiv INC_{v0} = \sum_i P_i \quad (CD_{vi}) + \overline{p_m}(M_v)$$

2.3. Government Consumption (GE)

Government consumption is divided into state and federal government demands. It is assumed that government entities purchase domestically produced goods (GD_{ig}) for all commodities and imported commodities(M_v). Government entities are assumed to have a Leontief utility function so as to enable constant levels of public goods provision subject to a budget constraint.

$$U_g = f_g \left(\{GD_{ig}\} \quad , M_{g,} \right) = \left[\left\{ \frac{GD_{ig}}{\alpha_{ig}} \right\}, \frac{M_g}{\alpha_g} \right]$$

The federal government (FG) is assumed to have an exogenous income

$$\overline{INC_{FG}} \equiv INC_{FG0} = \sum_i P_i \quad (GD_{iFG}) + \overline{p_m}(M_{FG})$$

The state government has a budget constraint consisting of endogenous general exercise tax with a rate (τ) and a lump-sum transfer (T_r). In this model, it is assumed that the level of government consumption stays constant so that government revenue is adjusted though a lump-sum transfer.

$$INC_{SG} = \sum_i P_i \quad (GD_{iSG}) + \overline{p_m}(M_{SG}) = \sum_i P_i \quad (Y_i)\bar{\tau} + T_r$$

3. Investment

The investment block consists of domestic and foreign investments. Both take the form of a Cobb-Douglas utility function, and may be regarded as ‘virtual banks’ purchasing investment goods subject to a budget constraint. The level of savings is assumed to be the difference between representative household’s endowment plus foreign exchange earnings and the levels of household consumption and lump-sum tax.

$$U_{DINV} = f_{DINV} \left(\{C_{iDINV}^{SNE}\}_{i \in SNE}, \{C_{iDINV}^{SE}\}_{j \in SE} \right)$$

$$= (C_{iDINV}^{SNE})^{\alpha_{inv}} \; (C_{iDINV}^{SE})^{1-\alpha_{inv}}$$

$$(C_{iDINV}^{SNE})_{i \in SNE} = \prod_{i \in SNE} C_{iDINV}$$

$$(C_{iDINV}^{SE})_{i \in SE} = \prod_{i \in SE} C_{iDINV}$$

$$U_{FINV} = f_{INV}(M_{FINV}) = M_{FINV}$$

5. Market Clearing Conditions

Equilibrium conditions for factor and commodity markets are as follows:

5.1. Factor Demand

The total labor force ($\bar{L}$) is assumed to be fully employed across all sectors and remain at the initial level of labor force endowment (L_0). Labor is assumed to be mobile across all sectors.

$$\bar{L} \equiv L_0 = \sum_i L_i$$

Similarly, total proprietors income ($\overline{\mathrm{PR}}$) and capital ($\overline{\mathrm{K}}$) are fully employed across all sectors, and remain at the initial levels of endowment (PR_0) and (K_0) respectively. They are also mobile cross all sectors.

$$\overline{PR} \quad \equiv PR_0 = \sum\nolimits_i PR_i$$

$$\overline{K} \quad \equiv K_0 = \sum\nolimits_i K_i$$

The total agricultural land ($\overline{\mathrm{LN}}^{\mathrm{AG}}$) remains at the initial level of endowment.

$$\overline{LN}^{AG} \equiv LN_0^{AG} = \sum\nolimits_{i \in AG} LN_i^{AG}$$

5.2. Commodity Demand

In equilibrium, the sum of all sector outputs (Y) must equal the sum of commodity demanded as intermediate good, final consumption and export.

$$Y_i \quad = \sum_j Q_{ij} + C_{ri} + C_{vi} + G_{gi} + C_{inv} + X_i$$

5.3. Balance of Payments

The model takes a ‘small economy’ assumption in which domestic economic activities do not affect world prices. The foreign exchange rate ($\overline{p_{fx}}$) is exogenously given and the balance of payment (BOP) holds as follows:

$$\overline{p_{fx}} \quad (BOP \quad) = \overline{p_m} M \quad - \overline{INC_v} - \overline{INC_{FG}} - \sum\nolimits_i \overline{p_{x_i}} \; (X_i)$$

Table 4-11: Elasticity Parameters

Elasticity	Value	Sector		Description	Sources
PRODUCTION BLOC					
σ_{AG_i}	0.6	SNE_A	top-nest	Elasticity of substitution between energy-material composite and value added	ADAGE Model (ROSS 2008)
σ_{REM_i}	0.6	SNE_A	2nd nest	Elasticity of substitution between land and energy-material composite	ADAGE Model (ROSS 2008)
σ_{EM_i}	0.3	SNE_A	3rd nest	Elasticity of substitution between energy and material inputs	ADAGE Model (ROSS 2008)
	0	SNE_NA	top-nest	Elasticity of substitution between energy-value added composite and material inputs	ADAGE Model (ROSS 2008)
σ_{EVA_i}	0.5	SNE_NA	2nd nest	Elasticity of substitution between energy composite and value added	ADAGE Model (ROSS 2008)
	0	SPET	top nest	Elasticity of substitution between intermediate, value added and energy input	ADAGE Model (ROSS 2008)
	0	SEL	top nest	Elasticity of substitution between intermediate, labor and capital-energy composite	Assumption specific to this study
$\sigma_{KP_{SEL}}$	0.5	SEL	2nd nest	Elasticity of substitution between capital and energy	Assumption specific to this study
Capital-Labor substitution					
	1	SNEL	varies	Elasticity of substitution between capital and labor	ADAGE Model (ROSS 2008)
	0	SEC	varies	Elasticity of substitution between labor and proprietors income	ADAGE Model (ROSS 2008)
Energy Composite					
σ_{ENE_i}	0.5	SNE	varies	Elasticity of substitution between electricity and non-electricity energy source	ADAGE Model (ROSS 2008)
σ_{NENE_i}	1.5	SNE	varies	Elasticity of substitution between non-energy source(GSL/NGSL)	ADAGE Model (ROSS 2008)
Armington elasticity of substitution					
σ_{IAR_i}	3	SEL/FDM	varies	Elasticity of substitution between imported and domestic goods	ADAGE Model (ROSS 2008)
$\sigma_{IAR_{SEL}}$	0.3	ELE/PET	varies	Elasticity of substitution between imported and domestic goods	ADAGE Model (ROSS 2008)
Elasticity for export					
σ_{EX_i}	5	SEC		Elasticity of transformation between domestically consumed and exported goods	Konan and Kim (2005)
Land transformation					

σ_{AG}	0.1	LND	top nest	Elasticity of transformation between Forest Non-Forest and Forest Land	Bouet (2010) (with modification as the original elasticity is between forest and non-forest land only)
σ_{NF}	0.15	LND	2nd nest	Elasticity of transformation between Crop and Pasture Land	Bouet (2010)
CONSUMPTION/GOVERMENT/INVESTMENT BLOCKS					
	1	PCE	top nest	Elasticity of substitution between transport and other commodity consumption	ADAGE Model (ROSS 2008)
α_r^{POC}	0.25	PCE	2nd nest	Elasticity of substitution between household energy goods and non-energy/non-transport goods	ADAGE Model (ROSS 2008)
α_r^{PHEN}	0.1	PCE	3rd nest	Elasticity of substitution between household energy (electricity and gas)	Assumption specific to this study
α_{ri}^{NE}	0.5	PCE	3rd nest	Elasticity of substitution within non-energy/non-transport composite	ADAGE Model (ROSS 2008)
σ_{PTC_r}	0.2	PCE	2nd nest	Elasticity of substitution between purchased transport (TRN,WTR,AIR) and personal transport (GSL)	ADAGE Model (ROSS 2008)
	1	PCE	3rd nest	Elasticity of substitution among purchased transport	Assumption specific to this study
	1	VS	1st nest	Elasticity of substitution among domestic, energy and imported goods	Konan and Kim (2005) with modification since no distinction is made originally on energy vs. non-energy goods
	1	VS	2nd nest	Elasticity of substitution within domestically produced and energy goods	Konan and Kim (2005) with modification since no distinction is made originally on energy vs. non-energy goods
	0	FG/G	1st nest	Elasticity of substitution among domestic and imported goods	Konan and Kim (2005)
	1	INVT	1st nest	Elasticity of substitution among domestic and energy goods	Konan and Kim (2005)
	1	INVT	2nd nest	Elasticity of substitution within domestically produced and energy goods	Konan and Kim (2005)

APPENDIX 4.2: ESTIMATING GASOLINE AND NON-GASOLINE CONSUMPTION BY I.O. SECTORS.

The EIA publishes annually the breakdown of fuel expenditure in each state. The fuel expenditure for petroleum resources in Hawai‘i in 2007 was recorded as follows (in million $)

Table 4-12: Breakdown of fuel expenditure

Gasoline + Bioethanol	Non-gasoline	Total Petroleum
1435.5	3437.6	4873.1

According to 2007 Hawai‘i IO table; however, petroleum expenditure is recorded as 4667.5 (in million $), and there exist a small discrepancy. Because of this discrepancy, following steps were taken to estimate the gasoline and non-gasoline portions of expenditure by sectors.

1) Using the EIA breakdown and the total petroleum sector expenditure based on Hawai‘i’s 2007 IO table, the portions of total gasoline (including bioethanol) vs. non-gasoline consumption were estimated.

2) For agricultural sectors (excluding animal/fish and forestry industry), it was assumed that the fuel breakdown corresponds to Schnepf (2004). The expenditure share for gasoline reported by Schnepf 2004 was multiplied by the total petroleum spending for each agricultural sector.

3) For personal consumption by resident households, a small portion of LPG is used while the rest of petroleum expenditure is used for gasoline consumption. The gasoline expenditure is estimated by subtracting the petroleum product expenditure by the expenditure on LPG.

4) For visitor expenditure, all petroleum expenditures were assumed to be used for gasoline consumption.

5) For military consumption, the fuel composition was estimated based on the average figure of all military fuel spending available from http://www.energy.dla.mil/library/Documents/Publications/Fact%20Book%20FY10.pdf.

6) The air/ water transport and power generation sectors were assumed to consume no gasoline.

7) For the remaining sectors, this study first subtracted the sum of steps (2) to (6) from the total gasoline expenditure as estimated in step (1)). This difference is them allocated across all remaining sectors, based on their respective petroleum expenditure share. (i.e. all the remaining sectors have the same proportions of gasoline vs. non-gasoline consumption.

Appendix 4.3: Life-Cycle GHG Emissions Calculation

For this study, the changes in life-cycle GHG emissions as a result of mandates were calculated in a following manner.

1. The changes in quantify of fuel used are estimated based on the changes in quantity of each sector output. To avoid double-counting, the changes in GHG emissions (GHG') were estimated as follows:

$$GHG' = \sum \alpha * GSL' + \beta * ELE' + \gamma * AIR' + \delta * OTHER' + \varepsilon * BIO + \eta * COAL' + \theta * NG'$$

   Where

   α = unit life-cycle GHG emissions of gasoline
   β = unit life-cycle GHG emissions of electricity
   γ = unit life-cycle GHG emissions of aviation fuel
   δ = unit life-cycle GHG emissions of other petroleum fuel
   ε = difference in unit life-cycle GHG emissions between imported and locally produced bioethanol (10% mandate); plus additional GHG difference between locally produced bioethanol and gasoline (20% mandate)
   η = unit life-cycle GHG emissions of industrial coal use
   θ = unit life-cycle GHG emissions of natural gas

   GSL'= changes in gasoline demand (in btu) estimated based on the gasoline sector output

   ELE'= changes in electricity demand (in btu) estimated based on the electricity sector output

   AIR'=changes in aviation fuel demand (in btu) estimated based on the air transport sector output

   OTHER'=changes in other petroleum fuel demand (in btu) estimated based on the non-gasoline petroleum sector output (subtracting demand for gasoline, electricity and air transportation sector).

   BIO= quantity of biofuels used (constant in the case of 10% mandate, increases in the case of 20% mandate)

   COAL'=changes in industrial coal demand (in btu) estimated based on the other manufacturing sector output

   NG'=changes in natural gas demand (in btu) estimated based on the gas sector output

2. Unit life-cycle GHG missions factors were estimated using the GREET model 2012 version.

Table 4-13: Unit life-cycle GHG emissions factors

α	Gasoline: 0.093774104 (g of CO2e/btu)
β	Electricity: 0.099453986 (g of CO2e/btu)
γ	Jet Fuel: 0.097046379 (g of CO2e/btu)
δ	Other Petroleum: 0.095927509 (g of CO2e/btu)
ε	Imported Biofuel: 0.056810853 (g of CO2e/btu) Switchgrass: 0.033374219 (g of CO2e/btu)
η	Coal: 0.1056008 (g of CO2e/btu)
θ	Natural Gas: 0.0785981 (g of CO2e/btu)

- α = unit life-cycle GHG emissions of gasoline

  Unit life-cycle GHG emissions of gasoline include crude oil extraction, refining, final vehicular use and transportation between each stage.

- β = unit life-cycle GHG emissions of electricity

  Unit life-cycle GHG emissions of electricity were estimated based on the current power generation mix in the state of Hawai‘i (Table 1). It includes GHG emissions related to extraction, refinery, power generation and transportation of fuel between each step.

Table 4-14: Power generation mix in Hawai‘i (EIA 2013)

In Trillion BTU

	Coal	Residual	Distillate	Hydroelectric	wood and waste	geothermal	solar	wind	total
2007	17.2	71.8	13.5	0.5	4.1	2.3	0	2.4	111.8

- γ = unit life-cycle GHG emissions of aviation fuel

Unit life-cycle GHG emissions of aviation fuel were estimated based on the conventional jet fuel for used in single passenger aisle planes. It includes GHG emissions related to extraction, refinery and use in plane as well as fuel transportation between each stage.

- δ = unit life-cycle GHG emissions of other petroleum fuel

Unit life-cycle GHG emissions of other petroleum fuel were estimated based on current mix of non-gasoline petroleum products demand (EIA 2013). For ‘other’ portion of the non-gasoline petroleum demand, GHG emissions of crude oil were used as a proxy, since the detailed breakdown was unknown.

Table 4-15: Non electricity, non-gasoline petroleum products demand (estimated based on EIA2013)

In Trillion BTU

	distillate fuel	residual	LPG	Jet fuel	Other
2007	40.6	30.8	1.6	72.3	16.6

- ε = difference in unit life-cycle GHG emissions between imported and locally produced bioethanol (10% mandate); plus additional GHG difference between locally produced bioethanol and gasoline (20% mandate).

  The life-cycle GHG emissions for imported biofuels were estimated based on the current mix of sugarcane-derived biofuel (from Caribbean) and corn-derived bioethanol (from other US states). For sugarcane-derived bioethanol, the life-cycle GHG emissions of Brazilian sugarcane were used as a proxy, making adjustments to barge shipment emissions to account for additional GHG emissions caused by the international shipment. For corn derived bioethanol, the default US values were used.

  The life-cycle emissions switchgrass were taken from the default assumptions in the GREET model.

- η = unit life-cycle GHG emissions of industrial coal use
  Unit life-cycle GHG emissions of industrial coal use is estimated based on the GREET 2012. The emissions factor including emissions related to coal mining, cleaning, transportation and final use in an industrial boiler.

- θ = unit life-cycle GHG emissions of natural gas
  Unit life-cycle GHG emissions of industrial coal use is estimated based on the GREET 2012. The emissions factor based on natural gas for stationary use is used. The end of emissions factor is based on the small industrial boiler use.

APPENDIX 4.4 USE TABLE BASED ON 2007 INPUT-OUTPUT TABLE (MILLION $)

Table 4-16: Use table as aggregated from 2007 IO Table

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Sugar	1	0.46											47.14													
Vegetable	2		1.27		0.06			0.00	0.00				8.73								13.09					
Ochard	3			0.64									39.78													
Pineapple	4				0.52								14.95				0.16				1.41					
Flower	5	0.05	0.06	0.07	0.04	7.09	0.04	0.03	0.04	1.82		1.53	1.69				0.35	0.40	0.57		1.98					
Agriculture Other	6		0.11				5.68	3.97	6.61			11.86	38.59				0.07	0.89	1.94		6.34				0.00	0.00
Livestock	7							1.02	0.01	0.19			23.00								3.01					
Aquaculture	8								3.00	1.30	0.01		1.68				0.06				45.68					
Agricultural Service	9	0.74	1.66	2.83	1.77	1.69	1.41	0.12	0.12	0.33	0.07		1.35	0.01	0.01	0.01		1.77	8.32	0.00	0.05	0.10	0.85	0.00		
Forestry	10					1.07				0.37	2.62		3.82		0.12						0.40				0.13	0.05
Construction	11																									
Manufacturing Other	12	1.06	2.34	3.97	6.16	2.24	2.84	1.41	9.35	2.00	0.02	596.64	456.26	67.84	3.09	8.83	144.52	156.32	390.17	5.70	907.12	65.51	89.27	80.99	7.69	3.21
Air Transportation	13	0.04	0.11	0.06	0.09	1.33	0.06	0.03	0.99	1.21	0.00	29.66	23.51	1.76	0.53	5.69	19.81	7.86	3.66	0.02	118.89	31.08	6.35	0.37	3.18	1.33
Water Transportation	14	0.01	0.01	0.01	0.01	0.47	0.36	0.10	0.52	0.04	0.00	57.79	32.41	6.76	6.59	0.30	4.19	0.11	2.68	0.05	37.85	5.33	0.39	0.74	6.57	2.75
Ground Transportation	15	0.37	0.92	0.50	0.47	0.53	0.83	0.50	2.16	0.32	0.01	74.79	58.05	12.57	61.95	94.44	17.70	20.30	15.49	0.19	215.98	17.70	17.19	2.80	1.20	0.50
Retail	16	1.64	2.03	2.04	1.43	3.15	3.41	0.63	3.28	2.14	0.02	824.36	415.11	28.19	6.60	28.60	156.08	31.43	101.64	0.33	606.07	29.97	30.49	4.79	14.08	5.88
Real Estate	17											266.20	76.73	18.13	19.24	20.48	844.32	923.53	137.03	0.25	2157.95	22.14	47.31	3.52	12.84	5.36
Rental Service	18	0.15	0.41	0.45	0.18	0.33	0.59	0.09	0.17	0.23	0.03	130.56	75.40	4.08	4.85	12.24	58.13	12.36	2.35	0.05	219.24	2.06	10.04	0.73	4.64	1.94
Gas and Other Utility	19	0.12	0.13	0.16	0.08	0.34	0.07	0.05	0.06	0.01	0.00	14.32	8.06	0.42	1.71	0.35	11.57	8.77	0.32	3.40	61.77	1.90	8.21	10.68	2.80	1.17
Other Services	20	1.74	2.07	3.59	2.34	4.14	3.52	0.75	3.49	0.73	0.09	1072.84	634.22	219.58	79.46	131.72	976.80	803.87	1009.08	2.28	5908.14	94.91	288.64	33.58	78.94	32.97
Federal Government	21								0.05			35.24	39.94	19.31	0.23	4.35	90.93		3.15	0.34	412.30	14.87	15.57	5.55	0.73	0.31
State Government	22		2.13	0.12		3.10		0.75	0.04				19.63	141.58	54.69	12.76	53.79	43.98	33.06	0.00	122.84	9.99	17.80	0.25	6.63	2.77
Electricity	23	1.04	1.20	1.39	0.75	2.66	0.63	0.43	0.53	0.11	0.02	124.90	67.80	3.68	14.15	3.14	96.03	84.37	2.87	0.04	541.55	16.88	71.90	13.22	23.70	9.90
Non-Gasoline Petroleum	24	2.07	1.21	4.91	2.87	2.36	3.10	0.77	14.47	0.17	0.21	95.73	145.68	731.73	69.65	90.22	95.40	12.90	108.25	30.67	204.60	10.88	81.95	693.05	122.05	50.97
Gasoline	25	0.80	0.47	1.89	1.11	0.91	1.19	0.29	5.57	0.07	0.09	39.95	60.80			37.66	39.82	5.38	45.18	12.80	85.39	4.54	34.20		50.94	21.27
Import		7.35	10.19	12.09	5.06	13.32	18.48	9.51	20.71	3.88	0.75	1565.95	1664.69	425.14	112.22	93.66	995.02	173.71	198.47	11.81	3307.46	122.29	245.04	178.85	2698.98	1127.06
Land		4.04	4.98	4.91	2.95	3.50	4.77	1.13	1.17	0.24	0.01															
Wage Labor		15.85	22.89	28.99	18.94	35.27	34.36	15.80	52.92	11.09	2.89	2466.30	1076.07	531.89	246.00	667.00	3339.00	480.00	168.00	32.36	14297.00	7773.00	5021.00	275.64	50.53	21.10
Proprietor Income		2.84	4.10	5.19	3.39	6.31	6.15	2.83	9.48	1.99	0.52	474.68	176.15		0.88	108.50	424.94	207.37	29.03	0.11	2240.29			0.95	9.90	4.13
Indirect Business Tax												65.09	45.91	335.00	24.00	146.00	1966.00	629.00	381.00	25.22	1460.00			214.78	5.64	2.36
Other Capital Cost		7.24	10.46	13.25	8.66	16.11	15.70	7.22	24.18	5.07	1.32	769.75	74.06	318.12	133.12	167.50	854.06	4406.48	5205.44	117.00	4153.71	712.00	516.00	672.94	191.40	79.93
Total Output		47.60	68.74	87.07	56.89	105.92	103.20	47.44	158.94	33.30	8.68	8718.14	5331.21	2865.78	839.08	1633.46	10188.74	8010.81	7847.70	242.62	37130.11	8935.16	6502.21	2193.43	3292.57	1374.94

		Private Consumer Expenditures	Visitor Expenditures	Gross Private Investment	State and Local Government Investment	State and Local Government Consumption	Federal Investment	Federal Consumption	Export	Total Demand for Products
Sugar	1									0.00
Vegetable	2	31.89	3.27			3.75			6.69	45.59
Ochard	3	7.77	4.52			0.30			34.06	46.65
Pineapple	4	2.30	5.33						32.21	39.84
Flower	5	32.17	4.88						53.09	90.14
Agriculture Other	6	12.54							14.60	27.13
Livestock	7	6.39	1.21			0.37		1.30	10.93	20.20
Aquaculture	8	50.93	1.10			0.37		0.01	54.79	107.20
Agricultural Service	9	10.04						0.06		10.10
Forestry	10							0.09		0.09
Construction	11			7366.92	774.80		575.60	0.81		8718.14
Manufacturing Other	12	793.47	84.32	164.92		51.45	0.14	303.52	918.82	2316.65
Air Transportation	13	529.48	2002.23	10.93	0.93	34.22		0.46	29.89	2608.16
Water Transportation	14	258.07	177.27	95.27	3.49	20.73	0.95	2.88	114.37	673.03
Ground Transportation	15	331.58	499.89	25.13	1.20	55.48	0.18	4.22	98.30	1016.00
Retail	16	6255.71	694.06	624.34	32.11	109.74	1.31	17.70	150.39	7885.36
Real Estate	17	2276.99	705.58	40.08	9.78	117.44		4.13	301.78	3455.78
Rental Service	22	6075.53	1197.52			31.47		1.88		7306.39
Gas and Other Utility	18	83.34				20.45		2.34		106.13
Other Services	19	16173.04	6835.16	502.34	5.67	253.39	95.85	340.27	1534.88	25740.61
Federal Government	20	738.80	75.60					7477.92		8292.31
State Government	21	734.78				5241.51				5976.29
Electricity	22	753.49				320.38		36.67		1110.53
Non-Gasoline Petroleum	23.00	11.52		6.42		60.73		90.01	548.04	716.72
Gasoline	24	879.50	15.68	2.68		25.35		1.40		924.61
Import		6163.00	2260.36	3724.43	72.81	463.75	228.01	564.84	819.54	

APPENDIX 4.5: MSPGE MODELING SYNTAX

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*============================================================================
*  Model Definition in MPSGE Vector Syntax
*============================================================================

$ONTEXT

$MODEL:ENERGY_BAU_REV

$ECHOP:TRUE

$SECTORS:
* Production
        Y(SEC)                  ! Domestic Output
        AR(SEC)                 ! Armington Nest for Imports and Domestics
        EVA(SNE_NAREA)          ! Energy and Value Added Nest
        ENER(SNE)               ! Energy Nest between Petroleum and Electricity
        VA(SNEL)                ! Value added
        INCOME(SEC)             ! Income Nest
        M                       ! Imports
        Bio$LocalBio            ! Local Biofuels
        Bana$LocalBio           ! Local Banagrass Production
        KP(SEL)                 ! KP nest
        LND                     ! Ag land transformation
        AGF                     ! Ag-Forest land nest
        REM(SNE_A)              ! Resource Energy Material Composite for Ag Sector
        ME(SNE_A)               ! Material Energy Composite for Ag sector
        NEL(SNE)                !Non-Electricty energy composite
*Final Demand
        X(SEC)$EX0(SEC)         !  Exports
        C                       ! PCE
        CC                      ! PCE Composite - Domestic & Imports
        FG                      ! Federal Government
        G                       ! State and Local Government
        INVT                    ! Investment expenditures
        INVF                    ! Foreign investment expenditures (Imported investment)
        V                       ! Visitor expenditures
        OC                      ! Other consumption
        TC                      ! Transport consumption
        HEN                     ! Household energy comp

$COMMODITIES:
        PD(SEC)                 ! Price of domestically consumed goods
        PI(SEC)                 ! Intermediate Inputs & Imports
        PE(SEC)$EX0(SEC  )      ! Price of exports
        PEVA(SNE_NAREA)         ! Price of Energy and Value Added Nest
        PEN(SNE)                ! Price of Energy Nest
        PVA(SNEL)               ! Price of Value Added Nest
        PM                      ! Price of Imports
        PINC                    ! Composite Price of Income
        PL                      ! Price of Sector Mobile Labor
        PPR                     ! Price of Proprietor Labor
        PMK                     ! Price of Sector Mobile Capital (Return to capital)
        PC                      ! Price of Household Consumption
        PCC                     ! Price of Household Consumption of Composite Domestic-Imported Good
```

```
        PG                          ! Price of State and Local Government
        PFX                         ! Exchange Rate
        PINV                        ! Price of Investment
        PV                          ! Price of Visitor Consumption
        PFC                         ! Price of Federal Government Consumption
        POC                         ! Price for personal other consumption nest
        PTC                         ! Price for personal transport consumptipon nest
        PHEN                        ! Price for household energy consumtion nest
        PKP(SEL)                    ! Price for cap-energy nest
        PRNT_A                      ! Price of Total Agricultural Land
        PRNT_CR                     ! Price of Crop Land
        PRNT_NF                     ! Price of Non-Forest Land Nest
        PRNT_FR                     ! Price of Forest Land
        PRNT_MIS                    ! Price of Misc. Land
        PRNT_PST                    ! Price of Pasture Land
        PREM(SNE_A)                 ! Energy Material Land Nest
        PME(SNE_A)                  ! Energy Material Nest
        PRNT_BANA$LAND              ! Land used for banagrass production
        PNEL(SNE)                   ! Non-electricity energy nest
** new bio industry
        PBio$LocalBio               !  Price of local biofuel
        PBana$LocalBio              !  Price of banagrass

$CONSUMERS:
        RA                          ! Representative Agent
        GOV                         ! State Government
        VIS                         ! Visitors
        FC                          ! Federal Government Consumption
        SUNK                        ! Outside agent

$AUXILIARY:
        UNEMP$UNEMPE                ! Endogenous Unemployment
       TAU_LUMP$FIXG                 ! Lump sum tax replacement
       TAU_LO$FIXG                   ! Lump sum tax replacement
       TAU_FUEL$FIXG_FUEL            ! Fuel tax on gasoline

*===============================================================================
* Production of Sectors Not Energy CROP (SNE_CR)
*===============================================================================
$PROD:Y(SNE_CR)     s:0.6     t:5
        O:PD(SNE_CR)              Q:DOMY0(SNE_CR)   P:PY0(SNE_CR)  A:GOV  T:TY0(SNE_CR)
        O:PE(SNE_CR)$EX0(SNE_CR)    Q:EX0(SNE_CR)     P:PY0(SNE_CR)  A:GOV  T:TY0(SNE_CR)
* Intermediate Inputs, Value Added & Energy
        I:PREM(SNE_CR)    Q:(RIOSEC("REA",SNE_CR)+((VAEN0(SNE_CR)-VA0(SNE_CR))+ (SUM(ROW_A,
IO0(ROW_A,SNE_CR)) + IM0(SNE_CR))))
        I:PVA(SNE_CR)       Q:(VA0(SNE_CR))

$PROD:REM(SNE_CR)  s:0.6
        O:PREM(SNE_CR)                Q: (RIOSEC("REA",SNE_CR)+((VAEN0(SNE_CR)-VA0(SNE_CR))+
(SUM(ROW_A, IO0(ROW_A,SNE_CR)) + IM0(SNE_CR))))
        I:PRNT_CR              Q:RIOSEC("REA",SNE_CR)
        I:PME (SNE_CR)      Q:((VAEN0(SNE_CR)-VA0(SNE_CR))+ (SUM(ROW_A, IO0(ROW_A,SNE_CR)) +
IM0(SNE_CR)) )

$PROD:ME(SNE_CR) s:0.3
```

```
        O:PME (SNE_CR)        Q:((VAEN0(SNE_CR)-VA0(SNE_CR))+ (SUM(ROW_A, IO0(ROW_A,SNE_CR)) +
IM0(SNE_CR)) )
        I:PEN(SNE_CR)         Q:(VAEN0(SNE_CR)-VA0(SNE_CR))
        I:PI(SNE_CR)                  Q:(SUM(ROW_A, IO0(ROW_A,SNE_CR)) + IM0(SNE_CR))

* Armington Nest for Production
$PROD:AR(SNE_CR)    s:3     a:0
        O:PI(SNE_CR)        Q:(SUM(ROW_A, IO0(ROW_A,SNE_CR)) + IM0(SNE_CR))
        I:PD(ROW_A)         Q:(IO0(ROW_A,SNE_CR)) a:
        I:PM                Q:IM0(SNE_CR)
* Value Added Nest
$PROD:VA(SNE_CR)    s:1
        O:PVA(SNE_CR)       Q:(VA0(SNE_CR))
        I:PINC                      Q:(LD0(SNE_CR)+PR0(SNE_CR))
        I:PMK                       Q:KD0(SNE_CR)

* Income Nest
$PROD:INCOME(SNE_CR) s:0
        O:PINC                      Q:(LD0(SNE_CR)+PR0(SNE_CR))
        I:PL                Q:LD0(SNE_CR)
        I:PPR               Q:PR0(SNE_CR)

* Energy Nest
$PROD:ENER(SNE_CR)  s:0.5
        O:PEN(SNE_CR)       Q:(VAEN0(SNE_CR)-VA0(SNE_CR))
        I:PD("ELE")         Q:RFACTOR("ELE",SNE_CR)
        I:PNEL(SNE_CR)      Q:(RFACTOR("NGSL",SNE_CR)+ RFACTOR("GSL",SNE_CR))

$PROD:NEL(SNE_CR) s:1.5
        O:PNEL(SNE_CR)   Q:(RFACTOR("NGSL",SNE_CR)+ RFACTOR("GSL",SNE_CR))
        I:PD("NGSL")        Q:RFACTOR("NGSL",SNE_CR)
        I:PD("GSL")         Q:RFACTOR("GSL",SNE_CR)          A:GOV  N:TAU_FUEL$FIXG_FUEL
*==============================================================================
* Production of Sectors Not Energy Pasture (SNE_PST)
*==============================================================================
$PROD:Y(SNE_PST)     s:0.6     t:5
        O:PD(SNE_PST)         Q:DOMY0(SNE_PST)   P:PY0(SNE_PST)  A:GOV  T:TY0(SNE_PST)
        O:PE(SNE_PST)$EX0(SNE_PST)    Q:EX0(SNE_PST)     P:PY0(SNE_PST)  A:GOV  T:TY0(SNE_PST)
* Intermediate Inputs, Value Added & Energy
        I:PREM(SNE_PST)    Q:(RIOSEC("REA",SNE_PST)+((VAEN0(SNE_PST)-VA0(SNE_PST))+
(SUM(ROW_A, IO0(ROW_A,SNE_PST)) + IM0(SNE_PST))))
        I:PVA(SNE_PST)      Q:(VA0(SNE_PST))

$PROD:REM(SNE_PST)  s:0.6
        O:PREM(SNE_PST)      Q: (RIOSEC("REA",SNE_PST)+((VAEN0(SNE_PST)-VA0(SNE_PST))+
(SUM(ROW_A, IO0(ROW_A,SNE_PST)) + IM0(SNE_PST))))
        I:PRNT_PST          Q:RIOSEC("REA",SNE_PST)
        I:PME (SNE_PST)      Q:((VAEN0(SNE_PST)-VA0(SNE_PST))+ (SUM(ROW_A, IO0(ROW_A,SNE_PST)) +
IM0(SNE_PST)) )

$PROD:ME(SNE_PST) s:0.3
        O:PME (SNE_PST)           Q:((VAEN0(SNE_PST)-VA0(SNE_PST))+ (SUM(ROW_A,
IO0(ROW_A,SNE_PST)) + IM0(SNE_PST)) )
        I:PEN(SNE_PST)         Q:(VAEN0(SNE_PST)-VA0(SNE_PST))
        I:PI(SNE_PST)          Q:(SUM(ROW_A, IO0(ROW_A,SNE_PST)) + IM0(SNE_PST))
```

```
* Armington Nest for Production
$PROD:AR(SNE_PST)    s:3     a:0
        O:PI(SNE_PST)        Q:(SUM(ROW_A, IO0(ROW_A,SNE_PST)) + IM0(SNE_PST))
        I:PD(ROW_A)          Q:(IO0(ROW_A,SNE_PST)) a:
        I:PM                 Q:IM0(SNE_PST)

* Value Added Nest
$PROD:VA(SNE_PST)    s:1
        O:PVA(SNE_PST)   Q:(VA0(SNE_PST))
        I:PINC                       Q:(LD0(SNE_PST)+PR0(SNE_PST))
        I:PMK                        Q:KD0(SNE_PST)

* Income Nest
$PROD:INCOME(SNE_PST) s:0
        O:PINC               Q:(LD0(SNE_PST)+PR0(SNE_PST))
        I:PL                 Q:LD0(SNE_PST)
        I:PPR                Q:PR0(SNE_PST)

* Energy Nest
$PROD:ENER(SNE_PST)  s:0.5
        O:PEN(SNE_PST)    Q:(VAEN0(SNE_PST)-VA0(SNE_PST))
        I:PD("ELE")          Q:RFACTOR("ELE",SNE_PST)
        I:PNEL(SNE_PST)   Q:(RFACTOR("NGSL",SNE_PST)+ RFACTOR("GSL",SNE_PST))

$PROD:NEL(SNE_PST) s:1.5
        O:PNEL(SNE_PST)  Q:(RFACTOR("NGSL",SNE_PST)+ RFACTOR("GSL",SNE_PST))
        I:PD("NGSL")         Q:RFACTOR("NGSL",SNE_PST)
        I:PD("GSL")          Q:RFACTOR("GSL",SNE_PST)          A:GOV  N:TAU_FUEL$FIXG_FUEL
*==============================================================================
* Production of Sectors Not Energy Forestry (SNE_FR)
*==============================================================================
$PROD:Y(SNE_FR)     s:0.6     t:5
        O:PD(SNE_FR)             Q:DOMY0(SNE_FR)   P:PY0(SNE_FR)  A:GOV  T:TY0(SNE_FR)
        O:PE(SNE_FR)$EX0(SNE_FR)    Q:EX0(SNE_FR)     P:PY0(SNE_FR)  A:GOV  T:TY0(SNE_FR)
* Intermediate Inputs, Value Added & Energy
        I:PREM(SNE_FR)     Q:(RIOSEC("REA",SNE_FR)+((VAEN0(SNE_FR)-VA0(SNE_FR))+ (SUM(ROW_A,
IO0(ROW_A,SNE_FR)) + IM0(SNE_FR))))
        I:PVA(SNE_FR)       Q:(VA0(SNE_FR))

$PROD:REM(SNE_FR)  s:0.6
        O:PREM(SNE_FR)      Q: (RIOSEC("REA",SNE_FR)+((VAEN0(SNE_FR)-VA0(SNE_FR))+ (SUM(ROW_A,
IO0(ROW_A,SNE_FR)) + IM0(SNE_FR))))
        I:PRNT_FR            Q:RIOSEC("REA",SNE_FR)
        I:PME (SNE_FR)      Q:((VAEN0(SNE_FR)-VA0(SNE_FR))+ (SUM(ROW_A, IO0(ROW_A,SNE_FR)) +
IM0(SNE_FR)) )

$PROD:ME(SNE_FR) s:0.3
        O:PME (SNE_FR)        Q:((VAEN0(SNE_FR)-VA0(SNE_FR))+ (SUM(ROW_A, IO0(ROW_A,SNE_FR)) +
IM0(SNE_FR)) )
        I:PEN(SNE_FR)           Q:(VAEN0(SNE_FR)-VA0(SNE_FR))
        I:PI(SNE_FR)            Q:(SUM(ROW_A, IO0(ROW_A,SNE_FR)) + IM0(SNE_FR))

* Armington Nest for Production
$PROD:AR(SNE_FR)    s:3     a:0
        O:PI(SNE_FR)         Q:(SUM(ROW_A, IO0(ROW_A,SNE_FR)) + IM0(SNE_FR))
        I:PD(ROW_A)          Q:(IO0(ROW_A,SNE_FR)) a:
```

```
        I:PM                    Q:IM0(SNE_FR)

* Value Added Nest
$PROD:VA(SNE_FR)    s:1
        O:PVA(SNE_FR)       Q:(VA0(SNE_FR))
        I:PINC                  Q:(LD0(SNE_FR)+PR0(SNE_FR))
        I:PMK                   Q:KD0(SNE_FR)

* Income Nest
$PROD:INCOME(SNE_FR) s:0
        O:PINC                          Q:(LD0(SNE_FR)+PR0(SNE_FR))
        I:PL                    Q:LD0(SNE_FR)
        I:PPR                   Q:PR0(SNE_FR)

* Energy Nest
$PROD:ENER(SNE_FR)  s:0.5
        O:PEN(SNE_FR)       Q:(VAEN0(SNE_FR)-VA0(SNE_FR))
        I:PD("ELE")         Q:RFACTOR("ELE",SNE_FR)
        I:PNEL(SNE_FR)      Q:(RFACTOR("NGSL",SNE_FR)+ RFACTOR("GSL",SNE_FR))

$PROD:NEL(SNE_FR) s:1.5
        O:PNEL(SNE_FR)    Q:(RFACTOR("NGSL",SNE_FR)+ RFACTOR("GSL",SNE_FR))
        I:PD("NGSL")        Q:RFACTOR("NGSL",SNE_FR)
        I:PD("GSL")         Q:RFACTOR("GSL",SNE_FR)          A:GOV  N:TAU_FUEL$FIXG_FUEL
*===========================================================================
* Production of Sectors Not Energy MIS Ag sectors (SNE_MIS)
*===========================================================================
$PROD:Y(SNE_MIS)     s:0.6     t:5
        O:PD(SNE_MIS)         Q:DOMY0(SNE_MIS)   P:PY0(SNE_MIS)  A:GOV  T:TY0(SNE_MIS)
        O:PE(SNE_MIS)$EX0(SNE_MIS)    Q:EX0(SNE_MIS)     P:PY0(SNE_MIS)  A:GOV  T:TY0(SNE_MIS)
* Intermediate Inputs, Value Added & Energy
        I:PREM(SNE_MIS)    Q:(RIOSEC("REA",SNE_MIS)+((VAEN0(SNE_MIS)-VA0(SNE_MIS))+
(SUM(ROW_A, IO0(ROW_A,SNE_MIS)) + IM0(SNE_MIS))))
        I:PVA(SNE_MIS)     Q:(VA0(SNE_MIS))

$PROD:REM(SNE_MIS)  s:0.6
        O:PREM(SNE_MIS)      Q: (RIOSEC("REA",SNE_MIS)+((VAEN0(SNE_MIS)-VA0(SNE_MIS))+
(SUM(ROW_A, IO0(ROW_A,SNE_MIS)) + IM0(SNE_MIS))))
        I:PRNT_MIS            Q:RIOSEC("REA",SNE_MIS)
        I:PME (SNE_MIS)      Q:((VAEN0(SNE_MIS)-VA0(SNE_MIS))+ (SUM(ROW_A, IO0(ROW_A,SNE_MIS))
+ IM0(SNE_MIS)) )

$PROD:ME(SNE_MIS) s:0.3
        O:PME (SNE_MIS)      Q:((VAEN0(SNE_MIS)-VA0(SNE_MIS))+ (SUM(ROW_A, IO0(ROW_A,SNE_MIS))
+ IM0(SNE_MIS)) )
        I:PEN(SNE_MIS)         Q:(VAEN0(SNE_MIS)-VA0(SNE_MIS))
        I:PI(SNE_MIS)            Q:(SUM(ROW_A, IO0(ROW_A,SNE_MIS)) + IM0(SNE_MIS))

* Armington Nest for Production
$PROD:AR(SNE_MIS)    s:3     a:0
        O:PI(SNE_MIS)        Q:(SUM(ROW_A, IO0(ROW_A,SNE_MIS)) + IM0(SNE_MIS))
        I:PD(ROW_A)          Q:(IO0(ROW_A,SNE_MIS)) a:
        I:PM                    Q:IM0(SNE_MIS)

* Value Added Nest
$PROD:VA(SNE_MIS)    s:1
```

```
        O:PVA(SNE_MIS)    Q:(VA0(SNE_MIS))
        I:PINC            Q:(LD0(SNE_MIS)+PR0(SNE_MIS))
        I:PMK             Q:KD0(SNE_MIS)

* Income Nest
$PROD:INCOME(SNE_MIS) s:0
        O:PINC            Q:(LD0(SNE_MIS)+PR0(SNE_MIS))
        I:PL              Q:LD0(SNE_MIS)
        I:PPR             Q:PR0(SNE_MIS)

* Energy Nest
$PROD:ENER(SNE_MIS)  s:0.5
        O:PEN(SNE_MIS)    Q:(VAEN0(SNE_MIS)-VA0(SNE_MIS))
        I:PD("ELE")       Q:RFACTOR("ELE",SNE_MIS)
        I:PNEL(SNE_MIS)   Q:(RFACTOR("NGSL",SNE_MIS)+ RFACTOR("GSL",SNE_MIS))

$PROD:NEL(SNE_MIS) s:1.5
        O:PNEL(SNE_MIS)           Q:(RFACTOR("NGSL",SNE_MIS)+ RFACTOR("GSL",SNE_MIS))
        I:PD("NGSL")      Q:RFACTOR("NGSL",SNE_MIS)
        I:PD("GSL")       Q:RFACTOR("GSL",SNE_MIS)        A:GOV  N:TAU_FUEL$FIXG_FUEL
*=============================================================================
* Production of Sectors Not Energy Non AG (SNE_NA)
*=============================================================================
$PROD:Y(SNE_NA)     s:0     t:5
        O:PD(SNE_NA)            Q:DOMY0(SNE_NA)   P:PY0(SNE_NA)  A:GOV  T:TY0(SNE_NA)
        O:PE(SNE_NA)$EX0(SNE_NA)   Q:EX0(SNE_NA)     P:PY0(SNE_NA)  A:GOV  T:TY0(SNE_NA)
* Intermediate Inputs, Value Added & Energy
        I:PI(SNE_NA)            Q:(SUM(ROW,IO0(ROW,SNE_NA)) +IM0(SNE_NA))
        I:PEVA(SNE_NA)          Q:(VAEN0(SNE_NA))

* Armington Nest for Production
$PROD:AR(SNE_NA)    s:3     a:0
        O:PI(SNE_NA)            Q:(SUM(ROW, IO0(ROW,SNE_NA)) + IM0(SNE_NA))
        I:PD(ROW)               Q:(IO0(ROW,SNE_NA)) a:
        I:PM              Q:IM0(SNE_NA)

* Energy and Value Added
*$PROD:EVA(SNE)
$PROD:EVA(SNE_NA)   s:0.5
        O:PEVA(SNE_NA)    Q:(VAEN0(SNE_NA))
        I:PVA(SNE_NA)     Q:(VA0(SNE_NA))
        I:PEN(SNE_NA)     Q:(VAEN0(SNE_NA)-VA0(SNE_NA))

* Value Added Nest
$PROD:VA(SNE_NA)    s:1
        O:PVA(SNE_NA)     Q:(VA0(SNE_NA))
        I:PINC            Q:(LD0(SNE_NA)+PR0(SNE_NA))
        I:PMK             Q:KD0(SNE_NA)

* Income Nest
$PROD:INCOME(SNE_NA) s:0
        O:PINC            Q:(LD0(SNE_NA)+PR0(SNE_NA))
        I:PL              Q:LD0(SNE_NA)
        I:PPR             Q:PR0(SNE_NA)

* Energy Nest
```

```
$PROD:ENER(SNE_NA)  s:0.5
        O:PEN(SNE_NA)      Q:(VAEN0(SNE_NA)-VA0(SNE_NA))
        I:PD("ELE")        Q:RFACTOR("ELE",SNE_NA)
        I:PNEL(SNE_NA)     Q:(RFACTOR("NGSL",SNE_NA)+ RFACTOR("GSL",SNE_NA))

$PROD:NEL(SNE_NA) s:1.5
        O:PNEL(SNE_NA)     Q:(RFACTOR("NGSL",SNE_NA)+ RFACTOR("GSL",SNE_NA))
        I:PD("NGSL")       Q:RFACTOR("NGSL",SNE_NA)
        I:PD("GSL")        Q:RFACTOR("GSL",SNE_NA)          A:GOV  N:TAU_FUEL$FIXG_FUEL
*===============================================================================
* Production of Sector for Non-agricultural land
*===============================================================================
$PROD:Y("REA")    s:0    t:5
        O:PD("REA")              Q:(DOMY0("REA"))  P:PY0("REA")  A:GOV  T:TY0("REA")
        O:PE("REA")$EX0("REA")        Q:EX0("REA")     P:PY0("REA")  A:GOV  T:TY0("REA")
* Intermediate Inputs, Value Added & Energy
        I:PI("REA")              Q:(SUM(ROW,IO0(ROW,"REA")) +IM0("REA"))
        I:PEVA("REA")             Q:(VAEN0("REA"))

* Armington Nest for Production
$PROD:AR("REA")   s:3    a:0
        O:PI("REA")        Q:(SUM(ROW, IO0(ROW,"REA")) + IM0("REA"))
        I:PD(ROW)          Q:(IO0(ROW,"REA")) a:
        I:PM               Q:IM0("REA")

* Energy, Land and Value Added
*$PROD:EVA("REA")
$PROD:EVA("REA")   s:0.5
        O:PEVA("REA")      Q:(VAEN0("REA"))
        I:PVA("REA")       Q:(VA0("REA"))
        I:PEN("REA")       Q:(VAEN0("REA")-VA0("REA"))

* Value Added Nest
$PROD:VA("REA")    s:1
        O:PVA("REA")       Q:(VA0("REA"))
        I:PINC             Q:(LD0("REA")+PR0("REA"))
        I:PMK              Q:(KD0("REA")-LL_A0)

* Income Nest
$PROD:INCOME("REA") s:0
        O:PINC             Q:(LD0("REA")+PR0("REA"))
        I:PL               Q:LD0("REA")
        I:PPR              Q:PR0("REA")

* Energy Nest
$PROD:ENER("REA")  s:0.5
        O:PEN("REA")       Q:(VAEN0("REA")-VA0("REA"))
        I:PD("ELE")        Q:RFACTOR("ELE","REA")
        I:PNEL("REA")      Q:(RFACTOR("NGSL","REA")+ RFACTOR("GSL","REA"))

$PROD:NEL("REA") s:1.5
        O:PNEL("REA")      Q:(RFACTOR("NGSL","REA")+ RFACTOR("GSL","REA"))
        I:PD("NGSL")       Q:RFACTOR("NGSL","REA")
        I:PD("GSL")        Q:RFACTOR("GSL","REA")          A:GOV  N:TAU_FUEL$FIXG_FUEL
*===============================================================================
* Production of Petroleum Manufacturing (SPET)
```

```
*================================================================================
$PROD:Y(SPET)     s:0     t:5
        O:PD(SPET)              Q:DOMY0(SPET)   P:PY0(SPET)  A:GOV  T:TY0(SPET)
        O:PE(SPET)$EX0(SPET)    Q:EX0(SPET)     P:PY0(SPET)  A:GOV  T:TY0(SPET)
* Intermediate Inputs, Value Added & Energy
        I:PI(SPET)              Q:(SUM(ROW,IO0(ROW,SPET)) +IM0(SPET))
        I:PVA(SPET)             Q:(VA0(SPET))
        I:PD("ELE")             Q:RFACTOR("ELE",SPET)
        I:PD("NGSL")            Q:RFACTOR("NGSL",SPET)
**Added gasoline consumption
       I:PD("GSL")              Q:RFACTOR("GSL",SPET)           A:GOV  N:TAU_FUEL$FIXG_FUEL

* Armington Nest for Production
$PROD:AR(SPET)    s:3     a:0
        O:PI(SPET)              Q:(SUM(ROW, IO0(ROW,SPET)) + IM0(SPET))
        I:PD(ROW)               Q:(IO0(ROW,SPET)) a:
        I:PM                    Q:IM0(SPET)      A:SUNK  T:(IMSHK-1)

* Value Added and Nest
$PROD:VA(SPET)    s:1
        O:PVA(SPET)             Q:(VA0(SPET))
        I:PINC                  Q:(LD0(SPET)+PR0(SPET))
        I:PMK                   Q:KD0(SPET)

* Income Nest
$PROD:INCOME(SPET) s:0
        O:PINC                              Q:(LD0(SPET)+PR0(SPET))
        I:PL                    Q:LD0(SPET)
        I:PPR                   Q:PR0(SPET)
*================================================================================
* Production of Gasoline Manufacturing (SGSL)
*================================================================================
$PROD:Y(SGSL)     s:0     t:5
        O:PD(SGSL)              Q:(DOMY0(SGSL))   P:PY0(SGSL)  A:GOV  T:TY0(SGSL)
        O:PE(SGSL)$EX0(SGSL)    Q:EX0(SGSL)     P:PY0(SGSL)  A:GOV  T:TY0(SGSL)
* Intermediate Inputs, Value Added & Energy
        I:PI(SGSL)              Q:(SUM(ROW,IO0(ROW,SGSL)) +IM0(SGSL)-BM0$LocalBio)
        I:PVA(SGSL)             Q:(VA0(SGSL))
        I:PD("ELE")             Q:RFACTOR("ELE",SGSL)
        I:PD("NGSL")            Q:RFACTOR("NGSL",SGSL)
        I:PD("GSL")             Q:(RFACTOR("GSL",SGSL)-BM0$MNDT_2)     A:GOV  N:TAU_FUEL$FIXG_FUEL
*         I:PMB$ImportBio       Q:BM0$ImportBio
        I:PBIO$LocalBio         Q:(BM0$LocalBio+BM0$MNDT_2) A:SUNK T:(-(1.01/3.04))$CREDIT

* Armington Nest for Production
$PROD:AR(SGSL)    s:3     a:0
        O:PI(SGSL)              Q:(SUM(ROW, IO0(ROW,SGSL)) + IM0(SGSL)-BM0$LocalBio)
        I:PD(ROW)               Q:(IO0(ROW,SGSL)) a:
        I:PM                    Q:(IM0(SGSL)-BM0$LocalBio)      A:SUNK  T:(IMSHK-1)

* Value Added Nest
$PROD:VA(SGSL)    s:1
        O:PVA(SGSL)             Q:(VA0(SGSL))
        I:PINC                  Q:(LD0(SGSL)+PR0(SGSL))
        I:PMK                   Q:KD0(SGSL)
```

```
* Income Nest
$PROD:INCOME(SGSL) s:0
        O:PINC                          Q:(LD0(SGSL)+PR0(SGSL))
        I:PL                    Q:LD0(SGSL)
        I:PPR                   Q:PR0(SGSL)

*=============================================================================
* Ag land transformation
*=============================================================================
$PROD:LND t:0.15
        O:PRNT_CR               Q:(sum(SNE_CR,RIOSEC("REA",SNE_CR)))
        O:PRNT_PST              Q:RIOSEC("REA","ANM")
        I:PRNT_NF               Q:(sum(SNE_CR,RIOSEC("REA",SNE_CR))+RIOSEC("REA","ANM"))

$PROD:AGF t:0.1

        O:PRNT_NF               Q: (sum(SNE_CR,RIOSEC("REA",SNE_CR))+RIOSEC("REA","ANM"))
        O:PRNT_FR               Q:RIOSEC("REA","FRT")
        O:PRNT_MIS              Q:(sum(SNE_MIS,RIOSEC("REA",SNE_MIS)))
        I:PRNT_A                Q:
((sum(SNE_CR,RIOSEC("REA",SNE_CR))+RIOSEC("REA","ANM"))+RIOSEC("REA","FRT")+(sum(SNE_MIS,
RIOSEC("REA",SNE_MIS))))

*=============================================================================
* Local Biofuel Industry
*=============================================================================


$PROD:Bio$LocalBio      s:0
        O:PBIO                  Q:(BM0+(BM0$MNDT_2))     A:GOV$subBio            T:-0.30$subBio
        I:PBana                 Q:(0.0504998-(0.0504998*0.15$MNDT)+0.0504998$MNDT_2)
        I:PD("OMN")             Q:(0.025318-(0.025318*0.15$MNDT)+0.025318$MNDT_2)
        I:PD("GSL")             Q:(0.001043-(0.001043*0.15$MNDT)+0.001043$MNDT_2)
        I:PD("ELE")             Q:(0.010353-(0.010353*0.15$MNDT)+0.010353$MNDT_2)
        I:PD("OSV")             Q:((0.000148+0.001174)-
((0.000148+0.001174)*0.15$MNDT)+((0.000148+0.001174)$MNDT_2))
        I:PD("GAS")             Q:(0.001276-(0.001276*0.15$MNDT)+0.001276$MNDT_2)   A:GOV
N:TAU_FUEL$FIXG_FUEL
        I:PD("WTR")             Q:(0.000878-(0.000878*0.15$MNDT)+0.000878$MNDT_2)
        I:PD("TRN")             Q:(0.001326-(0.001326*0.15$MNDT)+0.001326$MNDT_2)
        I:PMK                   Q:(0.044026-(0.044026*0.15$MNDT)+0.044026$MNDT_2)
        I:PL                    Q:(0.008135-(0.008135*0.15$MNDT)+0.008135$MNDT_2)
        I:PD("REA")             Q:(0.008135-(0.008135*0.15$MNDT)+0.008135$MNDT_2)

$PROD:Bana$LocalBio     s:0
        O:PBana                 Q:(0.0504998-(0.0504998*0.15$MNDT)+0.0504998$MNDT_2)  A:GOV$subBANA   T:-
0.30$subBANA
        I:PD("AGS")             Q:(0.003197-(0.003197*0.15$MNDT)+0.003197$MNDT_2)
        I:PD("OMN")             Q:(0.001227-(0.001227*0.15$MNDT)+0.001227$MNDT_2)
        I:PD("GSL")             Q:((0.003424*0.262726)-
((0.003424*0.262726)*0.15$MNDT)+((0.003424*0.262726)$MNDT_2))   A:GOV  N:TAU_FUEL$FIXG_FUEL
        I:PD("NGSL")            Q:((0.003424*0.737274)-
((0.003424*0.737274)*0.15$MNDT)+((0.003424*0.737274)$MNDT_2))
        I:PD("TRN")             Q:(0.0000645-(0.0000645*0.15$MNDT)+0.0000645$MNDT_2)
        I:PD("WTR")             Q:(0.0000323-(0.0000323*0.15$MNDT)+0.0000323$MNDT_2)
        I:PD("RTL")             Q:(0.000420-(0.000420*0.15$MNDT)+0.000420$MNDT_2)
```

```
        I:PD("ELE")             Q:(0.004629-(0.004629*0.15$MNDT)+0.004629$MNDT_2)
        I:PD("OSV")             Q:(0.000549-(0.000549*0.15$MNDT)+0.000549$MNDT_2)
        I:PMK                   Q:(0.009412-(0.009412*0.15$MNDT)+0.009412$MNDT_2)
        I:PL                    Q:(0.024288-(0.024288*0.15$MNDT)+0.024288$MNDT_2)
        I:PRNT_PST              Q:((0.0031005*0.112879)-
((0.0031005*0.112879)*0.15$MNDT)+((0.0031005*0.112879)$MNDT_2)-
LL_BANA0$LAND+(LL_BANA0*0.5$LAND_2))
        I:PM                    Q:(0.002907-(0.002907*0.15$MNDT)+0.002907$MNDT_2)
        I:PRNT_BANA$LAND Q:(LL_BANA0$LAND-(LL_BANA0*0.5$LAND_2))

*==============================================================================
* Production of Electricity (SEL)
*==============================================================================

$PROD:Y(SEL)     s:0     t:5
        O:PD(SEL)               Q:DOMY0(SEL)   P:PY0(SEL)  A:GOV  T:TY0(SEL)
        O:PE(SEL)$EX0(SEL)      Q:EX0(SEL)     P:PY0(SEL)  A:GOV  T:TY0(SEL)
* Intermediate Inputs, Value Added & Energy
        I:PI(SEL)               Q:(SUM(ROW,IO0(ROW,SEL)) +IM0(SEL))
        I:PD("ELE")             Q:RFACTOR("ELE",SEL)
        I:PINC                  Q:(LD0(SEL)+PR0(SEL))
        I:PKP(SEL)              Q:(RFACTOR("NGSL",SEL) +KD0(SEL)+RFACTOR("GSL",SEL))

* Armington Nest for Production
$PROD:AR(SEL)    s:0.3     a:0
        O:PI(SEL)               Q:(SUM(ROW, IO0(ROW,SEL)) + IM0(SEL))
        I:PD(ROW)               Q:(IO0(ROW,SEL)) a:
        I:PM                    Q:(IM0(SEL))

* Income Nest
$PROD:INCOME(SEL) s:0
        O:PINC                  Q:(LD0(SEL)+PR0(SEL))
        I:PL                    Q:(LD0(SEL))
        I:PPR                   Q:(PR0(SEL))

* Energy-Capital Nest
$PROD:KP(SEL)  s:0.5
        O:PKP(SEL)              Q:(RFACTOR("NGSL",SEL) +KD0(SEL)+RFACTOR("GSL",SEL))
        I:PMK                   Q:KD0(SEL)
        I:PD("NGSL")            Q:RFACTOR("NGSL",SEL)
*       I:PRNT_NA               Q:RFACTOR("LND_NA",SEL)
**included gasoline consumption ->this is not needed since SEL does not consume GSL
*       I:PD("GSL")             Q:RFACTOR("GSL",SEL)           A:GOV  N:TAU_FUEL$FIXG_FUEL

*==============================================================================
* Imports & Exports
*==============================================================================
$PROD:M
        O:PM                    Q:(M0 - RMFD("EXP"))
        I:PFX                   Q:(M0 - RMFD("EXP"))

$PROD:X(SEC)$EX0(SEC)
        O:PFX                   Q:EX0(SEC)
        I:PE(SEC)               Q:EX0(SEC)
*==============================================================================
* Final Demand
```

```
*===============================================================================
* Households
$PROD:C   s:1
        O:PC            Q:C0
        I:PTC           Q:(SUM(PTR,RFDCOL(PTR,"PCE")) + RENE("NGSL","PCE") +RENE("GSL","PCE"))
        I:POC
Q:(SUM(SNT,RFDCOL(SNT,"PCE"))+RMFD("PCE")+RENE("ELE","PCE")+RFDCOL("GAS","PCE"))

*$PROD:OC
$PROD:OC s:0.25
        O:POC
             Q:(SUM(SNT,RFDCOL(SNT,"PCE"))+RMFD("PCE")+RENE("ELE","PCE")+RFDCOL("GAS","PCE"))
        I:PCC           Q:(SUM(SNT,RFDCOL(SNT,"PCE"))+RMFD("PCE"))
        I:PHEN          Q:(RENE("ELE","PCE")+RFDCOL("GAS","PCE"))

$PROD:HEN   s:0.1
        O:PHEN          Q:(RENE("ELE","PCE")+RFDCOL("GAS","PCE"))
        I:PD("ELE")     Q:RENE("ELE","PCE")
        I:PD("GAS")     Q:RFDCOL("GAS","PCE")

$PROD:CC  s:3           a:0.5
        O:PCC           Q:(SUM(SNT,RFDCOL(SNT,"PCE"))+RMFD("PCE"))
        I:PD(SNT)       Q:(RFDCOL(SNT,"PCE"))       a:
*         I:PD("REA") Q:HD0("REA")
        I:PM            Q:RMFD("PCE")

$PROD:TC  s:0.2         a:1
        O:PTC           Q:(SUM(PTR,RFDCOL(PTR,"PCE")) + RENE("NGSL","PCE") +RENE("GSL","PCE"))
        I:PD(PTR)       Q:RFDCOL(PTR,"PCE")    a:
**NGSL is no consumed in PCE
        I:PD("NGSL")  Q:RENE("NGSL","PCE")
        I:PD("GSL")     Q:RENE("GSL","PCE")                 A:GOV  N:TAU_FUEL$FIXG_FUEL

* Visitors
$PROD:V   s:1      a:1
        O:PV                Q:CV0
        I:PD(ROW)           Q:(VD0(ROW))      a:
        I:PD(ENFD)          Q:VD0(ENFD)       a:
        I:PM                Q:VD0("MDM")

* Federal Government expenditures treated as exogenous
$PROD:FG  s:0  a:0
        O:PFC                   Q:FG0
        I:PD(ROW)#(FGV)         Q:(RFDCOL(ROW,FGV)) a:
        I:PD("ELE")#(FGV)       Q:RENE("ELE",FGV)
        I:PD("NGSL")#(FGV)      Q:RENE("NGSL",FGV)
**included gasoline consumption   02072013
        I:PD("GSL")#(FGV)       Q:RENE("GSL",FGV)           A:GOV  N:TAU_FUEL$FIXG_FUEL
        I:PM#(FGV)              Q:RMFD(FGV)

* State Government expenditures Leontief
$PROD:G  s:0  a:0
        O:PG                Q:SG0
        I:PD(ROW)#(SGV)         Q:(RFDCOL(ROW,SGV)) a:
        I:PD("ELE")#(SGV)       Q:RENE("ELE",SGV)
        I:PD("NGSL")#(SGV)      Q:RENE("NGSL",SGV)
```

```
**included gasolie consumption   02072013
        I:PD("GSL")#(SGV)      Q:RENE("GSL",SGV)            A:GOV  N:TAU_FUEL$FIXG_FUEL
        I:PM#(SGV)             Q:RMFD(SGV)

*==============================================================================
* Investment, Cobb-Douglas
*==============================================================================
$PROD:INVT  s:1  a:1
        O:PINV         Q:INVDOT
        I:PD(ROW)      Q:PI0(ROW) a:
        I:PD(ENFD)     Q:PI0(ENFD) a:

$PROD:INVF s:1
        O:PFX          Q:(INVTOT-INVDOT)
        I:PM           Q:PI0("MDM")
*==============================================================================
* Endowments
*==============================================================================
$DEMAND:VIS
        D:PV           Q:CV0
        E:PFX          Q:CV0E

$DEMAND:GOV
        D:PG           Q:SG0
        E:PG           Q:(-GDEF)
        E:PC           Q:1            R:TAU_LUMP$FIXG
        E:PC           Q:-1           R:TAU_LO$FIXG

$DEMAND:FC
        D:PFC          Q:FG0
        E:PFX          Q:FG0E

$DEMAND:SUNK
        D:PFX          Q:1
        E:PFX          Q:1

$DEMAND:RA
        D:PC           Q:C0
        D:PINV         Q:(INVDOT)
        D:PFX          Q:(INVTOT-INVDOT)
        E:PL$(NOT UNEMPE)     Q:(L0)
        E:PL$UNEMPE           Q:(L0/(1-U0))$UNEMPE
        E:PL$UNEMPE           Q:(-L0/(1-U0))$UNEMPE          R:UNEMP$UNEMPE
        E:PPR          Q:(R0)
        E:PFX          Q:(BOP0-BM0$LocalBio)
        E:PMK          Q:K0
        E:PG           Q:(GDEF)
        E:PRNT_A       Q:(LL_A0)
        E:PRNT_BANA$LAND Q:(LL_BANA0$LAND-(LL_BANA0*0.5$LAND_2))
        E:PC           Q:-1           R:TAU_LUMP$FIXG
        E:PC           Q:1            R:TAU_LO$FIXG

*==============================================================================
* Auxiliary constraints determine replacement tax rates
*==============================================================================
$CONSTRAINT:TAU_LUMP$FIXG
```

```
      G =E= 1;

$CONSTRAINT:TAU_LO$FIXG
      1 =E= G;

$CONSTRAINT:TAU_FUEL$FIXG_FUEL
      G =E= 1;

$CONSTRAINT:UNEMP$UNEMPE
* Nominal Wage cannot decline
*        PL =G= 1;
* Real Wage cannot decline
      PL =G= PC;

$OFFTEXT

*==============================================================================
* Calculate life-cycle greenhouse gas emissions from fuel uses
*==============================================================================

*Life cycle greenhouse gas from i)gasoline+biofuels ii) fossile based electricity iii) jet fuel
*iv)non-gasoline petroluem and v) coal and natural gas uses are ignored.


*        V:ELELE(SEL)          I:PD("ELE")           PROD:Y(SEL)
*        V:ELNGSL(SEL)         I:PD("NGSL")          PROD:KP(SEL)

Parameter
        GSL_CHNG(SGSL)             change in % of gasoline output quantity times emissions factor
        ELE_CHNG(SEL)              change in % of non-gasoline petro demand by power sector times emissions factor
        JET_CHNG                   change in % of non-gasoline petro fuel (jet)demand by air transp sector times
emissions factor
**this is to avoid double-counting of NGSL demand change
        IND_NGSL_CHNG              change in % of non-gasoline fuel demand by sectors excluding GSL ELE AIR
times emissions factor
        FDM_NGSL_CHNG              change in % of non-gasoline fuel demand by DEMCOL* emissions factor
        ETHN_CHNG                  change in % of ethanol fuel demand
*COAl and GAS are added in april 22, 2013
        COAL_CHNG                  change in % of coal demanded in non-power sector
        GAS_CHNG                   change in % of natural gas demanded
        GSL_BTU                    benchmark gasoline consumption (trillion btu)
        ELE_BTU                    benchmark non-gasoline petro fuel consumption by power sector (trillion btu)
        AIR_BTU                    benchmark non-gasoline petro (jet) fuel consumption by air sector (trillion btu)
        NGSL_BTU                   benchmark non-gasoline petro by sectors excluding GSL ELE AIR (trillion btu)
        ETHN_BTU                   benchmark ethanol consumption (in trillion btu)
        COAL_BTU                   benchmark coal non-electricty coal consumption (in trillion btu)
        GAS_BTU                    benchmark natural gas consumption (in trillion btu)
        GSL_EMSN_FCTR              gasoline GHG emission factor (g prt btu)
        ELE_EMSN_FCTR              power sector petro fuel GHG emission factor (g prt btu)
        AIR_EMSN_FCTR              jet fuel GHG emission factor (g prt btu)
        NGSL_EMSN_FCTR             non-power sector petro fuel GHG emission factor (g prt btu)
        IMP_ETHN_EMSN_FCTR         imported ethanol GHG emission factor
        LCL_ETHN_EMSN_FCTR         domestic ethanol GHG emission factor
        COAL_EMSN_FCTR             coal emissions factor
        GAS_EMSN_FCTR              natural gas emissions factor
        GSL_GHG(SGSL)              change in GHG emission (tonneCO2e) due to gasoline demand
```

```
        ELE_GHG(SEL)              change in GHG emission (tonneCO2e) due to electricity foss fuel demand
        JET_GHG                   change in GHG emission (tonneCO2e) due to jet fuel demand
        NGSL_GHG                  change in GHG emission (tonneCO2e) due to other non-gasoline petro demand
        ETHN_GHG                  change in GHG emission (tonneCO2e) due to ethanol demand
        ETHN_DIFF                 difference in emission between imported and domestic ethanol
        GSL_DIFF                  difference in emission between gasoline and domestic ethanol
        COAL_GHG                  change in GHG emission (tonneCO2e) due to non-power coal demand
        GAS_GHG                   change in GHG emission (tonneCO2e) due to natural gas demand
        TOTAL_GHG                 total change in GHG emission (tonne CO2e)
        TOTAL_GHG_PCTG            total change in GHG emissions %
        GHG(*,T)                  reporting parameter;
*initial energy demand is taken from EIA database for 2007
*emission factors are from GREET 2012
        GSL_BTU = 58.8           ;
*this is excluding coal
*        ELE_BTU = 85.3           ;
*this is including coal
        ELE_BTU = 102.5          ;
        AIR_BTU = 72.3           ;
        NGSL_BTU= 73.0            ;
        ETHN_BTU= 3.67            ;
        COAL_BTU= 1.8             ;
        GAS_BTU=0.2              ;

  GSL_EMSN_FCTR=0.093774104       ;
        ELE_EMSN_FCTR=0.099453986;
        AIR_EMSN_FCTR=0.097046379       ;
        NGSL_EMSN_FCTR=0.095927509     ;
       IMP_ETHN_EMSN_FCTR=   0.056810853 ;
* switchgrass GREET
       LCL_ETHN_EMSN_FCTR= 0.033374219;
       COAL_EMSN_FCTR=0.1056008;
       GAS_EMSN_FCTR=0.0785981;
       ETHN_DIFF= LCL_ETHN_EMSN_FCTR-IMP_ETHN_EMSN_FCTR;
       GSL_DIFF= LCL_ETHN_EMSN_FCTR-GSL_EMSN_FCTR;
       GSL_CHNG(SGSL)=(Y.L(SGSL)-1);
       ETHN_CHNG =(BIO.L$LOCALbio);
       COAL_CHNG=(Y.L("OMN")-1);
       GAS_CHNG=(Y.L("GAS")-1);
*        ELE_CHNG(SEL) = (ELNGSL.L(SEL)-NGSL0("ELE"))/NGSL0("ELE") ;
       ELE_CHNG(SEL) = 0.16*((INTER.L("OMN","ELE")-
IO0("OMN","ELE"))/IO0("OMN","ELE"))+0.84*((ELNGSL.L(SEL)-NGSL0("ELE"))/NGSL0("ELE")) ;
       JET_CHNG =(SNE_NGSL.L("AIR")-NGSL0("AIR"))/NGSL0("AIR");
       IND_NGSL_CHNG =(SNE_NGSL.L("SUG")+SNE_NGSL.L("VEG")+SNE_NGSL.L("ORC")+
       SNE_NGSL.L("PNA")+SNE_NGSL.L("FLW")+SNE_NGSL.L("OTH")+SNE_NGSL.L("ANM")+
       SNE_NGSL.L("FRT")+SNE_NGSL.L("AGS")+SNE_NGSL.L("CON")+SNE_NGSL.L("OMN")+
       SNE_NGSL.L("AQU")+SNE_NGSL.L("WTR")+SNE_NGSL.L("TRN")+SNE_NGSL.L("RTL")+
       SNE_NGSL.L("RTS")+SNE_NGSL.L("REA")+SNE_NGSL.L("GAS")+SNE_NGSL.L("OSV")+
       SNE_NGSL.L("FGT")+SNE_NGSL.L("SGT")+PET_NGSL.L("NGSL")
       - NGSL0("SUG")- NGSL0("VEG")- NGSL0("ORC")- NGSL0("PNA")- NGSL0("FLW")-
       NGSL0("OTH")- NGSL0("ANM")- NGSL0("FRT")- NGSL0("AGS")- NGSL0("CON")-
       NGSL0("OMN")- NGSL0("AQU")- NGSL0("WTR")- NGSL0("TRN")- NGSL0("RTL")-
       NGSL0("RTS")- NGSL0("REA")- NGSL0("GAS")- NGSL0("OSV")-
       NGSL0("FGT")- NGSL0("SGT")- NGSL0("NGSL"))
       /
       (NGSL0("SUG")+ NGSL0("VEG")+ NGSL0("ORC")+ NGSL0("PNA")+ NGSL0("FLW")+
```

```
        NGSL0("OTH")+ NGSL0("ANM")+ NGSL0("FRT")+ NGSL0("AGS")+ NGSL0("CON")+
        NGSL0("OMN")+ NGSL0("AQU")+ NGSL0("WTR")+ NGSL0("TRN")+ NGSL0("RTL")+
        NGSL0("RTS")+ NGSL0("REA")+ NGSL0("GAS")+ NGSL0("OSV")+
        NGSL0("FGT")+ NGSL0("SGT")+ NGSL0("NGSL"));
        FDM_NGSL_CHNG=
(CDP.L+VDD.L("NGSL")+GDD.L("NGSL")+FGDD.L("NGSL")+INDD.L("NGSL")+EXD.L("NGSL")-
        sum(DEMCOL,NGSLDM0(DEMCOL)))/ sum(DEMCOL,NGSLDM0(DEMCOL));

         GSL_GHG (SGSL)= GSL_CHNG(SGSL)*GSL_BTU*GSL_EMSN_FCTR*1000000000000/1000000;
         ELE_GHG (SEL)=  ELE_CHNG(SEL) *ELE_BTU*ELE_EMSN_FCTR*1000000000000/1000000;
         JET_GHG =AIR_BTU*JET_CHNG*AIR_EMSN_FCTR*1000000000000/1000000;
*weighted average of industrial and democol demand for NSGL
         NGSL_GHG
=(IND_NGSL_CHNG*1100/1816+FDM_NGSL_CHNG*716/1816)*NGSL_BTU*NGSL_EMSN_FCTR*10000000
00000/1000000;             ;
         ETHN_GHG =((ETHN_CHNG* ETHN_BTU*ETHN_DIFF)-(ETHN_CHNG*
ETHN_BTU*ETHN_DIFF)*0.15$MNDT+(ETHN_CHNG*
ETHN_BTU*ETHN_DIFF)$MNDT_2)*1000000000000/1000000;
         COAL_GHG =  COAL_CHNG*COAL_BTU*COAL_EMSN_FCTR*1000000000000/1000000 ;
         GAS_GHG =   GAS_CHNG*GAS_BTU*GAS_EMSN_FCTR*1000000000000/1000000;
         TOTAL_GHG = (sum(SGSL,GSL_GHG (SGSL))+sum(SEL, ELE_GHG (SEL))+JET_GHG+NGSL_GHG+
ETHN_GHG +COAL_GHG+GAS_GHG) ;
         TOTAL_GHG_PCTG=
TOTAL_GHG/((GSL_BTU*GSL_EMSN_FCTR+ELE_BTU*ELE_EMSN_FCTR+AIR_BTU*AIR_EMSN_FCTR+

NGSL_BTU*NGSL_EMSN_FCTR+ETHN_BTU*IMP_ETHN_EMSN_FCTR+COAL_BTU*COAL_EMSN_FCTR
+GAS_BTU*GAS_EMSN_FCTR)*1000000000000/1000000)*100;
*         TOTAL_GHG = (sum(SGSL,GSL_GHG (SGSL))+ ETHN_GHG) ;
*        TOTAL_GHG_PCTG=
TOTAL_GHG/((GSL_BTU*GSL_EMSN_FCTR+ETHN_BTU*IMP_ETHN_EMSN_FCTR)*1000000000000/10000
00)*100;

         GHG("TOTAL","2007")= TOTAL_GHG;
         GHG("TOTAL_PCTG","2007")=TOTAL_GHG_PCTG;
         GHG("ETHN","2007")= ETHN_GHG;
         GHG("GSL","2007")=sum(SGSL,GSL_GHG (SGSL));
         GHG("ELE","2007")=sum(SEL,ELE_GHG (SEL));
         GHG("JET","2007")=JET_GHG;
         GHG("NGSL","2007")=NGSL_GHG;
         GHG("COAL","2007")=COAL_GHG;
        GHG("GAS","2007")=GAS_GHG;
```

5. CHAPTER 5 CONCLUSION

This dissertation evaluated geospatial, environmental and economic impacts of lignocellulosic bioethanol production in the State of Hawai‘i through a series of three essays. The cross-disciplinary modelling exercise highlighted some of the important opportunities and concerns regarding this particular conversion platform and more generally regarding biofuels development in the state.

5.1 Major findings of this dissertation

One of the important findings highlighted in the study is that it is possible that the local production of banagrass-derived ethanol to meet the 20% AFS mandate could be technically and economically feasible, though these results should be interpreted with caution. Local biofuel production could be viable assuming that biochemical conversion technologies for lignocellulosic ethanol demonstrated at the bench scale and feedstock production demonstrated at field trials could be replicated at the commercial scale. Geospatial analysis in Chapter 2 demonstrated that the island of Hawai‘i alone offers enough fallow land area to support banagrass production of 1,040,325 dry tons/yr dry, sufficient to meet 20% of the State’s gasoline demand in 2010. Under the optimal supply chain configuration, per gallon cost of ethanol is estimated to range from $2.12 to $4.69 (for the 20% island scenario) and from $2.15 to $4.34 (from the 20% of state scenario) based on the Monte-Carlo simulations. Assuming that ethanol produced on the island of Hawai‘i is transported to the island of Oahu, per gallon cost of ethanol would be around $2.22 to $4.41 (for 20% of state’s scenario). Using the general equilibrium framework, Chapter 4 also demonstrated that the use of produced lignocellulosic leads to a small increase in real GSP under the federal tax credit of $1.01/gallon and a decline under the mandate only and mandate plus subsidy (financed through gasoline tax) cases. While consumer welfare was estimated to decline in all scenarios, the potential benefit of this locally produced alternative fuel should be carefully examined vis-à-vis the cost of supporting such an industry.

Another important finding of this study is that environmental benefits in the form of GHG emissions achieved through locally produced lignocellulosic ethanol might be limited, based on the current conversion technologies. This is due to two main reasons. First, as Chapter 3 demonstrated, the life-cycle GHG emissions of banagrass-derived ethanol estimated through technoeconomic analysis and bench scale data, is only slightly lower than conventional gasoline. Given the need for energy-intensive inputs such as enzymes and other chemicals, these hamper the GHG reduction potential of lignocellulosic ethanol. Unless further improvements in production technologies of these energy-intensive inputs are achieved, lignocellulosic ethanol will achieve little improvement compared to those of fossil fuel alternatives. Second, since the State of Hawai‘i currently consumes some 74% of its ethanol needs by importing sugarcane-based ethanol from Caribbean countries, GHG emissions reduction potential as compared to these ethanol options are further reduced. While biofuels policy in general is partially promoted on the grounds of GHG emissions reduction potential, this dissertation finds that such a claim may be unwarranted or at least should be viewed with caution, since the life-cycle GHG emissions potential of lignocellulosic ethanol appears small with the current level of technologies demonstrated at the bench scale.

This study also highlighted concerns regarding local biofuels production, some of which could be particularly challenging to those communities that host the local biofuels industry. First, as demonstrated in Chapter 2, logistical arrangements could pose problems when the most fertile – hence economic – patches of land are available around the edge of the island, and feedstock must be transported to processing sites. An increase in noise, air, and other pollution that may result from increased traffic could pose a challenge. Also, while building a plant within a contiguous patch of land may come at a cost of reduced land productivity. As demonstrated in Chapter 3, however, the choice of logistic arrangement will unlikely affect the overall GHG intensity of biofuels in any significant way, since emissions related to the transporting of biomass and fuel are limited compared to feedstock production and conversion.

Second, finding sufficient labor force to support the local ethanol industry could pose a challenge. As shown in Chapter 4, the lignocellulosic ethanol industry based on banagrass production will require an increase of approximately 1,600 workers consisting of 300 in processing and 1,300 in banagrass production, while other sectors will experience contraction in labor. While more detailed evaluation of in-and-out migration would be necessary to examine the full impacts on labor sector, a cursory evaluation based on the CGE model in Chapter 4 illustrates how attracting skilled labor with the necessary knowledge of feedstock production and conversion at a particular site may be difficult. In general, it is preferable that both feedstock production and conversion take place at a location sufficiently far from residential centers (Chapter2), and where they have sufficient land area. However, such needs must also be weighted with the potential to a recruit sufficient labor force, and for this, aspects such as community acceptance become important.

Third, while there is sufficient fallow land to support the 20% AFS mandate (Chapter 3), this does not guarantee that banagrass-derived ethanol will not compete for land currently under use by the existing agricultural sector, livestock production in particular. Incidents of land use competition could rise, especially in the short run. Before sufficient investment stimulates land preparation of existing fallow land, it is likely that active land may be diverted to biofuel production, crowding out other agricultural uses. The sector likely to be impacted first would be livestock production, since feedstock production occur in areas with low rents, which require little prior investment. As Chapter 4 demonstrated, direct competition of pasture land could increase rents by approximately 44.0% (the 10% mandate) and 152.9 % (the 20% mandate). While an appreciation of land value will benefit landowners, users will be adversely impacted. Livestock commodity prices could increase while output may contract.

Fourth, sensitivity analyses conducted in Chapters 3, 4 and 5 have shown that the range of uncertainties regarding economic and GHG impacts of the banagrass-derived bioethanol option is fairly high. This makes it difficult to provide a long-term view on banagrass lignocellulosic ethanol option. Sources of uncertainty stem from a number of factors. In the case of life-cycle GHG emissions, the primary source of uncertainty includes emissions intensity and efficiency of commercial enzymes, which are still under research and development. It remains uncertain as to how future improvement in the form of genetic modification of enzyme strains and further options would play out in lower emissions intensity and economic cost. Given the enzymes account for a large portion of GHG emissions and overall cost, this contributes to range of uncertainty in both GHG emissions and economic prospects of lignocelluloisc ethanol. In terms of economics, whether or not the banagrass ethanol option will be competitive against conventional ethanol and gasoline hinges on a number of factors, including future prices of gasoline and conventional ethanol, cost of inputs, availability of economic incentives and other policy instruments such as carbon pricing.

5.2 Further studies

Land suitability, GHG emissions and economy-wide impacts are important aspects for any evaluation of biofuels production, howe5.ver, there are a number of other concerns that should be addressed in providing a more comprehensive assessment of biofuels development in general, and banagrass-derived ethanol in particular. For a comprehensive study of biofuels option in Hawaiʻi, the following areas deserve further studies:

First, a more systematic analysis of alternate biofuel platforms would be helpful in defining future direction of alternative fuels development. While a comprehensive study in the form of the bioenergy master plan has been conducted within the State (DBEDT 2009), such an effort is yet to result in a census as to which biofuels platform would bring the optimal benefit. At the time of writing, there is competition between thermochemical and biochemical conversion as well as algal biofuel technologies, among feedstocks of banagrass, eucalyptus, and lucaena, potential uses in aviation, transportation and power sectors. All of these platforms are at varying stages of research and development. Given the limited financial and natural resources available locally, it is clear that not all options can be pursued simultaneously. Hence, systematic examination of these alternative biofuels options would be useful. Analytical tools such as the combined GIS and mixed integer linear programming framework developed in Chapter 2 could be used. In evaluating these options, development of alternative scenarios could be important, given the wide range of technological and economic uncertainty.

Second, a more community-level and site-specific evaluation could be useful in understanding the on-the-ground barriers and risks as well as opportunities for local biofuels development. As Chapter 4 has illustrated, while the economy-wide impacts of lignocellulosic ethanol is small, site-specific impacts could be significant in terms of labor supply, land use change, and other environmental impacts including air, water and noise pollution. Also, as banagrass is considered a non-native species, one must evaluate its impact on surrounding ecosystems. Such an evaluation will inherently be location-specific since how an introduction of a particular species may impact the environment depends in many ways on the composition and state of the surrounding environment itself. It is desirable that such an evaluation be done in a participatory manner, engaging a range of stakeholders, so as to foster the mutual understanding of science and on-the-ground reality.

Third, further studies regarding financial and policy barriers and enablers of advanced biofuels investment would also be helpful. Given a number of private sector investments in a range of advanced fuel options are taking place in Hawai‘i, it would be useful to evaluate factors that drive and/or hinder investment in this field. As the technoeconomic evaluation used in this study has demonstrated, advanced biofuel production in general is highly capital intensive, making initial barriers for investment high. Particularly in the presence of high policy and economic uncertainty, few investors are willing to take the risks of being the pioneers. Thus, studies evaluating investor perception toward a range of biofuels options and other policy incentives could be useful. Such a study may provide a reference as to how Hawai‘i might prioritize its focus within the portfolio of possible advanced biofuels options and to provide the links between policy, private sector and academic communities.

Fourth, given the likely competition of resources between the biofuels and local livestock industry, further studies should evaluate the potential ways in which these industrial activities may be integrated. Industrial symbiosis in the form of shared feed (i.e.banagrass and/or protein-rich fungal co-product), waste/energy (i.e. animal manure) between local biofuel and animal feed production could reap favourable environmental and economic benefits locally. Further studies evaluating the technical and economic feasibility of such options could be helpful.

Finally, all of the evaluations presented in this dissertation provide but a ‘snapshot’ of this advanced biofuels option. Given that biochemical conversion technologies of lignocellulosic ethanol is at the lab or initial demonstration stage, and ongoing technical improvements are taking place, environmental and economic assessment must be updated to reflect future technological improvements.

Reference

DBEDT (2009) *Hawai‘i Bioenergy Master Plan.* Available at: http://www.Hawai‘ienergypolicy.Hawai‘i.edu/EnergyBriefings/BioenergyMP09/BioenergyMP.pdf. [03.31.2013]

APPENDIX 5.1: TECHNOECONOMIC MODEL DESCRIPTION

Technoeconomic Model Development

For all three essays, a technoeconomic model provides an important input. This appendix explains the basic structure of the model and assumptions used in the study. The basic technoeconomic model of lignocellulosic bioethanol is taken from Kumar and Murthy (2011), using Super Pro Designer (Intelligen, Inc., Scotch Plains, NJ), which converts tall fescue to ethanol using dilute-acid pretreatment and saccharification and cofermentation (SSCoF). The model has a capacity of 704.5 dry metric ton of biomass per day.[40] The model follows the current state-of-the art lignocellulosic ethanol production process and encompass six major production sections: 1) biomass handling and storage, 2) pretreatment, 3) simultaneous saccharification and co-fermentation (SSCoF), 4) distillation and recovery, 5) waste water treatment, and 6) co-product generation. It consists of 37 major process units (equipment).

Following exiting technoeconomic modeling studies, this dissertation adopts an assumption of a 'nth plant design'— i.e. all technologies in this process have already been used at the commercial scale and that a plant does not incur additional cost inherent to a 'pioneering plant.' This assumption, while adopted widely, is not an accurate reflection of the current lignocellulosic ethanol production technologies. In practice, many of the technologies described in this model have only been demonstrated at the bench or pilot scales, and that commercialization of such technologies will likely involve significant barriers. Furthermore, many of the start-up production facilities will likely adopt scales that are significantly smaller than what is adopted in this study, which will likely increase production costs. While a detailed estimation of a pioneering plant cost deserves additional analysis, it is often concluded that production cost of a pioneering plant is significantly higher than that of a n-th plant. For example, Kazi et al. (2010) estimates that unit ethanol production cost is 69% more than that of a nth plant design, using acid dilute pretreatment and separate hydrolysis and fermentation and corn stover as the feedstock.

In addition, it is important to note that the accuracy of common technoeconomic model should be distinguished with that of detailed engineering studies conducted for financing and budgetary purposes by a plant owner. The common technoloeconomic model including the one adopted for this study are so-called 'factored estimates' which is considered accurate up to 30% (i.e. error might be as high as 30%), and used to assess the economic feasibility of the chosen technology. This contrasts with an economic estimation made for procurement and construction purposes, which demands up to 10% accuracy (Petrides 2000; Kumar and Murthy 2011), and used to budget an actual plant construction.

The following section describes other key assumptions adopted for this study.

Key Assumptions:

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[40] With 5 % trash and 7% moisture content for the base case.

a. Pretreatment condition

This study assumes that pretreatment—the first step in conversion of banagrass to ethanol— takes place using the dilute acid retreatment technology. For chapters 2 and 4, he conditions for pretreatment are taken directly from Kumar and Murthy (2011), based on Tall Fescue experimental data. For chapter 3, updated information based on banagrass pretreatment was used. As table 5.1 shows, pretreatment takes place in high temperature and high pressure conditions, in which the weak acid condition breaks the crystallinity of cellulose and enhance solubility of hemicellulose. The formation of fermentation inhibitors is a well-known issue in dilute acid pretreatment, and this study assume that xylose and glucose forms furfural and HMF respectively at a rate of 5%.

Table 5-1: Dilute Acid Pretreatment Condition used in chapters 2 and 4.

		Conditions
Pretreatment	Temperature	180 c
	Pressure	11 bar
	Residence time	15 min
	Solid Loading	20%
	Acid Concentration	1%
	Cellulose +0.111 H_2O= 1.111 Glucose	13.04%
	Hemicellulose + 0.136 H_2O=1.136 Xylose	60.26%
	Lignin -> Soluble lignin	5%
	Xylose->0.64 Furfural + 0.36 H_2O	5%
	Glucose -> 0.7 HMF+0.3 H_2O	5%

c. SSCoF conditions

Following dilute acid pretreatment, the plant uses SSCoF technology to hydrolyze and ferment sugars. The assumptions for SSCoF conditions are also taken directly from Kumar and Murthy (2011).

Table 5-2: SSCoF conditions used in chapters 2 and 4

SSCoF	Temperature	35 C
	Enzyme Loading	15g
	Time	5 days
	Cellulose +0.111 H_2O= 1.111 Glucose	79%
	Hemicellulose + 0.136 H_2O=1.136 Xylose	80%
	Glucose->0.489 CO_2+0.511 Ethanol	95%
	Xylose->0.489 CO_2 + 0.511 Ethanol	70%

b. Waste power generation

Power generation from lignin rich waste steam is an important element affecting the energy use and economic cost of lignocellulosic ethanol production. For this study, it is assumed that lignin rich waste stream and biogas generated from anaerobic digestion will be used to produce steam/HP steam and electricity used in the processing plant. Based on Kumar and Murthy (2011), methane is produced from a waste water stream (at a rate of 0.239 kg /kg of COD removal), along with carbon dioxide. These gases are then fed to a fluidized bed reactor, followed by power generation. The amount of power generated is calculated based on heating value of waste stream components, assuming 30% efficiency in power generation.

c. Economic Parameters

Capital cost is a significant component of any lignocellulosic bioethanol projects. Thus, credible data and appropriate assumptions are important in performing reliable economic analysis. Major assumptions regarding economic parameters are as follows.

Table 5-3: Key Financial Variables Used in the Study

Year of Analysis	2011
Project life	27 years
Depreciation	10 years
Equity/Debt Ratio	100% equity financing
Discount Rate	4%
Construction Period	Starts in 2011 for 24 month
DFC outlay	30%(1st year) 40%(2nd year) 30%(3rd year)
Salvage value	5%
Income tax	40%

To ensure that the assessment reflects the likely operational condition in Hawaiʻi, this study made the following assumptions and adjustments. First, the utility cost was adjusted upward including electricity price of 28.9 cents/kwh (estimated based on HELCO, 2012). The price of water is $1.6/ ton (estimated based on Hawaiʻi Department of Water Supply 2012). Waste water treatment fee is assumed as $21.19/1,000 gallons (estimated based on Hawaiʻi County 2012). Second, operator wage was adjusted based on May 2011 State Occupational Employment and Wage Estimates published by the U.S. Bureau of Labor Statistics. Finally, the additional cost of equipment shipping to Hawaiʻi was estimated to be on average around 1-2% of direct capital cost using vendor quotes and other information. Since this result was small compared to the error range inherent this type of estimate (i.e. around 30%), it was determined that difference in freight cost will make negligible impact on overall cost estimates, thus no adjustment was made in this regard. Finally, the feedstock price was taken from Black and Veatch (2010), which was adjusted as to 2011 price.

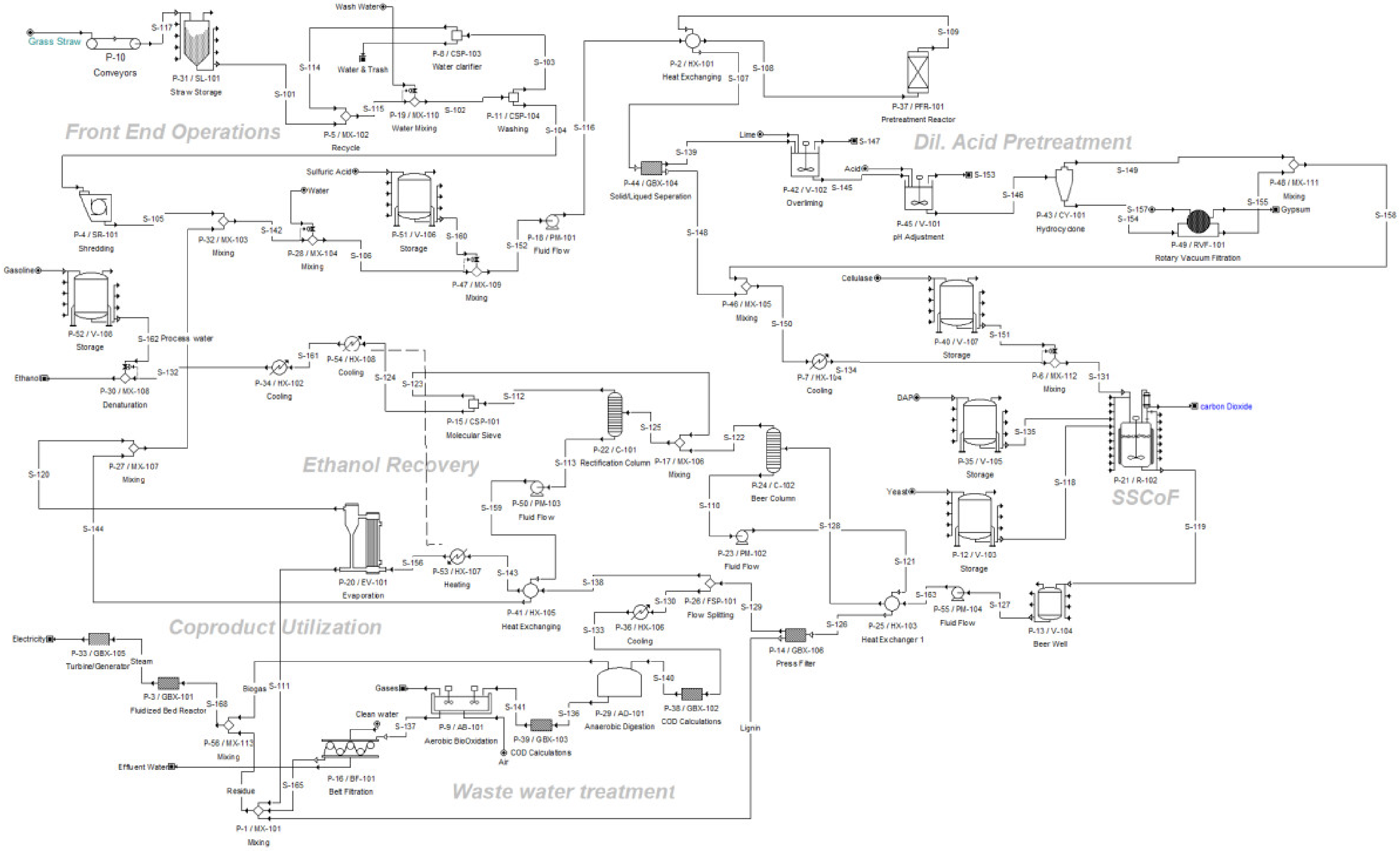

Figure 5-1: Technoeconomic Model of Lignocellulosic Bioethanol Production using Dilute Acid Pretreatment (Kumar and Murthy 2011)