

Article

Effect of Agricultural Feedstock to Energy Conversion Rate on Bioenergy and GHG Emissions

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Abstract: Taiwan is eager to develop renewable energy because it is vulnerable to energy price distortion and ocean level rise. Previous studies show bioenergy technologies can be applied mutually, but pay little attention on feedstocks to energy conversion rate, which has potential influences on policy making in renewable energy and environment. This study employs a price endogenous mathematical programming model to simultaneously simulate the market operations under various feedstocks to energy conversion rates, energy prices, and greenhouse gas (GHG) prices. The result shows pyrolysis-based electricity can reach up to 2.75 billion kWh annually, but it will be driven out at low conversion rate and high GHG price. Pyrolysis plus biochar application will be the optimal option in terms of carbon sequestration. Market valuation on potential threats of extreme weather could have substantial influences on ethanol and renewable electricity generation. To achieve aimed GHG emission reduction and/or bioenergy production, government intervention may be involved to align the market operation with Taiwan's environmental policy.

Keywords: bioenergy; energy conversion rate; greenhouse gases emissions; pyrolysis

1. Introduction

Climate change shift is an important challenge that many countries have been dealing with. The use of fossil fuels such as coal and crude oil emits numerous greenhouse gases (GHGs), which are believed to be the main cause of global climate change. Combined with the non-renewable property of fossil fuels, development of renewable and clean energy has been intensively investigated since 1980s [1,2]. A similar situation happens in Taiwan because less than 1% of the energy source can be domestically supplied and the climate change induced damages are very likely to impact the Taiwanese economy, environment and society. Bioenergy such as ethanol that can blend with gasoline and co-fire, which mixes bio-feedstocks with coal to generate electricity, is an attractive alternative to fossil fuels because Taiwan not only released substantial cropland after participation with the World Trade Organization (WTO), but also reduced the distortions that resulted from the global political issues [3]. In addition to co-fired ethanol, pyrolysis is another option, as it provides renewable energy, along with substantial economic and environmental benefits, from biochar application (byproduct of pyrolysis) [4–7]. With limited land available, it is necessary for Taiwan to consider the optimal bioenergy technology or technology combination to maximize its social welfare. Several studies have been performed on this issue [3,6,8] but failed to consider the feedstocks to energy conversion rate, which could influence the result significantly. Bioenergy is, in general, produced from agricultural commodities and, depending on the energy content of the commodities and the technology adopted, the amount of bioenergy can be produced varies. Therefore, the feedstocks to energy conversion is important, as it determines the quantity of bioenergy that can be produced per unit of materials and the amount of greenhouse gases (GHG) emissions that can be offset. For this reason, failing to incorporate this factor may distort the result and bring an unrealistic conclusion to policy makers. Moreover, different feedstocks to energy conversion rates may be available as various agricultural commodities are applied.

To examine how the development of bioenergy in Taiwan reduces reliance on foreign energy and potential damage resulting from extreme weather, incorporating a more realistic feedstock to energy conversion rate into the available bioenergy technologies is necessary. This study accommodates several conversion rates, along with the multiple feedstocks and bioenergy technologies, into a price endogenous mathematical programming model to explore the potential responses from Taiwan's bioenergy industry. In addition to conventional co-fired ethanol, the study examines pyrolysis in two mutually exclusive forms, fast pyrolysis and slow pyrolysis. Because slow pyrolysis yields more biochar, which sequesters more carbon dioxide but generates less electricity, markets operation via energy price changes would have significant influences on net bioenergy production and emission offset. With incorporation of the market effects and the multiple uses of biochar, the study makes contributions by exploring the changes of net bioenergy production and GHG emission offset at different levels of energy prices and energy conversion rates, along with the policy implication regarding the government strategy on bioenergy development. The results will help government officers in deciding related economic policies, such as tax and subsidy, or environmental policy, such as emission cuts. In addition, the results derived from the pyrolysis and biochar application provides additional information on development of bioenergy regarding policy intervention and technology changes.

2. Literature Review

Bioenergy has been considered to offset GHG emissions; however, Fargione *et al.* [9] mention that whether biofuel production is a potential low-carbon energy source is affected by feedstock and technology selection. Pyrolysis is another type of bioenergy, which involves heating biomass in the absence of oxygen and results in the decomposition of biomass into bio-oil, biogas and biochar [4], all of which can be used to generate electricity. However, simply burning biochar for energy may not be its optimal use. Some studies found that biochar, when used as a soil amendment, is able to bring significant environmental and economic benefits [4,5,7,10–12]. In terms of GHG offset, pyrolysis-based bioelectricity may be a better choice due to the existence of biochar. Moreover, pyrolysis can have offset efficiencies greater than 100% when compared with the emissions of the fossil fuel inputs that are replaced [7]. Therefore, pyrolysis is emphasized in this study as it brings bioelectricity as well as environmental benefits from its byproduct, biochar. However, studies such as [3,6,8], do not incorporate the potential change on feedstocks to energy conversion rates, because they treat the liquid part of pyrolysis as 100% bio-oil. This could be a wrong assumption, as water is inevitably blended in this liquid part and cannot be used to generate electricity. Removal of water and consideration of multiple feedstocks to energy conversion rate is thus necessary to obtain actual amount of electricity generation and GHG emissions reduction. This study separates the water from liquid parts for different feedstocks and calculates the potential true feedstock to energy conversion rate, which is more realistic.

Biochar also brings other environmental and economic benefits. First, biochar has the ability to improve nutrient retention. Deluca *et al.* [10] present bioavailable 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 yields an increase in net nitrification. Burning onsite crop residuals also induces a short-term influence on N availability but biochar may act to maintain this effect for years to decades. Second, biochar could increase crop yields by retaining more nutrients in the soil. Chan *et al.* [12] show that if biochar and N fertilizer are applied together, the biochar/nitrogen fertilizer interaction is significant and biochar can improve the N fertilizer efficiency. 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). Nehls [13] also indicates that rice yield may increase up to 320% with biochar application. Many studies examining the applications of biochar on crop yields have been studied since 1980 [14–19]. However, the results are likely region- and case-specific, and the exact effects from biochar application should be investigated further. Third, biochar can store carbon in a more stable form. Lehmann *et al.* [4] show that biochar is a relatively stable form of C and can stay in the soil up to several thousand years. Converting biomass C to biochar C 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). In this study, they also calculated that the carbon dioxide emissions offset can be 12%–84% greater if biochar is put back into the soil. It is important to note that, although gains from soil nutrient and crop yield increase may repeat over time, net CO₂ emission reduction should be counted only once. That is, net CO₂ sequestration should be calculated based on how much biochar has been applied rather than how long the biochar has been applied on the cropland. Moreover, Major *et al.* [20] show that the annual loss of biochar may be as high as 50% due to heavy rainfall and runoffs. Therefore, for regions

that have higher precipitation, economic and environmental gains from biochar application should be discounted with an appropriate rate.

Taiwan is starting to examine the possibility of bioenergy production. Chen *et al.* [21] investigate how much ethanol can be produced from sweet potatoes planted on set-aside land. The results show that Taiwan could produce 300 million liters of ethanol, increase social welfare and reduce CO₂ emissions by 75,390 metric tons. Tso and Su [22] also examine the energy output/input ratio for different energy crops and the consequent environmental benefits in terms of GHG emissions. In the existing studies of GHG emissions, the benchmark of evaluating the net energy to emission ratio comes from the laboratory. For example, Bransby's work [23] in Oak Ridge National Laboratory find that energy produced from 1 kg of coal produces about 6.15 kwh, so 1 kg of polar, willow and switchgrass are equivalent to 0.125, 0.154 and 0.149 kg of coal, respectively. However, the above benchmarks are generated in experiments, not from real land. Therefore, in order to reflect how energy conversion rate may affect the benefits from bioenergy production in the real world, it is necessary to incorporate the situations of lower rates of energy conversion that may actually happen.

3. Modeling Background

Bioenergy is a form of renewable energy that derives from agricultural commodities. Since agricultural land competes with the land requirement of urbanization, and agricultural commodities satisfy not only basic food demands of human beings, but also numerous raw materials for industrial uses, all of which, combined with bioenergy production, make the agricultural sector complex and highly interrelated in many regions. This work evaluates the bioenergy production and associated GHG emission effects on Taiwanese set-aside land under potential energy conversion rate, and various energy and carbon dioxide prices. To do this, it is necessary to present the fundamental features related to the bioenergy production and emission offsets in agricultural sector. Specifically, these features can be addressed in the following two categories.

- Greenhouses emissions arise from related agricultural activities.
- Market responses and welfare implications.

Both of these categories will be addressed clearly below.

3.1. Multiple Greenhouse Gases Implications

In general, three kinds of greenhouse gases are emitted from agricultural production activities: (1) carbon dioxide (CO₂); (2) methane (CH₄); and (3) nitrous dioxide (N₂O). These GHG emissions are either considered independently or jointly in current mitigation options. Therefore, in order to compare the GHG implications on bioenergy production, production, processing and transportation of agricultural commodities on set-aside land must be incorporated. Furthermore, activities of animal husbandry also have an influence. For instance, the quantity of livestock produced has significant influence on crop demand and land allocation, which in turn influences the carbon sequestered, nitrous oxide released, and methane emitted on croplands. Therefore, this study adopts an analytical approach [2,24] to simultaneously depict the interdependence between GHG mitigation strategies; crop

and livestock production; competition for cropland and pastureland; the feeding of livestock; product substitution; and feedstock to energy conversion rate; among other factors across the agricultural sector.

3.2. Market Responses and Welfare Implications

Bioenergy production consumes substantial amount of agricultural commodities and therefore, affects the domestic demand and supply of agricultural commodities. Prices of agricultural commodities will vary as new industries (*i.e.*, bioenergy industry) require certain shares of agricultural outputs, given fixed land availability and food consumption. The price of agricultural commodities determines the cost of bioenergy production, while energy prices determine the sales revenue, both of which jointly determine the profitability of bioenergy industry. For this reason, input and output prices are key factors for the successful establishment of bioenergy in Taiwan. As bioenergy brings benefits in terms of renewable energy supply and GHG emissions, market effects are thus important to net bioenergy production and climate mitigation. Therefore, domestic agricultural market along with the welfare of producers and consumers in Taiwan are very likely to be affected by the decision of the development of bioenergy and related climate mitigation policies. The study employs an analytical approach to represent domestic agricultural markets and their links to foreign markets based on [1], and investigates the influences on market operations to bioenergy production and GHG emission offset.

4. Model Structure

4.1. Formulation of Agricultural Sector Model

To evaluate how bioenergy production and GHG emission offset are influenced by the changes on energy prices, energy conversion rates, and crop competition on set-aside land, the study employs a price endogenous mathematical programming model. The theoretical formulation of this model is based on Samuelson [25] who shows that the maximization of the consumer surplus and producer surplus can result in the equilibrium in the perfect competition market. Based on this theory, Takayama and Judge [26] establish a mathematical programming model on spatial model while Duloy and Norton [27] apply this model in agriculture. McCarl and Spreen [1] show that the property of price endogeneity of this model is dominant in policy analysis by comparing the linear programming models used by other planned economic systems. They find that the price endogenous model can represent the economic system in a perfectly competitive market. Price endogenous modeling, then, started being used widely in the late 1970s for environmental and resource analyses, including biofuels [28], ozone [29], acid rain [30], soil conservation policy [31], global climate shift [22,32–35], climate change mitigation [24,36] and research evaluation [37,38].

To analyze the production and market issues affected by Taiwanese agricultural policies, the Taiwan Agricultural Sector Model (TASM) was developed by [39] and this empirical structure has been extensively employed to many policy-related studies, such as [8,40]. Because the mathematical model applied in this study is derived from a similar framework, the TASM will be depicted briefly. Suppose that there exist i agricultural crop commodities produced in k regions with associated production activities X_{ik} (for $i = 1, 2, \dots, I$; $k = 1, 2, \dots, K$) and each production activity is on a per hectare basis. The total production is calculated by multiplying per hectare yields (Y_{ik}) by production hectares

(X_{ik}). Assuming all commodities can be sold in wholesale markets and their demand functions can be represented by the following inverse demand functions:

$$P_i^Q = \psi(Q_i) \quad i = 1, 2, \dots, I \quad (1)$$

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

For regional inputs such as land, irrigation water and labor, Chang [40] assumes all of them are applied in each production activity and n inputs such as fertilizer and chemicals are purchased from the non-farm sector. The prices of N purchased inputs are assumed exogenous, but the prices of the regional inputs are endogenously determined by the demand and regional supply functions. Assume regional supply functions of these resources are integral and of the following form:

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

$$P_k^R = \beta_k(R_k) \quad k = 1, 2, \dots, K \quad (3)$$

where P_k^L, P_k^R represent land rent and the other resource prices and L_k, R_k represent the quantity supply of cropland and other resources, respectively.

The objective function is to maximize the sum of consumer surplus and producer surplus in a perfectly competitive market and is represented by the area between the product demand and factor supply curves to the left of their intersection. Mathematically, it is expressed as below:

$$\text{Max: } \sum_i \int \psi(Q_i) dQ_i - \sum_i \sum_k C_{ik} X_{ik} - \sum_k \int \alpha_k(L_k) dL_k - \sum_k \int \beta_k(R_k) dR_k - \sum_k \int \alpha(Q_k) dQ_k \quad (4)$$

The constraints are:

$$Q_i - \sum_k Y_{ik} X_{ik} \leq 0 \quad \text{for all } i \quad (5)$$

$$\sum_i X_{ik} - L_k \leq 0 \quad \text{for all } k \quad (6)$$

$$\sum_i f_{ik} X_{ik} - R_k \leq 0 \quad \text{for all } k \quad (7)$$

$$\sum_i g_{ik} X_{ik} - O_k \leq 0 \quad \text{for all } k \quad (8)$$

where the purchased input cost in region k used for production of i^{th} commodity is expressed by C_{ik} and per hectare yield Y_{ik} is the production of i^{th} commodity produced in region k . The i^{th} demand for labor in region k is depicted as f_{ik} , the i^{th} demand for other inputs in region k is expressed as g_{ik} , and Q_i is the consumption for i^{th} commodity, respectively. The land supply, labor supply and the other input supply in region k are denoted as L_k, R_k and O_k , respectively.

4.2. Modification of Taiwan Agricultural Sector Model (TASM)

The study employs the basic theoretical foundation of TASM and makes modification on it by incorporating the multiple energy crop possibilities, potential feedstock-energy conversion rates, multiple alternative bioenergy technologies, and associated environmental effects such as GHG emissions offset. The model accommodates more than 110 agricultural commodities, distribution of set-aside land, labor supply and annual crop mixes in Taiwan's four major production and processing regions. Since the market share of Taiwan's agricultural commodity is relatively small to the rest of the world, the modified TASM assumes the individual producers and consumers are price takers (that is, the change in Taiwan's agricultural production does not affect the world commodity prices). Market operations are assumed to be perfect competition with incorporation of input supply and price dependent demand curves. The values of commodities accommodated in the model account for more than 85 percent of Taiwan's agriculture. Production activities of each commodity, crop and livestock mixes and their constraints are specified at the sub-regional level while the inputs markets such as crop land, forest land and labor are specified at the regional level. The algebraic illustration of the model used in this study is shown briefly as following:

The objective function and constraints of modified TASM are shown as follows:

$$\begin{aligned}
 \text{Max } & \sum_i \int \psi(Q_i) dQ_i + \sum_e \int \mu(Q_e) dQ_e - \sum_k \int \alpha_k(L_k) dL_k - \sum_k \int \beta_k(R_k) dR_k \\
 & - \sum_i \sum_k C_{ik} X_{ik} + \sum_i \int ED(Q_i^M) dQ_i^M + \sum_i \int EXED(TRQ_i) dTRQ_i \\
 & - \sum_i \int ES(Q_i^X) dQ_i^X + \sum_i [tax_i \times Q_i^M + outtax_i \times TRQ_i] \\
 & + \sum_i P_i^G \times Q_i^G + \sum_k P^L \times AL_k \\
 & + \sum_j SUB_j \times AL_j - \sum_{ghg} P_{carbon} \times Q_{ghg}
 \end{aligned} \tag{9}$$

Subject to

$$Q_i + Q_i^X + Q_i^G - \sum_k Y_{ik} \times X_{ik} - (Q_i^M + TRQ_i) \leq 0 \forall i \tag{10}$$

$$\sum_i X_{ik} + AL_k + \sum_j EC_{jk} - L_k \leq 0 \forall k \tag{11}$$

$$\sum_i f_{ik} X_{ik} - R_k \leq 0 \forall k \tag{12}$$

$$\sum_{ik} E_{gik} X_{ik} - GHG_g \leq 0 \forall g \tag{13}$$

where Q_i^G is the government purchase quantity for price supported product i , Q_i^M is the import quantity of product i , Q_e is bioenergy technologies, Q_i is quantity of commodity i , TRQ_i is the import quantity exceeding the quota for TRQ product i , Q_i^X is export quantity of product i , $ED(Q_i^M)$ is the inverse excess import demand curve, $ES(Q_i^X)$ is the inverse excess export supply curve, $EXED(TRQ_i)$ is the inverse excess demand curve of commodities which import quantity is exceeding quota, tax_i is import

tariff for product i , $outtax_i$ is the out of quota tariff of product i , P^L is the set-aside subsidy, SUB_j is the subsidy on energy crop j , AL_k is the set-aside acreage in region k , EC_{jk} is the planted acreage of energy crop j in region k , $\alpha_k(L_k)$ is the land inverse supply in region k , $\beta_k(R_k)$ is the labor inverse supply in region k , P_i^G is the government purchase price of commodity i , C_{ik} is cost of input i in region k , X_{ik} is the production activity of commodity i in region k , Q_{ghg} is quantity of GHG emissions, Y_{ik} is the total production of commodity i in region k , P_{carbon} is the carbon-equivalent price, and GHG_g is net emission of greenhouse gas g .

Equation (9) is the objective function that incorporates Taiwan's agricultural activities with various domestic and trade policies. Government subsidies on rice purchase, set-aside land and energy crops plantation that are influencing the social welfare in terms of quantity supply and demand are incorporated. These terms represent the social welfare in a closed market. All GHG emissions from various sources will be converted into carbon equivalent and the international carbon trading price is the basis of GHG payment. The relationship between social welfare and net GHG emissions is negative.

Equation (10) balances commodities, showing that the demand of commodity plus import should be less than or equal to its supply plus export. Equations (11) and (12) represent the resource endowment constraints by balancing the land and other resources usage. Equation (13) balances greenhouse gas components by constraining the net emissions from agricultural sector such that they cannot be greater than Taiwan's total emissions. Because it is difficult to test the robustness of a mathematical model, as any change in policies, production data, output ratio and resource constraints may considerably influence the results, we compare the simulation results to actual statistics [3,8]. The total production and prices, and the crop yields are adjusted to calibrate TASM. The model validation result shows that most of the discrepancies between model results and actual agricultural data are within 6% range, indicating that the model should be suitable for simulation.

4.3. Scenario Setup

Before we can compute the net changes of social welfare (in terms of consumer surplus and producer surplus), it is necessary to setup a base scenario. The base scenario evaluates the total commodity outputs and social welfare, given known product demand and supply, market prices, tariffs and commodity elasticities. To analyze the potential economic and environmental responses from Taiwanese bioenergy development, the study set up 96 scenarios constituting two coal prices, three gasoline prices, four potential carbon equivalent prices and four feedstock-energy conversion rates. The base feedstock to energy conversion rate is based on the previous studies and an additional three potential levels of conversion rates adjust the removal of water content and non-flammable gases from bioenergy production. For example, when feedstock is pyrolyzed, all liquid components are treated as bio-oil and can be refined to generate electricity. However, water must be removed and the net electricity generation should be lower than assumed. These alternative scenarios are important because they show the influences on bioenergy development and climate change mitigation due to changes in market condition and energy conversion rates. In this study, bioenergy will be produced from any combination of ethanol, direct fire and pyrolysis where biochar produced from pyrolysis is applied on the cropland to obtain higher agricultural benefits and carbon sequestration. Fast pyrolysis, which

produces more bio-oil, and low pyrolysis, which produces more biochar, are simultaneously competing with each other during the pyrolysis system under market operations.

5. Result

Table 1 depicts the trend of ethanol production in various market conditions. It is clear that ethanol production is very sensitive to the GHG prices as its power of carbon sequestration is relatively lower. If the feedstock to energy conversion rate is set as baseline, the shrinkage of ethanol produced is not huge. Even in the worst case (*i.e.*, highest GHG price), about 130 million L of ethanol could be produced annually, accounting for about 43 percent of Taiwanese ethanol demand. However, the ethanol production drops dramatically when the conversion rate decreases. Most feedstocks will be used in other bioenergy technology, such as pyrolysis, and only about 4% of total ethanol demand will be produced. The low carbon sequestration property of ethanol makes it vulnerable in bioenergy development when climate shift catches more attention and the market places higher values on climate change mitigation.

Table 1. Ethanol production compared to baseline conversion rate.

	Case 1	Case 2	Case 3	Case 4
Gasoline price	NT 25/L	NT 25/L	NT 25/L	NT 25/L
Coal price	NT 1.7/kg	NT 1.7/kg	NT 1.7/kg	NT 1.7/kg
GHG price	NT 150/Ton	NT300/Ton	NT 450/Ton	NT 900/Ton
Ethanol Production (Per 1000 Liters)				
Base conversion rate	174,575	156,000	156,000	130,000
90% conversion rate	156,000	152,096	144,700	130,000
80% conversion rate	130,287	127,547	127,784	5200
70% conversion rate	127,897	106,147	103,151	5200

Table 2 presents the electricity generation under various market conditions and feedstock to energy conversion rates. The result shows that at low coal price and GHG price, few feedstocks will be used in electricity generation and in turn, the feedstocks are fermented for ethanol production. As long as the costs of acquiring coal and the environmental degradation seem to be low, market demand for ethanol is higher than that of renewable electricity. When either coal price or GHG price increases, renewable electricity from pyrolysis will dominate the conventional co-fire electricity. Under this circumstance, more electricity is generated in pyrolysis. One thing that needs to be addressed here is that when coal price increases, but GHG price remains low, pyrolysis-based electricity will be produced in the form of fast pyrolysis, since it generate more electricity on a per ton of feedstock basis. However, when GHG price keeps rising, electricity generation will shifted to slow pyrolysis to achieve higher carbon sequestration. In addition, the result indicates the increase in net social welfare may be even higher at high GHG price due to the biochar application on cropland, which improves crop yield and reduces the production cost on the farm. Feedstock to energy conversion rate also plays an important role in the development of pyrolysis, especially for low conversion rate scenarios. If the conversion rate is lower than the base rate, more contribution from pyrolysis development will be

placed on the climate change mitigation instead of renewable energy supply and therefore, the amount of feedstocks used in pyrolysis will be heavily relied on the GHG prices.

Table 2. Electricity production compared to baseline conversion rate.

Gasoline Price	NT 25/L	NT 25/L	NT 25/L	NT 25/L
Coal price	NT 1.7/kg	NT 1.7/kg	NT 1.7/kg	NT 1.7/kg
GHG price	NT 150/Ton	NT 300/Ton	NT 450/Ton	NT 900/Ton
Unit	1000 kWh	1000 kWh	1000 kWh	1000 kWh
Base conversion rate	773,500	997,544	1,006,157	1,369,776
90% conversion rate	773,500	773,500	77,3500	973,125
80% conversion rate	773,500	773,500	773,500	2,145,293
70% conversion rate	773,500	773,500	773,500	794,237

Figure 1 shows the sensitivity of net electricity generation for different feedstock to energy conversion rates. When pyrolysis-based electricity is available, in addition to conventional co-fired electricity, most renewable electricity is generated in the form of pyrolysis. Moreover, since fast pyrolysis generates higher electricity, ethanol production and electricity from slow pyrolysis will be reduced. The result shows that up to 2.75 billion kWh could be generated under high coal prices but only 1.4 billion kWh could be generated at a low coal price. When energy conversion rate declines, electricity generation will be reduced, even at a high coal price. At a low coal price, electricity generated from pyrolysis is not an attractive choice compared to the market valuation of climate change mitigation. For this reason, slow pyrolysis that produces more biochar, which sequesters carbon, becomes an attractive option.

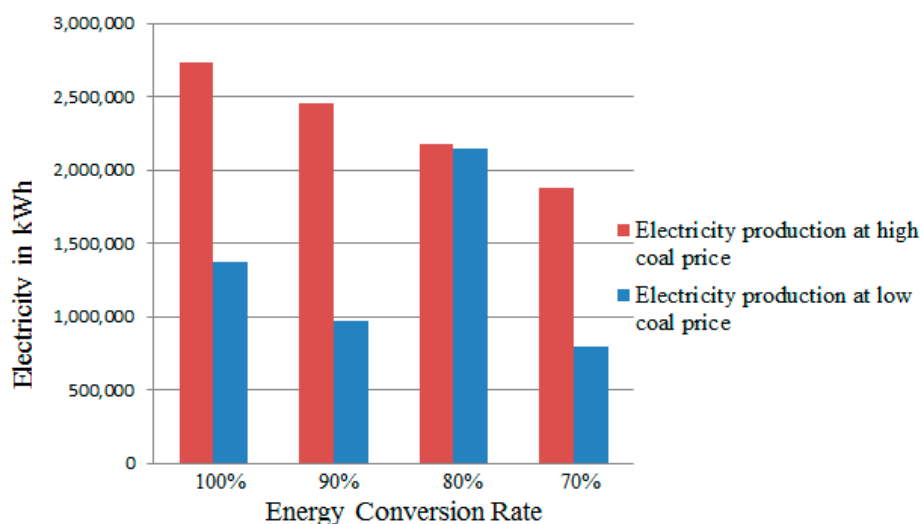


Figure 1. Electricity generation under various feedstock-energy conversion rates.

Table 3 shows the net GHG effect from various combinations of bioenergy strategies and market conditions. In general, the net GHG emission reduction increases as GHG price increases, primarily due to increased electricity generation from pyrolysis and biochar application. The result shows the relationship between net GHG emission reduction and ethanol is negative, if ethanol is produced; fewer feedstocks can be used to generate electricity that offset more GHG emissions. Unlike net

electricity generation and ethanol production, where the amount produced is declining at lower feedstock to energy conversion rates, net GHG emission offset increases at low conversion rates. This is because at low conversion rates, current bioenergy technologies do not seem to be an efficient way to generate energy; instead, they become an alternative way of combating climate change. Therefore, at low conversion rates, biochar that can be applied in soils to fix carbon is the dominant product in the pyrolysis process, rather than using bio-oil to generate electricity.

Table 3. Net greenhouse gases offset compared to baseline conversion rate.

Gasoline price	NT 25/L	NT 25/L	NT 25/L	NT 25/L
Coal price	NT 1.7/kg	NT 1.7/kg	NT 1.7/kg	NT 1.7/kg
GHG price	NT 150/Ton	NT 300/Ton	NT 450/Ton	NT 900/Ton
Unit	Tons	Tons	Tons	Tons
Base conversion rate	1,298,321	1,424,429	1,428,195	1,748,942
90% conversion rate	1,300,278	1,345,735	1,417,478	1,605,944
80% conversion rate	1,332,497	1,406,502	1,408,449	2,491,151
70% conversion rate	1,112,474	1,445,595	1,482,385	2,891,650

Figure 2 compares the net GHG emission offset at different GHG price levels under various energy conversion rates. It is not surprisingly that the net GHG emission reduction is high when the market values it more. Therefore, at high GHG prices, total emission reduction can reach up to 2.9 million tons annually. Emission reduction is more sensitive at high GHG prices and less sensitive at low GHG prices. At low GHG prices, producers will focus on other aspects, such as ethanol production and pyrolysis-based electricity, rather than on climate change mitigation. The result indicates that the bioenergy development is largely affected by the market operation, implying that the government subsidy must be made if the objective of the government is to mitigate climate change shift when facing low GHG prices. This situation is likely to occur as Taiwan is an island and is more vulnerable to the impacts of global climate change induced consequences, like ocean level rise.

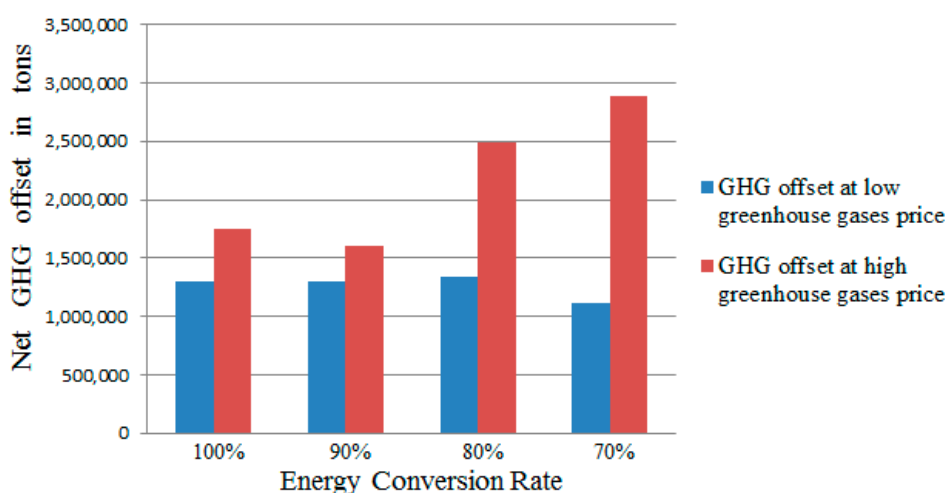


Figure 2. Net GHG offset under various feedstock-energy conversion rates.

6. Concluding Remarks

Many studies have been focusing on the renewable energy industry and its application. Pyrolysis and biochar are typical examples that derive from bioenergy with additional benefits, such as crop yield increase, fertilizer use reduction and carbon sequestration. However, even with such benefits to biochar application, the main theme is still put on the amount of bioenergy that can be produced via various bioenergy technologies and how this industry potentially replaces the use of fossil fuels. Feedstock to bioenergy conversion rates directly influence the amount of bioenergy that can be produced, thus play an important role in whether the various conversion rates may cause bioenergy to be less competitive to the other side benefits. This study focuses on the how change of conversion rates affect the bioenergy production, net GHG emission reduction, and bioenergy strategies in different market conditions. Because various agricultural and government subsidies are involved, the agricultural market in Taiwan is complex. The study employs a price endogenous mathematical programming model to simulate this complex market operation by accommodating a series of data, including domestic agricultural production activities and international trade. The result indicates that ethanol production is sensitive to gasoline prices, GHG prices and feedstock to energy conversion rates. This is because if producers do not make profits at low gasoline prices and low GHG prices, ethanol production will decline. Therefore, market valuation of the potential threats of extreme weather would have substantial influences on ethanol production. Energy conversion rates have similar, but greater, impacts on ethanol production because feedstocks will switch to pyrolysis, either in the form of electricity or biochar. The net amount of pyrolysis-based electricity fluctuates because multiple forms of pyrolysis compete with each other. Fast pyrolysis produces more bio-oil and thus electricity, while slow pyrolysis yields more biochar that can be applied in soil to gain agricultural profits and environmental benefits. Therefore, GHG price and the conversion rates have significant impacts on the switch between two types of pyrolysis and, consequently, the different amount of electricity and biochar. The result shows that the energy price, GHG price and energy conversion rate could influence the development of Taiwan's bioenergy industry under different market situations, implying government intervention, such as subsidy or tax, may be applied to align the market operations and environmental policies.

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Author Contributions

Chih-Chun Kung collects and analyzes the data with mathematical programming model. Both Meng-Shiuh Chang and Chih-Chun Kung analyze results with economic and environmental interpretation. Literature review section is mainly contributed by Meng-Shiuh Chang while introduction and methodology sections are contributed by Chih-Chun Kung. Both authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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