ESSAYS ON ECONOMIC AND ENVIRONMENTAL ANALYSIS OF TAIWANESE BIOENERGY PRODUCTION ON SET-ASIDE LAND

A Dissertation

by

CHIH-CHUN KUNG

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2010

Major Subject: Agricultural Economics

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ABSTRACT

Essays on Economic and Environmental Analysis of Taiwanese Bioenergy Production on Set-Aside Land. (December 2010)

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Domestic production of bioenergy by utilizing set-aside land in Taiwan can reduce Taiwan's reliance on expensive and politically insecure foreign fossil fuels while also reducing the combustion of fossil fuels, which emit substantial amounts of greenhouse gases. After joining the World Trade Organization, Taiwan's agricultural sector idled about one-third of the national cropland, hereafter called "set-aside land". This potentially provides the land base for Taiwan to develop a bioenergy industry. This dissertation examines Taiwan's potential for bioenergy production using feedstocks grown on set-aside land and discusses the consequent effects on Taiwan's energy security plus benefits and greenhouse gas (GHG) emissions.

The Taiwan Agricultural Sector Model (TASM) was used to simulate different agricultural policies related to bioenergy production. To do this simulation the TASM model was extended to include additional bioenergy production possibilities and GHG accounting. We find that Taiwan's bioenergy production portfolio depends on prices of ethanol, electricity and GHG. When GHG prices go up, ethanol production decreases and electricity production increases because of the relatively stronger GHG offset power of biopower.

Results from this pyrolysis study are then incorporated into the TASM model. Biochar from pyrolysis can be used in two ways: burn it or use it as a soil amendment. Considering both of these different uses of biochar, we examine bioenergy production and GHG offset to see to what extent Taiwan gets energy security benefits from the pyrolysis technology and how it contributes to climate change mitigation. Furthermore, by examining ethanol, electricity and pyrolysis together in the same framework, we are able to see how they affect each other under different GHG prices, coal prices and ethanol prices. Results show that ethanol is driven out by pyrolysis-based electricity when GHG price is high. We also find that when biochar is hauled back to the rice fields, GHG emission reduction is higher than that when biochar is burned for electricity; however, national electricity production is consequently higher when biochar is burned.

DEDICATION

To my family

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Bruce A. McCarl, for the opportunities he has provided me and for his guidance since Fall 2006. I deeply appreciate his patience, encouragement, and help when I felt frustrated and depressed. It is really my pleasure to be his student.

I would also like to thank my committee members, Dr. James W. Richardson, Dr. Dmitry V. Vedenov and Dr. Mahmoud El-Halwagi, for their help and guidance. Thanks also to Dr. Chen Chi-Chung, Dr. Amy D. Hagerman and Dr. Jerry Cornforth, for their valuable opinions and help during the modeling process. I also like to thank all of the professors and support staffs in our agricultural economics department who have made my entire graduate experience excellent.

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1. INTRODUCTION

Currently Taiwan imports 99.3% of its fossil fuel consumption. This makes Taiwan vulnerable to international market volatility; consequently energy security is a national concern. Bioenergy, derived from biomass, is one option among renewable energy alternatives. Producing bioenergy reduces the reliance on imported energy and increases energy security while it also reduces net GHG emission. Biomass provides a renewable energy. Annual crops, wood and agricultural and forestry residues are some of the possible feedstocks for renewable energy production. Typically, bioenergy has three forms: bioethanol, biodiesel and bioelectricity.

However, feedstock production requires land. After Taiwan joined the World Trade Organization (WTO), about one-third of agricultural land was idled, and this provides land for potential bioenergy feedstock production. Although there have been intensive studies on bioenergy in the United States and Europe, limited information is available in Taiwan. As Taiwan is interested in producing bioenergy in order to increase energy security and make some contribution on climate change mitigation, more bioenergy information that is related to local conditions is needed for Taiwan to determine feasible associated policies.

This dissertation follows the style of the *American Journal of Agricultural Economics.*

Food/ energy competition is another concern facing bioenergy, especially for the world's poor given the change in food prices. Generally, the rise in commodity prices will lead to an increase in prices for food commodities. Because the price increase has been simultaneous with the boom in bioenergy, bioenergy has been blamed. However, if crop residues can be effectively turned into cellulosic ethanol, competition between food and energy may be small because some forms of bioenergy come from feedstocks that are complement rather than a substitute.

Bioenergy also contributes to climate change mitigation, a challenge facing the world. The effects of climate change may be physical, ecological, social and economic. According to IPCC (2007), evidence of climate change is presented in the instrumental temperature record, rising sea level, and decreased snow cover in the Northern hemisphere. The IPCC report also indicates that climate change since the mid-20th century is "very likely" due to the observed increase in human greenhouse gas emissions and the resultant rise in atmospheric concentrations. Among all GHG emissions, CO_2 is the largest and mainly comes from the use of fossil fuels. Namely renewable fuels have the potential to reduce the GHG emission when gasoline, diesel or coal fired electricity is replaced. McCarl (2008) shows that 30.5% of GHG emission reduction can be achieved by using corn-based ethanol and 100% of GHG emission is offset when lignin is used to generate electricity with other possibilities on the continuum between.

Bioenergy can be produced by pyrolysis. Pyrolysis is a process by which biomass is heated in the absence of oxygen and consequently decomposed to bio-oil, bio-gas and biochar. Bio-oil can be cleaned and processed to produce higher-quality fuels (Czernik and Bridgwater, 2004), used to produce electricity, and refined to produce chemical feedstocks such as resins and slow-release fertilizers. While biochar was initially viewed as a source of energy for plant operation, there is increasing interest in its use as a soil amendment (Lehmann et al., 2003). In particular biochar can alter soil conditions in terms of available soil moisture for plant growth, moisture storage capacity and fertility, all of which are keys to crop production.

Studies show that biochar can improve the quality of soil by retaining nutrients, storing more water and storing carbon in a more stable form (Lehmann et al., 2003; Chan et al., 2007). These properties have the potential to increase crop yields and mitigate climate change. Crop yield increases are found by several experiments (Iswaran et al., 1980; Chidumayo, 1994; Glaser et al., 2002; Steiner et al., 2007; Chan et al., 2007). Lehmann (2007) shows that biochar is potentially carbon negative. Pyrolysis reduces the CO_2 concentration by absorbing carbon and containing it in the form of biochar.

1.1. Dissertation Objectives and Procedures

The objective of this work is to provide information for Taiwan on the potential of bioenergy crop production on set aside land, bioenergy markets and GHG offset potential from bioenergy use. More operationally this work:

- Extends the Taiwan Agricultural Sector Model (Chen and Chang, 2005) by incorporating GHG and bioenergy production features and then uses the modified model to study bioenergy production combinations.
- Examines the economic and environmental effects of producing bioenergy by planting multiple bioenergy crops on set-aside land.

- Discusses GHG net emission mitigation and energy contribution for ethanol, biopower and pyrolysis.

This work will make two principal contributions. First it will provide information on bioenergy production in Taiwan where this information include estimates of optimal bioenergy feedstock crop selection, form and amount of energy production, GHG mitigation, and change in farmers' revenue and social welfare. Second it examines pyrolysis and biochar in a total sectoral context examining the enhancement on energy security and GHG emission reduction.

In order to meet the objective, this dissertation will:

- Implement TASM so it embodies an economic/environmental model that evaluates bioenergy production responses in terms of welfare, market and GHG effects.
- Adopt a similar approach to a chapter I coauthored by McCarl et al. (2009) to analyze the economic viability of poplar-based biochar production, utilization and GHG offset from pyrolysis.
- Incorporate the pyrolysis result into the TASM economic/environmental model to do a sector wide comparison of bioenergy production technologies and the role of pyrolysis versus ethanol versus direct biomass fired electricity.

1.2. Plan of Dissertation

This dissertation consists of three essays in addition to introductory and conclusion sections: Section 2 contains the first essay that examines the economic and environmental effects of producing bioenergy in the forms of ethanol and/or electricity using sweet potato, poplar, willow and switchgrass produced on current set-aside land in Taiwan. This section reviews the literature on bioenergy production, GHG effects and some bioenergy studies in Taiwan. This essay also explains the theoretical foundation of the modified economic and environmental model used and rice purchase programs implemented in Taiwan. Three coal prices, four ethanol prices and three CO_2 prices are examined to see how markets respond to these prices change.

Section 3 contains the second essay that studies the economics of biochar production, utilization and GHG effects under fast and slow pyrolysis using poplar as a case study. We examine the costs of pyrolysis plant construction, poplar planting and harvest, transportation of feedstocks to the pyrolysis plant, feedstock storage, transportation of biochar from the pyrolysis plant to the field, and biochar application. We also examine the economic benefits from selling energy produced from biooil and biogas, saving on soil nutrients and irrigation water usage, and increasing crop yields. Environmental effects in terms of GHG emission reduction is also examined through lifecycle analysis. Sensitivity analysis is provided that discusses the profitability for both fast and slow pyrolysis and their sensitivity to the change on GHG price, biochar price, energy price and other factors.

Section 4 is the third and final essay that examines Taiwan's bioenergy production potential across ethanol, biopower and pyrolysis. In this essay, pyrolysis competes with the more traditional energy forms and biochar is considered. Biochar is produced from both fast and slow pyrolysis and we examine two different usages of biochar: burning to provide electricity and hauling it back to the rice field for application as a soil amendment. Net bioenergy production and GHG emission reduction are estimated and discussed to provide additional information to Taiwan. Section 5 contains general summary and conclusions.

2. BIOENERGY PROSPECTS IN TAIWAN USING SET-ASIDE LAND: AN ECONOMIC EVALUATION

2.1. Introduction

Lack of energy security is a serious problem facing Taiwan. Very little fossil fuel stock is found in Taiwan and more than 99.3% of Taiwan's energy is imported. This indicates that Taiwan is vulnerable to high energy prices and market distortions in the world energy market. To enhance Taiwan's energy security, there is interest for the Taiwanese to produce energy on her own. Due to the previously mentioned lack of fossil fuel stock, focus has been placed on renewable energies. Renewable energy sources that can potentially substitute for fossil fuels include wind and solar energy, hydro-power, geothermal energy and bio-energy (Turner et al., 1993).

Geographically, Taiwan is small. Taiwan's land area is about 14,000 square miles with 2/3 of that land being mountainous. Thus, land is a scarce resource in Taiwan and has been intensively utilized in different ways. Due to the limited land availability, production of renewable energy in the form of hydro-power and solar energy are under discussion. However, as hydro-power and solar energy usually depend on the weather condition such as precipitation (and consequently river flow) and sunny days plus high costs, large scale development of these two kinds of renewable energy is still under debate. At the same time, a bioenergy industry has been developed and expanded in the United States; Taiwan is also interested in this technology that helps alleviate its lack of energy security. However, producing bioenergy requires substantial amounts of land.

After joining the World Trade Organization (WTO), part of Taiwan's agricultural land was idled, which creates a potential land source for bioenergy feedstock production. Bioenergy production is a strategy that is heavily related to the agricultural sector (McCarl and Schneider, 2003). Bioenergy could partially replace traditional energy sources such as gasoline, diesel and coal. During the 1970's energy crisis in the U.S., bioenergy was discussed as a traditional energy replacement but was not produced at a large scale. However, bioenergy interest has been greatly stimulated by the recent petroleum price increase (McCarl, 2008). In addition domestic energy production using renewable energy sources has a side benefit to the world: combating climate change. Climate change is an emerging challenge facing the world. According to the 2007 report by the Intergovernmental Panel on Climate Change, the Earth is warming due to anthropogenic (i.e. human centric) emissions of greenhouse gases (GHGs). Such warming would have consequences ranging from increased desertification, a rise in ocean level and possible increased occurrences of hurricanes. Among these GHGs, CO_2 is the largest GHG in terms of total emissions. The CO_2 largely comes from combustion of fossil fuels. For example, combusting a gallon of petroleum-derived diesel and gasoline generates approximately 22.384 and 19.564 pounds of CO_2 respectively (Energy Information Administration, 2005). In addition, fossil fuels are non-renewable energy sources, which mean natural stocks will be depleted in the future through use. Therefore, in order to avoid unwelcome climate impacts and have enough energy for the future, nations are looking for renewable or substitutes and likely renewable energy is needed.

Bioenergy production using crops produced on agricultural land can help mitigate climate change. Taiwan is trying to adopt bioenergy to both help increase national energy security and decrease net GHG emissions. Chen (1998) estimated that 1990 Taiwanese GHG emissions were 149 million metric tons (MMT) carbon equivalent (CE) and would increase to 443 MMT CE by 2006. Almost 83% of these emissions were in the form of carbon dioxide largely from fossil fuel combustion of coal and petroleum. This places Taiwan 24th among all countries. Therefore, Taiwan has substantial GHG emissions and could have an interest in reducing these emissions.

The objective of this paper is to analyze the economics of bioenergy production for Taiwan in terms of agricultural sector effects. This study makes a contribution because while the Taiwanese government is interested in producing bioenergy for domestic use, but information on the economic and environmental impacts on bioenergy production alternatives is limited. Currently research has only been done for bioethanol production from sweet potatoes (Chen et al., 2009), plus another study for sugarcane and sweet sorghum is in progress. However, besides sweet potato, sugarcane and sweet sorghum, there are other alternative energy crops that can be planted for ethanol production such as corn, poplar and willow. In addition, the country could produce feedstocks for electricity generation that have both relatively higher carbon offsets and replace expensive imported coal. Furthermore, Taiwan has a limited land base and the joint potential for feedstocks as energy sources need to be simultaneously considered with crop production as they compete for resources. Therefore, this thesis will do an economic analysis on the prospects for ethanol production and electricity generation using multiple competing crops.

2.2. Background on Taiwanese Agriculture and Energy

Taiwan's agricultural sector is very productive. Although only about one-quarter of the land base is arable, virtually all farmland is intensively cultivated, with some areas suitable for double or triple planting a year. However, increases in agricultural production have been much slower than industrial growth. Although self-sufficient in rice production, Taiwan imports large amounts of feedgrains such as wheat, mostly from the United States. Meat production and consumption are rising sharply, reflecting a rising standard of living. Taiwan exports large amounts of frozen pork. Other agricultural exports include tuna, processed eel, fresh and frozen vegetables, feathers, shrimp, canned vegetables, sugar, tea, and rice. When bioenergy is emphasized to mitigate climate change, Taiwan could reduce GHG emissions by producing bioenergy but has limited land available given its size and food needs. As discussed by Chen, land may be available following the 2002 entry into the World Trade Organization (WTO). Taiwan's newly opened rice market resulted in expanded imports, reduced domestic prices, lower direct farm income and resulted in substantial idling of cropland. The government subsequently revised the cropland set-aside program by raising the subsidies for idle rice paddy fields. Currently about 280,000 hectares or one third of total Taiwanese cropland area (830,000 hectares in total) is idled under this program compared to 68,000 hectares idled agricultural land in 2001. This provides a potential stock of land for bioenergy feedstock production. However, not all idled land is able to sustain bioenergy crops. This is because there are other existing policies that subsidize farmers to plant soybeans, sugarcane, black beans and others.

Taiwanese annual gasoline consumption is about 10 billion liters with 97% of the gasoline being imported. Coal is used in Taiwan for electric power generation, as well as for the steel, cement and petrochemical industries. Domestic coal production stopped in 2000, and Taiwan meets its 55.8 million short ton demand entirely with imports, mainly from Indonesia, Australia and China. Thus the basic nature of this essay is to investigate the potential replacement of these imported fossil fuels with domestic produced biomass for bioenergy production on set-aside land.

2.3. Literature Review

Increasing energy use, climate change, and carbon dioxide (CO_2) emissions from fossil fuels make switching to low-carbon fuels a high priority. In addition, exploring new energy sources that enhance energy security, diversity and sustainability is another interest. As bioenergy is one of the substitutes that meets domestic energy needs, it has been studied widely and actually produced in the United States and Europe. Some reports claim that we need to be careful to avoid unintended consequences of biofuels and that increased use of biofuels will actually increase carbon dioxide emissions because of deforestation and a sudden major shift in land use (Fargione et al., 2008; Searchinger et al., 2008) and Fargione et al. (2008) mentioned that whether biofuel production is a potential low-carbon energy source depends on how it is produced. Field and Campbell (2008) also pointed out that the net effect of biomass energy on climate could be either cooling or warming, depending on the crop, the technology for converting biomass into useable energy, the difference in carbon stocks and reflectance of solar radiation between the biomass crop and the pre-existing vegetation. However, these studies do highlight the need for a comprehensive analysis of the effects of biofuel production. Efforts on these analyses were undertaken. The Intergovernmental Panel on Climate Change will produce a comprehensive Special Report on the GHG Mitigation Potential of Renewable Energy and the USDOE (U.S. Department of Energy) is committed to study a comprehensive life-cycle analysis of large-volume production of biofuel. Biofuel technology is also evolving. Arvizu (2008) mentioned that there is potential for second-generation biofuels to reduce carbon emissions when compared to first-generation biofuels technologies. He said, however, the challenge to the U.S. in reducing dependence on foreign oil is too great to abandon first-generation technology for fear of unintended consequences. Instead, scientist must learn from comprehensive life-cycle analysis to avoid those consequences as the biofuels market evolves.

Campiche et al. (2010) also studied the long-run effects of falling cellulosic ethanol production costs on the U.S. agricultural sector of the economy. They show that cellulosic ethanol production increases by a substantial amount as conversion technology improves. Corn production also increases after the introduction of cellulosic technology because farmers receive revenues from selling corn stover. McCarl and Schneider (2000) also conducted an economic modeling study that evaluated agricultural feedstocks for energy in the context of carbon displacement potential. In addition, McCarl (2008) also shows that emission offset rates for electricity are more than that for ethanol because the feedstock is burned with little transformative energy needed once it is at the processing site. He also shows co-firing generally has a higher degree of offsets because hauling distances are shorter as lower feedstock volumes are required and because of the hotter burning caused by the presence of coal which increases feedstock heat recovery.

Bioenergy production in the United States is encouraged and the government pays a subsidy on it. US bioenergy subsidization of ethanol began with the 1978 Energy Policy Act, which intended to enhance farm income and, to a lesser extent, energy security. In 1990, ethanol received another stimulus with the passage of the Clean Air Act. Between 1983 and 2003 the ethanol subsidy varied between 40 and 60 cents per gallon and the current subsidy is 51 cents per gallon. In 2007, there were 128 ethanol plants with annual production capacity totaling 6.78 billion gallons and an addition 85 plants were under construction in the U.S.. For the first six months of 2007, U.S. ethanol production increased 750 million gallons (with a yearly total of nearly 3 billion gallons) than the same period in 2006 (USDA, 2007). Another project was conducted by Daniel et al. (2007), which showed that if 10 billion gallons of ethanol are produced in 2010, 30 billion gallons in 2020 and 60 billion gallons in 2030, the cumulative displacement from 2007 to 2030 could be as high as 10.48 billion barrels of oil, causing a potential drop in import value of US$629 billion.

Taiwan is starting to examine the possibility of bioenergy production. Chen et al. (2009) investigated planting sweet potatoes on set-aside land where crop production is used for ethanol production and found that Taiwan could produce 300 million liters of ethanol while increasing agricultural social welfare and also reducing CO2 emissions by 75,390 metric tons. The Taiwan Institute of Economic Research (TIER) also suggests that Taiwan has the potential to improve current energy reliance by producing bioethanol using multiple crops. Their study showed sweet sorghum, sugarcane and sweet potato are potential energy crops because of high conversion rates. In addition, due to the weather conditions in areas where there is set-aside land, many crops can be harvested 2 to 3 times a year, which provides enough crops to support plant operations. Tso and Su (2009) also examine the energy output/input ratio for different energy crops and the consequent environmental benefits in terms of GHG emissions.

They show that the energy output/input ratio of corn, sugarcane, and sweet sorghum by incorporating byproduct utilization is greater than one (between 1.04 and 1.55), indicating that the use of domestic alcohol material sources will not cause an additional increase in energy depletion. Specifically, the energy output/input ratio is the highest (1.55) for sugarcane, while the energy efficiency of sweet potato alcohol on a wet basis excluding byproduct utilization is the lowest (0.79). In terms of environmental benefits, sugarcane produced the best results in the use of domestic alcohol to reduce greenhouse gas emissions. By using sugarcane alcohol as a substitute for gasoline, every liter of sugarcane alcohol leads to the reduction of CO_2e (carbon dioxide equivalent) by 1.25 kilograms. Excluding byproduct utilization, the greenhouse gas emissions of sweet sorghum, corn, and wet sweet potato is greater than gasoline. Collectively these few studies provide limited information for the Taiwanese government to determine the subsidy implications of different program designs along with feedstock and energy type choices. This paper is intended to provide information to policy makers to aid in bioenergy related policy structure decisions.

2.4. Modeling Background

The agricultural sector is complex and highly interrelated. In this work, we will do a broad economic and GHG net emissions analysis of multiple energy crops for ethanol and electricity production from feedstocks produced on Taiwanese set-aside land. Therefore, it is necessary to address some features needed to reasonably assess the economic and GHGs implications. These features are:

- Multiple gases arising from agricultural activities,
- Interdependence between GHG mitigation activities,
- Market/welfare implications,

and the way that each of these issues is addressed in the modeling framework is briefly addressed below.

2.4.1. Multiple Gas Implications

Agricultural production generally emits three greenhouse gases: carbon dioxide (CO_2), methane (CH_4) and nitrous dioxide (N_2O). GHG mitigation options independently and jointly impact emissions of these GHGs. To compare the GHG implications on bioenergy feedstock production on set-aside land, we might need to consider all these gases and convert their environmental impacts into CO_2 equivalent using their 100 year global warming potentials (GWP). Table 1 shows their GWP using 2007 IPCC reports.

Table 1. Greenhouse Gas Warming Potential (GWP)

	Carbon Dioxide-CO_2	Methane-CH_4	Nitrous Dioxide-N_2O
GWP	1	21	296

Source: IPCC, 2007

2.4.2. GHG Mitigation Alternative Interrelatedness

Actions that influence, for example, the quantity of livestock produced also influence crop demand and land allocation, which in turn influence the carbon sequestered on crop lands, the nitrous oxide released when fertilizers are used and the methane emitted from livestock production. This interdependence needs to be accounted for in order to understand the full implications of any GHG mitigation strategy. We can use an example addressed by McCarl (2008) to understand more about this issue. At the simplest level, if wheat or corn land is converted to switchgrass or to a grass cover crop, then it is no longer available for converting to conservation tillage. This study utilizes an analytical approach following McCarl and Schneider (2000) that simultaneously depicts crop and livestock production, the feeding of crop products to livestock, grazing, product substitution, and competition for land, among other factors across the agricultural sector.

2.4.3. Market/Welfare Implications

Variation in Taiwanese production influences prices in domestic market and global commodity markets. Thus it is possible that Taiwan GHG mitigation policies will also affect domestic and world market prices along with the welfare of producers and consumers in those markets. The analytical approach used here includes a representation of domestic agricultural markets and their links to foreign markets following McCarl and Spreen (1980).

2.5. Model Structure

The model used herein is based on price endogenous mathematical programming, which is originally illustrated by Samuelson (1950). Samuelson showed the equilibrium in the perfect competition market can be derived from the optimization model that maximizes the consumer surplus and producer surplus. Following Samuelson (1950), Takayama and Judge (1971) established a mathematical programming model on spatial model based on Samuelson's idea. Duloy and Norton (1973) applied this model in agriculture and built a Mexican agricultural sector model. McCarl and Spreen (1980) pointed out that this model is useful in policy analysis, especially in its property of price endogeneity. In addition, McCarl and Spreen (1980) compared the linear programming models used by other planned economic systems to the price endogenous model, and the results showed that the price endogenous model can represent the economic system in a perfectly competitive market and thus, can be useful in policy analysis. In the late 1970s, price endogenous modeling began to be used for environmental and resource analysis, first on biofuels (Tyner, 1979), then on ozone (Hamilton et al., 1985), acid rain (Adams et al., 1992), soil conservation policy (Chang et al., 1992), global climate change (Adams et al., 1986, 1992, 1999; McCarl et al., 1999; Reilly et al., 2002), and climate change mitigation (Adams et al., 1993; McCarl and Schneider, 2000). It has also been used extensively for research evaluation (Coble et al., 1992; Chang et al., 1991).

To analyze the Taiwanese agricultural policy in terms of production and market issues, Chen and Chang (2005) developed the Taiwan Agricultural Sector Model (TASM). I extended TASM to evaluate the potential economic and GHG implications of bioenergy crop production plus competition with other land uses. The TASM is a multi-product partial equilibrium model based on the previous work of Burton and Martin (1987), McCarl and Spreen (1980), Chang et al. (1992), and Coble et al. (1992). This empirical structure has been adapted to Taiwan and used in many policy-related studies such as Chang (2002) and Chen and Chang (2005). The current version of TASM accommodates more than 110 commodities in 15 subregions aggregated into 4 major production and processing regions. TASM simulates market operations under assumptions of perfect competition with individual producers and consumers as price-taker. It also incorporates price-dependent product demand and input supply curves.

Basically, TASM includes 60 traditional crops, 5 floral crops, 7 livestock species, 3 types of forests (conifers, hardwoods, and bamboo), 27 secondary commodities (including 2 timber products: conifer-timber and hardwood-timber). The total value of these primary commodities accounts for more than 85 percent of Taiwan’s total agricultural product value. Sub-regional production activities are specified in the model for each commodity. Crop and livestock mix activities and constraints are also specified at the sub-regional level, but the input markets for cropland, pasture land, forest land, and farm labor are specified at the regional level.

Because our empirical model used in this study is derived from TASM. It is necessary to depict the TASM briefly. Suppose that there exist I agricultural crop commodities that are produced in K regions through production activities X_{ik} (for i = 1,2,…,I ; k = 1,2,…,K). Each activity depicts production on a per hectare basis. Now we can calculate total production by multiplying per hectare yields (Y_{ik}) by hectares produced (X_{ik}). For product demand, we then assume all commodities are sold in wholesale markets, and assume wholesale level demand functions can be represented by the following inverse demand functions:

(1) $$P_i^Q = \psi(Q_i) \qquad i = 1,2,...,I$$

where Q_i is the total quantity of consumption and P_i^Q is the average wholesale price of commodity *i*.

For input markets, we assume each production activity applies regional inputs (land, irrigation water, and labor) and *N* inputs purchased from the non-farm sector (such as fertilizer and chemicals). The prices of *N* purchased inputs are assumed exogenous. However, the prices of the regional inputs are endogenously determined by the derived demand from the production activities and regional supply functions. Assume regional supply functions for cropland and other resource are integral and of the form as follows:

(2a) $$P_k^L = \alpha_k(L_k)$$

(2b) $$P_k^R = \beta_k(R_k) \qquad k = 1,2,...,K$$

where P_k^L, P_k^R are cropland rent and the user prices of other resources respectively and L_k, R_k are the cropland and other resource quantities supplied respectively.

The objective function maximizes the sum of consumers' plus producers' surplus and simulates a perfectly competitive market equilibrium following Samuelson (1950) and Takayama and Judge (1971). It is defined as the area between the product demand and factor supply curves to the left of their intersection as follows:

$$(3) \quad Max: \sum_i \int \psi(Q_i)dQ_i - \sum_i \sum_k C_{ik} X_{ik} - \sum_k \int \alpha_k (L_k) dL_k - \sum_k \int \beta_k (R_k) dR_k - \sum_k \int \omega(\mathrm{Q_k}) dQ_k$$

The constraints are:

$$(4) \quad Q_i - \sum_k Y_{ik} X_{ik} \leq 0 \qquad \text{for all I}$$

$$(5) \quad \sum_i X_{ik} - L_k \leq 0 \qquad \text{for all K}$$

$$(6) \quad \sum_i f_{ik} X_{ik} - R_k \leq 0 \qquad \text{for all K}$$

$$(7) \quad \sum_i g_{ik} X_{ik} - O_k \leq 0 \qquad \text{for all K}$$

where C_{ik} is the purchased input cost in region k for producing the i^{th} commodity, Y_{ik} is per hectare yield of i^{th} commodity produced in region k, f_{ik} is the i^{th} demand for labor in region k, and g_{ik} is the i^{th} demand for other inputs in region k. Q_i is the consumption for i^{th} commodity, L_k is the land supply in region k, R_k is labor supply in region k and Q_k is the other input supply in region k.

2.5.1. Modified Taiwan Agricultural Sector Model

TASM was constructed by Chen and Chang (2005) under this theory and for this analysis I will add features related to bioenergy. Specifically, to get a version for use herein, I have to address each of the following issues:

- Model farm support policy
- Model trade
- Model energy crops

In this subpart, we will first illustrate the algebraic form of the objective function of the modified TASM and its constraints, and then discuss the first order conditions of these equations. The objective function and constraints of modified TASM are shown as follows:

(8)

$$
\begin{aligned}
\text{Max} \quad & \sum_i \int \psi(Q_i)\,dQ_i \\
& - \sum_i \sum_k C_{ik} X_{ik} \\
& - \sum_k \int \alpha_k (L_k)\,dL_k \\
& - \sum_k \int \beta_k (R_k)\,dR_k \\
& + \sum_i P_i^G * Q_i^G \\
& + \sum_k P^L * AL_k \\
& + \sum_j \sum_k SUB_j * EC_{jk} \\
& + \sum_i \sum_i \int ED(Q_i^M)\,dQ_i^M \\
& - \sum_i \int ES(Q_i^X)\,dQ_i^X \\
& + \sum_i \int EXED(TRQ_i)\,dTRQ_i \\
& + \sum_i [tax_i * Q_i^M + outtax_i * TRQ_i] \\
& - PGHG \sum_g GWP_g GHG_g
\end{aligned}
$$

Subject to

(9) $Q_i + Q_i^X + Q_i^G - \sum_k Y_{ik} X_{ik} - (Q_i^M + TRQ_i) \le 0$ for all I

(10) $\sum_i X_{ik} + AL_k + \sum_j EC_{jk} - L_k \le 0$ for all k

(11) $\sum_i f_{ik} X_{ik} - R_k \le 0$ for all k

(12) $\sum_{i,k} E_{gik} X_{ik} - GHG_g \le 0$ for all g

Q_i^G	Government purchases quantity for price supported product i
Q_i^M	Import quantity of product i
TRQ_i	Import quantity exceeding the quota for TRQ product i
Q_i^X	Export quantity of product i
$ED(Q_i^M)$	Inverse excess import demand curve for product i
$ES(Q_i^X)$	Inverse excess export supply curve for product i
$EXED(TRQ_i)$	Inverse excess demand curve of product i that the import quantity is exceeding quota.
tax_i	Import tariff for product i
$outtax_i$	Out-of-quota tariff for product i
P^L	Set-aside subsidy
SUB_j	Subsidy on planting energy crop j

AL_k	Set-aside acreage in region k
EC_{jk}	Planted acreage of energy crop j in region k
$\alpha_k(L_k)$	Land inverse supply in region k
$\beta_k(R_k)$	Labor inverse supply in region k
P_i^G	Government purchase price on commodity i
Q_i^G	Commodity I purchased by government

Equation (8) is our objective function incorporating domestic and trade policies. The 1st term is the area under the domestic demand curve while the 2nd, 3rd and 4th terms are input costs, cropland rent and labor costs, respectively. The 5th, 6th and 7th terms reflect the government subsidy on rice purchase, set-aside lands and for planting energy crops. These terms represent the social welfare in a closed market. The 8th and 9th terms represent the area under the excess demand curve and the 10th term stands for the area under the excess supply curve. The 11th term is tariff revenue. Therefore, these 4 components in our objective function add in the trade surplus. The final term is the GHG payment using carbon prices. Other GHGs will be converted into CO_2 equivalent and then multiplied by the carbon price. The total quantity of net emissions is negative and for items like bioenergy production constitute revenue.

Equation (9) is the balance constraint for commodities. The first three terms give total demand which includes domestic demand (Q_i), export demand (Q_i^X), and government purchases (Q_i^G). The last two terms in the supply-demand balance constraint represents the supply side and include domestic production ($\sum_k Y_{ik} X_{ik}$) and imports ($Q_i^M + TRQ_i$).

Equation (10) and (11) are the resource endowment constraints. Equation (10) controls cropland and means the agricultural crops, energy crops and set-aside hectares are competing. In other words, it shows planted land plus set-aside land cannot exceed total land. Equation (11) is the other resource constraint. Equation (12) is the greenhouse gas balance which shows emissions emitted cannot be greater than total emissions.

We can also present the objective function and constraints using Lagrangian:

$$(13) \quad \mathrm{L} = \sum_i \int \psi(Q_i) dQ_i) - \sum_k \int \beta_k (R_k) dR_k - \sum_i \sum_k C_{ik} X_{ik} - \sum_k \int \alpha_k (L_k) dL_k$$

$$+ \sum_i \int ED(Q_i^M) dQ_i^M) + \sum_i \int EXED(TRQ_i) dTRQ_i)$$

$$+ \sum_i \left[tax * Q_i^M + outtax * TRQ_i \right] - \sum_i \int ES(Q_i^X) dQ_i^X$$

$$+ \sum_k P^L * AL_k + \sum_i P_i^G * Q_i^G - P_{GHG} * \sum_g GWP_g * GHG_g$$

$$- \sum_{\mathrm{i}} \delta_{\mathrm{i}} \left[Q_i + Q_i^X + Q_i^G - \sum_k Y_{ik} X_{ik} - \left(Q_i^M + TRQ_i \right) \right]$$

$$- \sum_{\mathrm{i}} \varphi_{\mathrm{i}} \left(\sum_i X_{\mathrm{ik}} + AL_k + \sum_j EC_{jk} - L_k \right) - \sum_{\mathrm{i}} \gamma_{\mathrm{i}} \left(\sum_i f_{\mathrm{ik}} X_{\mathrm{ik}} - R_k \right)$$

$$- \sum_{i,k} \theta_{i,k} \left(\sum_{i,k} E_{gik} X_{ik} - GHG_g \right)$$

Using Kuhn-Tucker condition we can derive the first order conditions that maximize X_{ik}, Q_i, L_k, R_k, δ_i, γ_i, φ_i, θ_{ik}.

- Condition for optimal production

(14) $$\frac{\partial L}{\partial X_{ik}} = -C_{ik} + \delta_i Y_{ik}$$

(15) $$\frac{\partial L}{\partial X_{ik}} X_{ik} = 0$$

(16) $$X_{ik} \geq 0$$

- Condition for optimal consumption

(17) $$\frac{\partial L}{\partial Q_i} = \psi(Q_i) - \delta_i \leq 0$$

(18) $$\frac{\partial L}{\partial Q_i} Q_i = [\psi(Q_i) - \delta_i] Q_i = 0$$

(19) $$Q_i \geq 0$$

- Condition for optimal input use

(20) $$\frac{\partial L}{\partial L_k} = -\alpha_k(L_k) + \omega_i$$

(21) $$\frac{\partial L}{\partial L_k} L_k = [-\alpha_k(L_k) + \omega_i] L_k = 0$$

(22) $$L_k \geq 0$$

(23) $$\frac{\partial L}{\partial R_k} = -\beta_k(R_k) + \gamma_i$$

(24) $$\frac{\partial L}{\partial R_k} R_k = [-\beta_k(R_k) + \gamma_i] R_k = 0$$

(25) $$R_k \geq 0$$

- Condition for optimal commodity price

(26) $$\frac{\partial L}{\partial \delta_i}\delta_i = \left[Q_i + Q_i^X + GQ_i - \sum_k Y_{ik} X_{ik} - \left(Q_i^M + TRQ_i \right) \right] \delta_i = 0$$

- Condition for optimal input price

(27) $$\frac{\partial L}{\partial \varphi_i}\varphi_i = \left(\sum_i X_{ik} + AL_k + \sum_j EC_{jk} - L_k \right) \varphi_i = 0$$

(28) $$\frac{\partial L}{\partial \gamma_i}\gamma_i = \left(\sum_i f_{ik} X_{ik} - R_k \right) \gamma_i = 0$$

- Condition for optimal GHG reduction

(29) $$\frac{\partial L}{\partial \theta_{ik}}\theta_{ik} = \left(\sum_{i,k} E_{gik} X_{ik} - GHG_g \right) \theta_{ik} = 0$$

If consumption of commodity i is positive (Q_i>0), then the first order condition of equation (18) becomes

(30) $$\psi(Q_i) = \delta_i$$

The commodity prices in this model are endogenously determined. In addition, if the production activity is positive, we see the equation (14) becomes

(31) $$C_{ik} = \delta_i Y_{ik}$$

Plugging equation (30) into equation (31), we get

(32) $$C_{ik} = \psi(Q_i) Y_{ik}$$

Equation (32) represents that the income from 1 unit of production equals the input costs. In other words, to determine the optimal production activity that maximizes profits, marginal revenue is equal to marginal cost. Using the same logic, if the supply of land and labor are positive ($L_k > 0$, $R_k > 0$), equation (20) and (23) tell us

(33) $\alpha_k(L_k) = \varphi_i$

(34) $\beta_k(R_k) = \gamma_i$

From equation (33) and (34), we see the prices of land and labor are also endogenously determined in the model.

2.5.2. Policy Analysis

2.5.2.1. Modeling Farm Support Policy

Taiwan currently has domestic policy to support rice prices and set-aside cropland. To incorporate these policies in TASM requires the addition of two sets of variables. The first set reflects the government rice purchasing program that provides farmers with a guaranteed price that is higher than the market equilibrium price. Letting P_i^G be the weighted government guaranteed purchase price and Q_i^G be the total amount of government purchase. The farm revenue realized from the government rice purchase program ($P_i^G * Q_i^G$) is added into the objective function as an additional farm revenue source. At the same time, it removes rice from the market place up to the amount allowed.

Another set of policy variables relates to the set-aside program. If farmers choose to participate in this program, then those farmers will receive a set-aside payment (P^L). In 2004 about 280,000 hectares joined this program and the subsidy was set equal to NT$ 90,000 per hectare per year. To incorporate these policies in our model, we add

$\sum_k P_k^L * AL_k + \sum_i P_i^G * Q_i^G$ to our objective function. Although our objective function includes consumer and producer surplus, it really wants to derive the equilibrium under a perfectly competitive market. We add the government expenditure to the objective function; however, this does not mean that we treat the government expenditure as social welfare but instead reflect the distorted demand function. We use a figure to illustrate this point.

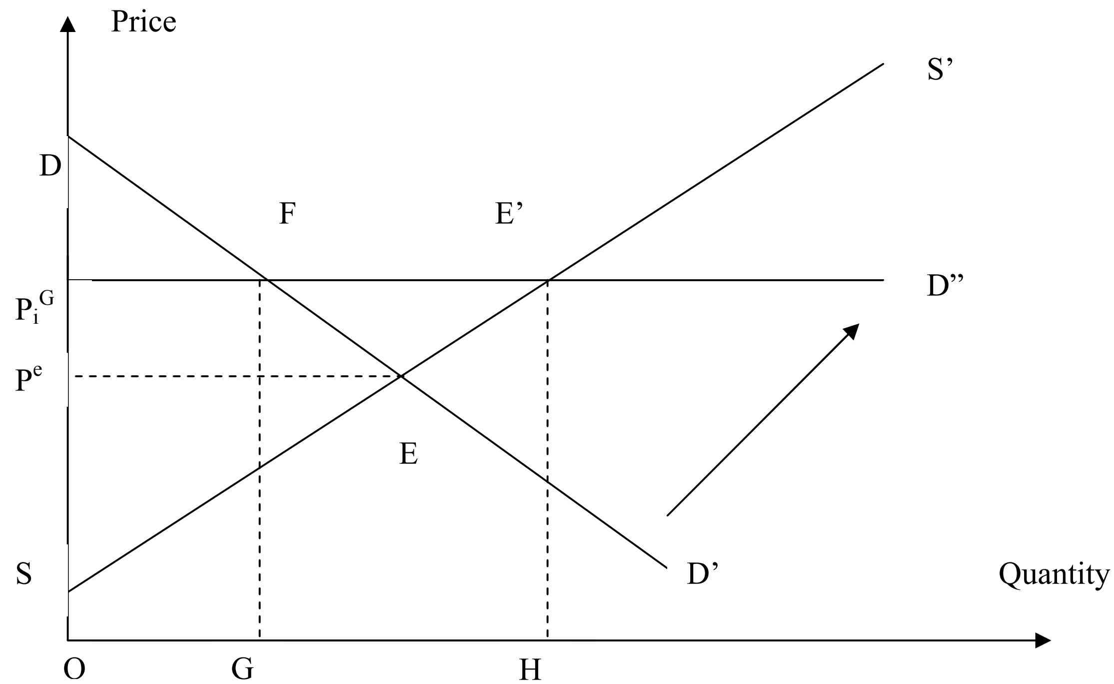

Figure 1. Intervention effect of government rice purchase program

Figure 1 shows the original demand for the commodity is DD' (without government intervention) and the equilibrium is at point E. Now the government intervenes in the market by purchasing this commodity at a higher price ($P_i^G > P^e$), and as a result the demand curve is kinked to DD" and the new equilibrium occurs at E'. Under the government purchase policy, the total supply increase to OH where OG is consumed by the society and GH is purchased by the government. Therefore, the objective function changes to SDE+EE'F from SDE, and SDE+EE'F is calculated by OGFD+GHE'F-OSE'H. This is why we add the government expenditure to the objective function.

2.5.2.2. Modeling Trade

Since Taiwan's import and export share in the global market is very small, import and export prices are assumed to be determined exogenously by supply and demand in the world market. Therefore, Taiwan is a price-taker in the international agricultural product and energy markets. We need to specify two types of trade policies such as tariff and tariff rate quota (TRQ) to reflect this fact. Grains, oilseeds and most horticultural and livestock products are imported with an associated import tariff while twenty-one sensitive products (including rice) are imported under the TRQ system. This is modeled as:

$$\sum_i \int ED(Q_i^M) dQ_i^M + \sum_i \int EXED(TRQ_i) dTRQ_i + \sum_i \left[tax * Q_i^M + outtax * TRQ_i \right]$$

This stands for the import quantity within the quota (lower tariff) plus the imports exceeding the quota (higher tariff). We need to consider imports and exports of agricultural commodities (and thus quotas and tariffs) because there are many commodities that are not only consumed domestically but also traded in the international market, even though the amount is relatively small. For example, Taiwan imports 3,949 tons of peanuts at a price of NT$17.16 per kg in 2005 and a tax rate is 25%. However, the quota is set equal to 2,618 tons of peanuts and when the amount of imported peanuts exceeds this quota, the rest of the peanuts must pay a higher tariff, which is 398%. Because there are many agricultural products involve imported and exported by Taiwan, we also want to model the trade to reflect this situation.

2.5.2.3. Modeling Energy Crops

Production activity for sweet potatoes, poplar, willow and switchgrass on set-aside land is incorporated into the TASM for this study as alternative production possibilities. Sweet potato is used to produce ethanol while poplar, willow and switchgrass are grown for either ethanol production or electricity production or both. Before we start estimating the impacts of planting energy crops for ethanol production, let us present some information on the modeling component of transforming energy crops to ethanol and electricity. Taiwan consumes about 10 billion liters of gasoline annually and the most acceptable ethanol/gas blend that could be used in existing cars is E3. In this study, we assume a liter of ethanol can replace a liter of gasoline. Therefore, the E3 ethanol demand is set equal to 3% of total gasoline consumption, which is 300 million liters. At the same time, Taiwan consumes 52 million tons of coal for electricity production. Since poplar, willow and switchgrass can replace coal and generate electricity, we also consider this alternative in our study.

Sweet potatoes are currently produced in Taiwan, but poplar, willow and switchgrass are not produced. For this reason, input costs and yields mainly come from the literature and established models. For willow, we assume a 22-yr lifespan of the willow plantation and that the first harvest takes place in the fourth year with a yield of 21 tons per hectare (t/ha). Thus the annual yield would be 5.25 t/ha based on Ericsson et al. (2005). However, other studies show the mean yield is between 7.14 and 10.71 t/ha per year (Aylott et al., 2009). To be conservative, the willow yield in our study will use 5.25 t/ha per year. The yield of poplar is generally from 5.77 to 9.59 t/ha per year (Aylott et al. 2009). This difference is usually caused by the quality of soil at the plantation and local weather. The lowest yield occurs in sandy soil and soil on Taiwan set-aside land is not sandy. Thus we will not take the lowest yield in our analysis; instead, we take the average yield, which is 7.6 t/ha per year.

'Alamo' switchgrass is a robust lowland variety of switchgrass most suited to the southern U.S. and has been tested in Auburn University test plots. It has frequently produced over 10 tons per acre per year; however on a commercial scale, it is more reasonable to expect 6 to 8 tons per acre. This is because test plots usually have perfect establishment, but commercial plantings almost always have weak spots in the field (Bransby, 2005). Some U.S. government projects show the yield of switchgrass is between 2 and 4 tons per acre per year, so we use the average yield from government studies in our analysis. Since 1 hectare is 2.471 acres. The annual yield of switchgrass is assumed to be 3*2.471= 7.4 t/ha per year. The annual yield of these three energy crops is obviously lower than that of sweet potato, but we still need to consider the combination of these crops since they have potential to produce biochar, which potentially increases the crop yields, reduces irrigation costs and stores carbon in a relative stable form.

Sweet potato to ethanol processing costs includes two parts; the first one is a fixed cost which is about NT$ 2.35 per liter while the second part is the operating cost which is about NT$ 8.26 per liter. The hauling cost is NT$ 0.88 per liter of ethanol, which is included in the operating cost. The hauling cost is estimated following McCarl et al. (2000) based on a metric adaptation of French's (1960) hauling cost formula

$$(35) \qquad \text{hauling cost} = \frac{38 + 2 * (.4714) * [M /(2.468 * den * (Y)]^{1/2}}{Load\ Size}$$

where Y is the yield per hectare (40 tons of sweet potatoes per hectare), *den* is the density of set-aside land in the region (38 %) and Load Size is 23 tons per truck load. The other constants cover loading and travel costs. We also use the same procedure to estimate the processing costs for poplar, willow and switchgrass where original cost data is from the Forestry and Agricultural Sector Optimization Model (FASOM) and we have converted the costs from U.S. dollars to NT$ and converted gallons to liters. The processing cost (including fixed cost, hauling cost and other costs) is NT$ 12.01 per liter for poplar, NT$ 12.01 per liter for willow and NT$11.23 per liter for switchgrass.

Sweet potato planted on set-aside land has the same cost as sweet potato currently produced. Since Taiwan currently does not plant poplar, willow and switchgrass, their elasticities are set equal to the elasticity of hardwood varieties that are planted in Taiwan. Outputs calculated based on the data of Ericsson et al. (2005) and Aylott et al. (2009). Input costs are calculated based on the information from FASOM

(July, 2007 version). Fertilizer and chemical costs per hectare are calculated to NT$11,885 for poplar, NT$12,527 for willow and NT$18,763 for switchgrass. Energy costs are calculated to NT$483.96/ha for willow, NT$706.57 per ha for poplar and NT$487.71 per ha for switchgrass and seed costs is NT$660 per ha for willow, NT$5,410 per ha for poplar and NT$306 per ha for switchgrass.

We also compute the net mitigation of carbon dioxide using an estimate from Weber and Johannes (1996). They show that net carbon dioxide emissions are reduced by 0.107 ton per 1000 liters of ethanol. The price of this carbon dioxide offset is assumed as NT$1,500 per ton based on the historical world GHG price. However, in our study, we adjust this high GHG price to a range of lower levels (NT$300, NT$500 and NT$1000) based on the historical GHG price. When poplar, willow and switchgrass are used to generate electricity, a contribution is also made to climate change mitigation. Electricity generated from a kg of poplar is 0.768 kwh, 0.919 kwh per kg for switchgrass and 0.946 kwh per kg for willow. According to Bransby's work (2005) in Oak Ridge National Laboratory, energy produced from 1 kg of coal produces about 6.15 kwh, so a kg of polar, willow and switchgrass are equivalent to 0.125 kg, 0.154 kg and 0.149 kg of coal, respectively. Then based on the result of McCarl (2008), poplar can offset about 71.3% of carbon dioxide emissions relative to the fossil fuel, 83.4% for willow and 75.1% for switchgrass. As one kg of coal emits about 3.667 kg of CO_2, we calculate that the emission reduction is 0.471 kg CO_2 per kg of willow, 0.327 kg CO_2 for poplar and 0.410 kg CO_2 for switchgrass. Then the net GHG emission is included as:

$$P_{GHG} * \sum_{g} GWP_g * GHG_g$$

in the model.

The data sources of agricultural commodities largely come from published government statistics and research reports, which include the Taiwan Agricultural Yearbook, Production Cost and Income of Farm Products Statistics, Commodity Price Statistics Monthly, Taiwan Agricultural Prices and Costs Monthly, Taiwan Area Agricultural Products Wholesale Market Yearbook, Trade Statistics of the Inspectorate-General of Customs, Forestry Statistics of Taiwan. Demand elasticities of agricultural products come from various sources and were gathered and sent by Chang and Chen in mid 2007.

2.6. Scenario Setup

We will include sweet potato, willow, poplar and switchgrass into the model while sweet potato is used to produce ethanol and willow, poplar and switchgrass can be used to produce ethanol or electricity. Under different ethanol prices, coal prices, carbon dioxide prices and given government subsidies, we can discuss the bioenergy production activities Taiwan may face.

This study wants to learn how changes on ethanol price, coal price, and carbon dioxide price affect the production of ethanol, displaced coal, GHG emissions reduction and social welfare, given a fixed level of government subsidy. The government subsidies are NT$50,000/ha for sweet potatoes and NT$45,000/ha for poplar, willow and switchgrass. The amounts of government subsidies are based on the professional opinion of Professor Chen Chi-Chung, who is familiar with Taiwan's agricultural policy. The ongoing gasoline and coal price in Taiwan is around NT$29 per liter and NT$1.7 per kg respectively. Ethanol prices are set equal to NT$ 20, NT$30, NT$40, and NT$50 a liter and coal prices are set equal to NT$1.7 per kg, NT$3.45 per kg, and NT$6 per kg. The reason we choose these prices is because since 2005, the lowest and highest gasoline price in Taiwan is between NT$20.1 to NT$37.7 per liter, respectively. Therefore, the price range of gasoline between NT$20 to NT$40 can happen in the real world and we add one more price (NT$50) in case the gasoline price hits to another peak in the future.

The current coal price is NT$1.7 per kg and was NT$4.35 in 2008, so we simulate 2 prices fall into this range and another higher price in case we face the future higher coal price. In addition, the GHG price is set equal to NT$300, NT$500 and NT$1000 per ton of CO_2. The CO_2 price was around NT$1100 per ton in the European Climate Exchange and NT$130 per ton in the Chicago climate Exchange in 2008. Because of the dramatic CO_2 price change, we set up our CO_2 price for the range of 30%, 50% and 90% of the high CO_2 price. Although the current CO_2 price is zero in Taiwan, we may explore some information about bioenergy production when CO_2 has value. Therefore, this study contains 36 scenarios for ethanol and electricity production using all crops under different prices.

2.7. Simulation Results and Policy Implications

36 scenarios have been simulated where scenarios 1-12 represent the 4 ethanol prices and 3 electricity prices under GHG price equal to NT$300 while scenarios 13-24 and scenarios 25-36 represent the 4 ethanol prices and 3 electricity prices under GHG price equal to NT$500 and NT$1000, respectively.

Throughout all scenarios, we see only sweet potato and switchgrass are produced. Poplar and willow are not competitive in that the value they generate from production is not large enough due to their relatively lower feedstock yield, plus the associated lower ethanol and electricity conversion rates. Ethanol production does not allow Taiwan to reach a full amount of E3 fuel and throughout the study, ethanol supply ranges from 30% to 90% of the volume required to achieve E3. When the price of ethanol goes up, the sweet potato planted hectares also increase. In addition to ethanol production, electricity is generated. The annual electricity provided from switchgrass ranges from 111,715 million watt hours (Mwh) to 346,203 Mwh. The total electricity demand is 221,000,000 Mwh in Taiwan, and bioelectricity can provide only 0.157% of total electricity demand with about 40% of the set-aside land used for switchgrass. The farmers' revenue and net social welfare also increases as the ethanol prices, coal prices and GHG prices increase. Figure 2 to Figure 4 represent the results from the first twelve scenarios with GHG price equal to NT$300.

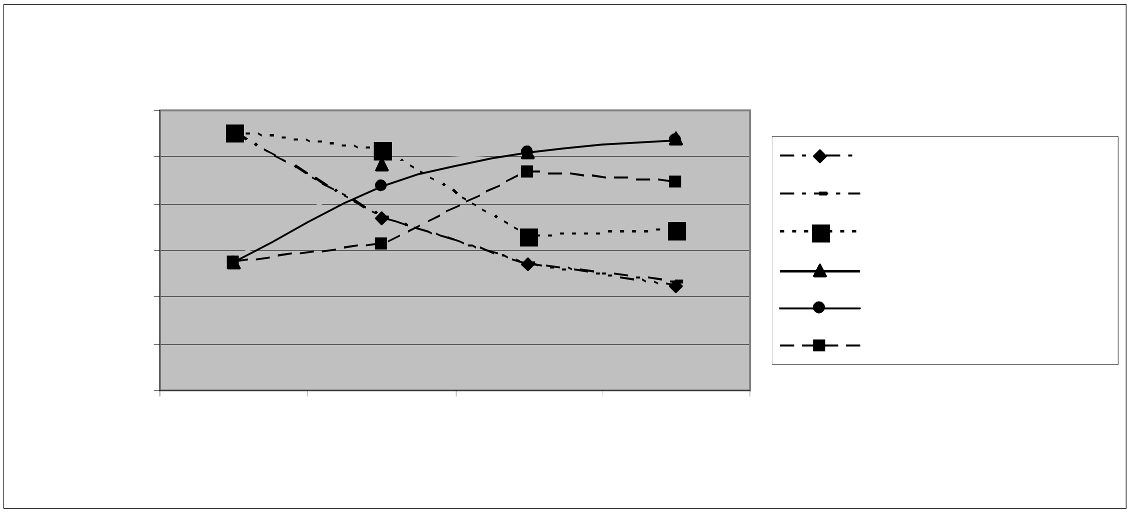

Figure 2. Electricity and ethanol production under different coal and ethanol prices for a carbon price of NT$300

In Figure 2, we see that electricity production decreases as ethanol price increases but increases as coal price increases. When coal price increases from NT$1.7 per kg to NT$3.45 per kg, electricity production only increases by a small amount. But when coal price goes to NT$6 per kg (around US$182 per short tonne), planting energy crops to substitute for the use of coal becomes more valuable and thus, on average, increases the total bioelectricity by about 22.4%. Ethanol production increases from 50% of total demand to 90% when ethanol price increases. However, when coal price hits its highest level, increasing ethanol price still increases ethanol production but the amount of ethanol production is less than that when facing lower coal prices. On average, ethanol production shrinks to 82.9% when highest and lowest coal price scenarios are compared.

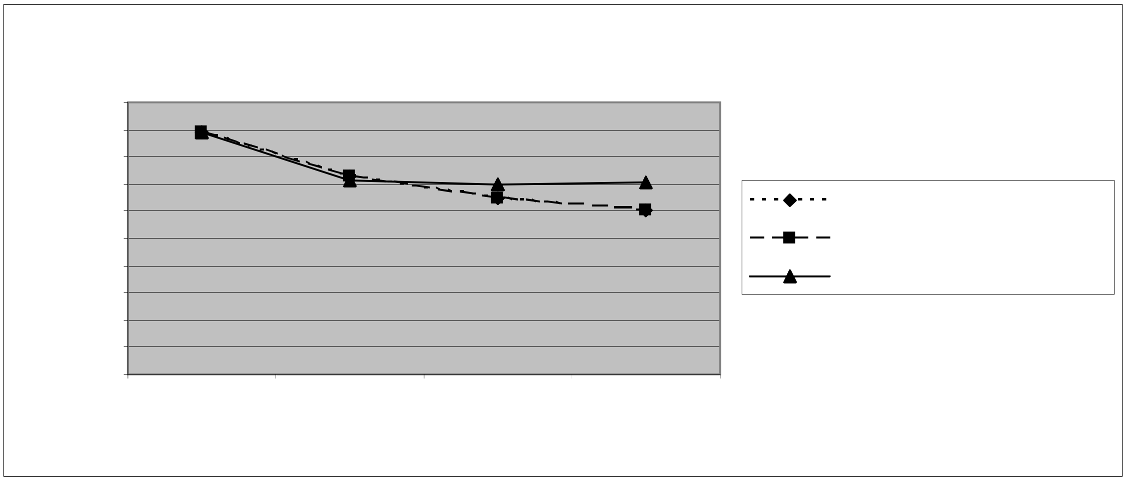

Figure 3. Carbon offset from bioenergy under a carbon price of NT$300

Figure 3 shows the net GHG emission reduction when bioenergy is produced. The net GHG emission offset is from 60,000 tons to 88,900 tons under different ethanol prices and coal prices. However, the amount of GHG emission reduction only accounts for 0.014% to 0.021% annual GHG emissions. The net GHG emission reduction decreases as the ethanol price increases. When ethanol price increases, farmers plant more sweet potatoes to produce ethanol and less switchgrass used for electricity. Since electricity offsets more GHG, expansion in ethanol production and shrinkage in electricity production results in a decrease in net GHG emission offsets. In addition, to achieve this environmental benefit the government needs to spend about NT$6 billion in subsidies annually.

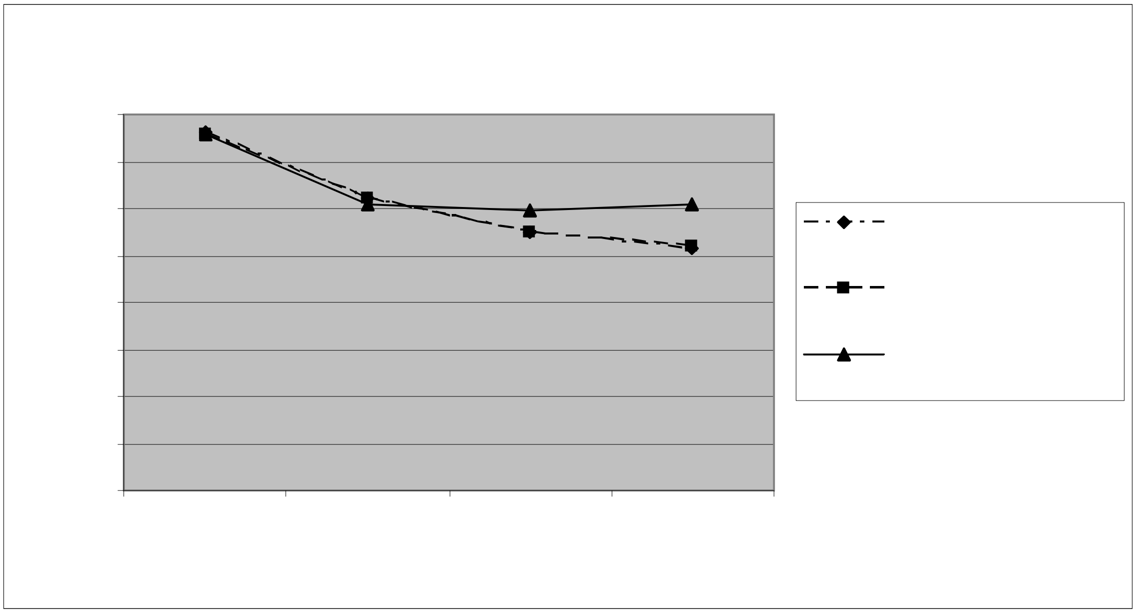

Figure 4. Carbon offset on a per hectare basis under varying ethanol and electricity prices with a carbon price of NT$300

We find that when ethanol prices increase, ethanol production increases but electricity production decreases. This causes the net GHG emissions reduction to decrease. On the per hectare level, the net GHG emission offset decreases from 762 kg to 520 kg when ethanol price increases from NT$20 to NT$50. Through all 36 scenarios, we see when GHG price increases, the net GHG offset increases. This is resulting from the decrease in ethanol production and increase in electricity production. This can be explained by the higher GHG offset rate of electricity compared to that of ethanol.

2.8. Summary

As there is a concern on energy security, Taiwan is interested in producing energy domestically. One option is to utilize set-aside land to produce bioenergy feedstocks. Bioenergy production helps Taiwan bolster energy security when distortions occur and fossil fuel prices rise in the international market. In addition, to enhance Taiwan's energy security, bioenergy production also makes a contribution to the world by reducing net GHG emissions. Climate change is a big challenge to the world and evidence shows that our world is becoming warmer. The main cause is likely greenhouse gases emitted from every corner of this world. This concern leads to a dilemma between economic development and environmental protection. For example, people use energy for economic development but too much energy consumption deteriorates our environment. Therefore, looking for clean and renewable energy is an important issue facing many developed and developing countries.

Taiwan currently has lots of idled cropland - about 280,000 hectares or 33% of total national cropland. So the government plans to use some of the idled land to plant energy crops to reduce net GHG emissions. In order to do so, a subsidy payment is being considered that will encourage farmers to plant energy crops. The amount of the subsidy used in this study is primarily based on the opinion of Professor Chen Chi-Chung, who is familiar and intensively involved in Taiwan's agricultural policy. We find that farmers' revenues increase when participating with the bioenergy crop production. When GHG price goes up, ethanol and bioelectricity that offset GHG emissions becomes more valuable and expansion on bioenergy occurs; therefore, demand for the inputs (which are sweet potatoes and switchgrass in this case) increases and the price of these inputs increases. Therefore, the results indicate that when we face a higher GHG price, the bioenergy production expands and the amount of land converted into bioenergy crops also increases. Farmers also receive higher revenues by selling their biofeedstocks when the GHG price gets higher. The same logic also applies for the rise in ethanol price and electricity prices where farmers benefit when these prices go up.

This study also has some policy implications. First, it indicates that if Taiwan wants to maximize its net GHG emissions reduction, it would be very difficult for Taiwan to meet its ethanol demand. This is because ethanol provides a relatively lower GHG emissions offset rate than that of electricity. Second, as land is limited, other agricultural policies that utilize set aside land may compete with the bioenergy program and if such policies are undertaken, there may be less land available for bioenergy feedstock production and a lower GHG emissions reduction can be achieved. For example, in 2009, Taiwan was planning to recycle carbon by afforestation with a subsidy of NT$90,000 per hectare. If farmers were participating with this program, then the land available for the bioenergy production would be reduced. Third, lack of energy security is a big problem in Taiwan. If the primary goal of bioenergy policies is to enhance energy security, it would be possible for Taiwan to concentrate on bioenergy production rather than focus on a GHG emissions reduction.

Generally, the world does not benefit that much from Taiwan's energy and environmental policy, but Taiwan indeed benefits from bioenergy production in terms of energy security by using currently idled land. However, the government needs to pay a subsidy for the increase in national energy security. Moreover, the use of poplar, willow and switchgrass do not yield a significant amount of ethanol production due to their relatively low output compared to sweet potatoes. However, these bioenergy crops have potential to produce electricity by replacing coal, which would have positive economic and environmental impacts. We find that when coal price increases, it leads to the expansion of electricity production from energy cropland when ethanol price increases, ethanol production expands. As the GHG price increases, both ethanol and electricity production increases and more set-aside land is converted to plant bioenergy crops. We also find that bioenergy production indeed increases energy security and reduces net GHG emissions. However, their contribution is not significant because less than 1% of fossil fuels can be replaced and less than 0.1 million tons of carbon dioxide emission reduction is achieved. Further expansion of bioenergy crop production depends on how much cropland could be converted to plant bioenergy crops. In the following essays, we will first analyze the economic and environmental effects of biochar utilization and then put those effects back into our ethanol/electricity study to examine the overall economic and environmental impacts.

3. ECONOMICS OF BIOCHAR PRODUCTION, APPLICATIONS AND GHG OFFSETS IN TAIWAN

3.1. Introduction

Ethanol and biopower are two possible ways to provide self-produced renewable energy for Taiwan. In essay 1, I examined bioenergy production and associated greenhouse gas (GHG) offsets in Taiwan, and the results showed that it is possible for Taiwan to gain some social and environmental benefits from the production and utilization of bioenergy feedstocks. Besides ethanol and biopower, pyrolysis is another option that Taiwan may adopt to produce bioenergy. Here I extend that work in the previous essay to also consider pyrolysis and biochar. The importance of doing so is that while pyrolysis generates energy as the primary product, the byproduct, biochar, can improve the quality of soil by keeping nutrients in the soil, storing more water and storing carbon in a more stable form (Lehman et al., 2003; Chan et al., 2007).

In addition, researchers found that after applying biochar as a soil amendment, agricultural commodities yield more outputs (Chan et al., 2007). However, for biochar to be applied on a large scale it must be economically attractive and hence I appraise the economics on a per hectare basis in the Taiwan case using poplar as a specific case study. In the next essay, I will add biochar into our model to appraise broader overall effects and to look at how competitive it is relative to other biofuel possibilities. Specifically, I examine the following components in this essay:

a) The costs of feedstock harvest, hauling, storage and use, along with implications for nutrient replacement and tillage alteration;

b) Value of energy production and the costs of associated processes;

c) Value of biochar application and subsequent implications for feedstock production;

d) GHG accounts involving

- offsets for displaced fossil fuels;
- emissions saved and increased from fossil fuels and manufactured agricultural inputs employed in the biochar production process (farm to pyrolysis, plant to farm);
- the sequestration enhancements and losses involved with residue recovery and biochar application;

e) Sensitivity analysis on profitability of fast and slow pyrolysis.

In examining these factors I will adopt a similar approach to a chapter I coauthored by McCarl et al. (2009) to analyze such a case but will consider the case of poplar (McCarl et al. examined corn stover). The reader should note that many items are uncertain and thus this is only a preliminary case study on net economic benefits and a simultaneous GHG life-cycle assessment. I will try to look at this uncertainty by exploring how net benefits in our study are affected by variations in assumptions involving alternative feedstocks, pyrolysis facility/operation costs, energy prices, carbon prices and other factors.

3.2. Pyrolysis and Biochar

I considered two pyrolysis systems and the outputs from pyrolysis. Biochar is produced by pyrolysis (Bridgwater and Peacocke, 2002; Demirbas and Arin, 2002) and, to a limited extent, can also be a by-product of gasification (Bridgwater, 2005). Pyrolysis is the chemical decomposition of organic materials by heating in the absence of oxygen where

- Fast pyrolysis involves biomass being rapidly (on the order of 5 to 10 seconds) heated to between 400℃ and 550 ℃ (Bridgwater, 2005).
- Slow pyrolysis involves slower heating to less than 400℃ (although other definitions have higher temperatures (Bridgwater, 2005)). The biomass is typically in the reactor for at least 30 minutes and possibly several hours.

During pyrolysis, biomass is converted into three products:

1. a liquid product that is commonly called bio-oil, pyrolysis oil or bio-crude;
2. a solid char that can be used in a range of applications, including use as a soil additive (then called ‘biochar’) or as a source of energy in the conversion process;
3. a non-condensable gas product containing carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), methane (CH_4) and higher hydrocarbons, which also can be called ‘syngas’ or ‘pyrolysis gas’.

Slow pyrolysis yields relatively more biochar, but less bio-oil. Wright et al. (2008) indicate that fast pyrolysis yields about 15 percent biochar, 70 percent bio-oil and 13 percent syngas. Ringer et al. (2006) indicate that under slow pyrolysis, about 35 percent of the feedstock ends up as biochar, 30 percent as bio-oil and 35 percent as syngas. In both cases, the bio-oil can then be cleaned and further processed to produce higher-quality fuels (Czernik and Bridgwater, 2004), gasified to produce electricity, or it can be refined to produce chemical feedstocks such as resins and slow-release fertilizers. Each of these is a potential source of value.

While biochar was initially viewed as a source of energy and can be burned to supply process energy, it can be used for water purification, gas cleaning, metallurgical industries and for charcoal in home cooking. In addition, it has lately been regarded as a potential source of several valuable environmental and agronomic benefits as mentioned before. Finally, the energy products and the biochars as a soil additive have GHG implications, displacing both fossil fuel use and nitrogen fertilizer along with associated emissions, plus sequestering carbon. In considering these GHG impacts, we must consider the full life cycle of GHGs released in the farm-to-factory-to-biochar application system.

Here we can use a simple picture to indicate that what will be done in our life cycle analysis. Figure 5 shows the important parts in our analysis related to GHG emissions and savings. Based on these steps, we can compute what the net GHG emissions/savings from biochar production and utilization will be.

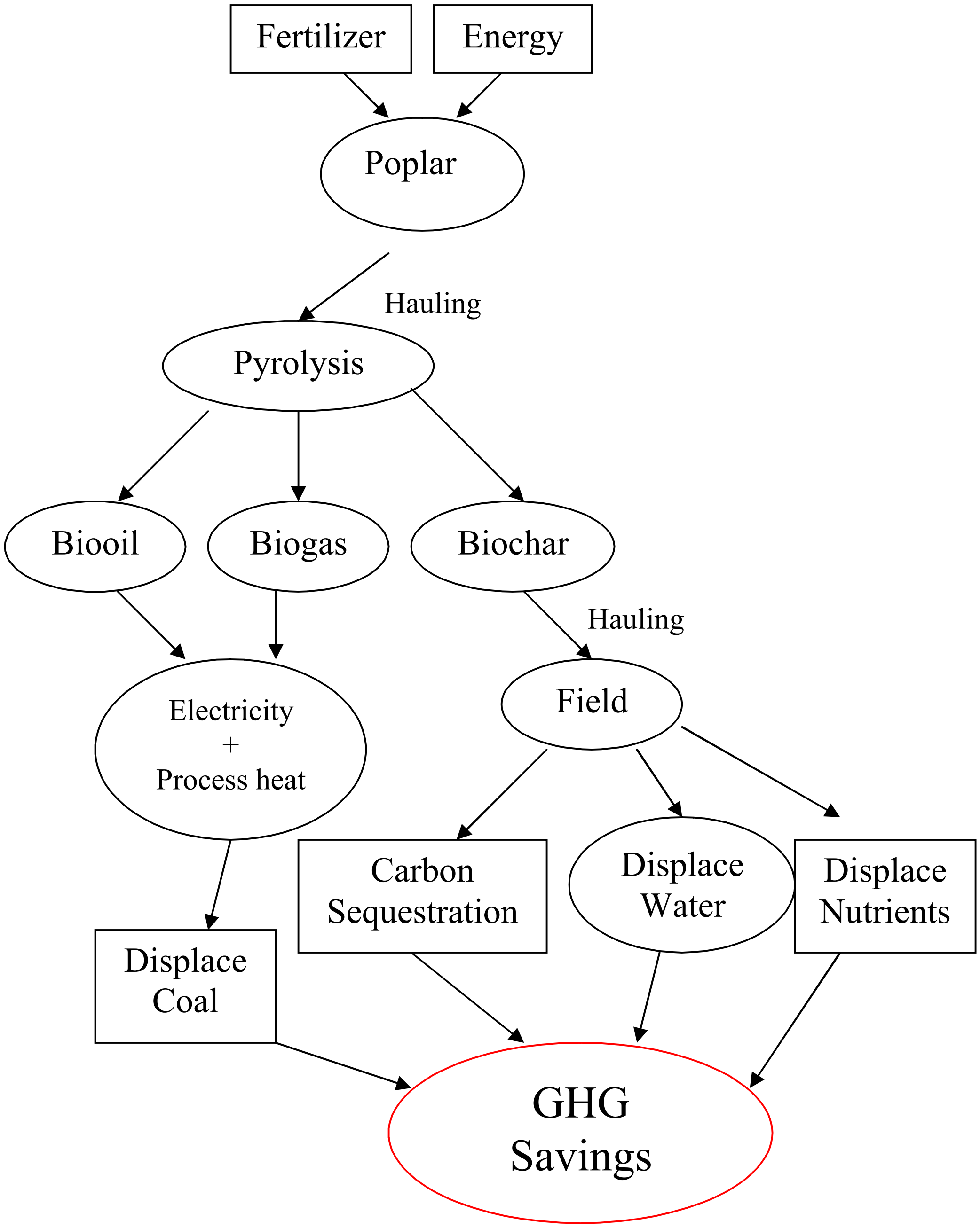

Figure 5. CO_2 emissions and savings during biochar production and utilization

3.3. Examination of a Biomass to Pyrolysis Feedstock Prospect

This section examines the economic and GHG value arising from producing biochar and other products under fast and slow pyrolysis using poplar. We present a somewhat general discussion of feedstock possibilities, along with a concrete application using data representative of the case of poplar as a feedstock. In calculating the value of such a prospect, we consider benefits and costs, first, and then examine implications from changes in the GHG balance.

3.3.1. Costs and Benefits

The economic costs and benefits of fast and slow pyrolysis, as well as the associated products, considered involve:

- feedstock production and collection;
- feedstock hauling;
- feedstock storage and pre-processing;
- feedstock processing;
- pyrolysis operation;
- energy sales;
- biochar hauling and application; and
- biochar-induced cropping system gains.

Each is discussed separately below.

3.3.1.1. Feedstock Production and Collection

Biomass requires some form of assembly, harvesting, collection and compaction, all of which involve costs (Caputo et al., 2005). In the case of:

- *Urban municipal wastes:* this could involve separation, assembly at a transport point, possibly compaction and then truck loading, and could involve a tipping fee to municipal agencies. We could also consider the value of saved landfill space (Read et al., 2008), as dealing with any materials such as nails or contaminants in the pyrolysis phase. However, there may be cases where these items may be obtained at no cost with the facility collecting a tipping fee in lieu of a disposal fee.
- *Energy crops such as switchgrass or hybrid poplar:* this would involve the costs of the inputs to raise and harvest the commodity, such as seed, rootstock, fertilizer, fossil fuels, equipment, labor and land value, along with movement to a transport point, compaction and loading.
- *Milling residues or processing by-products such as bagasse:* this could involve the cost of buying them away from their current use (or saving in cost if they are now a disposal item), as well as costs of moving to a transport site, compacting and loading along with the amount one might need to pay the processor for access.
- *Logging or cropping residues:* this would involve the inputs to harvest and transport to a hauling site, along with compaction and loading (Polagye et al., 2007), as well as the future productivity losses or nutrient replacement costs from

removal (unless the produced biochar is returned to the site from which the biomass originated or another appropriate soil amendment is used).

More specifically, costs for growing, harvesting and moving poplar to the field edge are assumed to equal US$ 64.85 per ton of biomass. This number is calculated by adding the costs of seed, fertilizer, energy and associated machine and labor used to grow poplar where the seed cost is equal to US$156 per hectare, fertilizer is US$29.1 per hectare and energy cost is US$14.67 per hectare, and the poplar yield is assumed to be 7.6 tons per year, based on the field experiment by Aylott et al. (2009). In addition, the machine plus labor cost is about US$285.4 per hectare. We also add US$10 per ton of bioenergy feedstock for a payment to the farmer. Moreover, since we use set-aside land to produce poplar, and farmers can only get the government subsidy when they produce energy crops, the opportunity cost for using the set-aside land is assumed to be zero. That is, if farmers choose to plant other crops, they will also lose the government subsidy on both the set-aside program and energy crop production. Based on these assumptions, each hectare produces 7.6 tons of feedstock at a farm gate price of US$74.85 per ton.

The use of other feedstocks would raise different issues and calculation procedures. Specifically, when using:

- *Crop residues*: one would need to consider the costs of collection and hauling biomass to the field edge, costs on field nutrients loss (cost on additional fertilizers), and benefits/costs on tillage efforts.

- *Logging residues*: one would employ essentially the crop residues procedures, examining the extra costs of harvest and hauling to the field edge, but might have to include the cost of on-site chipping and compaction, a differential loss factor in storage and hauling, and a savings in costs for handling residue such as the need for collection and burning, among others.
- *Dedicated energy crops*: one would need to consider the opportunity costs of the land in other usages (in this case, we assume it to be zero), such as conventional crop production along with rotation length and differential yields over time.
- *Municipal wastes*: one might encounter cases where firms may pay the pyrolysis plant a tipping fee to take waste materials. Sorting, separation and subsequent disposal of the wastes may reduce the income opportunity significantly.

3.3.1.2. Feedstock Hauling and Storage

A significant cost element when using some feedstocks is hauling costs. This may well be straightforward when looking at municipal wastes or processing by-products as it merely requires computation of distance and number of truckloads to obtain a total cost. However, when examining energy crops as well as logging residues, the calculation becomes more complex. In particular, one must take into account the size of the feedstock need and the service area required to supply that feedstock. Here we present an approach to this.

First, we consider the size of the operation. A pyrolysis operation using 70,000 tons per yr of biomass at 7.6 tons per ha with 5 percent loss in hauling and storage requires a land area of 9671 ha for production under a diverse landscape where the proportion of poplar area to total land area is close to 10 percent (as currently Taiwan does not grow poplar, we use U.S. data from FASOM). This implies a substantial hauling effort and associated cost.

We use McCarl et al.'s (2000) adaptation of French's (1960) procedure to approximate hauling cost, which assumes that the pyrolysis plant is in the centre of a square surrounded by a grid layout of roads. In turn, the hauling cost (H) and average hauling distance ($\overline{D}$) is given by the following formulae:

(36) $H = (b_0 + 2b_1\overline{D})S / Load$

and

(37) $\overline{D} = 0.4714\sqrt{\frac{S}{640Y}}$

where:

$\overline{D}$ is the average distance the feedstock is hauled in miles;

S is the amount of feedstock input for a bio-refinery to fuel the plant, which we assume is 1 Mt plus an adjustment for an assumed 5 percent loss in conveyance and storage;

Load is the truck load size, which we assume to be 23t;

Y is the crop yield (7.6 tons per ha, or 3.04 tons per acre) multiplied by an assumed crop (poplar) density of 10 percent based on U.S. data;

640 is a conversion factor for the number of acres per square mile;

B_0 is a fixed loading charge per truckload and is assumed to be US$90 per truckload for a 23 ton truck; and

B_1 is the charge for hauling including labor (per mile) and maintenance costs, which is assumed to equal US$2.20. This calculation includes 5 percent yield loss, a service area of 9,671 ha of cropland and an average hauling distance of 14.75 km (9.22 miles) with a cost of US$5.96 per ton.

The hauling cost is sensitive to the case at hand, which would vary across feedstocks and time as petroleum and other input costs change. Note that hauling costs can be cut in half, with much higher yields. In addition, the bio-density of crops also has a great impact on hauling cost as it can reduce the total truckload required and hauling distance when bio-density increases. The hauling cost in our study is close to 11 percent of feedstock costs and can be further reduced by being located close to a municipal waste source. However, if this is the case, we also need to consider costs associated with sorting, pre-processing and drying.

Finally, since biomass would need to be stored in some place intermediate to moving to the plant, we assume the need for secondary storage and handling to be US$25 per ton based on the opinion from EPA personnel. Again, we use this U.S. storage cost because we lack this sort of information in Taiwan. However, once we are able to obtain the storage cost in Taiwan, we should adjust this cost to meet the real situation. All of this together makes the feedstock cost US$105.81 per ton. Since this and most assumptions we made would vary with different feedstocks, a sensitivity analysis is performed across a spectrum of feedstock costs.

3.3.1.3. Cost of Plant Operation

Processing biomass into energy costs money. This cost is composed of a fixed and a variable cost component. The fixed cost would be an amortized one-year value of the equipment costs considering purchase price, loan terms, salvage value etc. The variable cost would involve the costs per unit of production including labor, energy, materials handling etc. Both are highly uncertain given that this is largely prospective technology that has not been applied at a commercial scale. In constructing the cost estimate, we assume the poplar was delivered in a wet form on a whole basis. The overall system consists of three modules:

- Module I: biomass preparation (reception, drying, comminution, storage, and feeding);
- Module II: fast pyrolysis to a bio-oil product (based on an integrated fluid-bed process using the biochar and syngas for process heat and fluidization, plus recovering the excess biochar for sale);
- Module III: electricity generation in a 2 x 7MWe dual fuel diesel engine fuelled by bio-oil and diesel.

For all three modules, costs associated with the system include an annual fixed cost of capital (here we assume all the capital is borrowed), as well as the annual operating costs of the plant. The operation costs include feedstock, labor, utilities, maintenance and overhead. The procedures under which these costs were derived were obtained from Peacocke et al. (2006) and Ashton University (2002). A base plant size of

10 tons per hour dry feed input was used and the fast and slow pyrolysis yields are given in Table 2.

Table 2. Fast and Slow Pyrolysis of Aspen Poplar: Summary of Modeling Assumptions Relative to Fast and Slow Pyrolysis

	Fast	Slow
Reactor temperature (℃)	500	420
Yields (weight%, dry feedstock basis)		
Biochar	14 %	31 %
Organics (pyrolysis liquid)	66 %	56 %
Water (of pyrolysis)	7 %	6 %
Pyrolysis gases	13 %	7 %

Source: Bridgwater and Peacocke, 2002

The process inputs and outputs are given in Table 3. The lower heating value of the char, recovered pyrolysis liquids and syngas are taken as 11.4MJ per kg (McCarl et al., 2009), 17.3 MJ per kg and 6.5 MJ per kg (Tola and Cau, 2007), respectively. Here we assume all the pyrolysis gas is used for processing heat, fluidizing and are oxidized in the biochar combustor prior to discharge. All the produced pyrolysis liquids are, in turn, used for electrical power generation in dual-fuelled diesel engines, which is an area still under development. Note that it is also possible to make use of a modified gas turbine, avoiding the need to use the diesel as a pilot fuel (alternatively, biodiesel could be used).

Table 3. Summary of Primary Inputs and Outputs

Process Inputs		Rate
Moisture content	(wt %)	5.20
Particle size	(mm)	1000
Feed rate	(kg/h)	2.10
Natural gas consumption	(kg/hr)	31
Cooling water consumption	(t/hr)	89
Diesel for fuel engines	(kg/hr)	83.6
Process outputs (wt%, dry wood basis)		
Water (reaction product)		9.7
Char		16.50
Organic Liquids (dry)		62.90
Total gas		11.50

Source: Bridgwater and Peacocke, 2002; McCarl et al., 2009

The equipment costs are based on actual or published costs in the U.S. at the end of 2007 and the associated estimated total capital costs are given in Table 4 (McCarl et al., 2009). These capital costs are then amortized over the life of the project for use in system cost estimation. Plant life is assumed to be 20 years for 80 percent availability with an interest rate of 12 percent. Feedstock preparation costs are assumed to be US$11.35 per ton (based on opinion of Peacocke) to dry, comminute, size and store the poplar prior to pyrolysis.

Table 4. Total Capital Investment Cost Estimates for the Three Plant Modules in Million US$ (2007 Basis)

Plant component	Capital Cost
Pretreatment Plant Cost	3.6
Pyrolysis Plant Cost	10.6
Power Generation Capital Costs	9.6
Total Capital Costs	23.7

Source: McCarl et al., 2009

Table 5. Annual Costs of Raw Pyrolysis Liquids Production in US$1000 per Year and Variation with Delivered Feedstock Cost

	Cost delivered (US$1000/ton (dry feedstock))			
	56	75	94	112
Pre-treatment capital cost (annualized)	367	367	367	367
Biomass pre-treatment operating cost	334	334	334	334
Cost pyrolysis capital	1080	1080	1080	1080
Feedstock cost	3920	5250	6580	7840
Utilities-water	3867	3867	3867	3867
Labour	900	900	900	900
Maintenance	423	423	423	423
Overhead	423	423	423	423
Liquids production cost	7234	8564	9893	11059

The liquids production costs for different poplar costs are given in Table 5. This involves the annual use of 70,000 tons of poplar yielding 51,100 tons of bio-oil (including the water from pyrolysis and that in the feedstock), which costs between US$141.5 and US$216.4 per ton of bio-oil. Costs of electricity generation include fixed and variable costs, and these two cost components are given in Table 6.

In Table 6, the first six rows account for the electricity cost only; in order to obtain total cost, we add the cost from bio-oil and arrive at an annual total cost. As we did before, we will also divide the annual total cost by the electricity output to obtain a cost per kilowatt hour. Based on the information available, we calculate that the total electricity generated is 205,423 Mwh (tons of bio-oil used multiply by the electricity generation per ton of bio-oil plus electricity generated from diesel and natural gas). Then we obtain the cost per kwh, it is between US$5.15 to US$7.01 cents kwh.

Comparing these costs to 2008 Taiwan industrial electricity cost, which is 6.06 cents per kwh, we find if we can obtain the feedstock at a lower price, the electricity generated from pyrolysis would be cheaper than the average electricity price. Until now we have not included the benefits from reducing the greenhouse gas emissions; this analysis will be done in a later section. The same cost structure was used for the scenario of a slow pyrolysis plant where we used exactly the same fixed pyrolysis cost for 1 ton of biomass. As the slow pyrolysis yields relatively less bio-oil, it generates less electricity (156,045 Mwh) and results in a 32 percent higher electricity cost.

Table 6. Cost of Electricity Production in US$ 1000 per Year and Their Variation with Delivered Feedstock Cost

Fast pyrolysis	Cost delivered (US$1000/ton (dry feedstock))			
	56	75	94	112
Bio-oil cost	7234	8564	9893	11059
Total cost of electricity and bio-oil	10573	11903	13232	14398
Electricity production cost (U.S. cents/ kwh)	5.15	5.79	6.44	7.01
Slow pyrolysis	**Cost delivered (US$1000/ton (dry feedstock))**			
	56	75	94	112
Total Electricity	3339	3339	3339	3339
Bio-oil cost	7234	8564	9893	11059
Total cost of electricity and bio-oil	10573	11903	13232	14398
Electricity production cost (U.S. cents/kwh)	6.78	7.63	8.48	9.23

3.3.1.4. Selling Energy

As we mentioned before, the pyrolysis plant yields bio-oil, pyrolysis gas and electricity. For this case study, the relative yields are assumed to be 66 percent of bio-oil, 13 percent of syngas for fast pyrolysis, and 56 percent of bio-oil, 7 percent of syngas for slow pyrolysis (see Table 2).

In the following, an approach is developed to value these items. For simplicity and based on available data, we assumed for both the fast and slow pyrolysis scenarios that the bio-oil and syngas were used in plant operations and electricity generation. For a fast pyrolysis plant, a ton of poplar produces 3.4 Mwh and 2.82 Mwh for slow pyrolysis plant. As computed by McCarl et al. (2009), the fast pyrolysis related generation faces an operating cost of US$26.64 per ton of feedstock with a fixed cost of US$20.18 per ton. For slow pyrolysis, we assume that the costs per unit of electricity were the same. Since we calculated that the slow pyrolysis electricity yield was about 81 percent of the electricity generated by fast pyrolysis, we assume the costs of electricity produced by slow pyrolysis were 81 percent of electricity costs of production by fast pyrolysis.

This information is summarized in Table 7. Using the 2008 Taiwan energy price of US$60.6 per Mwh, we obtain the sales revenue shown in Table 7 and observe that fast pyrolysis is profitable but slow pyrolysis is not. Fast pyrolysis gains more because it produces more energy. However, to see the final profitability of both pyrolysis, we need to consider biochar and GHGs as a source of income along with other chemicals. The biochar and GHG aspects will be evaluated in subsequent sections.

Table 7. Returns and Costs and Biochar Yields for Fast and Slow Pyrolysis as Value Items Are Applied

	Fast	Slow
Feedstock cost	-$105.81	-$105.81
Pyrolysis cost (Modules I and II)	-$46.82	-$46.82
Generating cost (Module III)	-$43.26	-$35.04
Electricity value	$206.00	$170.90
Net margin (electricity only)	$10.11	-$16.77
Biochar yield (t)	0.140	0.310
Biochar value	$1.95	$9.55
Biochar haul cost	-$1.03	-$2.28
Net margin (electricity + biochar)	$11.03	-$9.5
GHG value	$8.96	$8.48
Net margin all	$19.99	-$1.02

3.3.1.5. Net Saleable Biochar

In this study we assume that none of the biochar is used to supply energy for the fast and slow pyrolysis plants, rather biochar produced from both systems is sold in the market. In the fast pyrolysis plant, we assume the net yield of biochar is 0.14 ton biochar per ton feedstock, while in a slow pyrolysis plant we assume the 0.31 ton biochar per ton feedstock is produced.

3.3.1.6. Biochar as a Soil Amendment

Lehmann et al. (2003) found that application of biochar to soil led to a reduction of nitrogen leaching by 60 percent and increases of crop productivity by 38 to 45 percent, with accompanying 20 percent savings in fertilizer and 10 percent savings in irrigation and seeds. As rice is the most important agricultural commodity in Taiwan, we assume the poplar-based biochar is applied to rice production. With biochar application, rice yield can increase (Steiner et al., 2007) and the yield can increase from 115 percent to 320 percent (Nehls, 2002). However, since studies on rice yield are limited and crop yield would vary under different weather, soil fertility and other conditions, we assume the rice yield will not increase as high as findings in Nehls' study would indicate. In turn, we assume the rice yield will increase by 5 percent after 5 tons of biochar is applied.

Intensive irrigation is required for rice production. One hectare of rice production requires 12,500 m^3 of water and two crops of rice can be harvested per year for most parts of Taiwan. Annual water requirements for rice then become 12,500 x 2 = 25,000 m^3. Based on our assumption, the 10 percent annual irrigation saving is 2500 m^3. However, the sources of irrigation water are rivers, aquifers and precipitation; only 9 percent of irrigation water is purchased. Therefore, the annual irrigation saving is 225 m^3 or US$ 22.50 per year. For an average baseline rice yield of 7.96 tons per ha and rice selling for US$623.03 per ton, the value of the yield increase is US$247.96 per ha per yr. Nutrients and seed are also replaced. The value of that replacement based on the application rate under the Taiwan Agricultural Sector Model (Chen and Chang, 2005) amounts to a saving of US$126.94 per ha when biochar is applied. The net benefit from yield increases and input savings realized for crop production then calculates to US$374.90 per ha.

Biochar was considered to persist somewhat permanently after the application as the biochar remains in the soil without rapid degradation. However, Lehmann (2007) also mentioned a certain amount of carbon is initially lost from raw biochar applications. Major et al. (2009) found that about 50% of biochar is subject to removal from the field from erosion large-rainfall events in particular. We assume the 5 percent yield increase only occurred the first time that biochar is applied and that the biochar can be applied ten more times with out further gain. That is, we have 5 percent increase in rice but to keep this increase permanently, we need to apply biochar ten times. However, since 50% of biochar is gone after the first year, we assume the yield increase will reduce from 5 per cent to 2.5 percent and persist permanently. Thus we can treat the 2.5 percent yield increase as an annuity capitalized forever at 5 percent multiply by 20 plus another 2.5 percent yield gain in the first year to obtain the net present value.

Consequently, the net present value of net gain is calculated to US$562.35 per ha. Before we can gain, we need to haul biochar back to the site. The cost associated with biochar application is based on the current rice practice. Before farmers plant the rice seedlings, they put base fertilizers in the soil and then, plow the cropland to mix the soil and fertilizer well. Based on this practice, we assume the biochar is mixed with fertilizer and soil during this stage. This application cost is calculated to US$40.18 per ton. The net value of biochar after we deduct the costs of this application amounts to US$361.45 per ha, which means a net value per ton of biochar of US$72.29 at the field. This value is higher than the approximate combustion value of the biochar as of August 2008. At that time, coal was worth about US$139.30 for a short tonne, and contains 12,500 MmBtu per ton. We also assume the biochar has approximately 4,900 MmBtu per ton or 39.2 percent of that of the coal, making its combustion value approximately US$54.73 per ton. The price of coal has fallen in recent times to and this makes the net value of biochar as an agricultural input even higher (coal price is about US$61.15 in April 2010, yielding a biochar combustion value of US$23.97 per ton).

Now we need to determine the proportion of land and volume of biochar per unit area. This varies in different assessments between a few tonnes to several tens of tonnes without a universally applicable recommendation (Lehmann and Rondon, 2006). Although Nehls's study (2002) showed the rice yield would increase from 115 to 320 percent based on 7.9 tons per ha application of biochar, we don't want to use the same rice yield increase in Taiwan because of the different weather and soil conditions and a conservative purpose. In turn, we set the biochar application rate at 5 tons per ha. The pyrolysis plants use poplar from 9,671 ha and after the biochar shrinkage of 5 percent due to less than perfect recovery, conveyance, application, fire and other losses, the pyrolysis plants yield enough biochar annually to treat 19.25 percent of the land under fast pyrolysis and 42.63 percent under slow pyrolysis. Therefore, the value of applying biochar to the land where the rice is planted calculated to US$69.58 per ha under fast pyrolysis and US$154.09 per ha under slow pyrolysis. Convert these values to per ton of feedstock and we get that the net value of biochar on land is US$1.95 per ton feedstock for fast pyrolysis and US$9.55 per ton for slow pyrolysis.

3.3.1.7. Hauling Biochar to the Land

Before we can apply biochar as a soil amendment, we must firstly haul it back to the field. In our study, we still assume the hauling distance to cropland is the same as moving the feedstocks to the pyrolysis plants. We use the same cost structure when calculating the hauling cost, but only the amount of biochar produced will be moving in this sub-section. However, as biochar is flammable and its combustibility must be controlled, we increase the fixed cost per truckload by 50 percent to reflect this issue. Then we obtain a hauling cost estimate of US$7.36 per ton of biochar when using fast or slow pyrolysis. As the conversion rate of poplar to biochar is different for fast and slow pyrolysis, this biochar hauling cost amounts to US$1.03 per ton of the raw poplar feedstock under fast pyrolysis and US$2.28 per ton of the raw poplar feedstock when using slow pyrolysis.

As we summarized in Table 7, we see there is a net gain of US$11.03 per ton of feedstock for fast pyrolysis and a net loss of US$9.5 per ton of feedstock for slow pyrolysis after adding in the value of the biochar offset by its hauling cost.

3.3.2. Greenhouse Gas Offset

The net greenhouse gas effect is another possible component of value. To estimate the net GHG offset, we use life-cycle analysis to estimate the GHG emissions based on fossil fuel use during poplar harvest, feedstock hauling, pyrolysis plant operation, biochar hauling, and biochar application. There is also GHG reduction when we generate electricity from a renewable source, recycling carbon C rather than emitting the C stored in the fossil fuels, along with biochar-induced reductions in nutrient use, irrigation saving and increases in sequestration.

3.3.2.1. Feedstock Harvest, Collection and Package

The 2009 experimental study of Yichun, China showed the average fossil use of wood harvest, collection and load (on collection site) is 0.355 liter/ m^3 petroleum and 1.391 liter/ m^3 diesel. We compute the total GHG emissions from 73,500 tons of poplar will be 335.815 ton and the average GHG emission from the feedstock harvest, collection and package would be 0.005 ton CO_2e per ton of feedstock.

3.3.2.2. Feedstock and Biochar Transport

Hauling emissions also need to be factored in and we did this assuming that a diesel-powered truck was used travelling 2.133km per liter of diesel. The total hauling distance of moving feedstock to the pyrolysis plant is 94,282 km for round-trip and the hauling distance for biochar is 6,299 km under fast pyrolysis and is 13,924 km for slow pyrolysis. This amounted to 0.0022 ton and 0.0028 ton CO_2e per ton of feedstock harvested for fast and slow pyrolysis, respectively.

3.3.2.3. Plant Operation

Fossil fuel is also used in the pyrolysis plant. We assume that the operation requires 217 tons of natural gas and 586 tons of diesel, without any biochar being combusted. Using EPA emission factors, we arrive at an estimate that plant fossil fuel use generates an estimated level of 0.0297 ton CO_2e per ton of feedstock.

3.3.2.4. Fossil Fuel Offset

Biofuels are recycling C. Namely, crops absorb CO_2 from the atmosphere when they grow, and release sequestered C at the time of combustion. Therefore, the bio-oil and syngas produced in the generation of biochar and electricity are recycled C that is not a net addition, as would be the case if we use fossil fuels that were long stored in the ground. As a consequence, we credit for the C that would have been used to generate the electricity yielded by the plant. We also assume that the electricity from a pyrolysis plant will replace the electricity generated from a coal-fired power plant. Under the GREET assumptions and the electricity levels given above, this yields an offset rate of 2.081 tons CO_2e per ton of feedstock under fast pyrolysis and 1.726 tons CO_2e per ton of feedstock under slow pyrolysis.

3.3.2.5. Reduced Input and Irrigation

Application of biochar also reduces input needs at the farm level as a consequence of improved nutrient use and enhanced water availability, saving the emissions from making and applying nutrient supplement/ replacements, as well as the N_2O emissions arising from the nitrification and denitrification that derive from fertilized fields. We also assume that reductions in irrigation use do reduce energy consumption by 10%. On average, the fertilizer use of a hectare of rice field is 69.65 kg nitrogen (N), 41.79 kg phosphorous (P) and 111.44 kg potassium (K). With the 20 percent nutrient saving, the nutrient savings per ha from N, P and K fertilizers are 13.93 kg, 8.36 kg and 22.29 kg, respectively. By using a formula illustrated by EPA Draft Regulatory Impact Analysis, the direct N_2O emission for 1 % of non-volatilized N is calculated as below:

(38) $[N_s * (1-V_s) + N_o * (1-V_o)] * Ef_D$

where,

N_S: Nitrogen in synthetic N fertilizer (99.86 % of total N fertilizer) [kg/acre]

N_O: Nitrogen in organic N fertilizer (0.14 % of total N fertilizer) [kg/acre]

V_S: fraction of synthetic N volatilized (= 10% from IPCC)

V_O: fraction of organic N volatilized (= 20% from IPCC)

Ef_D: N_2O emission factor (=1% from IPCC)

We computed the saved emissions from nutrient saving as 0.0017 ton CO_2e per ton of feedstock for fast pyrolysis and 0.0038 ton CO_2e per ton for slow pyrolysis. We also computed the emissions saving using energy consumption data for irrigation of Esengun et al. (2007), and we obtain the energy saving from reduced irrigation is 39.38 kwh. We convert this energy saving to GHG reduction and obtain the emission saving for fast pyrolysis is 0.0007 ton CO_2e per ton of feedstock and 0.0015 ton CO_2e per ton of feedstock for slow pyrolysis.

3.3.2.6. Sequestration Enhancement

Biochar resides in the soil for a long period of time although we assume only about 50% of it makes it through the first year (Lehmann, 2007), and consists of approximately 75 percent C. As such, biochar sequesters the C held in the soil in a manner that overcomes many of the permanence and volatility issues that commonly arise in criticisms of biological sequestration possibilities (West and Post, 2002; Post et al., 2004; Kim et al., 2008). So we credit the total C content of the biochar as a sequestration offset and this GHG offset amounts to a credit of 0.193 ton CO_2e per ton of feedstock for fast and 0.427 ton CO_2e per ton of feedstock for slow pyrolysis.

3.3.2.7. Net Balance

The balance of all C credits is shown in Table 8 and equals a net offset of 2.239 tons CO_2e per ton of feedstock for fast pyrolysis and 2.1203 tons CO_2e per ton of feedstock for slow pyrolysis. This amounts to 117 percent of the coal equivalent emissions for the electricity generated under fast pyrolysis and 147 percent for slow pyrolysis. Therefore, the offset efficiency is greater than the power offset due to the sequestration, nutrient offset and reduced irrigation elements.

3.3.2.8. GHG Value

Now we turn to the value of the GHG offset. The current CO_2 prices are about US$4 per ton of CO_2e on the Chicago Climate Exchange and about US$18.6 on the European Climate Exchange. We use US$4 in our summary calculations below and consider higher values in the sensitivity analysis section.

Table 8. Estimated Carbon Dioxide Offsets for Fast and Slow Pyrolysis

Category	Discount	Fast Pyrolysis	Slow Pyrolysis
Collect feedstock on farm		0.005	0.005
Haul feedstock and biochar		0.0022	0.0028
Irrigation saving		-0.0007	-0.0015
Operate pyrolysis		0.0297	0.0297
Reduce nutrients used on farms		-0.0017	-0.0038
Credit for displacement of coal electricity		-2.081	-1.726
Sequestration gain from biochar		-0.1925	-0.4265
Net GHG effect		-2.239	-2.1203

3.4. Totality of Value

Table 9 summarizes the calculations in the above sections, yielding a total estimate of value. The results show that based on our assumptions made in this study, the fast pyrolysis has a net gain of about UD$20 but slow pyrolysis faces a loss of about UD$1 under current conditions in Taiwan. We find that fast pyrolysis yields more profits. This is because under fast pyrolysis, the plant generates more electricity and brings in more revenue plus has a greater GHG offset. We also see the biochar value can make a difference to some extent, so in the next section we will present a sensitivity analysis to investigate some assumptions and examine how they affect our results.

Table 9. Economic Assumption and Results Summary with Economics Results Reported per Tonne of Feedstock

	Fast pyrolysis	Slow pyrolysis
Main assumptions		
Size of plant (L yr^{-1})	70,000	70,000
Yield bio-oil (%)	73	62
Yield syngas (%)	13	7
Yield biochar (%)	14	31
Land used (ha)	9,671	9,671
Average feedstock hauling distance (km)	14.75	14.75
Results ($ t^{-1} feedstock)	Fast	Slow
Cost of feedstock	-$105.81	-$105.81
Value of energy created	$206.00	$170.90
Value of biochar	$1.95	$9.55
Biochar hauling cost	-$1.03	-$2.28
Pyrolysis cost	-$46.82	-$46.82
Operating cost	-$43.26	-$35.04
GHG market effect	$8.96	$8.48
Net value	$19.99	-$1.02

3.5. Sensitivity Analysis

Since our study is based on numerous assumptions, it is necessary to perform a sensitivity analysis to help draw inferences about how critical various factors are. Several investigations were performed, leading to the following results given that all other elements are held constant:

- Fast pyrolysis remains profitable as long as the electricity price does not fall below US$54.72 per Mwh while slow pyrolysis requires an electricity price above US$61 per Mwh to make it profitable. Higher energy prices favor fast pyrolysis since it yields more electricity.
- Fast pyrolysis can make profits when feedstock cost is below US$125.8 per ton and slow pyrolysis is profitable if feedstock cost is lower than US$104.8 per ton. That is, if feedstock cost raises more than 18.9 percent, fast pyrolysis will not be profitable. For slow pyrolysis to be profitable it requires a 1 percent reduction on feedstock cost; otherwise, slow pyrolysis will not be able to make profits.
- Fast pyrolysis can make profits no matter how GHG price changes since its profits are higher than zero regardless of the GHG price. This means even if the world does not put enough emphasis on GHG emissions and set the GHG price equal to zero, fast pyrolysis is still worth doing for Taiwan. If we use the higher European GHG price, then this higher price will further improve the profitability of fast pyrolysis. However, it requires a per ton GHG price above US$4.48 for slow pyrolysis to be profitable.

- There are a wide range of experimental findings on the yield implications of biochar application. We assumed that biochar application increases rice yield by 5 percent on land which it was applied and only led to gain once. If rice yield increase more than we assumed, then it further enhances the profitability of fast and slow pyrolysis. If rice yield does not increase as much as we assumed, fast pyrolysis is still profitable but just less than what it was under our assumption. Slow pyrolysis has a net loss of US$1.02 and this requires a yield increase of 5.5% so the slow pyrolysis can eventually make profits.
- Slow pyrolysis is less profitable than fast pyrolysis under the assumed yield increase (5 percent for the first year, and 2.5 percent afterward). However, if the rice yield increases to 18.4% (9.2% yield increase after the first year), then slow pyrolysis is more profitable than fast pyrolysis and the net gain from slow pyrolysis increases to US$25.33 per ha from a loss of US$1.02 per ha.
- The capital costs of construction are rather uncertain as are, to a lesser extent, the operating costs. If the pyrolysis construction cost increases by 42.7 percent for fast pyrolysis or doesn't decrease more than 2.2 percent for slow pyrolysis, then they will not be profitable. When pyrolysis costs remain the same, the operating costs can also affect the profitability of pyrolysis. When operating cost increases by 46.2 percent for fast pyrolysis, it also reduces the

profit of fast pyrolysis to zero. For slow pyrolysis to be profitable, the operation must reduce about 2.9%; otherwise slow pyrolysis faces a loss.

3.6. Summary

Pyrolysis and associated biochar are valuable in terms of nutrient reductions, irrigation saving, yield increases, bioenergy products and GHG offsets. These benefits are partly offset by the costs of production, hauling and processing, along with some increases in GHG emissions. In this study, we adopt a similar approach to that used in McCarl et al. (2009) to analyze corn stover but apply it to the case of poplar in Taiwan. Our case study, which is assumption laden (relying on highly uncertain data), finds fast pyrolysis is currently profitable but slow pyrolysis faces a loss. This difference of their profitability is largely due to the higher sales revenue from electricity generation of fast pyrolysis and partly due to cost savings and GHG reductions. We also find these results are sensitive to construction cost, feedstock cost and energy prices. Fast pyrolysis is more profitable than slow pyrolysis; however, a study of yield increases shows that if 18.4% of rice yield increase from biochar application is realized, then the profitability of slow pyrolysis exceeds that of fast pyrolysis. In addition, we do find the value of applying biochar as a soil amendment is higher than its value as an energy source.

4. ENVIRONMENTAL IMPACT AND ENERGY PRODUCTION: EVALUATION OF BIOCHAR APPLICATION ON TAIWANESE SET-ASIDE LAND

4.1. Introduction

Taiwan is interested in producing renewable energy for domestic use and reducing the reliance of imported fuels. More than 99% of fossil fuels are imported and this makes Taiwan extremely vulnerable to disruptions and high energy prices. As Taiwan has some idled cropland resultant from policies arising from their participation in the World Trade Organization (WTO), there is potential for Taiwan to begin producing bioenergy by utilizing this set aside land. In order to develop bioenergy production capability and make decisions on associated agricultural policies, however, information on choices of bioenergy crops, types of bioenergy produced, changes in welfare and GHG contribution must be provided to Taiwan. Biomass can be used in at least three ways to provide energy:

- by direct combustion to provide heat for use in electricity generation;
- by chemical transformation to provide liquid fuels for combustion or transportation; and
- by pyrolysis to provide a liquid fuel that can substitute for fuel oil in any static heating or electricity generation application. The liquid can also possibly be upgraded to produce a range of liquid fuels and specialty and commodity chemicals although we will not consider that herein.

Based on the available bioenergy techniques, Taiwan can produce bioenergy in the forms of ethanol, directly combustion biopower and biopower through pyrolysis. As these three technologies are not mutually exclusive, they can be employed at the same time and therefore it is necessary for us to consider all combinations. Pyrolysis involves heating biomass in the absence of oxygen and results in the decomposition of biomass into bio-oil, bio-gas and biochar. In this study, two types of pyrolysis techniques and two uses of biochar, a byproduct of pyrolysis, are incorporated.

Bioenergy enhances Taiwan's energy security while it also has a contribution to the world by mitigating the Greenhouse Effect. Climate change is one of the most important challenges facing the modern world. Increasing temperature trends have now been unequivocally observed and are occurring at an unprecedented rate (IPCC 2007). Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are important drivers of the anthropogenic greenhouse effect, all of which are released both through the burning of fossil and biomass fuels as well as through agricultural activity. Rising ocean level is another concern of Taiwan because Taiwan is an island on the Pacific and is threatened by the higher ocean level. To mitigate global climate change, renewable energy is of growing importance in satisfying environmental concerns over fossil fuel usage and its contribution to climate change. Wood, grasses and other forms of biomass are one of the main renewable energy resources available. Bioenergy such as bioethanol, biodiesel and biopower are currently encouraged and produced in the United States and Europe. However, liquid forms of bioenergy are under some criticism that, in certain cases, they generate more GHG emissions than they offset.

Another technology that can be employed is pyrolysis. Biochar, as one of the byproducts from pyrolysis, has been shown to improve agricultural productivity and the environment in several ways, is stable in the soil (Lehman et al., 2003) and has nutrient-retention properties that lead to increases in crop yields (Chan et al., 2007). In addition, biochar offers a chance to sequester carbon (Lehmann, 2007). As pyrolysis can provide bioenergy and offset more GHG emissions, it is a potential bioenergy technique that Taiwan may be interested in. The first essay explored the Taiwanese bioenergy production potential in the forms of ethanol and electricity and the second essay studies the bioenergy production potential and GHG mitigation potential from pyrolysis. This third essay unifies the first two and examines that how Taiwanese bioenergy production may be affected when all three bioenergy techniques become available alternatives.

In this study, we first examine the economics of energy production and GHG emissions reduction under fast and slow pyrolysis. Then we will examine all three production alternatives while the bio-oil and bio-gas from these two pyrolysis systems are used to generate electricity, while the biochar is either burned in the plant or hauled back to the agricultural cropland. This study makes a contribution as it provides additional information on Taiwan's ethanol, biopower and pyrolysis production and helps Taiwan to determine, when facing multiple bioenergy options, which bioenergy technology may help achieve the objectives of energy security and GHG mitigation.

4.2. Literature Review

Fast pyrolysis is a thermal decomposition process that occurs at moderate temperatures with a high heat transfer rate to the biomass particles and a short hot vapor residence time in the reaction zone. The rate of and extent of decomposition of biomass depends on the process parameters of pyrolysis temperature, biomass heating rate and pressure (USDOE, 2005; Bridgwater, 2005). Several reactor configurations have been shown to assure this condition and to achieve yields of liquid product as high as 75% based on the starting dry biomass weight (Ringer et al., 2006, Wright et al., 2008). According to the report of USDOE (2005), in the 1990s several fast pyrolysis technologies reached near-commercial status, and the largest pyrolysis plant, which can process 50 tons of bio-feedstock per day, was operated by Red Arrow Product Co., Inc. in Wisconsin. Finland, Canada, and the Netherlands also have smaller capacity pyrolysis plants. In general, slow pyrolysis yields more biochar and less bio-oil than fast pyrolysis. Wright et al. (2008) indicate fast pyrolysis yields about 15% biochar, 70% bio-oil and 13% bio-gas while Ringer et al. (2006) indicate that under slow pyrolysis about 35% of the feedstock carbon ends up as biochar, 30% as bio-oil and 35% as bio-gas.

However, the yields and properties of the generated liquid product, bio-oil, depend on the feedstock, the process type and conditions, and the product collection efficiency (USDOE, 2005). For example, Bridgwater and Peacocke (2002) showed that if Aspen poplar is fed in pyrolysis, the yields of bio-oil, bio-gas and bio-char are 66%, 13% and 14% respectively. Radlein (2007) shows that bark yields more biochar than bagasse or wheat straw, but bagasse yields relatively more bio-oil than bark or wheat straw.

During the process of pyrolysis, bio-oil, bio-gas and bio-char are produced. As bio-oil and bio-char are generally used to produce energy, biochar used as a soil amendment has been studied intensively. Land application of biochar is not a new concept. Sombroek (2003) shows that in the Amazon Basin, soil has received large amounts of charred materials and Erickson (2003) shows that these biochar applications were most likely a result of both habitation activities and deliberate soil application by native populations before the arrival of Europeans. Biochar has the potential to improve nutrient retention. Deluca et al. (2009) presents a potential mechanism for how biochar modifies nutrient transformations. They show bio-available C may be adsorbed to biochar surfaces, thereby reducing the potential for immobilization of nitrates formed under biochar stimulation of nitrification. Thus adding biochar to soil with an organic N source yielded an increase in net nitrification. Fire also induces a short-term influence on N availability but biochar may act to maintain this effect for years to decades,

Chan et al. (2007) showed if N fertilizer was not added, biochar application did not increase the yield of radishes even with 100 tons per ha biochar rate. They find, however, if biochar and N fertilizer are applied together, the biochar/nitrogen fertilizer interaction is significant and biochar can improve the N fertilizer use efficiency of the plant. For example, in their experiment the dry material of radishes increased from 95% to 266% under different biochar application rates (10, 50 and 100 tons per ha). Applications of biochar (or similar materials such as volcanic ash) on crop yields have been studied since 1980 (Iswaran et al., 1980; Kishimoto & Sugiura, 1985; Chidumayo, 1994; Glaser et al., 2002; and Oguntunde et al., 2004; Steiner et al., 2007). Crops that have been studied included maize, soybeans, Sugi trees, Bauhinia trees, peas, cowpeas and Mung beans. Throughout these studies, we see there is no consensus on how much biochar should be applied. In these studies, biochar was applied ranging from 0.5 to 135 tons per hectare and most of these applications result in the increase of crop yields except for Kishimoto & Sugiura (1985) with a 5 and 15 tons per hectare application of volcanic ash on soybean fields.

In terms of GHG offsets, the precise duration of biochar's storage time is important because of the permanence concern. That is, if biochar decomposes very soon, the carbon the biochar can recycle from the atmosphere may not be significant. Fortunately, Lehmann et al. (2006) shows that biochar is a relatively stable form of C and can stay in the soil from several hundred to several thousand years. When converting biomass C to biochar C, it leads to sequestration of about 50% of the initial C compared to the low amounts retained after burning (3%) and biological decomposition (less than 10-20% after 5-10 years). Lehmann et al. (2006) also calculates that the carbon dioxide emission offset can be 12-84% greater if biochar is put back into the soil instead of being burned to offset fossil fuel use. McCarl et al. (2009) shows that pyrolysis can have offset efficiencies greater than 100% when compared with the emissions of the fossil fuel inputs that are replaced.

4.3. Study Setup

In this study, sweet potato, poplar, willow and switchgrass will be examined as potential pyrolysis feedstocks. Bio-oil and bio-gas from fast and slow pyrolysis are used for electricity generation. For biochar, we have two alternatives. First, biochar is burned to provide electricity. Second, we apply biochar to cropland and obtain agricultural benefits (i.e. higher crop yields etc.).

4.3.1. Outputs from Pyrolysis

Table 10 shows the pyrolysis outputs for poplar and sweet potato. Note the biochar/biooil/biogas yields for willow and switchgrass are assumed to be the same as poplar and the yield for sweet potato is assumed to be the same as corn stover from McCarl et al. (2009).

Table 10. Outputs from Fast and Slow Pyrolysis

	Output	Poplar	Sweet potato
Fast Pyrolysis	Biooil	66%	70%
	Biogas	13%	15%
	Biochar	14%	13%
Slow Pyrolysis	Biooil	56%	30%
	Biogas	7%	35%
	Biochar	31%	35%

4.3.2. Electricity Produced from Pyrolysis

In Table 11 we provide information about the electricity generated from a ton of feedstock. However, electricity generated in Table 11 is only from the use of bio-oil and bio-gas. In the first part of our study, which address the burning biochar, we need to compute the electricity generated from biochar. The lower heating value per kg of biochar is taken as 11.4 MJ (McCarl et al., 2009) and we calculate the electricity from burning biochar is 0.141, 1.11 Mwh per ton of feedstock for sweet potato-based fast and slow pyrolysis and 0.443, 0.981 Mwh for poplar-based fast and slow pyrolysis, respectively. In McCarl et al. (2009), fast pyrolysis produces 1.25 Mwh per ton of corn stover and this amount of electricity includes burning of some biochar (so the biochar can be used as a soil amendment which reduces biochar yield to 4.45% of feedstock rather than 13%). Therefore, in our calculation, we don't want to use 13% biochar yield in fast pyrolysis when sweet potato is the feedstock; instead, we use 4.45% so the calculation could be consistent with McCarl et al. (2009).

Table 11. Electricity from Fast and Slow Pyrolysis (without Biochar)

Unit (Mwh)	Sweet Potato	Poplar
Fast Elec	1.25	3.4
Slow Elec	0.31	2.82

Adding bio-oil, bio-gas and biochar together, the electricity generated from biomass through pyrolysis is shown in Table 12. In addition, we also assume that electricity produced by willow and switchgrass are the same as poplar.

Table 12. Electricity from Fast and Slow Pyrolysis (with Biochar)

Unit (Mwh)	Sweet Potato	Poplar
Fast Pyrolysis	1.391	3.843
Slow Pyrolysis	1.420	3.801

4.3.3. GHG Offsets from Pyrolysis

In Table 13, we show the net GHG emission offsets from burning bio-oil, bio-gas and biochar. We need to modify the amount of GHG offsets from McCarl et al. (2009) as used in section 3 because when burning biochar, the biochar is used to provide energy and not hauled back to the farm. For this reason, we ignore the GHG emission from transporting biochar to the field, the reductions from reduced fertilizer application and the sequestration enhancement from biochar, but we need to add in the GHG emission offset from burning biochar in the pyrolysis plant as it displaces fossil fuels.

Table 13. Carbon Dioxide Offset from Burning Bio-oil, Bio-gas and Biochar

CO_2e/t feedstock	Sweet Potato	Poplar
Fast Pyrolysis	0.769	2.318
Slow Pyrolysis	0.810	2.258

4.3.4. Create New Budget with Biochar Application

For sweet potatoes, the amount of electricity generated can be obtained from McCarl et al. (2009), but we need to adjust the hauling costs to be appropriate for Taiwan. Again, we use McCarl et al.'s (2000) adaptation of French's (1960) procedure to approximate hauling cost, which assumes that the pyrolysis plant is in the center of a square surrounded by a grid layout of roads. In turn, the hauling cost (H) and average hauling distance ($\overline{D}$) is given by the following formulae:

(39) $$H = (b_0 + 2b_1\overline{D})\ S / \text{Load}$$

and

(40) $$\overline{D} = 0.4714\sqrt{\frac{S}{640Y}}$$

where:

$\overline{D}$ is the average distance that the feedstock is hauled in miles;

S is the amount of feedstock input for a bio-refinery to fuel the plant, which we assume is 1 Mt plus an adjustment for an assumed 5 percent loss in conveyance and storage;

Load is the truck load size, which we assume to be 23t;

Y is the crop yield (57.98 tons per ha, or 23.19 tons per acre) multiplied by an assumed crop (sweet potato) density of 38 percent;

640 is a conversion factor for the number of acres per square mile;

B_0 is a fixed loading charge per truckload and is assumed to be US$90 per truckload for a 23 ton truck; and

B_1 is the charge for hauling including labor (per mile) and maintenance costs, which is assumed to equal US$2.20.

This calculation includes 5 percent yield loss during transportation, a service area of 1,268 ha of cropland and an average hauling distance of 2.723 km (1.7 miles) with a cost of US$4.45 per ton. This cost represents the hauling cost that transports biomass to the pyrolysis plant. There is no hauling cost on biochar if it is used to generate power. However, in the analysis of using biochar as a soil amendment, we need to consider the hauling cost associated with hauling biochar back to the rice field.

4.3.4.1. Location of Pyrolysis Plant

Before we can calculate the hauling distance from the pyrolysis plant, we need to determine where the pyrolysis plant will be built. We also assume that farmers purchase biochar directly from the plant. Based on the information available, labor and land are relatively cheaper in south Taiwan than in other areas. We assume that the pyrolysis plant locates in Chiayi and distributes biochar to other subregions. Since biochar is flammable, we increase the fixed cost by 50% and calculate the hauling distance from Chiayi to other counties. We assume that the average biochar hauling distance is within 10 km of Chiayi and increases an additional 25 km to transport biochar to another county. For example, average hauling distance within Chiayi is 10 km, and it increases to 35 km to transport biochar to Yunlin and 60 km to Changhua. The longest hauling distance is from Chiayi to Ilan and is assumed to be 210 km. With assumed average hauling distance, we calculate hauling costs using McCarl et al. (2000) and include them in our alternative crop budgets. This means when a hectare receives 5 tons of biochar, an additional two cost items must be considered. They are (1) cost of purchasing biochar and (2) cost of hauling biochar from the plant to the cropland. As coal price is around NT$1.7 per kg and biochar contains about 40% of energy relative to coal, we assume the price of biochar to be NT$1.0 per kg.

4.3.4.2. Biochar Effects on Cropland

Biochar has impacts on soils when used as a soil amendment. In terms of water holding capacity, Tryon (1948) shows that charcoal added to sandy soil can enhance the soil's available moisture and Glaser et al. (2002) show that soil water retention increased by 18% after biochar application. For this reason, we assume that, with biochar application, irrigation water savings can reach 10%. In terms of crop yield enhancement, Lehmann (2007) shows that biochar increases the plants available nutrients in the soil thus offering the possibility of improving crop yields. This is due to that the biochar's enhancement of the ability of soils to retain cations in an exchangeable and thus plant-available form, which is also called CEC. Crop yield increases have been shown in other studies (Iswaran et al., 1980; Kishimoto & Sugiura, 1985; Chidumayo, 1994; Glaser et al., 2002; and Oguntunde et al., 2004; Steiner et al., 2007) and the increases ranged from 44% to 249% for different crops and biochar application rates.

Nehls (2002) also shows that with a 7.9 tons ha^{-1} of biochar application, rice yield would increase from 115% to 320%. To be conservative, we then assume that rice yield will increase by 5% in this study. In terms of seed and nutrient savings, the application of biochar increases the efficiency of nutrients by a higher uptake/leach ratio (Steiner et al., 2007). Lehmann et al. (2003) also presents that biochar application would lead to a reduction of N leaching by 60 percent with an accompanying 20% savings in fertilizer and 10% savings in seeds. Several studies find that biochar can improve seed germination rate; however, they did not indicate how many seeds are actually saved (Chan et al., 2007; Free et al., 2010). We assume that the seed and nutrient savings are based on Lehmann et al.'s 2003 study.

4.3.4.3. Yield Risk

In this study, crop yields are based on the observed data from 1990 to 2003. However, crop yield may be affected dramatically by various factors. For example, typhoon is a natural disaster to Taiwan and on average, attacks Taiwan several times a year. High precipitation, flood, and mud flow are common consequences resulted from typhoons. This usually destroys the agricultural crops and results in a loss to farmers. However, woods such as poplar and willow may still stay in the crop fields but some crops such as sweet potato may be gone. This indicates that crop yields can be affected differently when facing the same impacts. This study does not take the probability of occurrence of typhoon (and the consequent loss in bioenergy feedstock) into account, but it is necessary that this kind of impacts can potentially affect the bioenergy feedstock production and bioenergy production.

4.3.5. Scenario Setup

In this study, two types of scenarios (burn biochar & use biochar as a soil amendment) will be compared under different GHG prices, ethanol prices and coal prices. In addition, we examine two kinds of option bundles for each type of scenario. The first bundle includes only pyrolysis and the second bundle includes ethanol, biopower and pyrolysis. The work of the first bundle is used to compare the result of first essay, which only examines ethanol and biopower. The second bundle includes all bioenergy alternatives and is an extension of essay 1 and the first bundle.

4.4. Results

We first present the results when pyrolysis is the only option and then present the results when ethanol, biopower and pyrolysis are competing with each other.

4.4.1. Results of Pyrolysis Only

Table 14 shows the result of burning bio-oil, bio-gas and biochar in the pyrolysis plant. It shows that slow pyrolysis produces more electricity than fast pyrolysis. Fast pyrolysis provides a quantity of electricity equivalent to 1.70% to 1.84% of Taiwan's electricity demand and slow pyrolysis provides 1.74% to 1.88%. Electricity produced from pyrolysis is higher than the biopower results in essay 1, which provides 0.157% of electricity. In either fast or slow pyrolysis, sweet potatoes obviously dominate other bioenergy crops. In fast pyrolysis, poplar planted area decreases from about 7,500 hectares to 2,690 hectares when GHG price and coal price increase while sweet potato planted area increases from 109,790 hectares to 126,030 hectares when these prices increase.

Poplar, willow and switchgrass are less competitive than sweet potato, a consequence of their relatively low yield. Sweet potato, on average, yields 57.98 tons per ha per year and is much higher than the yields of poplar, willow and switchgrass. For this reason, even though wood-based pyrolysis yields more electricity on a per ton feedstock basis, their lesser yields per ha make them less competitive. We also see that poplar enters into the bioenergy production when pyrolysis is the only choice while switchgrass is produced and processed in the ethanol/electricity study (essay 1). The reason that poplar replaces switchgrass in this study is based on our yield assumption. In essay 1, poplar, willow and switchgrass have different ethanol/electricity conversion rates and thus have different GHG offset rates. However, in the pyrolysis study, electricity production and GHG offsets for willow and switchgrass are assumed to be the same as poplar and these three bioenergy crops only differ in their crop yield and production costs. Sweet potato used in slow pyrolysis yields more electricity than in fast pyrolysis while poplar, willow and switchgrass used in slow pyrolysis yield less electricity than in fast pyrolysis. This makes wood-based pyrolysis even less competitive and only sweet potatoes are produced in slow pyrolysis scenarios.

Table 14. Simulation of Fast and Slow Pyrolysis with Biochar Burned for Power

Pyrolysis		Fast	Slow	Fast	Slow
GHG Price	NT$/ton	300	300	300	300
Coal Price	NT$/kg	1.7	1.7	3.45	3.45
Electricity Production	1000 kwh	3764627	3848648	3764056	3973143
Electricity Supply	%	1.703	1.741	1.703	1.798
CO2 Emission Reduction (b1)	Tons	2082357.3	2194258.5	2082030.7	2265237.7
CO2 Reduction	%	0.467	0.492	0.467	0.508
GHG Price	NT$/ton	500	500	500	500
Coal Price	NT$/kg	1.7	1.7	3.45	3.45
Electricity Production	1000 kwh	3934166	4021518	4065598	4147184
Electricity Supply	%	1.780	1.820	1.840	1.877
CO2 Emission Reduction (b1)	Tons	2175883.6	2292818.3	2244770.7	2364464.8
CO2 Reduction	%	0.488	0.514	0.503	0.530

Table 15 shows the results when bio-oil and bio-gas are used for electricity generation and biochar is used as a soil amendment. In terms of electricity generation, fast pyrolysis produces about 3.5 times more electricity than slow pyrolysis and satisfies 1.602%-1.647% of annual electricity demand. Slow pyrolysis produces relatively less electricity and only provides about 0.429% to 0.496% of electricity demand. However, slow pyrolysis offsets more carbon dioxide than fast pyrolysis as biochar is able to store carbon in a more stable form. More biochar means more carbon is kept in the soil and, therefore, net GHG emission offsets from slow pyrolysis are higher, even with lower electricity production. When coal price increases from NT$1.7 per kg to NT$3.45, the electricity produced generally increases and more set-aside land is converted to grow bioenergy crops. However, we find that in slow pyrolysis, as GHG price increases from NT$300 to NT$500, net GHG emission offsets increase but electricity production decreases. This is because on a per hectare basis, sweet potato-based pyrolysis offsets more GHGs and farmers plant more sweet potatoes and less poplar, despite the result that poplar-based pyrolysis provides more electricity.

In this study, poplar dominates willow and switchgrass when pyrolysis technology is chosen. This may be explained by the original assumption that poplar, willow and switchgrass yield exactly the same amount of bio-oil, bio-gas and biochar, and thus the same GHG offset ratio. This assumption may be adjusted after some studies on the pyrolysis output yields and the net GHG offset of willow and switchgrass are compared.

The results also indicate a high GHG emissions offset on a per hectare basis and, on average, slow pyrolysis offsets more GHGs than fast pyrolysis. This high offset ratio is primarily due to the high crop yield of sweet potatoes. Annual GHG emissions reduction from pyrolysis is from 2.34 to 3.25 million tons under fast and slow pyrolysis respectively. Compared to the about 0.06% of total GHG emissions reduction reported in essay 1, pyrolysis can offset GHG emissions up to 0.72% of annual emissions, using the estimated 443 million tons of CO_2e in 2005. As slow pyrolysis yields more biochar,

biochar can be applied on more hectares as more sweet potatoes are planted and sent to the pyrolysis plant.

Table 15. Simulation of Fast and Slow Pyrolysis with Biochar Applied to Rice Fields

Pyrolysis		Fast	Slow	Fast	Slow
GHG Price	NT$/ton	300	300	300	300
Electricity Price	NT$/kg	1.7	1.7	3.45	3.45
Electricity Production	1000 kwh	3539502	948108	3547496	1096976
Electricity Supply	%	1.6016	0.429	1.6052	0.4964
CO2 Emission Reduction (b1)	Tons	2335412	3109549	2340746	3014350
CO2 Reduction	%	0.5236	0.6972	0.5248	0.6759
CO2 Emission Reduction per hectare (d1)= (b1)/(a1+a2)	kg/ha	18922.4	25107.3	18965.	23412.4
Pyrolysis		Fast	Slow	Fast	Slow
GHG Price	NT$/ton	500	500	500	500
Electricity Price	NT$/kg	1.7	1.7	3.45	3.45
Electricity Production	1000 kwh	3604663	905326	3640701	972990
Electricity Supply	%	1.6311	0.4097	1.6474	0.4403
CO2 Emission Reduction (b1)	Tons	2378467	3248791	2402246	3198332
CO2 Reduction	%	0.5333	0.7284	0.5386	0.7171
CO2 Emission Reduction per hectare (d1)= (b1)/(a1+a2)	kg/ha	18854.2	25233.3	18658.2	24841.4

We also find the hectares that receive biochar in different counties under fast and slow pyrolysis would be different. Amounts of biochar produced in the fast pyrolysis process are less than that in the slow pyrolysis process. On average, about 25,500 hectares of rice fields receive biochar as a soil amendment. Interestingly, Chiayi, the county where we assume the pyrolysis plant is built, does not receive biochar for its cropland; instead, biochar is transported to counties that are further away. This indicates that benefits in terms of cost savings, and yield increases of rice fields in Chiayi is lower than the benefits obtained in Changhua, Pingtung and Ilan. As slow pyrolysis produces more biochar, more hectares in more counties receive biochar. But we see most of the counties that receive biochar are located in southern and central Taiwan, where rice yields are higher, input costs are lower and transportation costs are lower.

4.4.2. Results of Ethanol, Biopower and Pyrolysis

Production of ethanol and biopower is affected by the existence of pyrolysis as they are competing with the same land and bioenergy feedstocks. Therefore, it is expected that bioenergy production in the forms of ethanol and biopower will change when pyrolysis is an alternative. This subsection presents the results of including all three alternatives (ethanol, biopower, and pyrolysis).

In this study, 5 GHG prices (NT$ 5 per ton of CO_2, NT$10, NT$15, NT$20 and NT$30), 3 ethanol prices (NT$20 per liter of ethanol, NT$30, and NT$40) and 2 coal prices (NT$1.7 per kg of coal and NT$3.45) are simulated for both burning and hauling biochar in fast and slow pyrolysis. In Figures 6 to 13 presented below, two types of labels (A_{ij} and B_{ij}) are shown where A stands for burning biochar and B stands for applying biochar in rice fields. The subscripts i represents the ethanol price (i=1 when ethanol price = 20) and j represents the coal price (j=1 when coal price = 1.7).

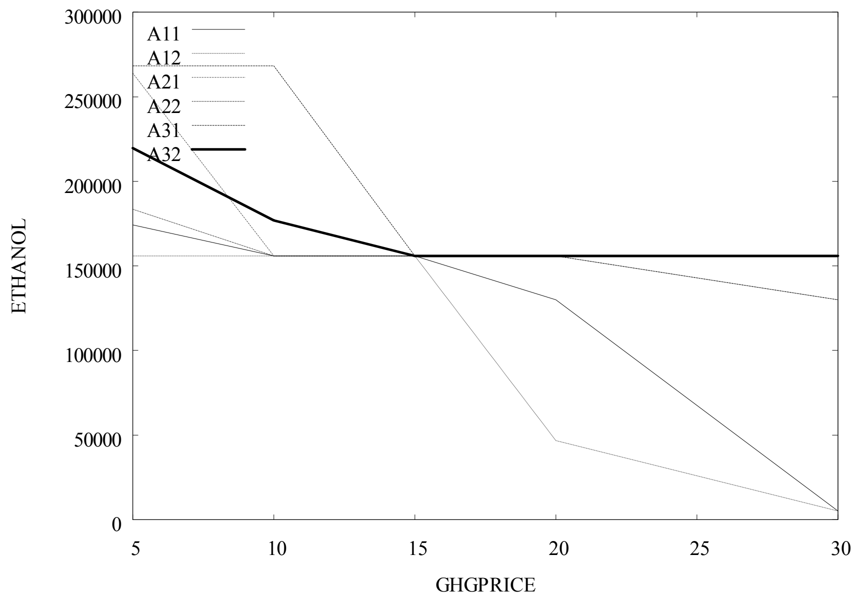

Figure 6. Ethanol production (in 1000 liters) under varying carbon prices when biochar is burned

Figure 6 shows how ethanol production is affected by GHG process when biochar is burned in the pyrolysis plant. Basically, ethanol production decreases when GHG prices rise. When GHG price keeps rising, ethanol production at a lower ethanol price decreases faster than at a higher ethanol price. If the ethanol price is NT$40, ethanol production does not decrease so much even with the high GHG price. Higher ethanol price means more ethanol production, but the amount of ethanol produced is not able to fulfill Taiwan's E3 ethanol demand. As we face higher GHG price, ethanol production shrinks due to the competition of biopower and pyrolysis, which offset more GHG emissions. A similar situation occurs when biochar is applied in the rice fields (Figure 7). However, when biochar is applied the net GHG offset is a little bit higher than that of burning biochar. The higher GHG contribution of using biochar as a soil amendment leads to a bigger decrease of ethanol production, mainly due to the lower

GHG emissions contribution of ethanol. When ethanol price is low, a reduction of ethanol production is more obvious.

We also find that when biochar is burned for electricity generation, that ethanol production is higher than when biochar is used as a soil amendment. This can be explained by that when biochar is used as a soil amendment, it sequesters more GHG and thus, as GHG prices rise, more sweet potatoes are sent to the pyrolysis plant. Therefore, fewer sweet potatoes are used to produce ethanol and this situation expands as GHG price increases. Because of the GHG offset ability, bioenergy production shifts to pyrolysis-based electricity when GHG price increases but when ethanol price is high, ethanol production does not reduce that much facing high GHG prices.

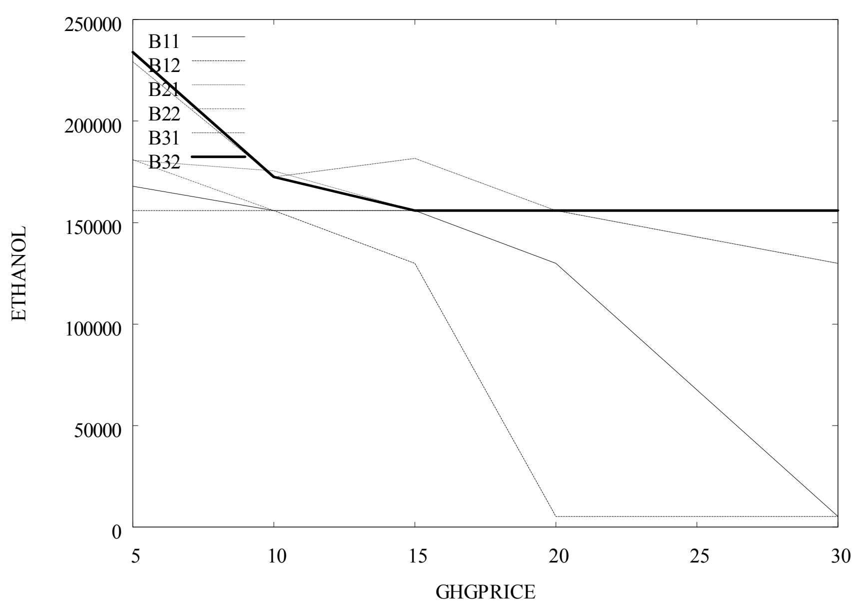

Figure 7. Ethanol production under varying carbon prices when biochar is applied

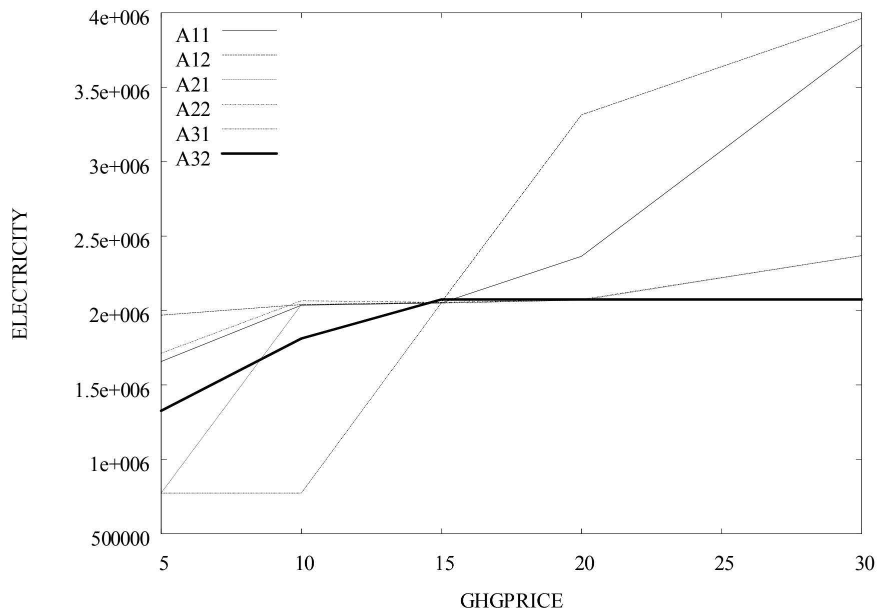

Figure 8. Electricity production under varying carbon prices when biochar is burned

Figures 8 and Figure 9 present the electricity production results. When pyrolysis is simultaneously considered as an energy production alternative, traditional electricity production is reduced to a very low amount and most of the electricity is produced from pyrolysis because a ton of biofeedstock generates a higher amount of electricity in pyrolysis. In addition, we find that electricity production is higher when biochar is used as an energy source. In the burning biochar case, about 1.79% of electricity demand can be satisfied from pyrolysis at high GHG and coal prices and this percentage reduces to about 0.35% when the GHG price is low and ethanol price is high. If we hold the ethanol price constant, GHG price increases leads to an expansion of pyrolysis-based electricity. We also find that when biochar is applied in the rice fields, bioelectricity provides about 1.24% of electricity demand when GHG price reaches NT$30 per ton of CO_2.When GHG price is low, the difference of electricity production between the uses of biochar is not significant. This may be explained as follows: when GHG price is low, ethanol production remains high and there is less room for electricity production. Coal prices affect electricity production. We find that when coal price doubles, the electricity production increases for burning biochar and applying biochar as a soil amendment also increases.

Moreover, we can see that when biochar is burned, electricity production increases more than when biochar is put back into the rice fields. This is likely because burning biochar directly provides more valuable products (electricity) when coal price rises. As pyrolysis-based electricity also offers significant amounts of GHG offsets relative to the ethanol and coal-fired electricity production, GHG price changes have bigger impacts on expansion of pyrolysis-based electricity production.

We also find that when GHG price and ethanol price are low but coal price is high, fast pyrolysis dominates slow pyrolysis because fast pyrolysis produces more electricity. However, when GHG price increases, biochar becomes more valuable. Because slow pyrolysis produces more biochar, it dominates fast pyrolysis when we face higher GHG prices.

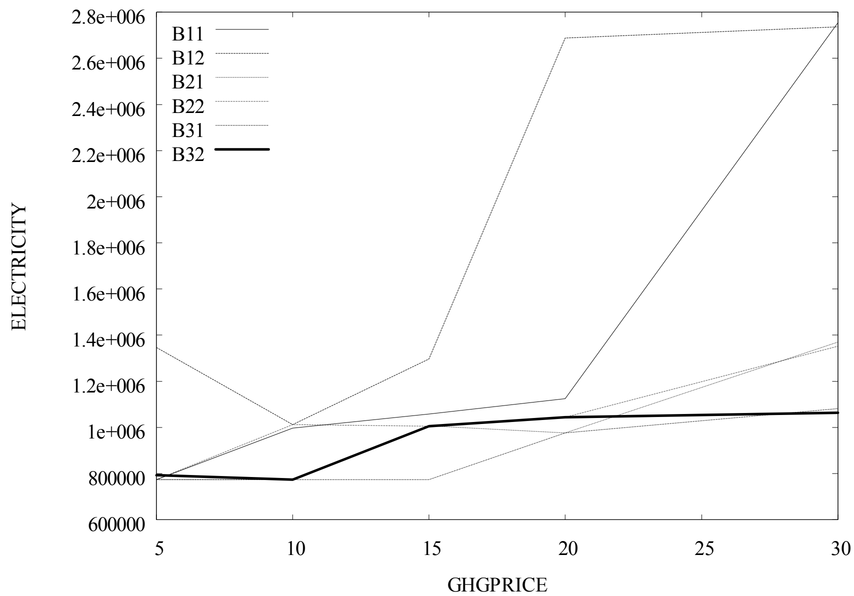

Figure 9. Electricity production under varying carbon prices when biochar is applied

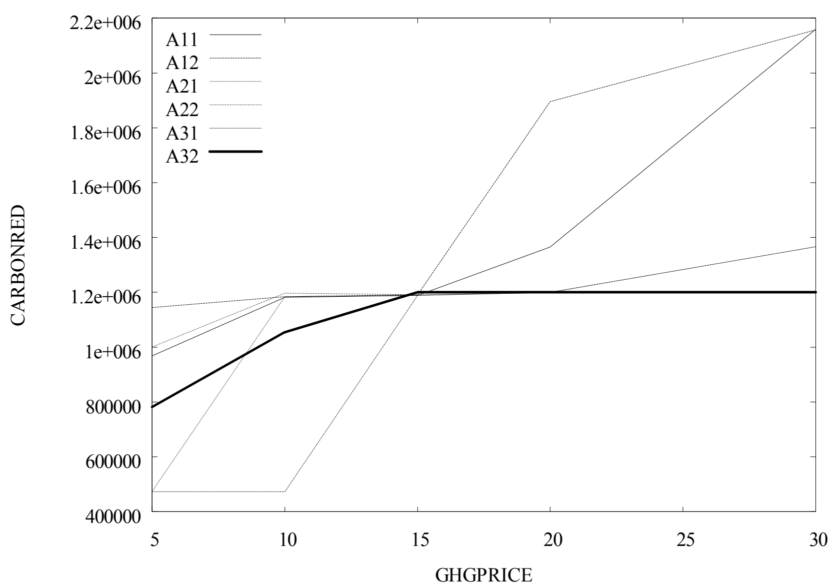

Figure 10. CO_2 reduction under varying carbon prices when biochar is burned

Figures 10 and Figure 11 present the carbon reduction results from both cases. In Figure 10, we can see that net carbon reduction increases as GHG prices increase. When ethanol price is low, ethanol production is lower and more pyrolysis-based electricity is produced (from Figure 6 and Figure 8). As ethanol provides relatively less GHG contribution, lower ethanol production and higher electricity production make the total GHG reduction higher. When ethanol price is at higher level, more ethanol is produced and less biofeedstock can be used for pyrolysis, thus it decreases total GHG offsets. By comparing Figures 10 and Figure 11, we find that the net GHG offset is higher when biochar is used as a soil amendment and the difference becomes larger when GHG price increases.

Although there is GHG emissions involved in the transportation and application of biochar, biochar also sequesters carbon in the soil and provides larger carbon sequestration ability than when it is used as a soil amendment. For this reason, if we put biochar back into the soil, net GHG offsets are higher. However, since we lose the electricity produced from biochar, the net electricity production in the hauling biochar case is obviously lower. The net GHG offset from producing bioenergy can be as high as 0.57% of Taiwan's total annual GHG emissions when biochar is hauled back to the fields, and even when biochar is burned, net GHG emissions reduction can be 0.48% of total emissions.

In terms of welfare, producing bioenergy using set-aside land results in a positive welfare change. The welfare is calculated by adding consumer and producer surplus minus the government subsidy on bioenergy crops. As GHG price, coal price and ethanol price increase, more production of bioenergy increases welfare along with more government subsidies paid to farmers. This is because when energy and GHG prices go up, more land is converted into bioenergy crop production and increases government expenditures.

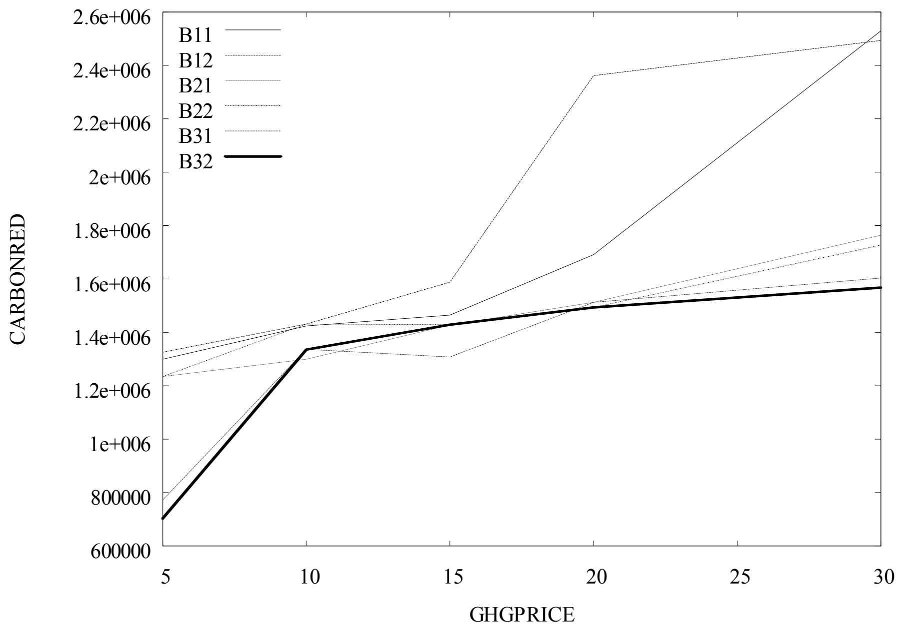

Figure 11. CO_2 reduction under varying carbon prices when biochar is applied

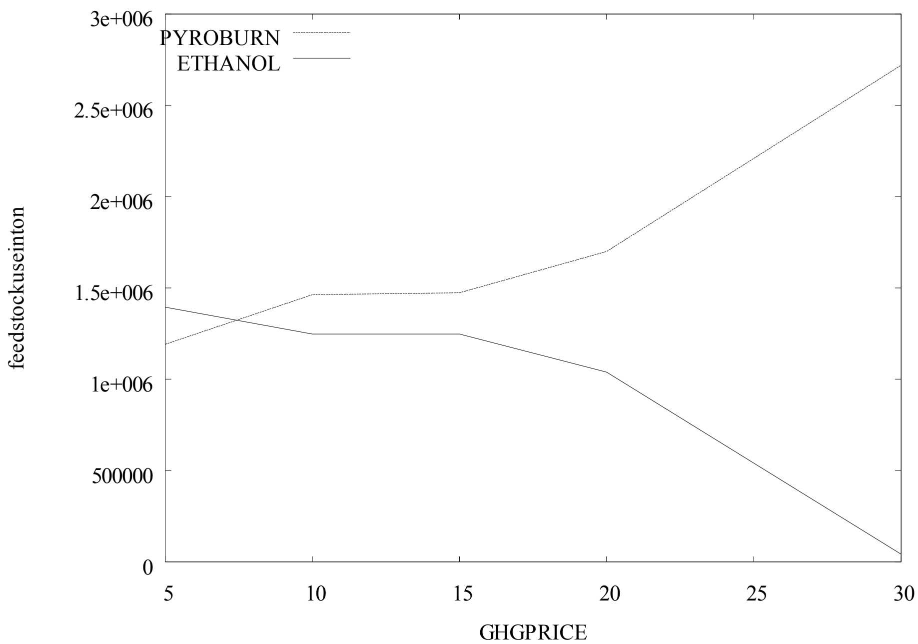

Figure 12. Sweet potatoes used for pyrolysis electricity and ethanol production under different carbon prices when biochar is burned

Figure 12 and Figure 13 show the use of sweet potato in different bioenergy technologies. When GHG price is low, ethanol production remains high and relatively more sweet potatoes are used in ethanol production. However, because pyrolysis offsets more GHG emissions, more sweet potatoes are used in pyrolysis when we have a higher GHG prices. As GHG price keeps rising, more and more sweet potatoes are used in the pyrolysis plant and therefore, ethanol is driven out. Biopower is driven out no matter how high the GHG price is. This is because pyrolysis strictly dominates biopower: per unit of sweet potato used in pyrolysis can generate much more electricity and offset more GHG emissions than biopower. However, this result is based on our previously assumption that sweet potato has exactly the same amount of pyrolysis output yield, electricity generation and GHG offsets as corn stover. This assumption may not be true and once those rates are altered, the result will vary.

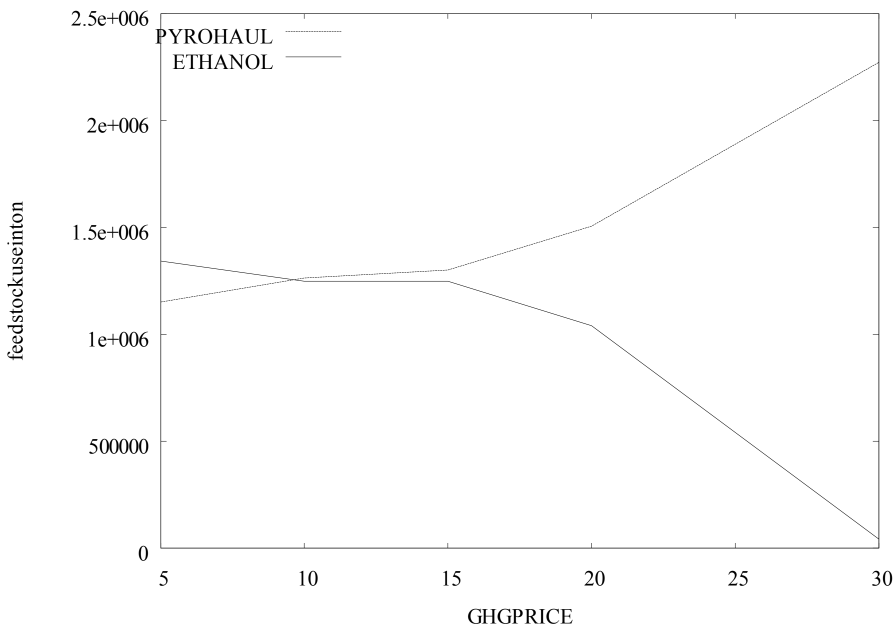

Figure 13. Sweet potatoes used for pyrolysis electricity (haul biochar) and ethanol production under different carbon prices

4.5. Summary

This study examines two ways that pyrolysis can join into bioenergy production. The first part is to study pyrolysis alone and the second part is to study when ethanol, coal-fired electricity and pyrolysis can compete with each other, which is very possible in the real world. In the first part of the study, we examine the alternative bioenergy technology that produces electricity and offsets GHGs. Pyrolysis has potential as a method of offsetting GHGs as shown in McCarl et al. (2009). Taiwan faces a situation that more than 99.3% of energy is imported and the country may be willing to utilize set aside land to produce clean and renewable energy to satisfy part of domestic energy demand while also making a contribution to global climate mitigation. While pyrolysis produces bio-oil, bio-gas and biochar that can be burned to provide energy and displace fossil fuels, biochar can be used as a soil amendment that enhances crop yields, reduces fertilizer and irrigation costs and stores carbon in a more stable form. Therefore, the alternative uses of biochar are examined in this study.

When biochar is burned with bio-oil and bio-gas in the pyrolysis plant, pyrolysis provides 1.7%-1.84% of Taiwan's annual electricity demand and offsets up to 0.53% of Taiwan's annual GHG emissions. Biochar used as a soil amendment generally reduces the electricity output but enhances the total GHG offset. More than 0.72% of total GHG emissions can be offset from pyrolysis when biochar is hauled back to the cropland, but total electricity production reduces to 0.44% of total energy demand. There is a tradeoff of energy production and GHG offsets between burning and hauling biochar. To increase energy security, Taiwan may want to adopt pyrolysis to generate more electricity and reduce GHG emissions. In this study, most of the biochar is applied in the southern and central counties of Taiwan. This is because, in those areas, rice yields are generally higher and input costs are lower.

However, this condition pointed out another issue that needed to be investigated further: the location of the pyrolysis plant. We assume that the location of the pyrolysis is in Chiayi as the land and labor are relatively cheap in the southern part of Taiwan. We choose the plant to be located in Chiayi, which is closer to the central Taiwan, to reduce the hauling distance to other counties. With a different plant location, rice hectares and counties that receive biochar may change dramatically. In the real world, even Taiwan's government is going to take the pyrolysis technology to produce energy; it is very possible for decision makers to choose another location to build the pyrolysis plant. In addition, another important assumption that has been made is the pyrolysis outputs from sweet potato, willow and switchgrass are assumed using the study from McCarl et al. (2009) and essay 2. This assumption could be inappropriate as those bioenergy crops are unlikely to yield exactly the same amount of bio-oil, bio-gas and biochar. Therefore, this study provides only a preliminary result under assumptions of the possible location and pyrolysis outputs and could be modified as information is released and gathered.

Extensions of the bioenergy study from essay are also presented in the later part of this section. We examined the situation when pyrolysis is competing with ethanol and coal-fired electricity. We find that when GHG price is high, ethanol is driven out by pyrolysis-based electricity. When biochar is burned, the value of the electricity provided is greater than that of hauling biochar back to the rice fields. However, in terms of GHG emission reduction, using biochar as a soil amendment offsets more GHG emissions and reduces Taiwan's total emissions by about 0.57% while burning biochar offsets about 0.48% of annual emissions.

For Taiwan to gain economic and environmental benefits plus enhance of energy security, she needs to:

(a) Determine a subsidy for farmers participating in the bioenergy program. This subsidy provides an incentive to farmers to convert the set aside land and grow bioenergy crops. If the subsidy is set too low, there may be less cropland converted into bioenergy crop production; however, if it is set too high, there may be cropland converted from its current use and thus land allocation deviates from the social optimum. The amount of subsidy used in this study is based on the opinion of Taiwan's famous agronomist, Dr. Chen Chi-Chung, who is intensively involved in Taiwan's agricultural policy decisions.

(b) Determine the primary goal of bioenergy production. In this study, we see bioenergy production increases domestic energy supply and reduces net GHG emissions. However, when ethanol, electricity and pyrolysis are competing with each other, and when GHG price goes up, pyrolysis drives out ethanol and electricity. In addition, biochar used in different ways in the pyrolysis process would result in different GHG offsets and electricity production. For example, if Taiwan wants to focus on climate change mitigation and reduce her GHG emissions, she probably wants to use the pyrolysis process and puts biochar back onto the cropland. If she wants to reduce the reliance of the imported expensive and unsecured fossil fuels, she may choose to increase the production of ethanol or electricity and put GHG emissions reduction as a secondary concern.

(c) Compare other agricultural policies that may compete on the set aside land because land is a scare resource in Taiwan. If certain agricultural policies are undertaken and utilize set aside land, ethanol, electricity and pyrolysis may not be produced to the amounts shown in this study because land is converted to other uses.

This study also assumes that burning biochar and hauling biochar back to the fields are mutually exclusive, and only one use of biochar can be achieved. The reason that we made this assumption is to study how the different uses of biochar affects the bioenergy production and associated GHG offsets and welfare. However, in the real world, it is also possible that people may burn some biochar and haul the rest to the crop fields. This can happen when certain soil types are not suitable for biochar or for some crops that biochar is toxic to.

5. CONCLUSION

Energy security is a big concern facing Taiwan. More than 99% of the country's fossil fuel consumption is imported, costing billions of dollars. This makes Taiwan very vulnerable to market disruptions and raises concerns over energy security. To overcome this, Taiwan is considering the development of a bioenergy industry. While bioenergy requires land to produce feedstocks, Taiwan is land limited. However, after joining the World Trade Organization (WTO), there was a substantial amount of agricultural land idled in Taiwan. This raises the opportunity for Taiwan to start bioenergy production. Although bioenergy has been studied extensively in the United States and Europe, there is limited bioenergy information on Taiwan's situation. Namely, there are neither cross crop bioenergy comparisons nor studies of alternative forms of bioenergy production. Climate change is also a concern with GHG emissions in Taiwan largely arising from fossil fuels combustion. Currently, a subsidy payment is being considered that will encourage farmers to plant energy crops.

This study focuses on evaluating economic and environmental implications of bioenergy production using Taiwan's set-aside land and examines how ethanol, biopower and pyrolysis based fuels may perform. As such this dissertation makes contributions of:

- Providing information on bioenergy production to Taiwan regarding bioenergy crops selection, amount of energy production potential, GHG mitigation potential, and change in farmers' revenue and social welfare.

- Doing the first level economic and GHG evaluation of pyrolysis and biochar in a sectoral context.

Results from essay 1 show that Taiwan's bioenergy policy does not contribute much to Taiwan's energy security or climate change mitigation as the volume of set aside land that can be used to produce bioenergy feedstocks is limited. Taiwan, indeed, get benefits from the production of bioenergy by reducing the need to purchase expensive and politically insecure energy sources from other countries, but they amount to less than 2% of energy demand. Furthermore, the government needs to pay subsidies for the increase in national energy security.

I also find that poplar, willow and switchgrass are not significant producers of ethanol output compared to sweet potatoes. However, I do find that these bioenergy crops have the potential to produce electricity, replace coal and have positive economic and environmental impacts. We find that when coal price increases, it leads to the expansion of bioelectricity from sweet potatoes and when ethanol price increases, ethanol production expands. As the GHG price increases, both ethanol and electricity production increase and more set aside land is converted to planting bioenergy crops.

Essay 2 examines the economics of pyrolysis and associated biochar production, utilization and GHG offsets using poplar as the primary biofeedstock. Pyrolysis and associated biochar production holds value in terms of energy production, nutrient reductions, irrigation saving, yield increases, and GHG offsets. These benefits are partly offset by the costs of production, hauling and processing, along with some increases in GHG emissions. In this study, we adopt a similar approach to that used in McCarl et al.

(2009) to analyze corn stover but apply it to the case of poplar. Our case study finds that fast pyrolysis and slow pyrolysis are profitable under current conditions. This is largely due to the sales revenue from electricity generation and partly due to the associated cost savings and GHG reductions. Some important factors such as energy prices, biochar prices, GHG prices and crop yield would potentially vary our result and we provide a sensitivity analysis for these factors. We find that these results are sensitive to construction cost, feedstock cost and energy prices. Fast pyrolysis is more profitable than slow pyrolysis; however, a study of yield increases indicates that, if a 16.8% rice yield increase is realized, then slow pyrolysis has higher profitability than fast pyrolysis. In addition, we do find the value of biochar applied as a soil additive is higher than its value as an energy source. As the coal price reduced rapidly recently, biochar use as a soil amendment in agriculture will creates even higher value relative to its combustion value.

Essay 3 examines all the bioenergy alternatives competing with each other. We find that when ethanol, pyrolysis and coal-fired electricity are competing, pyrolysis based electricity dominates biopower and ethanol. This situation is more apparent when facing high GHG prices and low ethanol prices. There is a tradeoff between energy production and GHG emissions reduction between burning and hauling biochar. To increase energy security, Taiwan may want to adopt pyrolysis to generate more electricity and reduce GHG emissions. In this study, most of the biochar is applied in the southern and central Taiwan rice fields. This is because in those areas, rice yields are generally higher and input costs are lower.

Throughout this dissertation, we generally find that there is potential for Taiwan to produce bioenergy in the forms of ethanol and/or electricity. They all increase the energy domestically produced and enhance Taiwan's energy security. Electricity basically offset more GHGs than ethanol. Electricity produced from fast and slow pyrolysis seems to have a higher GHG offset ratio than from coal-fired power plant and pyrolysis is basically an economically viable option without any government subsidy. However, due to limited land availability, the total energy produced is only a small ratio of current energy demand and the total amount compared to Taiwan's and world net GHG emissions is small; therefore, Taiwan's bioenergy production contributes less to the climate change mitigation. In addition, there is a necessity for Taiwan to determine its primary goal of bioenergy related policy because maximization of GHG emission offsets and maximization of bioenergy production may not occur at the same time. This happens when biochar is used in different ways. If the primary goal of a bioenergy program is to improve Taiwan's energy security, then the agricultural policy may focus on the encouragement of bioenergy production rather than the GHG emissions reduction.

5.1. Limitations

This work has some limitations including:

- The conversion rates of biomass-to-ethanol are assumed to remain the same over time. This assumes that ethanol is a mature technology and no future change will occur on the conversion rate. This may not be the case when newer biofuel technology is developed.

- Pyrolysis data for sweet potatoes is assumed to be the same as corn stover while that of willow and switchgrass is assumed to be the same as poplar. This is a strict and possibly unrealistic assumption. Therefore it will be necessary to reinvestigate the result once pyrolysis yield experiments on these three crops have been done and released. This also affects the net GHG offset. As different pyrolysis output yields directly affect the amount of electricity that can be produced and biochar that can be used as a soil amendment, differences on pyrolysis output yield directly influence the amount of GHG offsets.
- This study makes assumptions on the location of pyrolysis plant. If a different plant location is chosen, hauling cost will differ and the amount of rice fields that receive biochar will be different. Thus plant location needs to be investigated further.
- Yield risk is not incorporated in this study. However, yield risk may have big effects to the result because Taiwan is affected by typhoons several times a year. This natural disaster can reduce or destroy biofeedstock yields but different crops may be affected differently. Results will vary when these kinds of impacts happen and it is necessary to investigate this impact further.
- This study assumes that biooil produced from fast and slow pyrolysis has the same energy content. However, professor Mahmoud El-Halwagi points out that biooil produced from slow pyrolysis is inferior and thus its heating value may be lower. In addition, biooil produced from different bioenergy feedstocks may not have the same chemical composition and this can be studied further.

- The biochar induced rice yield increase is assumed the same regardless of soil and weather conditions. It is very possible that this assumption is not true since studies have shown that biochar has a larger effect on crop yields when the soil is less fertile. In addition to the same rice yield increase, we adopt a more conservative yield assumption (i.e. the 5% yield increase), but others have shown far greater yield increases. For example Nehls (2002) shows that rice yield increase from 115% to 320% with 7.9 tons of biochar application.
- It assumes the government subsidy is fixed. We didn't simulate the study using multiple government subsidies and once the government decides to pay different amounts of subsidy, hectares that participate in bioenergy production will be affected.

5.2. Further Research

This study can be extended in several directions. First, Taiwan also grows sugarcane and sweet sorghum, which can be used to produce ethanol and these could be added to the feedstocks studies as other possibilities. Second, crop yield enhancement, fertilizer and irrigation savings under biochar application could be studied further. Third, GHG emissions change due to land use change from set-aside to active cropping is not incorporated in this study and this could be included. Fourth, pyrolysis costs, benefits, output yields and GHG offset of multiple bioenergy crops need to be studied rather than simply using calculated data from other crops. This would help enhance the accuracy of the study and provide more useful information for Taiwan.

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