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Prospect of China's renewable energy development from pyrolysis and biochar applications under climate change

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ABSTRACT

Pyrolysis is considered to be an effective technology that not only provides renewable energy but also mitigates climate change. Biochar, one by-product of pyrolysis, can be utilized in multiple ways by different biochar applications, which could result in considerable changes in renewable energy production and carbon sequestration. In existing literature, however, the economic and environmental benefits of pyrolysis and biochar applications are rately discussed, thus, a thorough investigation on conjunctive applications of pyrolysis and biochar should be conducted. This study (1) reviews the pyrolysis outputs from various inputs such as energy crops, crop residuals, animal manures, municipal solid wastes, and sewer sludge; (2) discusses the economic and environmental consequences from pyrolysis and biochar applications through the investigation of a lifecycle assessment; and (3) illustrates the potential climate-induced impacts on agriculture and stability of feedstock supply. To do this, this paper adopts a sector-wide model to compare the effectiveness and efficiency of pyrolysis and biochar applications with and without impacts of climate change for a specific region as a case study; and addresses the influential factors that potentially affect the large-scale development of pyrolysis. The results show that, in the absence of climate change impacts, conjunctive applications of pyrolysis and biochar can reduce more than 2.69 million tons of CO_2 emission and generate electricity of 3,962 MWh annually. In the cases where climate-induced impacts do have influences on crop yields, transitions among pyrolysis technologies and agricultural practice would occur. Under such a circumstance, net electricity generation and emission reduction would decrease by 1.72% and 3.19%, respectively. Thus,taking potential climate change impacts into account is necessary to avoid considerable deviations from the target.

1. Introduction

Development of modern economy is highly dependent on the use of fossil fuels which would be depleted and thus reliance on such non-renewable sources would not achieve sustainable social development [1,2]. Under such a consideration, numerous efforts have been undertaken to explore alternative resources and technologies to replace fossil fuels [3]. Bioenergy has been considered as a potential source for energy [4] because of its renewable nature and balanced CO_2 emissions through the photosynthesis cycle [5]. Additionally, resources that can be utilized in bioenergy production are not limited to biomass per se because an emerging and promising technology called "pyrolysis" can consume almost all organic materials such as energy crops, crop residuals, wood residue, animal manure, sewer sludge, and municipal solid wastes [6–9].

Pyrolysis generally decomposes feedstocks into a range of products such as bio-oil, biogas, biochar, and ash [10] while the output yield would vary, depending on the feedstock selection, types of pyrolysis used, and particle size [11]. For example, Wright et al. [12] show that fast pyrolysis yields about 15% biochar, 70% bio-oil and 13% syngas while Ringer et al. [13] show that under slow pyrolysis approximately 35% of the feedstock carbon ends up as biochar, 30% as bio-oil and 35% as biogas. Based on various experimental data, studies have shown that the net energy may be generated from pyrolysis ranges from 10 EJ/year to 270 EJ/year [14–16]. Even with such a large divergence, these studies still point out that pyrolysis has great potential in generating electricity. Another important aspect of developing renewable energy is to combat climate change. Intensified greenhouse gas effect is considered to result from the unprecedented increase of anthropogenic emissions. Therefore, it is also necessary to take environmental benefits into account when evaluating specific renewable energy technologies.

Biochar, one of the primary by-products of pyrolysis, is a charred

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organic matter. This carbon-rich solid product conventionally is treated as an energy source that usually burned with bio-oil and biogas [17]. With such an application, cost of per kWh can be reduced significantly [18]. However, some studies also point out that if biochar is used as a soil amendment, its environmental benefit is likely to outweigh the benefit from simply burning it [19–22]. Specifically, field experiments indicate that with appropriate application of biochar, crop yield can be improved [23,24], irrigation and feed efficiency can be increased [25–27], and carbon can be stored in a more stable form [28–31].

Moreover, the world is experiencing the unprecedented global climate change, which could have direct and considerable impact on entire agricultural sector and consequently bioenergy production. Under such a circumstance, conventional deterministic bioenergy analyses that do not take climate change into account are likely to present results significantly deviating from the reality. To explore how climate-induced impacts would alter the efficiency and effectiveness of bioenergy, incorporation of uncertainty is necessary. The perspective of this study is to provide an overview of recent applications in pyrolysis and biochar and illustrate how climate-induced impacts may influence the effectiveness and efficiency. Since the climate change is not evenly affecting the entire world, such impacts must be analyzed regional specifically. Therefore, a case study in Taiwan is also examined because Taiwan is lack of energy stocks and the large-scale development of renewable energy is of particular interested. The usefulness of the result presented from this case study is not limited only to Taiwan; rather its insights of uncertain climate impacts on renewable production can be applied universally.

This study makes contributions in several ways. First, it summarizes the recent pyrolysis studies and illustrates how bioenergy application may be adjusted in the face of climate-induced impacts. Specifically, this study employs a stochastic programming approach to compare the aggregate effects of bioenergy development under different climate impact scenarios. Second, this study analyzes the stability of feedstock supply under various climate impacts, as well as the distributions of resources engaged in agricultural activities. Based on this result, the government will be able to understand the interrelationship among bioenergy production, agricultural activities, emission reduction, and climate change. Finally, the alternative application of biochar is also examined to investigate whether the use of biochar in cropland can sustain crop yields and stabilize bioenergy production under climate-induced crop yield changes.

2. Applications of pyrolysis and biochar

Pyrolysis is a thermochemical decomposition process that converts organic materials into liquid, solid, and volatile products by heating in the absence of oxygen [32]. Pyrolysis technologies can be applied in several modes such as fast, intermediate, slow, flash, and gasification [33]. Table 1 displays the outputs from various pyrolysis technologies. The major difference resulting in different output yields among modes is the heating temperature and residence time. The liquid product is commonly called bio-oil, pyrolysis oil or bio-crude, which can be stored and refined for energy production. However, the energy density of raw bio-oil is low due to the high content of water, water acids, aldehydes, and oxygen [54,55]. The volatile fraction during pyrolysis process also contains a mixture of the non-condensable gases such as carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), methane (CH_4) and higher hydrocarbons, all of which are usually called pyrolysis gas or syngas [9,33]. The solid product of this process is a high carbon content, which is called biochar that can be used as a source of energy in the conversion process or as a soil amendment.

2.1. Fast pyrolysis

In fast pyrolysis process, the biomass is heated up to 1000 °C within tens of seconds. Akhtar [56] and Bridgewater [57] show that during fast pyrolysis process, approximately 60–75% of biomass will end up at bio-oil, while about 15–25% will become biochar. And as indicated by Wright et al. [12], fast pyrolysis is generally a dominant technology for the production of electricity. Although Bridgewater and Peacocke [10] have mentioned several important features of pyrolysis, there is a merit to understand that output yields are not constant across feedstocks [58]. For example, woody biomass such as poplar and forest residues can generally result in highest bio-oil yields [59,60] Additionally, Suttibak et al. [61] and Paenpong et al. [62] find that because many water acids are mixed with liquid products, the pH value of bio-oil is generally between 3.1 and 3.6. Consequently, the raw liquid product is thus highly corrosive.

Since bio-oil has high moisture content, it causes problems in direct combustion [34,63]. For example, the high heating value (HHV) of bio-oil is only about half of that of crude oil, and it is necessary to upgrade it so that bio-oil can be burnt more efficiently [64,65] or refined into transportation fuels such as gasoline or biodiesel [66]. In recent years, fast pyrolysis is also employed in other applications including the production of food flavors and valuable chemicals [2,67].

2.2. Slow pyrolysis

Slow pyrolysis that involves slow heating rate and long residence time of the biomass is the conventional method to produce charcoal. In this process the biomass is generally heated up to 300–950 °C [33–37] for a time ranging between 5 and 30 min, or even several days [68–70]. Unlike fast pyrolysis, slow pyrolysis can produce a much larger quantity of biochar because lower heating rate and longer heating time can help the formation of solid carbonaceous biochar [2,32]. However, it does not mean that the higher the temperature the biomass is pyrolyzed, the more quantity of biochar will be obtained. As indicated by Muradov et al. [71] and Demirbas [72], biochar yield will decrease as temperature increases due to the combustion of organic materials and the detriment of cellulose and hemicellulose. Therefore, the output yields and their subsequent heating values thus depend on the feedstock properties and operation conditions [56,73,74], implying that the appropriate selection of feedstocks plays a significant role in energy production and improvement of the operating system [75,76]. Table 2

Table 1
Overview of pyrolysis and biochar parameters for various modes.

Mode	Temperature (°C)	Residence time (seconds)	Heating rate (°C/s)	Yield (wt %)			Source
				biooil	biogas	biochar	
Slow	300–950	30 s to days	0.1–1.0	20–50	< 35	20–70	[33–39]
Intermediate	300–450	10–20 s	3.0–10	35–50	20–30	25–40	[33,34,36,37,40]
Fast	300–1000	1–2 s	10–200	60–75	10–30	10–25	[10,32,34,38–42]
Flash	500–1200	0.5–1 s	10–1000	60–75	< 12	< 13	[33,34,36,37,43,44]
Gasification	750–1000	5–20 s	NA	~5	~85	~10	[33,45–47]
Vacuum	300–600	0.001–1 s	0.1–1.0	NA	NA	NA	[48,49]
Hydrothermal carbonization	180–600	1–16 h	10–300	5–20	2–5	30–80	[50–53]
Torrefacation	~290	< 1 h	NA	0	~20	~80	[44,46,47]

Table 2
Pyrolysis outputs of feedstocks [77–82].

Raw Materials	Pyrolysis Type					
	Fast			Slow		
	Biochar	Bio-oil	Biogas	Biochar	Bio-oil	Biogas
	% of feedstock (dry ton)					
Poplar	14	66	13	31	56	7
Corn Stover	17	62	21	30	20	50
Rice Straw	27	47	26	48	15	37
Sewage Sludge	39	29	32	52	20	20
Orchards Wastes	25	41	26	–	–	–
Corncob	20	54	21	34	48	12
Animal Wastes	60	33	7	–	–	–
Open Pasture Wastes	23	43	25	–	–	–

Table 3
Onsite benefits of biochar application in China [18,89].

Inputs	Mode	Land Use (ha)	Hauling Distance (km)	Hauling Cost ($/ton)	Onsite Benefit ($/ton)
Poplar	Fast	16,733–96,710	5.26–20.01	$3.27~ $10.35	$2.85~ $10.5
Poplar	Slow	16,733–96,710	7.83–22.58	$3.72~ $12.16	$10.98~ $23.02
Corn Stover	Fast	45,251	8.2	$3.78	$8.21
Corn Stover	Slow	45,251	10.9	$4.25	$16.10
Rice Straw	Fast	27,517	7.31	$3.63	$12.08
Rice Straw	Slow	27,517	9.75	$4.05	$21.79
Orchard Waste	Fast	88,889	9.95	$4.09	$3.27
Animal Waste	Fast	3,600	10.9	$4.25	$81.43
Open Pasture	Fast	29,333	6.75	$3.53	$29.70

provides pyrolysis yields of common biomass and crop residues.

3. Economics of pyrolysis and biochar applications

3.1. Economics of biochar application

Biochar can be burned to improve the operating performance of the system. However, studies indicate that the alternative use of biochar could result in higher economic and environmental benefits [19,23–31]. Lehmann et al. [19] point out that because biochar is a relatively stable formation of carbon, it can stay in the soil for thousands of years, and thus can be potentially used to store and sequester carbon. Gaunt and Lehmann [20] calculate that the CO_2 emissions can be reduced by up to 84% if biochar is applied as a soil addition rather than as an energy source. Lehmann et al. [19], Lehmann [22], and Deluca et al. [83] thus conclude that with the appropriate use of biochar the pyrolysis can be considered as a “carbon negative technology”, and such applications might be useful in climate change mitigation.

Various benefits are found with such biochar applications. Crop yield is believed to be improved when biochar is simultaneously applied with fertilizers [84–86], but Chan et al. [29] point out that such an improvement can be achieved only when biochar is conjunctively applied with N-fertilizers. Irrigation saving and more efficient use of inputs may also be achieved with biochar application [30], but those gains may not sustain if biochar is lost due to heavy rainfall and runoffs [87]. Therefore, it is also necessary to investigate this uncertainty when applying biochar. McCarl et al. [21] take a potential loss of biochar into account and show that a dynamic application of biochar could alleviate this problem with only a small increase in application cost. Biochar is also found to reduce the leaching of soil nutrients so that more nutrients are available for plants and consequently, fewer nutrients will be washed out from the soils and the quality of nearby watershed may be enhanced [88]. Since changes in crop yield from biochar application would vary across crops, no single parameter about per hectare biochar application rate can be universally applied, and the net benefits from biochar application should be adjusted, depending on the biomass density, loss in transportation, collection cost, hauling distance, etc. Table 3 shows the application coats and onsite benefits of biochar utilization.

Table 4 presents the economics for various biochar application rates. Studies estimate that biochar application cost can vary significantly in different regions, depending on the application type and labor costs [21,89]. Since there is no consensus about the exact application rate of biochar, it has been applied ranging from 0.5 to 60 tons per hectare [23,24,30,90–97]. Since positive onsite benefits displayed in Table 3 is calculated with a 5-ton biochar application rate, they are very likely to decrease considerably if the application rate increases without considerable increases in benefits. The results imply that if agro-economic benefits are not gradually or linearly improved with higher application rates, onsite benefits from biochar application may be totally offset. Additionally, large application rates may further reduce the total onsite benefits (i.e., per hectare onsite benefit times applied land) because less land can have access to biochar, given a constant amount of biochar production.

3.2. Economics of pyrolysis

Large scale development of pyrolysis-based bioenergy and biochar utilization could be highly dependent on multiple economic factors such as energy price, production costs associate with plant production, collection, transportation, and processing, and trade prices of greenhouse gases. As discussed by McCarl et al. [21], pyrolysis and biochar application must be economically feasible in order for producers to participate with this technology. Therefore, knowing the onsite benefit of biochar only provides partial information about this information, and a comprehensive analysis should be provided. Whether the application of pyrolysis can succeed in a large scale depends on the amount of energy generation and its subsequent sales, which also depend on the regional electricity prices [18,21,89]. From an economic point of view, the production cost per unit of energy (kWh) thus will be very important because if it is too high, the renewable energy produced from pyrolysis will be less competitive unless a great amount of subsidy is paid. Therefore, although it seems that biochar application would derive considerable benefits in agricultural sector, an overall economic evaluation of pyrolysis operation should be assessed. This section provides a general appraisal of the economics of pyrolysis and biochar application.

Table 5 shows the per kWh cost for various crops. The electricity production cost for fast pyrolysis is generally lower than that for slow pyrolysis because more bio-oil and biogas are produced in fast pyrolysis, and thus more electricity can be generated with gradually decreased average production cost. The divergence of production costs between modes is ranging from 21.74% to 98.41%, depending on the feedstock selection. The results merit more discussion because of the alternative uses of biochar. In these studies, biochar is assumed to be applied as a soil addition and no electricity is generated from the burning of biochar. This is why the large divergence of production costs between technologies exists. If biochar is used as an energy source, the per kWh cost for both technologies will reduce, and the difference between technologies will be smaller because more biochar produced from slow pyrolysis can now be burned for electricity.

To verify to what extent biochar can reduce energy production cost, the lower heating value (LHV) estimated by Tola and Cau [98] is used to calculate the energy content of biochar. The results are also presented in the parentheses of China section. The results show that if biochar is burned for electricity, per kWh cost of electricity can be reduced by about 11–52%, depending on the type of feedstock used.

Table 4
Biochar application rate and potential onsite benefits.

Biochar source	Biochar application rate (ton/ha)	Fertilizer use (kg/ha)	Emission	Estimated benefits ($/ton)	Source
Corn stalk	24	250	63% of CH_4 emission decreases	−12.24	[90]
Maize residue	20	400	77% of N_2O emission decreases	−8.68	[91]
Maize residue	40	400	82% of N_2O emission decreases	−19.34	[91]
Wheat Straw	40	300	34% of CH_4 emission increases, 40–51% of N_2O emission decreases	−19.34	[92]
Wheat Straw	40	0	41% of CH_4 emission increases, 21–28% of N_2O emission decreases	−19.34	[92]
Pourltry Manure	20	45	CO_2 emission fluctuated, N_2O emission decreases by 14–73%	−8.68	[93]
Pourltry Manure	30	45	CO_2 emission fluctuated, N_2O emission decreases by 23–52%	−15.79	[94]
Pinua Radiata	10	760	No difference	12.63	[95]
Pinua Radiata	10	133	N_2O emission decreases by 70%	12.63	[96]
Wood	30	222	26–76% of N_2O emission decreases	−15.79	[97]
Wood	60	222	59–88% of N_2O emission decreases	−22.89	[97]

While this seems to be a desirable result, it is noteworthy to keep in mind that once biochar is burned, economic and environmental benefits that will be gained in cropland will diminish, and whether the benefit of cost reduction in electricity generation outweighs the benefit of agro-economic must be further investigated. In general, the levels of commodity prices, energy prices, and the GHG prices will influence the results considerably.

Additionally, various factors such as feedstock selection, crop density, electricity price, and logistics jointly influence the profitability of pyrolysis [99–101]. Several studies [18,59,99] show that per ton feedstock cost is generally within a wide range of $50 to $112, which is a primary factor affecting the profitability of pyrolysis. Kung et al. [18] apply a lifecycle analysis and show that if feedstock cost is higher than $74.3 dollars per ton, both fast and slow pyrolysis application will suffer a loss. For a large scale of pyrolysis development, profitability can be improved by amortizing fixed costs to a longer period [99,102]. Fig. 1 calculates the costs associated with the feedstock collection, transportation, and application. The plant construction and maintenance cost consists of the major expenses in pyrolysis operation, following by the feedstock expense and generating expense.

3.3. *Economics of joint applications*

Table 6 presents the economic assessments of pyrolysis and biochar application in large scale development. Energy sale is the major source of the economic profits whose level would be highly dependent on the regional electricity price. Moreover, even onsite biochar application would bring various benefits such as irrigation savings, higher fertilizer efficiency, yield enhancement, and carbon sequestration, these benefits only consist of a relatively small share of total benefits (except manure application). This occurs because high biochar application rate increases total costs and thus a greater portion of onsite benefits would be offset. For crops that require more biochar to result in these agricultural benefits, the net benefits from biochar application may be negative and under such circumstances, treating biochar as an energy source could be a better choice.

Application of pyrolysis is considered as a means to reduce net GHG emissions, but it is also necessary to investigate the emission from each stage of the production so that the producers and policy makers can have a broader picture about the emission consequences. Fig. 2 presents the major emission sources of different feedstocks. It is obvious that the transportation of feedstock usually involves the highest emission, following by the fuels used in plant operation. Constructing more plants can significantly reduce the average hauling distance of feedstocks, but this will result in a higher construction cost and more emissions from plant operation, leading to an ambiguous emission consequence. Yang et al. [103] provide a comprehensive discussion about GHG emissions consequences of pyrolysis plant for China.

Both electricity generation and biochar application sequester GHG emissions, but the net offset would also vary significantly across feedstocks. Based on the assessment of Kung et al. [89], Fig. 3 shows the net emission offset from pyrolysis electricity and onsite biochar application. Emission offset from renewable electricity is usually higher than that from onsite biochar applications. This occurs because that agricultural wastes such as orchard waste, rice straw, and corn stover will end up with higher bio-oil and biogas after pyrolysis, less biochar will be produced and applied, thereby reducing the onsite emission offset. The result also implies that if the government focuses on the improvement of agricultural practice via pyrolysis technology, animal manures may be a better choice since more biochar can be pyrolyzed from manure and thus more land will enjoy the agronomic benefits.

4. Bioenergy potential under climate change

Pyrolysis has been demonstrated to have positive effects on renewable energy production and emission reduction. However, most of

Table 5
Electricity production cost (cent/kWh) for various crops.

Region	Crops	Mode	Feedstock costs ($/dry ton) {Electricity Production Cost (cent/kWh)}			
The U.S [21].			**33**	**44**	**55**	**66**
	Maize residue	Fast	*9.7*	*10.5*	*11.4*	*12.2*
China [89]			**20**	**25**	**30**	**35**
	Corn stover	Fast	4.7 (4.1*)	5.1 (4.4*)	5.6 (4.8*)	6.1 (5.3*)
	Corn stover	Slow	8.4 (5.6*)	9.3 (6.2*)	10.2 (6.8*)	11.1 (7.4*)
	Rice straw	Fast	5.7 (4.3*)	6.3 (4.8*)	7 (5.3*)	7.6 (5.8*)
	Rice straw	Slow	11.3 (5.4*)	12.5 (6.0*)	13.7 (6.5*)	14.9 (7.1*)
	Poplar	Fast	4.6 (4.1*)	5.1 (4.5*)	5.6 (5.0*)	6.1 (5.4*)
	Poplar	Slow	5.6 (4.2*)	6.2 (4.6*)	6.8 (5.0*)	7.4 (5.5*)
	Orchard Waste	Fast	6.4 (4.8*)	7.1 (5.4*)	7.8 (5.9*)	8.5 (6.4*)
	Animal Waste	Fast	9.1 (4.3*)	10.1 (4.8*)	11.1 (5.3*)	12 (5.7*)
	Open pasture waste	Fast	6.2 (4.8*)	6.9 (5.4*)	7.5 (5.8*)	8.2 (6.4*)
Taiwan [18]			**56**	**75**	**94**	**112**
	Poplar	Fast	8.4	9.4	10.3	11.2
	Poplar	Slow	10.7	11.9	13.2	14.4

Note: the per kWh cost denoted by asterisk (*) considered the energy use of biochar.

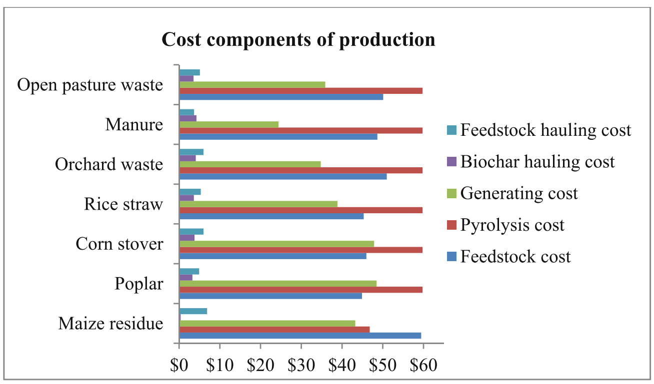

Fig. 1. Costs for pyrolysis and biochar application for various feedstocks.

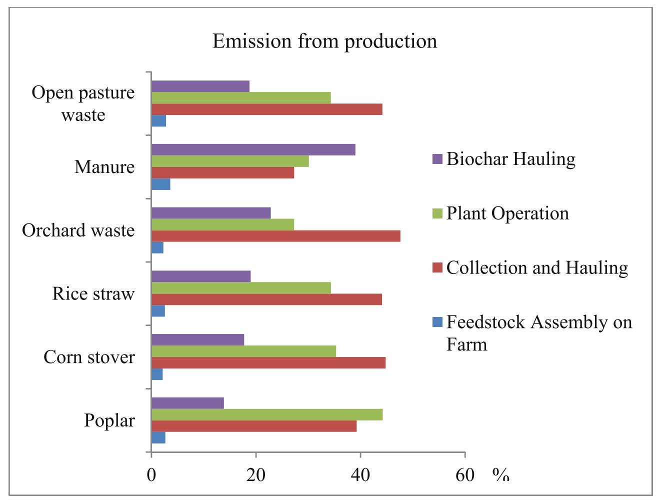

Fig. 2. Emission intensity of pyrolysis development.

Table 6
Lifecycle assessment of pyrolysis and biochar application in large scale [21,89].

Crop	Maize residue	Poplar	Corn Stover	Rice Straw	Orchard Waste	Animal Waste	Open Pasture Waste
Pyrolysis Type	**Fast**						
Feedstock cost	($59.4)	($44.9)	($46.0)	($45.3)	($51.0)	($48.7)	($50.1)
Pyrolysis cost	($46.8)	($59.8)	($59.8)	($59.8)	($59.8)	($59.8)	($59.8)
Generating cost	($43.3)	($48.5)	($47.9)	($38.9)	($34.8)	($24.4)	($35.9)
Electricity value	$100.0	$317.2	$297.9	$225.9	$197.0	$158.6	$206.6
Biochar value	$2.0	$10.5	$8.2	$12.1	$3.3	$81.4	$29.7
Biochar haul cost	$(0.4)	($3.3)	($3.8)	($3.6)	($4.1)	($4.3)	($3.5)
Net margin	($47.1)	$167.9	$181.8	$120.6	$86.2	$134.1	$121.4
GHG value	$3.3	$17.8	$15.5	$16.5	$9.2	$61.5	$27.9
Net margin all	($43.8)	$189.1	$164.2	$106.8	$59.8	$164.4	$114.9

Crop	Maize residue	Poplar	Corn Stover	Rice Straw
Pyrolysis Type	**Slow**			
Feedstock cost	($59.4)	($44.9)	($46.0)	($45.3)
Pyrolysis cost	($42.1)	($59.8)	($59.8)	($59.8)
Generating cost	($10.8)	($44.7)	($26.6)	($19.8)
Electricity value	$25.0	$269.1	$96.1	$72.1
Biochar value	$15.8	$23.0	$16.1	$21.8
Biochar haul cost	($3.1)	($3.7)	($4.6)	($4.1)
Net margin	($68.4)	$135.3	$4.6	($8.5)
GHG value	$4.6	$24.4	$11.2	$18.5
Net margin all	($63.8)	$163.4	($13.5)	($16.5)

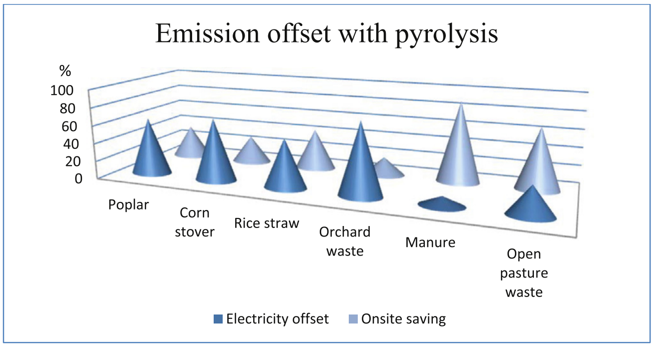

Fig. 3. Emission offset from various sources.

previous pyrolysis studies did not take climate-induced impact into account. Ignoring the potential influences from climate change may reduce the reliability of the results in several ways. For example, many pyrolysis feedstocks (i.e., energy crops, crop residuals, etc.) come from agricultural sector, which is highly vulnerable to the shift of temperature and precipitation [104–106]. Studies have indicated that crop yield in many regions has been altered by climate change and agricultural activities may be switched from current practice to other patterns [105,107–110]. Therefore, since the effectiveness of any forms of bioenergy production and efficiency of any renewable energy promotion policies depend on the agricultural activities, fluctuation in crop yield must be incorporated into the analysis to provide a more robust result so that decision makers could design, reform, or formulate policies based on the more realistic information.

Since the climate impacts can differ from regions to regions, a case specific analysis must be conducted to understand the true effects of potential study area. In this study Taiwan is examined as a case study because of following reasons. In 2017, Taiwanese government announces that nuclear power will phased out from its energy structure before 2025, which currently provides approximately 16% or 32 billion kWh of total electricity. This portion of electricity will primarily come from the renewable energy, especially bioenergy, offering a potential candidate for large scale development of pyrolysis electricity. Moreover, Taiwan's agriculture has been influenced by climate change in decades [106,109,110], and thus the potential influences on the Taiwan's bioenergy development and the application of pyrolysis technology can be compared under different crop yield scenarios. It is also noteworthy to point out that although Taiwan is examined, the analytical approach could be applicable to other countries and regions.

4.1. Framework of previous studies

To analyze the overall agricultural activities, a sector-level model is required so that the social welfare consequences, environmental benefits, agricultural activities, and resource allocation may be well portrayed. To aggregate these issues, Chen and Chang [108] extend the general agricultural sector model and develop a multi-product partial equilibrium framework called the Taiwan Agricultural Sector Model (TASM). Since the price endogenous property of this model is considered to be very useful in policy analysis [111], many subsequent studies that focus on the various agricultural, economic, environmental, and energy policies have been examined [18,89,112–115]. To specify the Taiwan's bioenergy production, Chen et al. [116] modify the previous version of the TASM by incorporating the GHG emissions, renewable energy promotion policy and carbon trades. Theoretically, the objective function and constraints of the modified model are shown as follows:

$$\begin{aligned} Max\ & \sum_i \int \psi(Q_i)dQ_i - \sum_i\sum_k C_{ik}X_{ik} - \sum_k \int \alpha_k(L_k)dL_k \\ & - \sum_k \int \beta_k(R_k)dR_k + \sum_i P_i^G{}_* Q_i^G + \sum_k P^L{}_* AL_k + \sum_j\sum_k SUB_{j*} \\ & EC_{jk} + \sum_i \int ED(Q_i^M)dQ_i^M - \sum_i \int ES(Q_i^X)dQ_i^X - \sum_i\sum_k C_{ik*}^R \\ & Q_{ik}^R + \sum_i \int EXED(TRQ_i)dTRQ_i + \sum_i [tax_{i*}Q_i^M + outtax_{i*}TRQ_i] \\ & - P_{GHG*}\sum_g GWP_{g*}GHG_g \end{aligned} \tag{1}$$

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

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

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

$$\sum_{i,k} E_{gik}X_{ik} - GHG_g \le 0 \qquad \forall\ g \tag{5}$$

where.

Q_i	Domestic demand of i^{th} product
	Government purchases quantity for price supported i^{th}product
	Import quantity of i^{th} product
	Export quantity of i^{th} product
	Quantity of ith agricultural wastes collected
	Inverse demand function of i^{th} product
	Government purchase price on i^{th} product
	Purchased input cost in k^{th} region for producing i^{th} product
	Collected and transported costs of ith wastes in kth region
	Land used for i^{th} commodities in k^{th} region
	Land supply in k^{th} region
	Land inverse supply ink^{th} region
	Labor supply in k^{th} region
	Labor inverse supply ink^{th} region
	Set-aside subsidy
	Set-aside acreage ink^{th} region
	Subsidy on planting j^{th}energycrop
	Planted acreage of j^{th} energy crop ink^{th} region
	Inverse excess import demand curve for i^{th} product
	Inverse excess export supply curve for i^{th} product
	Import quantity exceeding the quota for i^{th} product
	Inverse excess demand curve of i^{th} product that the import quantity is exceeding quota.
	Import tariff for i^{th} product
	Out-of-quota tariff for i^{th} product
	Per hectare yield of i^{th}commodity produced ink^{th} region
	g^{th} greenhouse gas emission from i^{th} product in k^{th} region
	Price of GHG gas
	Global warming potential of g^{th} greenhouse gas
	Net greenhouse gas emissions of g^{th} *gas*
f_{ik}	Labor required per hectare of commodity $i$in region k

While the methodological details for this model can be found in previous studies [112,114,115], a short introduction is provided so that readers can find insights of this model. equation (1) is the objective function which specifies the domestic and international trade policies. Equation (2) balances the quantity of commodity so that the quantity you sell cannot exceed the quantity you produce. Analogous constraints for resource uses and emission reduction are specified in equations (3)–(5).

With such a formulation, it is also important to verify whether this

Table 7
Validation of the model structure [116,117].

Products	Production (ton)		Price (NT$/kg)	
	Observation	Deviation	Observation	Deviation
Rice	1,187,596	0.07%	24.30	2.63%
Hog	911,449	−0.11%	53.64	−2.21%
Broiler Chicken	279,951	5.00%	52.68	1.38%
Native Chicken	258,110	−0.23%	36.81	0.38%
	Planted area (1000 ha)			
	Observation	Deviation		
Rice Planted Area	269.02	−2.91%		
Set-Aside Area	258.18	0.41%		

analytical model can effectively and efficiently portray the regional agricultural sector and resource allocation. The model is validated following Chen et al.'s [116] and Kung et al.'s [117] approaches with updated dataset. The validation result indicate that the model can be representative because by comparing the productions of major agricultural and livestock commodities, land use patterns, and market prices of these commodities, the deviations between simulation results and actual data are pretty small, implying the results should be reliable. Table 7 presented the validation result.

4.2. An extension with uncertainty

Although the above model is validated and has been considered to be an effective tool to analyze Taiwan's bioenergy production [112,114,116], climate-induced impacts have not been accommodated. Since bioenergy development is highly dependent on the utilization of agricultural products, the stability of input supply thus plays a crucial role in bioenergy development. Therefore, climate-induced impacts that potentially influence the crop yields and agricultural activities should be simultaneously investigated. For this reason, the deterministic modeling framework may not be suitable when environmental risks are taken into account. To reflect this uncertainty, altering the model to a stochastic structure may be more appropriate. Additionally, considering that farmers are usually able to adjust their behavior in the later period, the TASM is extended to a stochastic programming with recourse (SPR) version.

The modification is made in several points. First, because the situation (i.e., weather and crop yields) farmers are facing during plow, plant, and harvest periods cannot be precisely predicted at the beginning stage, farmers must predetermine what crop to plant and calculate possible revenues under various states of nature. This implies that the objective function is to maximize the expected profits. Mathematically, the objective function with uncertainty is expressed as

$$Max\ W = \sum_{s} \rho(s)_{*} \Big\{ \sum_{i} \int \psi(Q_{is})dQ_{is} - \sum_{k} \int \alpha_k(L_k)dL_k - \sum_{k} \int \beta_k(R_k)dR_k - \sum_{i}\sum_{k} C_{ik}X_{ik} + \sum_{i} \int ED(Q_{is}^{M})dQ_{is}^{M} + \sum_{i} \int EXED(TRQ_{is})dTRQ_{is} - \sum_{i} \int ES(Q_i^{X})dQ_i^{X} + \sum_{i} [tax_{i*}Q_{is}^{M} + outtax_{i*}TRQ_{is}] \Big\} + \sum_{i} P_i^{G}{}_{*}Q_i^{G} + \sum_{k} P^{L}{}_{*} AL_k + \sum_{j} SUB_{j*}AL_j - P_{GHG*} \sum_{g} GWP_{g*}GHG_g \quad (6)$$

Second, since the crop yield could change in different states, the parameter representing per hectare crop yield must be modified to $(1 + CCYIELD_i) * X_{ik}$. Chang [111] have estimated the potential impacts of climate change on Taiwan's agriculture while Chang et al. [112] provide a detailed description about potential crop yield change under different Intergovernmental Panel on Climate Change (IPCC) projections. This study incoporates these estimates to compare the bioenergy production, pyrolysis effects, biochar utilization, and potential GHG consequences under deterministic and stochastic models.

Table 8
Percentage change in crop yields under IPCC-HADCM scenarios [112].

Group	Products	Climate Change HADCM Scenario A2	B2	Group	Products	Climate Change HADCM Scenario A2	B2
Rice	Rice	−0.71	−1.66	Fruits	Banana	−2.04	−7.51
Cereal	Corn	−1.24	−3.02		Pineapple	−1.35	−11.40
	Wheat	0.15	0.09		Ponkan	−0.28	0.55
	Sorghum	7.16	17.9		Tankan	0.55	8.79
Pulses	Soybeans	3.76	2.86		Wentan	2.02	5.94
	Peanuts	−0.03	0.95		Liucheng	2.52	2.25
	Adzuki bean	−2.63	−10.13		Lemon	1.02	−3.11
Roots	Sweet-Potatoes	−2.26	−2.76		Grapefruit	−1.69	−7.19
	Potatoes	0.97	3.17		Mango	−6.46	−4.12
Special	Tea	−1.65	−1.45		Betel	−0.94	−8.43
	Cane for process	1.03	−1.87		Guava	1.25	3.38
	Cane for fresh	1.03	−1.87		Wax apple	1.96	14.86
	Sesame	1.14	−5.07		Grape	5.23	0.91
Vegetables	Radish	1.14	1.67		Loquat	−3.22	−2.59
	Carrot	−0.31	7.34		Plum	1.55	3.27
	Ginger	1.71	6.38		Peach	0.84	3.53
	Scallion	0.81	9.69		Persimmons	1.32	4.97
	Garlic bulb	5.25	5.89		Apricot	2.4	0.87
	Leek	−1.44	1.96		Liche	−2.36	1.66
	Bamboo	−1.20	2.9		Carambolas	1.13	−1.05
	Asparagus	2.37	−1.18		Pear	0.11	−2.53
	Water bamboo	2.37	−1.18		Apple	−5.72	−22.86
	Cabbage	−1.02	−0.05		Papaya	−2.13	−4.74
	Cauliflower	−1.02	−0.05		Sugar apple	−2.99	−7.26
	Cucumber	−1.90	−2.69		Passion fruit	−2.47	−9.21
	Bitter	0.89	7.8		Coconut	−3.05	−5.64
	Tomato	−1.03	1.69				
	Pea	−0.38	−1.65				
	Watermelon	−2.72	−1.10				

Table 9
Pyrolysis electricity and societal effects without climate change consideration [111].

Biochar for energy scenarios										
Gasoline Price	$/liter	**0.67**	**1**	**1.33**	**0.67**	**1**	**1.33**	**0.67**	**1**	**1.33**
Coal price	$/kg	**0.057**	**0.057**	**0.057**	**0.057**	**0.057**	**0.057**	**0.057**	**0.057**	**0.057**
GHG Price	$/ton	**5**	**5**	**5**	**15**	**15**	**15**	**30**	**30**	**30**
Electricity	1000 kWh	1,657,500	773,500	773,500	2,051,092	2,050,883	2,051,097	3,782,625	2,369,387	2,074,027
Land utilized	1000 ha	112.13	115.96	117.12	117.14	117.14	117.14	117.21	117.21	117.21
Waste contribution	%	43.36%	92.91%	92.91%	35.04%	35.04%	35.04%	19.00%	30.33%	34.65%
Biochar land	1000 ha	NA	NA	NA	NA	NA	NA	NA	NA	NA
Government expense	million $	5,569.3	5,738.2	5,842.5	5,843.8	5,843.5	5,843.8	5,847.1	5,861.0	5,861.0
Emission reduction	ton	1,167,307	673,081	671,302	1,387,485	1,387,366	1,387,488	2,358,301	1,564,847	1,399,279
Social welfare	million $	14,720.2	29,424.8	49,773.0	30,831.5	43,593.3	56,487.0	53,349.1	60,564.7	71,136.5
Gasoline Price	$/liter	**0.67**	**1**	**1.33**	**0.67**	**1**	**1.33**	**0.67**	**1**	**1.33**
Coal price	$/kg	**0.115**	**0.115**	**0.115**	**0.115**	**0.115**	**0.115**	**0.115**	**0.115**	**0.115**
GHG Price	$/ton	**5**	**5**	**5**	**15**	**15**	**15**	**30**	**30**	**30**
Electricity	1000 kWh	1,968,977	1,712,750	1,326,000	2,054,807	2,054,807	2,074,460	3,962,109	2,369,272	2,073,912
Land utilized	1000 ha	114.42	116.81	117.12	117.23	117.23	117.25	117.25	117.21	117.21
Waste contribution	%	36.50%	41.96%	54.20%	34.97%	34.97%	34.64%	18.14%	30.33%	34.65%
Biochar land	1000 ha	NA	NA	NA	NA	NA	NA	NA	NA	NA
Government expense	million $	5,684.0	5,803.5	5,842.5	5,848.1	5,848.1	5,862.4	5,849.1	5,860.0	5,860.0
Emission reduction	ton	1,342,926	1,199,857	981,014	1,389,604	1,389,604	1,399,527	2,356,005	1,564,782	1,399,214
Social welfare	million $	31,169.6	45,023.6	63,350.4	43,037.5	55,677.6	74,023.7	74,499.7	81,496.6	91,796.5
Biochar as a soil amendment scenarios										
Gasoline Price	$/liter	**0.67**	**1**	**1.33**	**0.67**	**1**	**1.33**	**0.67**	**1**	**1.33**
Coal price	$/kg	**0.057**	**0.057**	**0.057**	**0.057**	**0.057**	**0.057**	**0.057**	**0.057**	**0.057**
GHG Price	$/ton	**5**	**5**	**5**	**15**	**15**	**15**	**30**	**30**	**30**
Electricity	1000 kWh	1,492,160	1,492,160	1,492,160	1,777,031	1,724,817	3,473,141	2,088,437	1,799,957	1,724,144
Land utilized	1000 ha	113.42	114.26	115.09	119.20	115.40	122.91	122.91	122.91	115.21
Waste contribution	%	48.16%	48.16%	48.16%	40.44%	41.67%	20.69%	34.41%	39.93%	41.68%
Biochar land	1000 ha	126.01	116.27	46.53	127.05	125.95	127.04	145.87	145.87	145.87
Government expense	million $	5,657.6	5,699.6	5,754.7	5,960.0	5,770.0	6,145.5	6,145.5	6,145.5	5,760.5
Emission reduction	ton	1,497,667	1,433,324	971,776	1,663,712	1,626,931	2,727,769	1,962,238	1,802,752	1,627,704
Social welfare	million $	28,168.4	40,718.4	52,197.2	38,763.3	51,965.6	68,983.9	75,908.2	86,679.8	76,701.6
Gasoline Price	$/liter	**0.67**	**1**	**1.33**	**0.67**	**1**	**1.33**	**0.67**	**1**	**1.33**
Coal price	$/kg	**0.057**	**0.057**	**0.057**	**0.057**	**0.057**	**0.057**	**0.057**	**0.057**	**0.057**
GHG Price	$/ton	**5**	**5**	**5**	**15**	**15**	**15**	**30**	**30**	**30**
Electricity	1000 kWh	2,064,610	1,492,160	1,511,014	1,492,160	2,014,727	1,724,144	3,455,234	2,070,530	1,782,050
Land utilized	1000 ha	116.31	114.26	114.60	119.20	115.42	115.21	120.55	120.55	120.55
Waste contribution	%	34.81%	48.16%	47.56%	48.16%	35.67%	41.68%	20.80%	34.71%	40.33%
Biochar land	1000 ha	82.09	116.27	34.38	125.94	126.12	126.12	142.00	142.00	142.00
Government expense	million $	5,815.4	5,713.0	5,730.0	5,960.0	5,771.0	5,760.5	6,027.3	6,027.3	6,027.3
Emission reduction	ton	1,524,211	1,433,875	901,442	1,506,156	1,787,122	1,627,704	2,691,719	1,926,278	1,766,702
Social welfare	million $	38,778.2	52,369.9	64,388.9	64,295.6	52,828.7	64,061.7	86,318.5	89,665.0	99,691.2

Table 8 presents the potential crop yield change in Taiwan under moderate climate change scenarios. The scenario HADCM-A2 represents an assumed 1% increase in temperature with a 6% increase in precipitation, and HADCM-B2 assumes a 6% increase in temperature with a 9% increase in precipitation [112].

4.3. Results comparison

The climate-induced impacts on bioenergy production and biochar application thus can be perceived from the changes in crop yields. Table 9 and Table 10 summarize the most important results of Taiwan's bioenergy production under different consideration of climate change. Specifically, Table 9 points out how energy and GHG prices may affect Taiwan's bioenergy production and the differences between the uses of biochar, given historical crop yield patterns where there are no climate-induced impacts. On the contrary, Table 10 considers how biochar application can be useful in maintaining crop yield and stabilizing subsequent feedstock supply and bioenergy production when climate-induced crop yield changes do occur.

The results show that when climate-induced impacts have been incorporated in the model, the changes in crop yield could alter the current agricultural practices, thereby resulting in considerable difference in the net electricity generation. The net impact is trivial when crop yield change is insignificant or the impact resulted by climate change is unlikely. Under such a circumstance, the net bioenergy production would be at a level similar to the cases where there are no climate impacts. However, when the likelihood of occurrence of climate change increases, net electricity generation and emission reduction may reduce because more resources will be allocated to food commodities, depending on the price elasticity of all commodities and total demand of other crops.

The selection of technology pyrolysis and the use of byproducts, as well as the climate change impacts, conjunctively determine the electricity generation. As have been seen in Table 9, the slow pyrolysis that yields more biochar will not be selected when climate change mitigation is not the first priority or when the GHG price is low; instead, the fast pyrolysis will be used under such a circumstance. Namely, when the government is not focusing on the emission mitigation, the fast pyrolysis that yields higher electricity output would dominate other alternatives. Additionally, when the market does not consider the emission reduction as a valuable product, slow pyrolysis that is sequestering more carbon would be rarely adopted.

Market operations also play a crucial role in technology selection. Given the moderate coal and GHG prices, most of electricity generation comes from the fast pyrolysis, especially when biochar is also used as an energy input. However, under such a circumstance, benefits from agricultural practices such as irrigation saving, fertilizer efficiency improvement, and crop yield enhancement will not be obtained. Conversely, when emission mitigation is considered as the primary goal (i.e., under the consideration of Paris Agreement or Tokyo Protocol), slow pyrolysis that sequesters more CO_2 will become a dominant technology. For example, when climate change mitigation is the primary focus of bioenergy development, the government may want to increase the production of biochar that sequesters and stores more

Table 10
Pyrolysis electricity and biochar application (soil amendment) with climate change consideration.

Large yield change (B2 Scenario)										
Prob. of yield change		Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/Liter	**20**	**20**	**20**	**25**	**25**	**25**	**30**	**30**	**30**
Coal Price	NT/kg	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**
GHG Price	NT/ton	**25**	**25**	**25**	**25**	**25**	**25**	**25**	**25**	**25**
Electricity @SWP	1000 kWh	2,857,590	2,838,892	2,766,423	2,758,568	2,838,892	2,838,153	2,679,061	2,838,791	2,670,835
Electricity @ SWPvine	1000 kWh	771,129	776,939	777,251	770,942	776,939	774,628	775,877	777,002	774,628
Electricity @ rice straw	1000 kWh	279,033	279,033	279,033	279,033	279,033	279,033	279,033	279,033	279,033
Net Electricity	1000 kWh	3,907,752	3,894,864	3,822,707	3,808,542	3,894,864	3,891,814	3,733,971	3,894,826	3,724,495
Electricity @ SWP	%	91.1%	91.1%	90.8%	90.8%	91.1%	91.0%	90.6%	91.1%	90.5%
Electricity @ rice straw	%	8.9%	8.9%	9.2%	9.2%	8.9%	9.0%	9.4%	8.9%	9.5%
Net Reduction	ton	2,802,942	2,830,527	2,837,355	2,875,459	2,830,527	2,801,200	2,738,000	2,830,475	2,707,010
SWP Subsidy	Million NT	6,171	6,218	6,220	6,170	6,218	6,200	6,209	6,219	6,200
SWP Planted Ha	1000 ha	123.43	124.36	124.41	123.4	124.36	123.99	124.19	124.37	123.99
Prob. of yield change		Low	Moderate	High	Low	Moderate	High			
Gasoline Price	NT/Liter	**35**	**35**	**35**	**40**	**40**	**40**			
Coal Price	NT/kg	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**			
GHG Price	NT/ton	**25**	**25**	**25**	**25**	**25**	**25**			
Electricity @ SWP	1000 kWh	2,638,218	2,762,500	2,629,228	1,680,682	1,926,448	1,420,678			
Electricity @ SWPvine	1000 kWh	776,689	777,376	789,372	776,689	777,501	788,185			
Electricity @ rice straw	1000 kWh	279,033	279,033	279,033	279,033	279,033	279,033			
Net Electricity	1000 kWh	3,693,940	3,818,909	3,697,632	2,736,404	2,982,982	2,487,896			
Electricity @ SWP	%	90.4%	90.8%	90.4%	85.8%	87.3%	83.6%			
Electricity @ rice straw	%	9.6%	9.2%	9.6%	14.2%	12.7%	16.4%			
Net Reduction	ton	2,386,711	2,652,457	2,545,323	1,847,776	1,904,553	1,973,129			
SWP Subsidy	Million NT	6,216	6,221	6,318	6,216	6,223	6,308			
SWP Planted Ha	1000 ha	124.32	124.43	126.35	124.32	124.45	126.16			
Small yield change (A2 Scenario)										
Prob. of yield change		Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/Liter	**20**	**20**	**20**	**25**	**25**	**25**	**30**	**30**	**30**
Coal Price	NT/kg	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**
GHG Price	NT/ton	**25**	**25**	**25**	**25**	**25**	**25**	**25**	**25**	**25**
Electricity @ SWP	1000 kWh	2,857,590	2,839,035	2,766,419	2,758,567	2,839,256	2,821,662	2,679,060	2,839,256	2,654,344
Electricity @ SWPvine	1000 kWh	279,032	279,032	279,032	279,032	279,032	279,032	279,032	279,032	279,032
Electricity @rice straw	1000 kWh	771,128	776,751	776,626	770,941	776,876	775,752	775,877	776,876	775,752
Net Electricity	1000 kWh	3,907,752	3,894,820	3,822,078	3,808,541	3,895,165	3,876,447	3,733,970	3,895,165	3,709,128
Electricity @ SWP	%	91.1%	91.1%	90.8%	90.8%	91.1%	91.0%	90.6%	91.1%	90.5%
Electricity @ rice straw	%	8.9%	8.9%	9.2%	9.2%	8.9%	9.0%	9.4%	8.9%	9.5%
Net Reduction	ton	2,802,941	2,830,683	2,834,188	2,875,459	2,830,506	2,812,234	2,737,999	2,830,506	2,718,044
SWP Subsidy	Million NT	6,171	6,216	6,215	6,169	6,217	6,208	6,209	6,217	6,208
SWP Planted Ha	1000 ha	123	124	124	123	124	124	124	124	124
Prob. of yield change		Low	Moderate	High	Low	Moderate	High			
Gasoline Price	NT/Liter	**35**	**35**	**35**	**40**	**40**	**40**			
Coal Price	NT/kg	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**			
GHG Price	NT/ton	**25**	**25**	**25**	**25**	**25**	**25**			
Electricity @ SWP	1000 kWh	2,638,218	2,762,500	2,649,692	1,680,682	1,826,456	1,443,907			
Electricity @ SWPvine	1000 kWh	279,033	279,033	279,033	279,033	279,033	279,033			
Electricity @rice straw	1000 kWh	776,689	776,377	777,251	776,689	777,501	795,619			
Net Electricity	1000 kWh	3,693,940	3,817,910	3,705,976	2,736,404	2,882,990	2,518,559			
Electricity @ SWP	%	90.4%	90.8%	90.5%	85.8%	86.7%	83.8%			
Electricity @ rice straw	%	9.6%	9.2%	9.5%	14.2%	13.3%	16.2%			
Net Reduction	ton	2,386,711	2,675,573	2,330,725	1,847,776	1,935,381	1,991,214			
SWP Subsidy	Million NT	6,216	6,213	6,220	6,216	6,223	6,368			
SWP Planted Ha	1000 ha	124.32	124.27	124.41	124.32	124.45	127.35			

carbon, implying that the greater development of slow pyrolysis would be necessary.

Climate change that influences regional temperature and precipitation can also alter the current agricultural practice, and consequently affect the bioenergy production. As indicated in Table 10, climate-induced crop yield change encourages the adoption of slow pyrolysis since the biochar is found to improve the crop yield and reduce production costs, both of which help sustain the profits when climate impacts do occur. In Table 10, the climate-induced impacts only result in a small change in land use and resource reallocation, and the total electricity generation would still stay at a satisfactory level. This situation merits more investigation because the crop yield change used in this study is relatively small, and in regions where climate impacts are greater and more significant, resource allocation may be altered considerably and thus have direct influences on bioenergy production.

Market power still is a key factor affecting bioenergy production, regardless of the projections of climate change. When energy price increases, benefits from electricity generation may outweigh the benefits of biochar application. Under such a circumstance, the fast pyrolysis may still dominate and thus in order to obtain mitigation benefits the government may need to propose additional policies or subsidies to support the development of slow pyrolysis. When aside program and energy crop subsidy are simultaneously initiated, farmers with bare land will choose to participate in the aside land program and switch their cultivars to energy crops so that they can enjoy both types of subsidies. Therefore, when climate-induced impacts are more likely to occur or when changes in crop yields are expected to be large, more bioenergy can be produced because more farmers are likely to participate with the bioenergy programs to received guaranteed subsidies rather than uncertain income streams from existing cultivars. Therefore, a greater likelihood of occurrence of climate change would help sustain the supply of energy crops and subsequent bioenergy production. However, since greater participation in bioenergy program means a greater subsidy, it must be kept in mind that the society as a whole will bear a higher total cost. This situation will become more complex when capital rationing exists (i.e., the total number of cropland that can participate in support programs is limited and thus which cropland is eligible to participate with the programs must be pre-determined, making things more complicated).

4.4. Policy implications

The results show that pyrolysis and biochar application can be helpful in terms of the renewable energy supply and climate change mitigation. However, the results are limited under certain real world considerations, which thus constrain the usefulness of the result, and thus such limitations and possible policy implications merit more discussion to provide more useful information to decision-makers. These points are discussed below:

(1) Moisture content of pyrolyzed materials. Various organic sources such as municipal solid waste, sewer sludge, biomass, agricultural wastes, and animal manures can be used in pyrolysis process. However, before these materials are sent to pyrolysis plants the moisture containing in the feedstocks must be removed to improve the transforming efficiency. For some materials such as municipal solid waste and sewer sludge [118] that contain a greater portion of water, it will cost more time and cost in the drying process. Proper classifying and insolating these materials during the collection stage may be one possible solution, but the associated economic consequences regarding their transportation and storage may require additional investigation.
(2) Level of climate impacts. Not all input supply may be severely influenced by climate change. For example, feedstocks such as municipal solid wastes and sewer sludge whose supply are more dependent on demographic measures and infrastructure may not fluctuate considerably under climate change, but feedstocks come from agricultural and livestock sectors may suffer. Although the results indicate that market power has greater influences on bioenergy production than changes in crop yields, it also implies that the agricultural practice could be sensitive to climate change. Therefore, to analyze the bioenergy potential, it is necessary to take potential climate-induced impacts into account before exploring the net effects from bioenergy production because for regions where climate-induced impacts are more severe agricultural practice may be altered considerably. Since the results also imply that farmers' willingness to participate with the bioenergy program may also depend on the level of climate change, the government is responsible to provide more information about climate and its trend so that the development of pyrolysis could still optimize the social welfare. If this information is insufficient, too much or too little bioenergy will be produced, resulting in a greater deviation from the optimal development path.
(3) Market conditions. The results explicitly show that the market conditions such as coal price and GHG price could affect selection of technology and bioenergy production. Since there has a tradeoff between bioenergy production and agricultural benefits, decision-makers must design or reform current policies to best fit the goals: energy first or environment first. Namely, the government must have policies that can accurately serve the predetermined goals; otherwise the market power could easily alter the development objectives. For example, if the government believes that they want to adopt pyrolysis to combat climate change, they probably need to set up a floor price for emission reduction so that slow pyrolysis would be preferred and more environmental benefits can be achieved. Such a policy may involve a substantial amount of subsidy when the market emission price is low, and thus the efficient floor price should be investigated to balance the environmental benefits and social costs.

5. Conclusions

This study summarizes the most important results from pyrolysis and biochar application that helps decision makers to evaluate the investment requirement, effectiveness of existing energy policies, efficiency of bioenergy production, and climate change mitigation potentials.

Various organic matters can be used as pyrolysis feedstocks, and utilization of certain wastes such as sewer sludge and municipal solid wastes can ultimately improve the resource recycling and improve intergenerational equity. Whether to use a material as the primary feedstock depends on several factors. First, availability of this material must be stable. Locally abundant materials would reduce the collection and transportation costs, but the cyclical (or seasonal) effect of such materials also needs to be evaluated so that the stability of input supply can be ensured. Second, cost-benefit analysis should be applied to determine the overall effects. Costs of pre-processing and treatment of certain organic materials such as municipal solid waste and sewer sludge could be much higher than those of agricultural residuals and animal manures because the formers may contain more toxic matters or heavy metals that must be removed. Additionally, depending on the feedstocks utilized, the water content that decreases the pyrolysis efficiency should be removed, and the associated pre-treatment cost may also be incorporated in the cost-benefit analysis. Third, the support policy is keyed to the large-scale development of pyrolysis because pyrolysis plants must be built, plantation of energy crops must be encouraged, input supply chain must be contracted, and producers must be subsidized through future tax cuts or low-interest loans. Since various departments are involved (i.e., agriculture, commerce, energy, environment, etc.), interdepartmental negotiations may be needed to minimize the conflicts among parties so that the policies can be launched effectively.

The usefulness of the results may be limited to the countries or regions in which whose climate has been greatly shifted. This study uses general IPCC projections to examine the potential of pyrolysis and biochar application under various climate-induced impacts, but since numerous climate change patterns have been observed in different areas, alternative scenarios may be applied for countries whose climate-induced impacts are significantly different from this case study. However, this study illustrates an effective and useful approach for researchers to deal with such uncertain climate impacts and the insights can be applied widely.

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