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Article

Biofuel for Energy Security: An Examination on Pyrolysis Systems with Emissions from Fertilizer and Land-Use Change

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Abstract: One of the most important concerns facing Taiwan is lack of energy security. The study examines to what extent the Taiwan energy security can be enhanced through bioenergy production and how bioenergy affects net greenhouse gases emissions. Ethanol, conventional bioelectricity and pyrolysis based electricity are analyzed and emissions from fertilizer use and land use change are also incorporated. The study employs the Modified Taiwan Agricultural Sector Model (MTASM) for economic and environmental analysis. The results indicate that Taiwan indeed increases its energy security from bioenergy production but net greenhouse gases emissions are also increased. Emissions from fertilizer use and land use change have significant impacts on emissions reduction and pyrolysis does not always provide net greenhouse emissions offset. Some policy implications including goal determination, land availability and emissions trading systems are also provided for potential policy decision making.

Keywords: pyrolysis system; fertilizer use; land use change; bioenergy production; greenhouse gases emissions

1. Introduction

Taiwan is vulnerable to high energy prices and market distortions in the world energy market because only a small fossil fuel stock is found in Taiwan and most of Taiwan's energy is imported [1]. To enhance Taiwan's energy security, there is interest for the Taiwanese to produce energy on its own. In addition to the energy insecurity, another serious challenge facing Taiwan is climate change. According to the 2007 report by the Intergovernmental Panel on Climate Change [2], the Earth is warming due to anthropogenic emissions of greenhouse gases (GHGs) and its temperature is very likely to increase in the next decades. Such warming would have consequences ranging from increased desertification, a rise in the ocean level to the possible increased occurrences of hurricanes, which may bring potential significant damages to Taiwan. As the 25th largest CO_2 emissions country [3], Taiwan is willing to reduce CO_2 emissions and mitigate global climate shift to avoid unwelcome climate impacts, once the energy security issue is resolved. Renewable energy sources that can potentially substitute fossil fuels and provide some of the domestic energy supply include wind and solar energy, hydro-power, geothermal energy and bio-energy [4]. Among these renewable energy alternatives, Taiwan has been developing bioenergy for several years. Geographically, Taiwan's land area is about 14,000 square miles with 67% of that land being mountainous. Land is a scarce resource in Taiwan and has been intensively utilized in various ways. From this point of view, Taiwan would not be able to produce bioenergy because a substantial amount of land is required for bioenergy production. However, participation in the World Trade Organization (WTO) offers a possibility of development of bioenergy in Taiwan because Taiwan's agricultural sector is less competitive and part of Taiwan's agricultural land has been idle. Net idled cropland has increased from 68,000 hectares to 280,000 hectares, which provides a potential stock of land for bioenergy feedstock production [1].

Although bioenergy can potentially enhance Taiwan's energy security and reduce GHG emissions [5,6], two important factors, the GHG emissions from land use change and fertilizer use, have been ignored. When agricultural land is converted into other uses, NO_x emissions will change and result in different CO_2 equivalent (CO_2e hereafter) emissions [7–9]. If the change in NO_x is small, neglecting to consider this factor may not significantly affect the result. However, this change is usually large [10,11]. Snyder *et al.* [12] also point out that the most important GHG issue from agriculture is N_2O, mainly from soils and N inputs to crop and soil systems. They show that, from the global warming potential (GWP) point of view, even though N_2O is a small part of the overall GHG issue, agriculture is considered to be the main source that is linked to soil management and fertilizer use. Therefore, examining bioenergy production and GHG emissions offset without considering associated GHG emissions from land use change and fertilizer use may result in the disaster. This study aims to examine the GHG emissions from various bioenergy production levels under different gasoline, coal and GHG prices. The work makes contributions by integrating multiple bioenergy technologies (ethanol, co-fire and pyrolysis), energy crops, energy and GHG prices and emissions from land use change and fertilizer use into a single study, which provides information about potential enhancement of Taiwan's energy security and GHG emissions offset to the Taiwanese government.

2. Literature Review

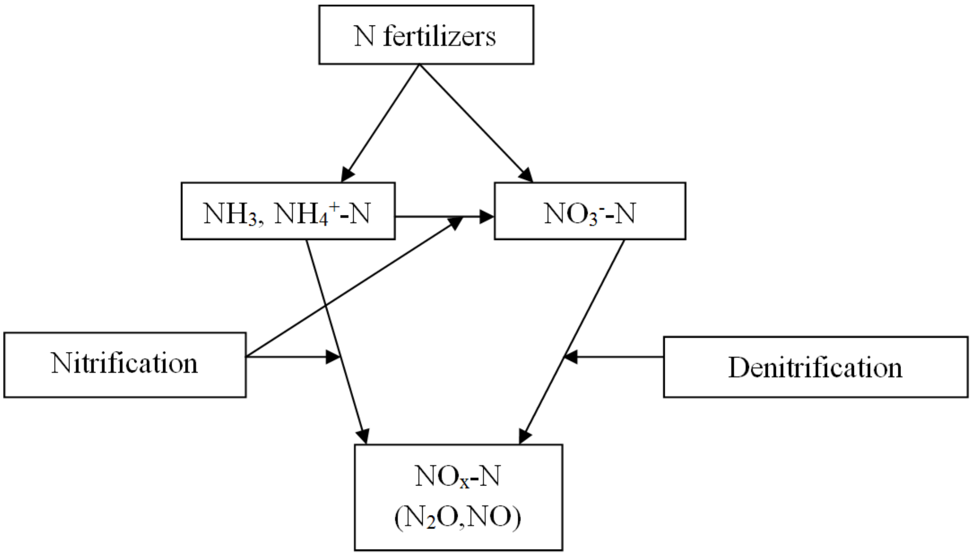
Among available bioenergy techniques, Taiwan can produce bioenergy in the forms of ethanol, direct combustion biopower (conventional bioelectricity) and biopower through pyrolysis (pyrolysis-based electricity). Because these technologies are not mutually exclusive and can be employed at the same time, it is necessary for us to consider all combinations. Bioenergy involving ethanol and conventional electricity have been examined and applied for more than a decade, but bioenergy produced from pyrolysis is intensively studied only in recent years. Pyrolysis involves heating biomass in the absence of oxygen and results in the decomposition of biomass into biooil, biogas and biochar. Biooil and biogas are used to generate electricity in the pyrolysis plant while biochar was also used as an energy source but many studies found that biochar can bring significant environmental and associated economic benefits when it is used as a soil amendment [13–17]. In general, pyrolysis can be categorized as fast pyrolysis, medium pyrolysis, slow pyrolysis and gasification. In this study, we examine the two popular types of pyrolysis techniques (fast and slow pyrolysis), and two uses of biochar (burn biochar in the pyrolysis plant or haul biochar back to the cropland) are incorporated in our bioenergy production framework.

The reason that we would like to examine biochar is because it has been shown to improve agricultural productivity and the environment in several ways. Specifically, biochar is stable in the soil [13] and has nutrient-retention properties that lead to increases in crop yields [18]. Moreover, biochar offers a chance to sequester carbon [13]. As pyrolysis can provide a significant amount of renewable energy and offset more GHG emissions [5,6,16], it is a potential bioenergy technique that Taiwan is interested in.

Lifecycle analysis of GHG emissions has been examined widely in bioenergy production [7,13,16,19] and land use changes [10,11,20–22]. Some studies examined the impacts of emissions from global land use changes on the lifecycle emissions of corn ethanol [7,9] and other studies focused on the land use change emissions when specific land types are cultivated for cropland use [22–24]. Land use change has also been examined in large scale. For example, Timilsina *et al.* [25] analyzed the long-term impacts of large-scale expansion of biofuels on land use change, food supply and prices, and the overall economy in various countries or regions, while Kwon *et al.* [26] examined the state-level soil carbon emissions for direct land use change in the United States. Land use change also has various GHG effects. Schaufler *et al.* [21] found that different land-use strongly affected GHG fluxes in cropland, grassland, forests and wetland. N_2O and CO_2 emissions are highest in grassland soils while NO emissions are highest in forest soils, which are also positively correlated with N input. Moreover, Baldos [20] utilized the Land Use Change Emissions (LUCE) modules and found that the direct lifecycle GHG emissions of corn ethanol fuel can exceed the 20% GHG reduction requirement in the US EISA given the data and assumptions during corn farming and ethanol production. Wang *et al.* [8] also developed a widely applied modeling approach (including GREET model and CCLUB model (Carbon Calculator for Land Use Change from Biofuels Production)) in the US to study biofuel life cycle. Baggs *et al.* [19] found that zero tillage resulted in higher N_2O emissions than conventional tillage and N_2O emissions were generally correlated with CO_2 emissions. However, this result must be adopted very carefully when different land types are examined. Grover *et al.* [11] indicated that soil-based GHG emissions will increase from 53 to 70 t CO_2-equivalents after land use change. Farquharson and Baldock [27] indicated that adding N fertilizers will increase N_2O emissions due to nitrification and denitrification process where the ammonium (NH^{4+}) is available for nitrification.

Synder *et al.* [12] also showed that fertilizer induced N_2O emissions from soil equates to a GWP of 4.65 kg CO_2 kg^{-1} of N applied. Therefore, when we change crops and associated N fertilizer application, it will lead to different NO_x emissions. Qin *et al.* [28] developed an agroecosystem model (AgTEM) that was incorporated with biogeochemical and ecophysiological processes. They found that N_2O emitted from croplands with high N application rates is mostly larger than those with lower N input levels. The average N_2O flux is 1.8 kg N ha^{-1} and most of the simulation results are within a reasonable range (e.g., less than 5 kg N ha^{-1}). Their recent work [29] also examined carbon and nitrogen dynamics for maize and cellulosic crops. They indicated that for maize the global warming potential (GWP) amounts to 1–2 Mg CO_2eq ha^{-1} yr^{-1}, with a dominant contribution of over 90% from N_2O emissions while cellulosic crops contribute to the GWP of less than 0.3 Mg CO_2eq ha^{-1} yr^{-1}. The general process of NO_x emissions is depicted as Figure 1.

Figure 1. N_2O emissions due to N fertilizer application (Source: [28]).



However, they also point out that this estimate will vary depending on local climates since NH_3 volatilization and NO^{3-} leaching are heavily affected by the climate. These studies focus on how many GHG emissions are produced during bioenergy production or the mechanism of GHG emissions from land use change, all of which have provided significant contributions to the literature, but the relationship between bioenergy production strategies and GHG emissions from land use change are usually not linked. Therefore, in order to know how land use GHG emissions may affect the benefits from bioenergy production, it is necessary to incorporate the emissions from fertilizer and change on land use into the bioenergy production to present a more general lifecycle analysis on bioenergy.

3. Model Structure

The model used herein is based on price endogenous mathematical programming, which is originally illustrated by Samuelson [30]. Samuelson shows the equilibrium in the perfect competition market can be derived from the optimization model that maximizes the consumer surplus and producer surplus. Takayama and Judge [31] establish a mathematical programming model on spatial model based on

Samuelson's idea while McCarl and Spreen [32] point out that this model is useful in policy analysis, especially in its property of price endogeneity. In addition, McCarl and Spreen [32] compare 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 including soil conservation policy [33], global climate change [34–36], and climate change mitigation [37]. It has also been applied extensively for research evaluation [38,39].

Chen and Chang [40] develop the Taiwan Agricultural Sector Model (TASM) to analyze the Taiwanese agricultural policy in terms of production and market issues. The TASM is a multi-product partial equilibrium model based on the previous work [32,33,39,41]. This empirical structure has been adapted to Taiwan and used in many policy-related studies [40,42,43]. The current version of TASM accommodates more than 110 commodities in 15 subregions aggregated into four major production and processing regions. We extended the TASM to evaluate the potential economic and GHG implications of bioenergy crop production plus competition with other land uses. GHG emissions from land and fertilizer use are also incorporated into the modified TASM. The modified 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.

3.1. Modified Taiwan Agricultural Sector Model

TASM was constructed by Chen and Chang [41] under above theory and for this analysis we extend this model by adding features related to bioenergy and N_2O emissions. Specifically, to get a version for use herein, we have to address how energy crops and GHG emissions are incorporated in the modified TASM. We illustrate the algebraic form of the objective function of the modified TASM and its constraints. The objective function and constraints of modified TASM are shown as follows:

$$\begin{aligned} Max \ & \sum_i \int \psi(Q_i)\,dQ_i - \sum_i \sum_k C_{ik} X_{ik} - \sum_k \int \alpha_k(L_k) dL_k - \sum_k \int \beta_k(R_k) dR_k \\ & + \sum_i P_i^G * Q_i^G + \sum_k P^L * AL_k + \sum_j \sum_k SUB_j * EC_{jk} + \sum_i \int ED\left(Q_i^M\right) dQ_i^M \\ & - \sum_i \int ES\left(Q_i^X\right) dQ_i^X + \sum_i \int EXED(TRQ_i) dTRQ_i \\ & + \sum_i \left[tax_i * Q_i^M + outtax_i * TRQ_i\right] - P_{GHG} * \sum_g GWP_g * GHG_g \end{aligned} \tag{1}$$

Subject to:

$$\mathrm{Q_i + Q_i^X + Q_i^G - \textstyle\sum_k Y_{ik} X_{ik} - \sum_j EC_{jk} X_{jk} - (Q_i^M + TRQ_i) \le 0} \qquad \text{for all } i, \tag{2}$$

$$\mathrm{\textstyle\sum_i X_{ik} + AL_k + \sum_j EC_{jk} - L_k \le 0} \qquad \text{for all } k, \tag{3}$$

$$\textstyle\sum_i f_{ik} X_{ik} - \sum_j f_{jk} X_{jk} - R_k \le 0 \qquad \text{for all } k, \tag{4}$$

$$\textstyle\sum_{i,k} E_{gik} X_{ik} - Baseline_g = GHG_g \qquad \text{for all } g. \tag{5}$$

Table 1 details the variables using in the objective function and constraints.

Table 1. Variables.

Variable	Description of Variables
Q_i	Domestic demand of i^{th} product
Q_i^G	Government purchases quantity for price supported i^{th} product
Q_i^M	Import quantity of i^{th} product
Q_i^X	Export quantity of i^{th} product
$\psi(Q_i)$	Inverse demand function of i^{th} product
P_i^G	Government purchase price on i^{th} product
C_{ik}	Purchased input cost in k^{th} region for producing i^{th} product
X_{ik}	Land used for i^{th} commodities in k^{th} region
L_k	Land supply in k^{th} region
$\alpha_k(L_k)$	Land inverse supply in k^{th} region
R_k	Labor supply in k^{th} region
$\beta_k(R_k)$	Labor inverse supply in k^{th} region
P^L	Set-aside subsidy
AL_k	Set-aside acreage in k^{th} region
SUB_j	Subsidy on planting j^{th} energy crop
EC_{jk}	Planted acreage of j^{th} energy crop in k^{th} region
$ED(Q_i^M)$	Inverse excess import demand curve for i^{th} product
$ES(Q_i^X)$	Inverse excess export supply curve for i^{th} product
TRQ_i	Import quantity exceeding the quota for i^{th} product
$EXED(TRQ_i)$	Inverse excess demand curve of i^{th} product that the import quantity is exceeding quota.
tax_i	Import tariff for i^{th} product
$outtax_i$	Out-of-quota tariff for i^{th} product
Y_{ik}	Per hectare yield of i^{th} commodity produced in k^{th} region
E_{gik}	g^{th} greenhouse gas emission from i^{th} product in k^{th} region
P_{GHG}	Price of GHG gas
GWP_g	Global warming potential of g^{th} greenhouse gas
GHG_g	Net greenhouse gas emissions of g^{th} gas
$Baseline_g$	Greenhouse gas emissions under the baseline of the g^{th} gas
f_{ik}	Labor required per hectare of commodity i in region k

The objective function of the modified TASM model incorporates the domestic and trade policies where the first term is the area under the domestic demand curve and the second, third and fourth terms stand for input costs, cropland rent and labor costs, respectively. The fifth, sixth and seventh terms reflect the government subsidy on rice purchase, set-aside lands and for planting energy crops to represent the social welfare in a closed market. The eighth and ninth 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. GHG emission is modified in the last term to reflect that GHG emissions reduce social welfare. Equation (2) is the balance constraint for commodities. Equations (3) and (4) are the resource endowment constraints. Equation (3) controls cropland and Equation (4) is the other resource constraint. Equation (5) is further modified to reflect the greenhouse gas balance which shows emissions emitted of CO_2e (including emissions from bioenergy production, land use change and fertilizer use but CH_4 emissions from animal manures) cannot be greater than total emissions.

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.

4. Study Setup

This study examines Taiwan's bioenergy production from ethanol, conventional bioelectricity and pyrolysis based electricity, and GHG emissions offset by utilizing current set-aside land with the consideration of the emissions from fertilizer use and land use change. Three gasoline prices (NT$20, 30, 40 per liter), two coal prices (NT$1.7, 3.45 per kg), six GHG prices (NT$ 5, 10, 15, 20, 25, 30 per ton) plus estimated emissions from fertilizer use and land use change. The simulated gasoline and coal prices are selected based on the ranges of their market prices in 2012. Since Taiwan has not established a GHG trading mechanism and GHG emission is currently of no value in Taiwan, the study examines several potential GHG prices based on the opinion of Professor Chi-Chung Chen, who is familiar with and engaged in Taiwanese agricultural and environmental policies.

The net mitigation of CO_2 from ethanol is estimated by [44]. They show that net CO_2 emissions are reduced by 0.107 ton per 1000 liters of ethanol. For conventional electricity, McCarl [45] shows that poplar can offset about 71.3% of carbon dioxide emissions relative to the fossil fuel and 75.1% for switchgrass. We calculate that the emissions reduction is 0.195 kg CO_2 for poplar and 0.246 kg CO_2 for switchgrass.

GHG emissions from land use change are estimated by Liu *et al.* [10], who calculate that annual mean GHG fluxes from soil of plantation and orchard are 4.70 and 14.72 Mg CO_2-C ha^{-1} yr^{-1}, −2.57 and −2.61 kg CH_4-C ha^{-1} yr^{-1} and 3.03 and 8.64 kg N_2O-N ha^{-1} yr^{-1}, respectively. Qin *et al.* [29] also indicated that the average N_2O flux is 1.8 kg N ha^{-1} and most of the simulation results are less than 5 kg N ha^{-1}. Because CO_2 and N_2O emissions are highly correlated with each other [19], we assume that the emission profile of CO_2 and N_2O are staying at the same level. In addition, Snyder *et al.* [12] show that fertilizer induced N_2O emissions from soil equates to a GWP of 4.65 kg CO_2 kg^{-1} of N applied. With these estimates, we arrive at the estimated emission level from fertilizer use and land use change (Table 2). Biochar also offers GHG emissions offset potential. This study also incorporates the GHG effect for different uses of biochar to see how it affects the GHG emissions reduction, based on Kung *et al.*'s estimates [5].

Table 2. Estimated emission level from fertilizer use and land use change.

	GHG	Units	Estimated emission level
GHG emissions from fertilizer and land use change	CO_2	Mg ha^{-1} yr^{-1}	4.7
	CH_4	kg ha^{-1} yr^{-1}	−2.57
	N_2O	kg ha^{-1} yr^{-1}	26.86
Net emissions	CO_2e	Mg ha^{-1} yr^{-1}	11.62

5. Results, Policy Implications

The simulation result indicates that when Taiwan tries to enhance its energy security by developing bioenergy, net GHG emissions are likely to increase, especially when GHG price is low (see Figures 2 and 3). As indicated in Figure 2, emissions reduction from Taiwan's bioenergy production is lower than the emissions increased from fertilizer use and land use change. Only when GHG price is high and gasoline price is low, net emissions reduction may be achieved, and when the gasoline price keeps increasing, net emissions will increase (Figure 3).

Figure 2. Estimated emissions from bioenergy production, fertilizer use and land use change at low greenhouse gas (GHG) price.

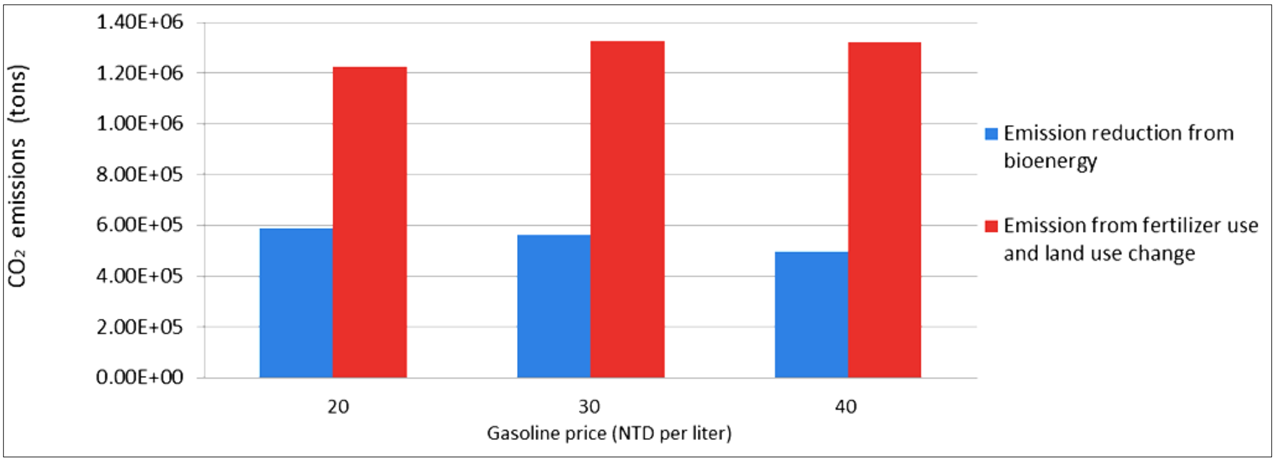
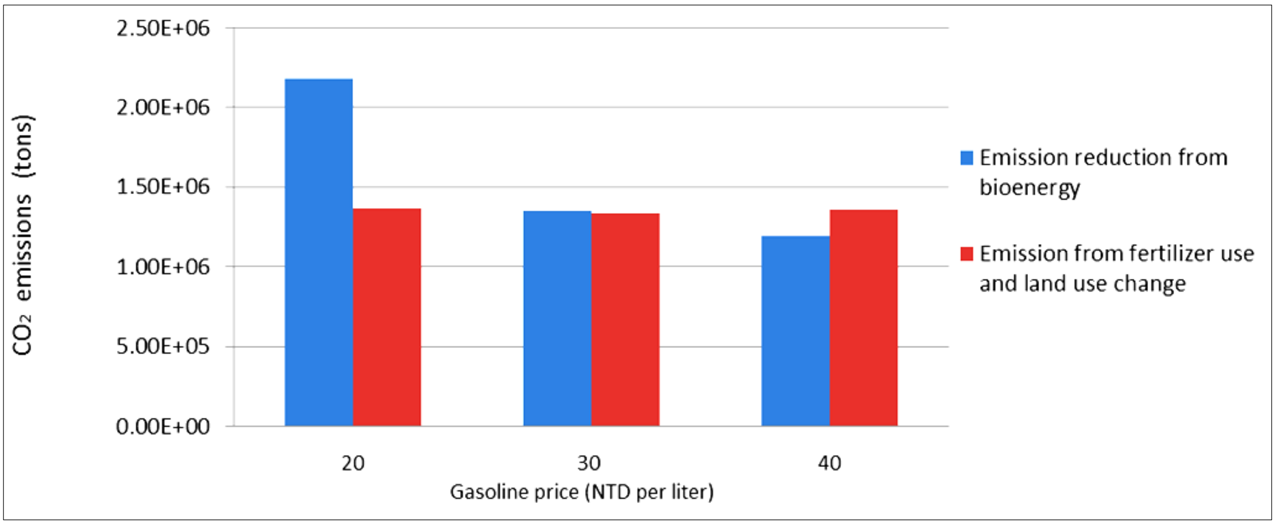


Figure 3. Estimated emissions from bioenergy production, fertilizer use and land use change at high GHG price.



The result shows that when energy security is the first priority of Taiwanese government, net GHG emissions will not be reduced in most cases. In other words, the study indicates that Taiwan gains energy security at a cost of emitting more. This is partly due to the fact that the emission offset ability of ethanol is lower than that of pyrolysis based electricity. When the gasoline price is low, feedstocks will be used in ethanol and electricity production but when the gasoline price increases, more feedstocks are converted into the ethanol production and the total amount of emissions offset is reduced. Market price also affects the net emissions from fertilizer use and land use change. Under low energy prices, bioenergy production is less profitable and less set-aside land is used for energy crop plantation. Fewer plantations require fewer fertilizer and therefore, emissions from fertilizer use and land use change will be smaller. When energy prices increase, more land is converted and brings higher emissions from land use change and fertilizer use. Although bioenergy is considered as a carbon sequestration technology, lifecycle analysis including fertilizer use and land use change indicates that ethanol does not bring GHG emissions reduction while pyrolysis is possible to offset emissions under certain conditions.

In this study, bioenergy comes from various sources including ethanol, conventional bioelectricity and pyrolysis based electricity. The result indicates that conventional bioelectricity is driven out by pyrolysis based electricity and electricity is solely produced via pyrolysis. In general, pyrolysis produces three outputs including biooil, biogas and biochar, all of which can be used to generate electricity. Because biochar is found to enhance crop yield and store carbon in a more stable form when used as a soil amendment, various uses of biochar are incorporated into the study. The result indicates that when biochar is used as a soil amendment, bioenergy production is relatively lower than when biochar is burned in the pyrolysis plant (Figures 4, 5 and Appendix). However, if biochar is burned to provide electricity, it is unlikely to provide net GHG emissions offset. Using biochar as a soil amendment is possible to offset GHG emissions only when the GHG price is high. If the GHG price is low, ethanol production is high and fast pyrolysis that will generate more electricity will dominate slow pyrolysis that yields more biochar. Only when the GHG price increases to a certain level, slow pyrolysis becomes a dominant technology and ethanol production decreases.

Figure 4. Net emissions from bioenergy production when biochar is used as a soil amendment. Net offset (L,M and H) represents the low, medium and high gasoline prices, respectively.

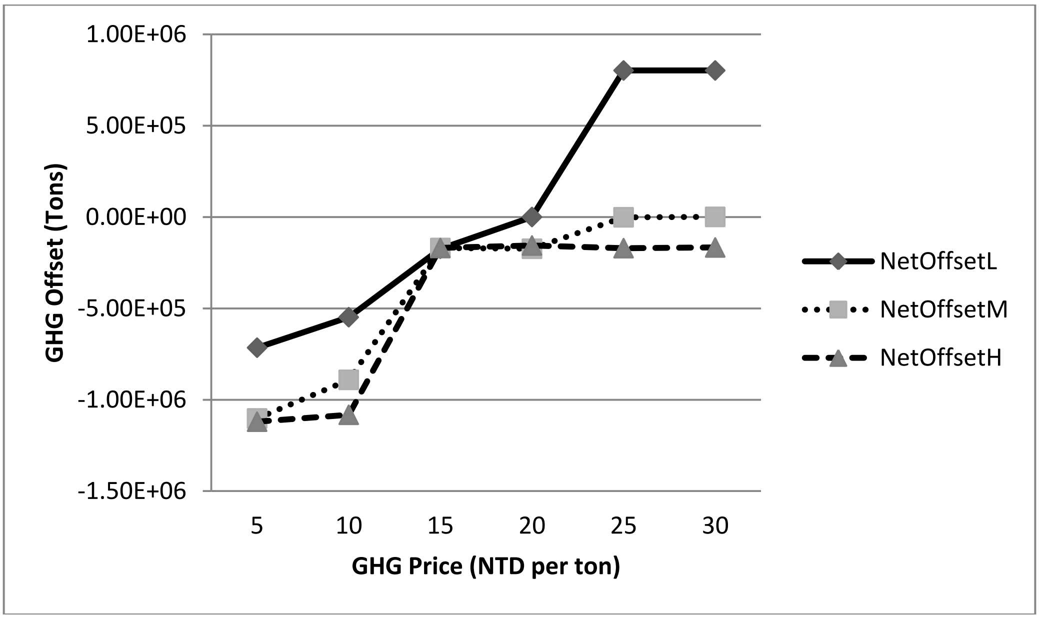
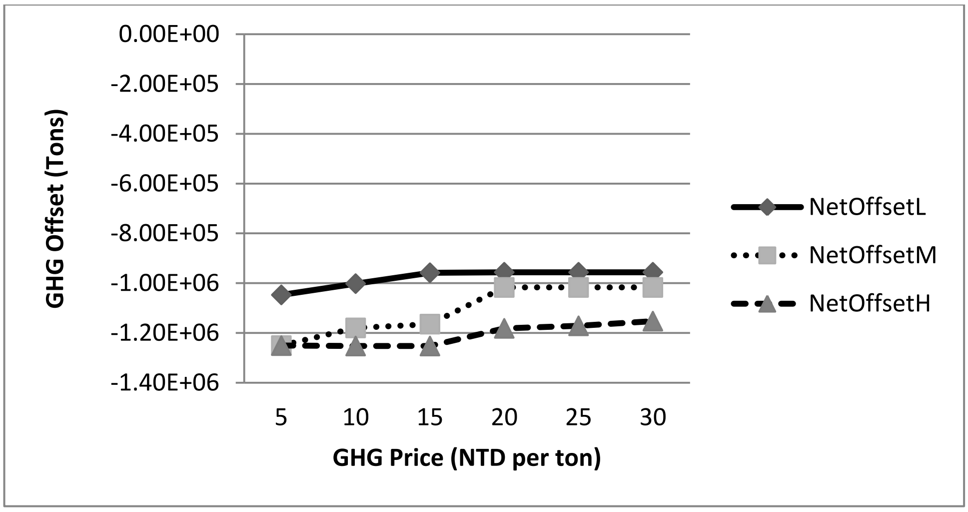


Figure 5. Net emissions from bioenergy production when biochar is used as an energy source. Net offset (L,M and H) represents the low, medium and high gasoline prices, respectively.



Policy Implications

The study provides some insights about environmental effects on Taiwan's energy security concern via bioenergy production. The result shows that Taiwan's energy security can be enhanced by producing ethanol and electricity using currently set-aside land. However, bioenergy does not bring environmental benefits in most of cases when land GHG and fertilizer emissions are incorporated. In other words, bioenergy does not always offset GHG emissions in a broader lifecycle analysis. Some policy implications for Taiwan to gain economic and environmental benefits plus enhancement of energy security are provided including:

(a) When Taiwan tries to develop a GHG emissions trading mechanism, effects of the trading system on domestic renewable energy production must be incorporated. As the study shows, bioenergy production is heavily impacted by GHG prices. Therefore, under a marketable GHG emissions trading system, effectiveness of energy security enhancement from bioenergy must be validated;

(b) Development of the bioenergy industry requires long term planning. The simulation result indicates that Taiwan can enhance energy security from bioenergy production at a cost of higher emissions. However, under low energy prices, less set-aside land will be converted into the energy crop plantation and results in a net emissions offset. Bioenergy production will shrink under this situation. Therefore, in order to ensure energy security enhancement when the energy price is low, some government subsidies may be required for farmers to convert set-aside land into energy crop plantations;

(c) This study shows that GHG emissions from fertilizer use and land use change are significant and have important impacts on both bioenergy production and net GHG emissions offset. Therefore, a proper estimation of these emission rates is required. The study examines the bioenergy production and GHG effects on Taiwan's set-aside land, located in the four major areas in Taiwan. Due to local soil and weather conditions, NO_x emission rates from land use change and fertilizer application should not be the same in these areas and future studies must be conducted in order to draw a more realistic picture;

(d) Although energy security is the prior concern on Taiwan's bioenergy development, it may not always be so. As Taiwan is facing direct challenges from global climate shifts, GHG mitigation is another important issue that the Taiwanese must address. Bioenergy is one possible way to increase domestic energy supply, but it may not be an appropriate method for GHG emissions offset, especially for the significant effects from fertilizer and land use change emissions. As the result shows, Taiwan is not able to achieve the maximal bioenergy production and GHG emissions offset at the same time. The Taiwanese government must take this into account for future policy decisions;

(e) Not all set-aside land can be used for bioenergy production. Joining the WTO releases some agricultural land but the Taiwanese government has been trying to utilize the idle land for other economic purposes including development of recreation sites and high economic value commodities. Therefore, using all set-aside land in bioenergy production may not be feasible. Further adjustments combining all existing and potential agricultural and associated policies may be required.

6. Conclusions

The study examines how much bioenergy can be produced and the consequent GHG emissions effect as Taiwan attempts to enhance its energy security. Simulation results indicate that while bioenergy indeed increases Taiwan's energy security, it is likely to increase net GHG emissions. This is somewhat contradictory to previous studies showing bioenergy provides both renewable energy and GHG emissions mitigation. Our result shows that emissions reduction by bioenergy is offset by the emissions of fertilizer use and land use change. Throughout 72 scenarios, only eight cases show net GHG emissions offset. GHG price is another important factor influencing the bioenergy production and GHG emissions offset. At a higher GHG price, ethanol production will shrink to a very low level and slow pyrolysis dominates all other bioenergy technologies. However, when Taiwan places energy security as its first priority, the impacts of GHG price on bioenergy production will be small.

Limitations

The study has some limitations that must be addressed. First, potential uncertainties exist for many important factors. Depending on land types, GHG emissions from land use change, fertilizer use and soil carbon sequestration may differ, all of which lead to a different result. Second, Taiwan's GHG trading system has not been established and therefore, GHG prices used in this study are only based on the professional opinions rather than real market data. Further investigation is needed when the GHG emissions trading market is built. Third, the hauling distance of biofuel and biochar is estimated from McCarl *et al.*'s study [46], which assumes the pyrolysis plant is in the centre of a square surrounded by a grid layout of roads. This assumption may be released by combining GIS method to reflect a more accurate hauling distance and associated GHG emissions. Finally, CH_4 is another important GHG in agriculture, especially for rice paddies and animal manure. This study does not incorporate CH_4 emissions from specific agricultural commodities; instead, the study focuses on the CH_4 emissions from the land used for bioenergy crop plantation. CH_4 emissions must be incorporated into the analysis when rice straw and manure are used in bioenergy production (e.g., pyrolysis).

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Appendix

Table A1. Simulation results of bioenergy production and GHG emissions

Term	Unit	Haul biochar to the cropland as soil amendment					
Ethanol Price	NT$/liter	20	30	40	20	30	40
GHG Price	NT$/ton	5	5	5	5	5	5
Electricity Price	NT$/kg	1.7	1.7	1.7	3.45	3.45	3.45
Electricity Prod.	1000kwh	2,607,800	773,500	773,500	2,519,400	2,475,200	2,165,800
Electricity Supp.	%	0.0118	0.0035	0.0035	0.0114	0.0112	0.0098
Ethanol Prod.	1000liter	156,000	284,650	287,430	179,070	202,828	217,112
Total Planted Ha	1000 Ha	113.5	113.5	113.73	105.59	114.14	113.73
CO_2 Emission Reduction	Tons	603,841	216,557	201,581	587,067	564,761	498,605
Emissions (FU & LUC)	Tons	1,318,870	1,318,870	1,321,543	1,226,956	1,326,307	1,321,543
Net offset	Tons	−715,029	−1,102,313	−1,119,962	−639,889	−761,546	−822,938
Ethanol Price	NT$/liter	20	30	40	20	30	40
GHG Price	NT$/ton	10	10	10	10	10	10
Electricity Price	NT$/kg	1.7	1.7	1.7	3.45	3.45	3.45
Electricity Prod.	1000kwh	3,291,299	1,657,000	773,500	2,041,242	3,270,318	2,652,000
Electricity Supp.	%	0.0149	0.0075	0.0035	0.0092	0.0148	0.0120
Ethanol Prod.	1000liter	156,000	236,901	282,260	156,000	156,000	187,384
Total Planted Ha	1000 Ha	114.34	113.84	114.07	114.36	106.57	114.07
CO_2 Emission Reduction	Tons	780,618	431,894	243,388	1,076,035	776,024	644,134
Emissions (FU & LUC)	Tons	1,328,631	1,322,821	1,325,493	1,328,863	1,238,343	1,325,493
Net offset	Tons	−548,013	−890,927	−1,082,105	−252,828	−462,319	−681,359
Ethanol Price	NT$/liter	20	30	40	20	30	40
GHG Price	NT$/ton	15	15	15	15	15	15
Electricity Price	NT$/kg	1.7	1.7	1.7	3.45	3.45	3.45
Electricity Prod.	1000kwh	1,740,322	1,743,157	1,748,897	1,740,847	1,745,286	3,274,577
Electricity Supp.	%	0.0079	0.0079	0.0079	0.0079	0.0079	0.0148
Ethanol Prod.	1000liter	156,000	156,000	156,000	156,000	156,000	156,000
Total Planted Ha	1000 Ha	115.06	114.85	115.15	114.97	115.05	106.63
CO_2 Emission Reduction	Tons	1,163,300	1,165,167	1,168,946	1,163,646	1,166,568	776,957
Emissions (FU & LUC)	Tons	1,336,997	1,334,557	1,338,043	1,335,951	1,336,881	1,239,041
Net offset	Tons	−173,697	−169,390	−169,097	−172,305	−170,313	−462,084
Ethanol Price	NT$/liter	20	30	40	20	30	40
GHG Price	NT$/ton	20	20	20	20	20	20
Electricity Price	NT$/kg	1.7	1.7	1.7	3.45	3.45	3.45
Electricity Prod.	1000kwh	2,007,884	1,732,932	1,790,653	2,009,107	1,745,573	1,749,992
Electricity Supp.	%	0.0091	0.0078	0.0081	0.0091	0.0079	0.0079
Ethanol Prod.	1000liter	130,000	156,000	156,000	130,000	156,000	156,000

Table A1. *Cont.*

Term	**Unit**	**Haul biochar to the cropland as soil amendment**					
Total Planted Ha	1000 Ha	115	114.62	116.36	114.89	114.85	115.04
CO_2 Emission Reduction	Tons	1,336,551	1,158,434	1,196,438	1,337,356	1,166,757	1,169,667
Emissions (FU & LUC)	Tons	1,336,300	1,331,884	1,352,103	1,335,022	1,334,557	1,336,765
Net offset	Tons	251	−173,450	−155,665	2,334	−167,800	−167,098
Ethanol Price	NT$/liter	20	30	40	20	30	40
GHG Price	NT$/ton	25	25	25	25	25	25
Electricity Price	NT$/kg	1.7	1.7	1.7	3.45	3.45	3.45
Electricity Prod.	1000kwh	3,353,326	2,003,550	1,743,007	3,315,000	2,088,495	1,752,801
Electricity Supp.	%	0.0152	0.0091	0.0079	0.0150	0.0095	0.0079
Ethanol Prod.	1000liter	5,200	130,000	156,000	8,861	130,000	156,000
Total Planted Ha	1000 Ha	121.01	114.89	114.92	120.97	120.58	115.02
CO_2 Emission Reduction	Tons	2,208,412	1,333,697	1,165,068	2,183,588	1,389,625	1,171,517
Emissions (FU & LUC)	Tons	1,406,136	1,335,022	1,335,370	1,405,671	1,401,140	1,336,532
Net offset	Tons	802,276	−1,325	−170,302	777,917	−11,515	−165,015
Ethanol Price	NT$/liter	20	30	40	20	30	40
GHG Price	NT$/ton	30	30	30	30	30	30
Electricity Price	NT$/kg	1.7	1.7	1.7	3.45	3.45	3.45
Electricity Prod.	1000kwh	3353,446	2,043,067	1,788,248	3,308,116	2,028,091	1,788,649
Electricity Supp.	%	0.0152	0.0092	0.0081	0.0150	0.0092	0.0081
Ethanol Prod.	1000liter	5,200	130,000	156,000	5,200	130,000	156,000
Total Planted Ha	1000 Ha	121.02	116.94	117.15	117.3	115.24	117.16
CO_2 Emission Reduction	Tons	2,208,492	1,359,715	1,194,854	2,178,646	1,349,855	1,195,118
Emissions (FU & LUC)	Tons	1,406,252	1,358,843	1,361,283	1,363,026	1,339,089	1,361,399
Net offset	Tons	802,240	872	−166,429	815,620	10,766	−166,281
Term	**Unit**	**Burn biochar at pyrolysis plant to generate electricity**					
Ethanol Price	NT$/liter	20	30	40	20	30	40
GHG Price	NT$/ton	5	5	5	5	5	5
Electricity Price	NT$/kg	1.7	1.7	1.7	3.45	3.45	3.45
Electricity Prod.	1000kwh	2,364,700	773,500	773,500	2,475,200	2,408,900	2,187,900
Electricity Supp.	%	0.0107	0.0035	0.0035	0.0112	0.0109	0.0099
Ethanol Prod.	1000liter	228,822	306,243	306,797	224,533	242,777	251,907
Total Planted Ha	1000 Ha	111.91	117	117	111.91	117	117.11
CO_2 Emission Reduction	Tons	253,214	108,743	108,806	263,370	259,032	238,785
Emissions (FU & LUC)	Tons	1,300,394	1,359,540	1,359,540	1,300,394	1,359,540	1,360,818
Net offset	Tons	−1,047,180	−1,250,797	−1,250,734	−1,037,024	−1,100,508	−1,122,033
Ethanol Price	NT$/liter	20	30	40	20	30	40

Table A1. *Cont.*

Term	Unit	Burn biochar at pyrolysis plant to generate electricity					
GHG Price	NT$/ton	10	10	10	10	10	10
Electricity Price	NT$/kg	1.7	1.7	1.7	3.45	3.45	3.45
Electricity Prod.	1000kwh	2,873,000	1,547,000	773,500	2,762,500	2,652,000	2,364,700
Electricity Supp.	%	0.013	0.007	0.0035	0.0125	0.012	0.0107
Ethanol Prod.	1000liter	209,628	276,271	306,954	213,916	233,389	245,114
Total Planted Ha	1000 Ha	112.04	117.01	117.15	112.04	117.01	117.1
CO_2 Emission Reduction	Tons	299,986	179,831	108,823	289,831	281,377	255,040
Emissions (FU & LUC)	Tons	1,301,905	1,359,656	1,361,283	1,301,905	1,359,656	1,360,702
Net offset	Tons	−1,001,919	−1,179,825	−1,252,460	−1,012,074	−1,078,279	−1,105,662
Ethanol Price	NT$/liter	20	30	40	20	30	40
GHG Price	NT$/ton	15	15	15	15	15	15
Electricity Price	NT$/kg	1.7	1.7	1.7	3.45	3.45	3.45
Electricity Prod.	1000kwh	3,315,000	1,712,750	773,500	3,094,000	2,983,500	2,607,800
Electricity Supp.	%	0.015	0.00775	0.0035	0.014	0.0135	0.0118
Ethanol Prod.	1000liter	192,163	269,840	306,954	201,321	220,524	235,769
Total Planted Ha	1000 Ha	111.77	117.01	117.15	112.11	117.01	117.15
CO_2 Emission Reduction	Tons	340,569	195,062	108,823	320,325	311,840	277,390
Emissions (FU & LUC)	Tons	1,298,767	1,359,656	1,361,283	1,302,718	1,359,656	1,361,283
Net offset	Tons	−958,198	−1,164,594	−1,252,460	−982,393	−1,047,816	−1,083,893
Ethanol Price	NT$/liter	20	30	40	20	30	40
GHG Price	NT$/ton	20	20	20	20	20	20
Electricity Price	NT$/kg	1.7	1.7	1.7	3.45	3.45	3.45
Electricity Prod.	1000kwh	3,315,000	3,315,000	1,547,000	3,315,000	3,315,000	2,873,000
Electricity Supp.	%	0.015	0.015	0.007	0.015	0.015	0.013
Ethanol Prod.	1000liter	192,100	207,660	276,973	192,057	207,660	225,514
Total Planted Ha	1000 Ha	111.6	117	117.16	111.59	117.01	117.16
CO_2 Emission Reduction	Tons	340,562	342,305	179,910	340,557	342,305	301,765
Emissions (FU & LUC)	Tons	1,296,792	1,359,540	1,361,399	1,296,676	1,359,656	1,361,399
Net offset	Tons	−956,230	−1,017,235	−1,181,489	−956,119	−1,017,351	−1,059,634
Ethanol Price	NT$/liter	20	30	40	20	30	40
GHG Price	NT$/ton	25	25	25	25	25	25
Electricity Price	NT$/kg	1.7	1.7	1.7	3.45	3.45	3.45
Electricity Prod.	1000kwh	3,315,000	3,315,000	1,657,000	3,315,000	3,315,000	3,315,000
Electricity Supp.	%	0.0150	0.0150	0.0075	0.0150	0.0150	0.0150
Ethanol Prod.	1000liter	192,140	207,660	272,685	192,098	207,660	208,361
Total Planted Ha	1000 Ha	111.61	117	117.16	111.6	117.01	117.16
CO_2 Emission Reduction	Tons	340,567	342,305	190,064	340,562	342,305	342,383

Table A1. *Cont.*

Term	**Unit**	**Burn biochar at pyrolysis plant to generate electricity**					
Emissions (FU & LUC)	Tons	1,296,908	1,359,540	1,361,399	1,296,792	1,359,656	1,361,399
Net offset	Tons	−956,341	−1,017,235	−1,171,335	−956,230	−1,017,351	−1,019,016
Ethanol Price	NT$/liter	20	30	40	20	30	40
GHG Price	NT$/ton	30	30	30	30	30	30
Electricity Price	NT$/kg	1.7	1.7	1.7	3.45	3.45	3.45
Electricity Prod.	1000kwh	3,315,000	3,315,000	1,856,400	3,315,000	3,315,000	3,315,000
Electricity Supp.	%	0.015	0.015	0.0084	0.015	0.015	0.015
Ethanol Prod.	1000liter	192,096	207,660	264,866	192,097	207,660	208,261
Total Planted Ha	1000 Ha	111.6	117	117.11	111.6	117.01	117.11
CO_2 Emission Reduction	Tons	340,562	342,305	208,331	340,562	342,305	342,372
Emissions (FU & LUC)	Tons	1,296,792	1,359,540	1,360,818	1,296,792	1,359,656	1,360,818
Net offset	Tons	−956,230	−1,017,235	−1,152,487	−956,230	−1,017,351	−1,018,446

Note: FU and LUC stand for fertilizer and land use change, respectively.

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