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How government subsidy leads to sustainable bioenergy development

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ABSTRACT

Sustainable development requires energy source stability and environmental maintenance. Over-exploitation and the intensive use of nonrenewable fossil fuels thus eventually hamper the development of human society. Bioenergy is one solution to this problem. This study formulates a price endogenous, partial equilibrium mathematical model to simulate the economic and environmental effects of bioenergy development in Jiangxi province, China. The result indicates that the farmers' revenue primarily originates from energy sales, government subsidies and emission reduction. An inappropriate subsidy amount will result in inefficient resource allocation; in addition, the marginal benefit from bioenergy production is fairly small. The result also shows that the joint production of bio-electricity and ethanol could be a better choice if climate change mitigation is considered.

1. Introduction

Economic development consumes various natural resources such as fossil fuels, clean water, wetland and primeval forests for which quantities are limited. Although it may not be a problem in the short-run, over-depletion and the inefficient allocation of these resources will slow the future growth rate and eliminate the possibility of future generations to obtain long-term access to such resources (Martinez et al., 2015; United Nations, 2014). For example, China is a large nation and has been rapidly growing for decades. Huge amount of resources have been extracted and utilized to improve its economic, and living standards. However, all of the gains obtained today are offset by the deterioration of the environment and the inefficient use of its resources, which is obviously not a sustainable approach (Huang et al., 2007). Therefore, to reduce these unsustainable consequences, seeking a means to ensure the sustainable and efficient development of human society has garnered tremendous attention by governments and academia.

Two of the most valuable resources in the world are probably fossil fuels and the environment; all industries, sectors and governments are involved. However, fossil fuel is not a sustainable resource because of its limited stock. New energy sources must be explored in an economically feasible manner to ensure that society can constantly develop. In addition, during the production and consumption process of goods, plenty of wastes are produced and emitted, which inevitably deteriorates the environment. For example, the excessive use of fossil fuel emits significant quantities of greenhouse gases (GHG), which has been considered as a primary cause that has induced a global climate shift and resulted in the rise of the sea level and in extreme events (IPCC, 2007). Renewable energy is treated as a potential technology that can be used to overcome the problems of an insufficient energy source and a degraded environmental quality (Chen et al., 2011; Kung et al., 2013; McCarl et al., 2009) because it is produced from the utilization of renewable resources such as wind, solar and agricultural commodities; in addition, it reduce the wastes released to the environment.

To make renewable energy successful, it must be economically feasible to attract producers and consumers. Thus, adequate economic incentives play an important role in the development of renewable energy. Compared with other nations, China consumes a significant portion of fossil fuels annually. This study analyzes how Chinese producers and consumers will react if renewable energy becomes a new alternative and explores how this market operation may affect renewable energy production and the environment. This study selects the Jiangxi province as the study object for several reasons. First, Poyang Lake, the largest wetland area in China, is located in Jiangxi, which is the most important water source for more than 20 million people. This lake is also crucial for environmental systems such as bio-diversification, watershed protection and forest conservation. Second, agriculture is the primary industry that engages more than 50% of residents in this area. Farmer revenue is low and suffers from an unsatisfactory living standard. This agricultural-based area provides an opportunity for bioenergy development. Third, according to the 12th five-year plan of China, there is a consensus to reduce fossil fuel consumption and GHG emissions. In accordance with this consensus, the Jiangxi government

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subsidizes the energy that is produced from agricultural commodities. This policy is useful to help determine how bioenergy may be affected under market operation and policy incentives.

This study examines the net economic and environmental effects from bioenergy development, including changes in farmer revenue, net bioenergy production, net GHG emissions offset and cultivation patterns under various government subsidies and market conditions. Ethanol and bio-electricity are bioenergy technologies used in this study. Ethanol is selected because the Jiangxi government has employed a gasoline subsidy on ethanol. Bio-electricity is not subsidized thus far; however, it is necessary to consider the utilization of electricity due to its high emission offset properties (McCarl, 2008). This study begins with an analysis of ethanol production and then expands to joint production of ethanol and pyrolysis-based electricity. Because the Chinese government is eager to develop renewable and clean energy to protect its energy security and environment, this study contributes by providing information to decision makers regarding what economic and environmental effects will be when ethanol is produced and regarding how things may be altered if electricity is simultaneously produced. Because this study employs existing policies and simulates their potential impacts, market responses from such policies can be explored and quantitatively measured. Moreover, the results can also be useful for related agricultural and environmental policy decisions because potential future government subsidies and changes in farmer revenue can be determined.

The paper is organized as follows: The next section outlines the relevant literature on ethanol and pyrolysis-based electricity. Section 3 depicts the methodology and the model formulation process, as well as the data used in the empirical analysis. Section 4 presents the results, discussions and policy implications. The last section concludes this paper.

2. Literature review

The intensive and excessive use of non-renewable fossil fuels emits a considerable quantity of GHG emissions, resulting in global climate change, which potentially has significant and irreversible impacts to human society and the world (IPCC, 2007). To avoid these undesirable results, it is a high priority to find a low-carbon fuel that ensures both the sustainability of human society and climate stability (Eom et al., 2015; Kung and Zhang, 2015; Lyer et al., 2015). Bioenergy meets such needs and has been studied and adopted in the USA and Europe for decades. However, certain literature indicates that bioenergy may not achieve the goal of carbon sequestration if it is not produced properly or if it results in a sudden major shift in land use (Fargione et al., 2008; Searchinger et al., 2008). Fargione et al. (2008) note that the production process of bioenergy is the key to make it a potential low-carbon source because it significantly affects the net effect of biomass energy (Field and Campbell, 2008). With such uncertainties, the researchers note that it is necessary to conduct a comprehensive analysis regarding the effects of biofuel production. Because several studies have shown that energy prices, emission tax and government subsidy can largely affect the production of bioenergy (Drabik et al., 2015; Rivers and Schaufele, 2015; Storm et al., 2015), the work analyzes the production effects on agricultural commodities and bioenergy by simulating several potential energy prices and subsidies.

Lifecycle analysis is a typical method involved in such comprehensive analysis to examine the net GHG offset ability of bioenergy. Wang (2007) shows that ethanol can offset significant CO_2 emissions in a well-to-wheel analysis. Moreover, innovation on ethanol technology reduces the net emission from production process and makes it more environmentally friendly (Arvizu, 2008). Tso and Su (2009) indicate that, if ethanol is produced by sweet sorghum, corn and wet sweet potato, it can effectively offset emissions, which implies a positive effect on the environment and on climate change mitigation. Although the production cost of ethanol is high and requires government support to sustain its production, it is very likely to decline as biomass-to-ethanol conversion technology improves (Campiche et al., 2010). For example, ethanol electricity is another important form of bioenergy. McCarl and Schneider (2000) employ an economic model to evaluate the carbon displacement potential from agricultural feedstocks. Moreover, McCarl (2008) shows that the emissions offset rate for electricity is higher than that for ethanol because the hauling distance is, in general, shorter because lower feedstock volumes are required and because the hotter burning caused by the presence of coal increases the feedstock heat recovery. In addition to co-firing, pyrolysis is another means to generate electricity. With proper application, pyrolysis can grab carbon from the atmosphere and actually reduce the CO_2 concentration (Deluca et al., 2009; Lehmann, 2007; Lehmann et al., 2006). McCarl et al. (2009) shows that pyrolysis can have offset efficiencies greater than 100% when compared with the emissions of the fossil fuel inputs that are replaced. Therefore, in contrast to the ethanol and conventional electricity that continue to emit CO_2, pyrolysis is considered as a better technology because of its carbon negative property. To achieve this environmental benefit, biochar, a byproduct, must be applied as a soil amendment simultaneously.

Biochar provides potential environmental and economic benefits in the following manner. First, biochar improves nutrient retention and reduces production costs. Deluca et al. (2009) illustrates that nutrient transformations can be modified by biochar. The researchers' findings indicate that an increase in net nitrification could be achieved if biochar is added to soil with organic N sources. The slash-and-burn method is commonly used in China and many other nations to have a short-term influence on N availability. However, biochar may maintain this effect for decades (Glaser et al., 2002). Second, biochar could increase crop yields, which imply the possibility to increase farmer revenue. Chan et al. (2007) show that, if biochar and N fertilizer are applied jointly, more nutrients are retained, and N fertilizer efficiency can be improved. Finally, biochar stores carbon in a stable form and can remain in the soil from several hundred to several thousand years (Lehmann et al., 2006). However, this benefit may be uncertain because, in certain regions whose precipitation is high, the loss of biochar may be a maximum of 50% of biochar due to rainfall and runoffs (Major et al., 2009).

Although such benefits may be significant and attractive, pyrolysis-based electricity will be generated only if it is technologically and economically feasible. Studies show that, if the by-product of pyrolysis is jointly applied with electricity generation, total production costs can be covered in most cases, and producers will enjoy a considerable profit (McCarl et al., 2009; Kung et al., 2015; Song and Guan, 2015). With these findings, this study examines the potential contributions to the economy and environment of bioenergy development with feasible technologies such as ethanol and pyrolysis.

3. Methodology

Sustainability is a complex issue. To achieve sustainable development, many factors in economic, environmental and social sectors must be considered simultaneously by the government. The basic concept to model these types of problems involves the maximization of producer and consumer welfare, which is originally illustrated by Samuelson (1950). The price endogenous modeling is then derived by this concept and has been used in many environmental and resource studies (Adams et al., 1992; Chang et al., 1992; Hamilton et al., 1985; McCarl and Schneider, 2000; McCarl and Spreen, 1980; McCarl et al., 1999; Reilly et al., 2002; McCarl and Schneider, 2003). This study develops a Jiangxi Agricultural and Environmental Sectors Model (JAESM) to examine the feasibility and potential contributions of renewable energy development in terms of bioenergy production, farmer revenue, government expenditure (subsidy) and environmental benefits (GHG emission reduction). The agricultural sector, international trade and tariffs, energy and government

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subsidies must also be incorporated. Specifically, the modeling process includes:

(1) Supply and demand of agricultural commodities
(2) Transportation of raw materials and tariffs effects
(3) Environmental effects from bioenergy
(4) Potential government subsidies on energy crops and bioenergy.

3.1. Modeling supply and demand of agricultural commodities

Bioenergy is primarily produced by agricultural commodities, which requires substantial land, labor and many other inputs. Given a fixed quantity of land, energy crops are competing with other commodities, and the market supply of nearly all agricultural commodities will change. Before integrating all components together, we depict how a farmer may act under this situation.

Suppose with j available production alternatives, a profit maximizing farmer will choose to maximize total profits. Each production alternative yields i products, uses inputs with a fixed market price k and uses resources that are available in fixed quantity m. With these indices, the formulation of this model needs to define three types of variables. (1) X_i defines the total quantity of the i^{th} product sold, (2) Y_j defines the quantity used in the j^{th} production alternative, and (3) Z_k defines the quantity of the k^{th} input purchased. To express the total profits of the farmer, prices and costs should be defined. Suppose the sales price of i^{th} commodity is E_i, the purchase cost of k^{th} input is C_k, and any other production costs associated with production j is D_j. The objective function of this profit maximizing farmer can then be written as

$$\text{Max } \sum_i E_i X_i - \sum_j D_j Y_j - \sum_k C_k Z_k \tag{1}$$

$$\text{s.t.} \quad X_i - \sum_j q_{ij} \leq 0 \quad \textit{for all } p \tag{2}$$

$$\sum_j r_{kj} Y_j - Z_k \leq 0 \textit{ for all } k \tag{3}$$

$$\sum_j s_{mj} Y_j \leq b_m \textit{ for all } m \tag{4}$$

$$X_i, Y_j, Z_k \geq 0 \textit{ for all } i, j, k. \tag{5}$$

Eq. (2) balances the commodities sold; this should be less than or equal to the quantity produced, where q_{ij} gives the yield of i^{th} product by each production alternative. Eq. (3) balances the input usage that should not exceed the quantity purchased, and Eq. (4) shows that the sum of the total production alternatives cannot be greater than the available land. Eq. (5) defines that the quantity produced and sold and the input purchased must be non-negative.

Extending this problem to multiple regions and assuming that the wholesale level demand function can be represented by inverse demand functions, input prices are exogenous and integral input supply functions. In addition, the new objective function now maximizes the sum of consumers' plus producers' surplus and simulates a perfectly competitive market equilibrium (Samuelson, 1950; Takayama and Judge, 1971). This function is defined as the area between the product demand and factor supply curves to the left of their intersection as follows:

$$\text{Max } \sum_i \int \varphi(Q_i) dQ_i - \sum_i \sum_k C_{ik} X_{ik} - \sum_k \int \alpha_k(L_k) dL_k - \sum_k \int \beta_k(R_k) dR_k - \sum_k \int \omega_k(Q_k) dQ_k \tag{6}$$

$$s.t. Q_i - \sum_k Y_{ik} X_{ik} \leq 0 \text{ for all } i \tag{7}$$

$$\sum_i X_{ik} - L_k \leq 0 \text{ for all } k \tag{8}$$

$$\sum_i f_{ik} X_{ik} - R_k \leq 0 \text{ for all } k \tag{9}$$

where Q_i is the total quantity of consumption, and P_i^Q is the average wholesale price of commodity i; hectare yields Y_{ik} is hectare yields, and X_{ik} is land used in region k for i^{th} commodity. P_k^L, P_k^R are cropland rent and the user prices of other resources, respectively, and L_k, R_k are the cropland and other resource quantities supplied, respectively.

3.2. Modeling transportation

3.2.1. Regional transportation costs

The objective function depicts the minimization of total cost across all possible shipment routes. This depiction involves the definition of a parameter C_{uv}, which depicts the cost of shipping X_{uv} units from supply point u to demand point v. The objective function of this idea is expressed as below:

$$\text{Min } \sum_u \sum_v C_{uv} X_{uv} \tag{10}$$

$$\text{s.t.} \sum_v X_{uv} \leq s_u \textit{ for all } u \tag{11}$$

$$\sum_u X_{uv} \geq d_v \textit{ for all } v \tag{12}$$

$$X_{uv} \geq 0 \textit{ for all } u, v. \tag{13}$$

This simple formulation depicts the basic nature of the transportation costs and implies that it will be minimized in the welfare calculation. It is worth noting that, if international trade is involved, quota limits and tariffs must be incorporated into the objective function.

3.2.2. Modeling parameter of transportation costs

To calculate Eq. (10), the hauling cost of C_{uv} must be defined. This hauling cost is estimated in accordance with McCarl et al. (2000) based on a metric adaptation of French's (1960) hauling cost formula and expressed as below:

$$\text{hauling cost} = \frac{38 + 2 * (.4714) * [M/(2.468 * den * (Y)]^{1/2}}{Load\ \ Size}. \tag{14}$$

where Y is the crop yield per hectare, *den* is the density of land available for energy crop production in the region, *Load Size* is 23 tons per truck load and M is the quantity of materials transported. The other constants cover loading and travel costs.

3.3. Modeling GHG components

GHG emissions from agricultural activities are complex and usually involve carbon dioxide (CO_2), methane (CH_4) and nitrous dioxide (N_2O). For example, studies have shown that N fertilizers will increase N2O emissions due to the nitrification and denitrification process (Liu et al., 2007; Grover et al., 2012). Therefore, to fully analyze the overall greenhouse gases (GHG) emissions from the agricultural sector, it is necessary to consider the emissions from the use of N fertilizers. This study uses the GWP published by IPCC (2007) to convert these emissions into a CO_2e basis. In general, the net GHG emission is included as:

$$P_{GHG} \times \sum_g GWP_g \times GHG_g$$

The P_{GHG} is the CO_2 price based on the Chicago Climate Exchange; the latter terms specify the conversion process.

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3.4. Modeling crop support policy and government subsidy

Occasionally, the local government may purchase a fixed quantity of crops to ensure the farmers do not suffer from low prices. The demand is then intervened by the government's purchase, which involves a potential expenditure that can be expressed as $P_i^G \times Q_i^G$ for i^{th} crop support policy. To encourage the plantation of energy crops, we assume that the government will pay a fixed subsidy P_k^L for land that participates in the energy program SL_k in region k. These effects will be incorporated into the bioenergy production. In algebraic terms, these effects will be expressed as

$$\sum_k P_k^L \times SL_k + \sum_i P_i^G \times Q_i^G.$$

3.5. Formulation of Jiangxi agricultural and environmental sectors model

The above features are the components that a region may confront when integrating agriculture and bioenergy (Chen and Chang, 2005). By combining these components and assuming the imports and exports of commodities, the objective functions and associated constraints of JAESM may be depicted as below:

$$\begin{aligned} Max \sum_i \int \psi(Q_i) dQ_i - \sum_i \sum_k C_{ik} X_{ik} - \sum_k \int \alpha_k(L_k) dL_k - \sum_k \int \beta_k(R_k) dR_k \\ + \sum_i P_i^G * Q_i^G + \sum_k P^L * SL_k + \sum_j \sum_k SUB_j * EC_{jk} \\ + \sum_i \int ED\left(Q_i^M\right) dQ_i^M - \sum_i \int ES\left(Q_i^X\right) dQ_i^X + \sum_i \int EXED(TRQ_i) dTRQ_i \\ + \sum_i \left[tax_i * Q_i^M + outtax_i * TRQ_i\right] - P_{GHG} * \sum_g GWP_g * GHG_g. \end{aligned} \tag{15}$$

Subject to

$$s.t. \mathrm{Q_i} + \mathrm{Q_i^X} + \mathrm{Q_i^G} - \sum_k \mathrm{Y_{ik} X_{ik}} - \sum_j \mathrm{EC_{jk} X_{jk}} - \left(\mathrm{Q_i^M} + \mathrm{TRQ_i}\right) \le 0 \text{ for all } i \tag{16}$$

$$\sum_i \mathrm{X_{ik}} + \mathrm{SL_k} + \sum_j \mathrm{EC_{jk}} - \mathrm{L_k} \le 0 \text{ for all } k \tag{17}$$

$$\sum_i f_{ik} X_{ik} - \sum_j f_{jk} X_{jk} - R_k \le 0 \text{ for all } k \tag{18}$$

$$\sum_{i,k} E_{gik} X_{ik} - Baseline_g = GHG_g \text{ for all } g \tag{19}$$

where

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
SL_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*
fR_{ik}	Labor required per hectare of commodity i in region k

The objective function of the JAESM model incorporates the domestic and trade policies. Emission components are included, which reflects that GHG emissions reduce social welfare. Eq. (16) is the balance constraint for commodities, whereas Eqs. (17) and (18) balance the resource endowments. Eq. (16) ensures that the quantity of commodities supplied plus exports must be greater than or equal to the quantity of commodities consumed plus imports. Eq. (17) is a land constraint controlling cropland utilization that must be smaller than or equal to the total cropland available, and Eq. (18) is the other resource constraint. Eq. (19) reflects the greenhouse gas balance by controlling the emissions from various sources; this should be smaller than the total emissions. The price endogenous partial equilibrium model is useful in this study because of several advantages accommodated by the model. First, existing agricultural production pattern will change under different market operations. The price of every commodity can be endogenous decided in the model. Second, more than 2 million hectares of cropland distributing in many counties are incorporated, this model can deal with such spatial characteristics by integrating them into several major production regions. Third, policy effects can be incorporated by inserting their influences on supply and demand functions.

Data used in this study originates from various sources including a field survey, Annual Statistic Report of Jiangxi Province, Chicago Climate Exchange, China National Petroleum Corporation. Key parameters such as biomass conversion rates and price elasticities are obtained from literature and personal communications.[1]

4. Result and discussion

This study analyzes the net economic and environmental impacts from the development of bioenergy by incorporating potential bioenergy technologies and an existing bioenergy subsidy under market operations. Two pyrolysis types will be simultaneously examined because the rapid pyrolysis generates more electricity, whereas the slow pyrolysis yields more biochar and emissions reduction. The range of simulated gasoline prices is based on China's historical prices, whereas the simulated coal prices originate from the historical trading prices of thermal coal. The value of GHG emissions reduction is based on the Chicago Climate Exchange and is added to the welfare measures. Because the current policy only subsidizes bioenergy from ethanol, this study first examines how the bioenergy development from ethanol can be affected and then incorporates electricity generation to examine the competition between different bioenergy technologies under various market conditions. The units of gasoline, coal and emission price are converted to US$ per liter, US$ per kg and US$ per ton, respectively.

4.1. Ethanol only

Table 1 presents the simulation result of net ethanol production and the change in farmer revenue. The result shows that, if the Jiangxi province chooses ethanol as its primary bioenergy, the gasoline price and the GHG emissions price are the two important factors that affect ethanol production. The net change in social welfare is positive; however, it increases at a lower rate in accordance with the increase of gasoline prices

[1] Data and the framework of the model are available upon request.

Table 1
Changes in farmer revenue and ethanol production

GHG price	US$/ton	$0.14	$0.28	$0.42	$0.56	$0.70
Gasoline price	US$/liter	$0.73	$0.73	$0.73	$0.73	$0.73
Ethanol production	1000 liter	390,905	390,905	395,050	395,050	395,050
Farmer revenue	US$/ha	$11,135.7	$11,178.9	$11,222.1	$11,222.1	$11,308.5
Gasoline price	US$/liter	$0.83	$0.83	$0.83	$0.83	$0.83
Ethanol production	1000 liter	387,930	390,092	390,091	390,091	390,094
Farmer's revenue	US$/ha	$12,421.1	$12,464.3	$12,507.5	$12,550.6	$12,593.8
Gasoline price	US$/liter	$0.93	$0.93	$0.93	$0.93	$0.93
Ethanol production	1000 liter	400,816	400,826	400,826	400,826	400,827
Farmer revenue	US$/ha	$13,706.4	$13,749.6	$13,749.6	$13,836.0	$13,879.2
Gasoline price	US$/liter	$1.03	$1.03	$1.03	$1.03	$1.03
Ethanol production	1000 liter	408,222	408,222	408,222	408,222	408,222
Farmer revenue	US$/ha	$14,991.8	$15,035.0	$15,078.2	$15,121.4	$15,121.4

because, when more land is converted into energy crop production, the supply of other commodities will decrease. Consequently, the reduction of the commodities' supply implies that higher prices must be paid to obtain these commodities. However, when GHG emissions are more valuable, things become more complicated. Although more land is used for energy crops instead of conventional commodities, the social welfare slightly increases as the GHG price increases. A potential explanation for this situation is that, although consumers may be hurt by higher commodity prices, all consumers and producers enjoy the environmental benefits (i.e., emissions reduction).

In general, with an ethanol subsidy, the net welfare changes from the agricultural and environmental sectors range from $809 to $1851 million dollars annually. Most economic gains are obtained by farmers and ethanol producers, whereas the entire society enjoys the environmental benefit. However, the benefits are accompanied by substantial costs. The annual government subsidy on energy crops ranges from approximately $225.8 to $245.7 million dollars. In addition, due to land availability, ethanol production peaks at gasoline price of $1.13 per liter, and the net emission reduction is approximately 46,771 tons. Regardless of the renewable property of ethanol, the environmental benefit from Jiangxi's ethanol production does not have a significant contribution to China's total emissions. Despite the tiny environmental effects, approximately 408 million l of ethanol could be supplied, which replaces a considerable quantity of fossil fuels.

The result also shows that the revenue of farmers who engaged in the energy crop plantation can be improved. The range of annual economic profits is between $11,136 and $15,121 per hectare, depending on the gasoline and GHG prices. However, the available cropland for a typical Chinese farmer usually is between one and two Chinese hectares (Mu), which is approximately 0.067 ha or 0.167 acre. Therefore, 6.7 to 13.3% of simulated gain may be realized by a farmer, and this situation could be worse for agricultural provinces such as Jiangxi in which farmer density is very high.

Table 2 shows the GHG effect of ethanol production on a per hectare basis. The result indicates that approximately 317 to 324 kg of CO_2 can be offset from ethanol production. The net emissions reduction slightly increases due to the expansion of ethanol production at higher gasoline prices. However, when more infertile land begins energy crop plantation at high gasoline prices, the per hectare emissions reduction decreases. In terms of the emissions offset efficiency, this figure may not be satisfactory. Although a general concern is that a significant quantity of CO_2 and N_2O could be released from the changes on land-use and cultivation patterns, the small quantity of per hectare emissions offset could easily be absorbed by these changes.

Table 2
Environmental benefits with ethanol production

GHG price	US$/ton	$0.14	$0.28	$0.42	$0.56	$0.70
Gasoline price	US$/liter	$0.73	$0.73	$0.73	$0.73	$0.73
Emissions reduction	kg/ha	324.3	322.0	322.0	322.0	322.0
Gasoline price	US$/liter	$0.83	$0.83	$0.83	$0.83	$0.83
Emissions reduction	kg/ha	322.1	322.0	322.0	322.0	322.0
Gasoline price	US$/liter	$0.93	$0.93	$0.93	$0.93	$0.93
Emissions reduction	kg/ha	319.1	319.1	322.0	322.0	322.0
Gasoline price	US$/liter	$1.03	$1.03	$1.03	$1.03	$1.03
Emissions reduction	kg/ha	319.2	319.2	319.2	319.2	319.2
Gasoline price	US$/liter	$1.13	$1.13	$1.13	$1.13	$1.13
Emissions reduction	kg/ha	317.3	317.3	317.3	317.3	317.3

4.2. Joint production of bio-electricity and ethanol

Bio-electricity is not subsidized by Jiangxi; however, it is another important form of bioenergy that bioenergy development should focus greatly on. Table 3 presents how multiple bioenergy technologies may affect the bioenergy production. When electricity is jointly produced with ethanol, the prices of coal, gasoline and GHG emissions are the most important factors that affect bioenergy development strategies. The results indicate that ethanol could be produced to a maximum of 417.6 million l annually for most cases at ongoing GHG prices ($ 0.14 per ton of CO_2). Under this emission price, electricity is probably a negligible choice for farmers because the monetary benefit from GHG emissions reduction is very small.

Fig. 1 depicts this relation between ethanol production and bio-electricity generation under various gasoline prices, given high (−H) or low (−L) emission prices.

Table 3
Results for the joint production of electricity and ethanol

GHG price	US$/ton	$0.14	$0.28	$0.42	$0.56	$0.70
Coal price	$cent/kg	$0.07	$0.07	$0.07	$0.07	$0.07
Gasoline price	US$/liter	$0.73	$0.73	$0.73	$0.73	$0.73
Electricity	1000 kWh	63,943	1,473,500	1,473,500	1,473,500	1,473,500
Ethanol	1000 l	386,212	273,448	274,137	269,244	246,571
GHG price	US$/ton	$0.14	$0.28	$0.42	$0.56	$0.70
Coal price	$cent/kg	$0.07	$0.07	$0.07	$0.07	$0.07
Gasoline price	US$/liter	$1.03	$1.03	$1.03	$1.03	$1.03
Electricity	1000 kWh	54,205	54,205	744,132	1,473,500	1,473,500
Ethanol	1000 l	402,873	402,873	348,000	275,042	295,252
GHG price	US$/ton	$0.14	$0.28	$0.42	$0.56	$0.70
Coal price	$cent/kg	$0.09	$0.09	$0.09	$0.09	$0.09
Gasoline price	US$/liter	$0.73	$0.73	$0.73	$0.73	$0.73
Electricity	1000 kWh	303,559	1,000,004	1,473,500	1,473,500	1,473,500
Ethanol	1000 l	348,000	266,534	266,534	250,910	246,571
GHG price	US$/ton	$0.14	$0.28	$0.42	$0.56	$0.70
Coal price	$cent/kg	$0.09	$0.09	$0.09	$0.09	$0.09
Gasoline price	US$/liter	$1.03	$1.03	$1.03	$1.03	$1.03
Electricity	1000 kWh	55,621	86,237	55,621	1,473,500	1,473,500
Ethanol	1000 l	394,078	394,078	394,078	292,824	282,664

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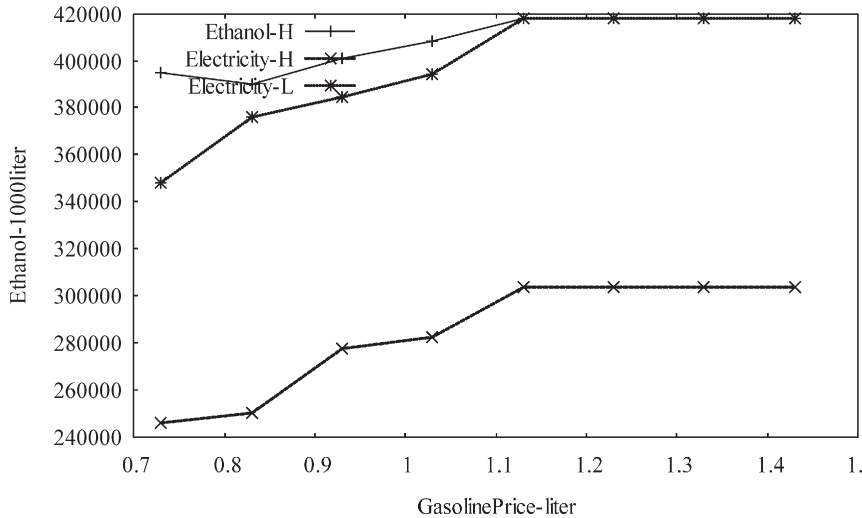

Fig. 1. Ethanol and bio-electricity production under various emission prices.

In addition, the result shows that the ethanol production is sensitive to coal, gasoline and emission prices. When the per kg price of coal increases to nine cents, the ethanol production decreases 9.9%; however, a 29.2% reduction may occur if the emissions price increases. The electricity begins to play a role at high coal prices and emission prices. The maximum quantity of electricity ranges from 54.2 million to 1.47 billion kWh annually in all scenarios. At higher emission prices ($0.56 to $0.70/ton) and coal prices ($ 0.1/kg), changes in gasoline prices do not have significant effects on the electricity generation. At such prices, farmers enjoy a higher net profit from energy sales and carbon trading through electricity generation rather than ethanol production.

Table 4 summarizes the benefits enjoyed by farmers, the cost incurred by the government and the emissions offset from joint production. It is clear that, when emission prices increases, the demand for the high offset technology, pyrolysis-based electricity, is higher, and more biomass is used to generate bio-electricity; in addition, more gains from emission trades can be obtained. This result is consistent with the net electricity generation presented in Table 3. In this scenario, farmer revenue is higher in joint production scenarios because the competition between bio-electricity and ethanol pushes up the input price. That is, the input demand curve shifts out and becomes a new equilibrium with a higher price. However, as noted earlier, the gain is estimated on a per hectare basis, and the farmers' gain from this price increase for energy crops could be much less than the simulated results.

The environmental benefit in joint production scenarios is much higher than that in pure ethanol cases. A maximum of 1.28 million tons of emissions could be offset annually at high emissions prices, primarily due to the pyrolysis-based electricity generation. At a low emissions price, the advantage in the emissions reduction of bio-electricity decreases. In this scenario, the annual emissions reduction may decrease to 81,076 tons, which is approximately 6.34% compared with high emissions price scenarios. This number is also an interesting finding that emissions reduction will not achieve its optimum when both coal and emissions prices are high. When the coal price also increases, some biomass used in pyrolysis will shift to rapid pyrolysis to gain from energy sales. If coal prices are low, slow pyrolysis will dominate rapid pyrolysis. More biochar is produced and used to offset emissions.

To successfully achieve such environmental and economic benefits, a government subsidy is inevitably involved. To develop bioenergy, the annual government expenditure may range from 183.1 to 260.3

Table 4
Changes in farmer revenue and emissions reduction

GHG price	US$/ton	$0.14	$0.28	$0.42	$0.56	$0.70
Coal price	$cent/kg	$0.07	$0.07	$0.07	$0.07	$0.07
Gasoline price	US$/liter	$0.73	$0.73	$0.73	$0.73	$0.73
Farmer revenue	US$/ha	$11,136	$19,506	$19,549	$19,592	$19,636
GHG reduction	Ton	85,355	1,000,779	1,000,856	1,000,308	1,278,156
Government subsidy	US million	$227.57	$246.53	$247.00	$229.10	$244.75
GHG price	US$/ton	$0.14	$0.28	$0.42	$0.56	$0.70
Coal price	$cent/kg	$0.07	$0.07	$0.07	$0.07	$0.07
Gasoline price	US$/liter	$1.03	$1.03	$1.03	$1.03	$1.03
Farmer revenue	US$/ha	$14,992	$15,035	$27,981	$26,855	$26,898
GHG reduction	Ton	87,221	87,222	528,912	1,000,957	1,003,221
Government subsidy	US million	$238.13	$238.13	$247.94	$224.24	$257.70
GHG price	US$/ton	$0.14	$0.28	$0.42	$0.56	$0.70
Coal price	$cent/kg	$0.09	$0.09	$0.09	$0.09	$0.09
Gasoline price	US$/liter	$0.73	$0.73	$0.73	$0.73	$0.73
Farmer revenue	US$/ha	$12,354	$19,506	$19,549	$19,592	$19,636
GHG reduction	Ton	81,076	1,000,004	1,000,004	1,237,550	1,278,156
Government subsidy	US million	$183.10	$241.34	$241.33	$244.78	$244.75
GHG price	US$/ton	$0.14	$0.28	$0.42	$0.56	$0.70
Coal price	$cent/kg	$0.09	$0.09	$0.09	$0.09	$0.09
Gasoline price	US$/liter	$1.03	$1.03	$1.03	$1.03	$1.03
Farmer revenue	US$/ha	$14,992	$15,035	$15,078	$26,855	$26,898
GHG reduction	Ton	86,237	86,237	86,237	1,002,948	1,187,228
Government subsidy	US million	$226.73	$226.72	$226.73	$256.63	$260.33

million dollars. However, at low gasoline, coal and emission prices, farmers with infertile land are less willing to participate with bioenergy because the economic gain from energy sales and emissions trade is small, resulting in a low level of net bioenergy production and emissions reduction. Thus, the government subsidy plays an important role in the determination of farmers' overall production.

4.3. Limitation and policy implications

The simulation results indicate that bioenergy development can be helpful in terms of the renewable energy supply, the enhancement of farmers' revenue and GHG emissions reduction. However, the results may be limited under certain real world considerations, which thus constrain the usefulness of the result. Therefore, it is important to note such limitations, and policy makers may obtain insights regarding the results and establish more suitable strategies. These points are specified as below:

(1) Although bioenergy is considered a mature technology in the field of renewables, the net effects in different scenarios could vary significantly. For example, the simulation results indicate that the joint production of bio-electricity and ethanol could be a better combination instead of a pure ethanol strategy. Many other factors such as site location, biomass density and collection, transportation and labor costs will eventually affect the success of bioenergy development. Particularly for nations such as China in which bioenergy has not been applied on a large, commercial scale, the net effects from bioenergy are more uncertain.

(2) The subsidy from public financial sources will inevitably decrease government expenditure in other sectors. A higher subsidy attracts farmers whose land has higher marginal production costs, whereas those with lower marginal production would have been engaged in the energy crop plantation at a low subsidy. An increase of the subsidy will only increase a small portion of bioenergy production; however, all land (new entry and previously utilized land) will receive a high subsidy. Therefore, establishing a proper designed subsidy that reflects the land fertility may be useful achieve an efficient production pattern.

(3) The result shows that the bio-electricity generation can vary significantly under changes in coal prices. The result is based on an assumption that producers could reflect the input cost (i.e., coal price) in the output price (energy sale). If this assumption is not the case, the net generation of bio-electricity and its associated benefits will be highly uncertain. For example, the electricity price has only increased $0.33 cents in the past six years in Jiangxi. The government does not allow high volatility of the electricity price to ensure that paupers continue to have access to it; this is partly a political concern rather an economic analysis. Therefore, more than pure economic and environmental issues must be considered simultaneously, and the bioenergy selection strategies and their net effects may be assessed further.

5. Conclusion

Bioenergy is considered as an effective approach to provide sustainable energy sources and mitigate climate change. This study formulates a price endogenous, partial equilibrium model to examine the potential economic and environmental effects of bioenergy production in Jiangxi province. The results show that pure ethanol technology can replace approximately 400.8 million l gasoline but does not contribute much to climate change mitigation. Instead, joint production patterns can provide a significant quantity of emissions reduction and bioenergy production with a lower ethanol production. The total government expenditure is, in general, higher for joint production scenarios; however, the farmer revenue is also higher. However, the development of bioenergy can involve complicated issues such as electricity price volatility, land-use shift and appropriate subsidy design. In addition, to avoid the high cost from homogenous subsidy, a discriminated form of subsidy may be designed. That is, if the government can distinguish the land fertility (i.e. input–output ratio), net social cost can be reduced because the less fertile land will receive lower subsidies. Economic and environmental benefits are one side of the bioenergy development and thus require a more comprehensive analysis to better access its net influences and impacts in other sectors.

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Appendix A

This section describes some important data used in the study. The data comes from various sources such as Annual Statistic Report of Jiangxi Province, Chicago Climate Exchange, China National Petroleum Corporation. Key parameters such as biomass conversion rates and price elasticities are obtained from literatures and personal communications. Data are available upon request.

A.1. Commodity demand and their price

Commodity	Price(¥)	Quantity(ton)	Commodity	Price(¥)	Quantity(ton)
Japonica	4.10	2,295,652.17	Grapefur	3.40	29,845.39
Corn	1.11	321,215.30	Mango	7.03	338,788.52
Sorghum	1.15	33,558.61	Guava	2.76	349,591.48
Soybean	2.29	652.35	Waxapple	10.53	131,401.22
Peanut	7.83	136,392.35	Grape	11.15	228,358.09
Adzuki	11.58	20,174.96	Loquat	21.27	13,002.96
Swpotato	2.69	335,591.83	Plum	7.13	70,285.22
Potato	2.04	85,652.70	Peach	7.20	133,348.70
Tea	28.94	38,628.17	Persim	3.84	69,554.43
Caneproc	0.16	220,286.96	Apricot	5.28	108,144.35
Canefresh	1.65	125,612.35	Liche	5.40	149,733.91
Sesame	3.59	78,737.04	Caram	3.97	50,726.26
Radish	1.53	240,812.00	Longan	6.44	195,775.13
Carrot	1.65	172,198.78	Jujube	9.63	60,524.87
Ginger	5.59	76,238.61	Pear	2.93	262,672.35
Scallion	6.38	240,482.96	Apple	7.52	211,073.74
Onion	1.73	140,591.48	Papaya	3.77	255,358.78
Garbulb	7.60	118,032.87	Sugarap	9.22	170,622.43
Leek	3.98	75,982.26	Passion	5.45	8727.30
Bamboo	5.40	593,602.09	Coconut	0.93	113,030.26
Aspara	9.37	25,630.96	Chrysan	7.31	50,443.13
Waterba	7.13	80,608.00	Gladio	11.76	17,976.87
Cabbage	2.06	642,685.04	Rose	9.60	27,855.83
Cauli	4.06	174,467.65	Babys	10.06	862.78
Mustard	3.68	179,093.39	Otherflo	10.17	57,001.04
Chinesecab	1.79	263,167.83	Cattle	18.44	121,834.09
Cucum	2.87	110,030.61	Hog	11.80	1,792,372.52
Bitter	6.47	67,216.70	Goat	86.95	5322.09
Tomato	4.95	297,019.13	Geese	19.84	49,742.96
Pea	9.42	29,965.91	Duck	11.71	112,112.00
Vesoy	2.74	152,699.13	Native	11.92	535,552.70
Wamelon	2.20	607,077.57	Broiler	8.41	658,106.09
Canta	5.70	150,742.09	Leg	11.98	130,634.09

(continued on next page)

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(*continued*)

Commodity	Price(￥)	Quantity(ton)	Commodity	Price(￥)	Quantity(ton)
Mushroom	10.40	9377.74	Breast	9.61	269,383.30
Betel	15.17	273,262.96	Wing	16.02	53,088.87
Banana	3.57	328,582.43	Gut	21.36	118,346.61
Pineapple	2.92	874,848.17	Egg	0.32	13,426,976.87
Ponkan	4.35	204,969.22	Milk	3.99	595,243.48
Tankan	6.62	108,691.48	Hardwood	533.93	0.00
Wentan	4.99	167,006.78	Poplar	1.17	0.00
Liucheng	2.57	425,185.39	Willow	0.63	0.00
Lemon	5.20	37,258.43	Switchgrass	0.10	0.00

A.2. Elasticity of commodity

Commodity	Elasticity	Commodity	Elasticity
Japonica	−0.2284	Grapefur	−0.64
Corn	−0.4	Mango	−0.45
Sorghum	−0.4	Guava	−0.85
Soybean	−1.56	Waxapple	−0.85
Peanut	−0.1	Grape	−0.5
Adzuki	−1.2	Loquat	−0.5
Swpotato	−0.4	Plum	−0.5
Potato	−0.1	Peach	−0.5
Tea	−1.45	Persim	−0.5
Caneproc	0	Apricot	−0.5
Canefresh	−0.455	Liche	−0.5
Sesame	−0.6	Caram	−0.5
Radish	−0.58	Longan	−0.5
Carrot	−0.58	Jujube	−0.5
Ginger	−0.58	Pear	−0.5
Scallion	−0.28	Apple	−0.5
Onion	−0.58	Papaya	−0.5
Garbulb	−1.1	Sugarap	−0.7
Leek	−0.58	Passion	−0.7
Bamboo	−0.58	Coconut	−0.7
Aspara	−0.58	Chrysan	−0.72
Waterba	−0.58	Gladio	−0.625
Cabbage	−0.58	Rose	−0.347
Cauli	−0.58	Babys	−0.444
Mustard	−0.5	Otherflo	−0.649
Chinesecab	−0.5	Cattle	0
Cucum	−0.68	Hog	0
Bitter	−0.68	Goat	−0.812
Tomato	−0.68	Geese	−0.812
Pea	−0.68	Duck	−0.93
Vesoy	−0.68	Native	−0.812
Wamelon	−1.45	Broiler	0
Canta	−1.45	Leg	−0.93
Mushroom	−1.25	Breast	−0.93
Betel	−0.45	Wing	−0.93
Banana	−0.64	Gut	−0.93
Pineapple	−1.25	Egg	−0.15
Ponkan	−0.64	Milk	−0.35
Tankan	−0.64	Hardwood	0
Wentan	−0.64	Poplar	0
Liucheng	−0.64	Willow	0
Lemon	−0.64	Switchgrass	0

A.3. Crop mix data

	Pingxiang. japonica.1	Yingtan. japonica.1	Ganzhou. japonica.1	Yichun. japonica.1
1990	3321	14,224	22,606	9528
1991	2648	12,746	21,230	9098
1992	1979	12,858	20,822	8762
1993	1633	12,329	19,604	8449
1994	1085	12,402	15,584	7824
1995	1166	12,043	17,586	7867
1996	752	11,921	13,945	7142
1997	911	12,594	17,753	7723
1998	730	12,265	18,140	7681
1999	680	12,153	16,936	7358
2000	608	11,942	15,981	7050
2001	543	11,538	14,853	6758
2002	458	10,531	12,599	5012
2003	332	10,430	5456	3211

+

	Jian.japonica.1	Xinyu. japonica.1	Shangrao. japonica.1	Jingdezhen. japonica.1
1990	13,983	21,477	36,476	6038
1991	12,837	20,472	34,232	5746
1992	11,966	20,304	33,645	4999
1993	11,370	19,188	32,056	4453
1994	11,114	17,481	31,760	4203
1995	10,348	17,670	30,331	3717
1996	10,018	16,960	29,878	3477
1997	10,111	17,572	30,829	3428
1998	10,067	17,156	29,962	3221
1999	9454	16,897	29,097	3286
2000	9520	16,277	29,374	1895
2001	8984	16,124	28,271	3036
2002	7615	15,634	28,219	2879
2003	7832	15,533	27,365	2546

+

	Jiujiang.japonica.1	Nanchang.japonica.1	Fuzhou.japonica.1
1990	34,516	20,647	21,141
1991	32,284	20,175	21,252
1992	29,967	17,115	14,380
1993	31,668	19,630	20,998
1994	31,771	17,932	14,680
1995	28,549	18,835	20,864
1996	29,816	16,228	13,808
1997	31,514	19,017	20,727
1998	31,366	19,908	20,891
1999	31,103	19,488	20,886
2000	30,834	19,989	21,192
2001	28,711	19,852	20,396
2002	28,990	18,652	19,051
2003	27,898	17,766	15,822

+

	Pingxiang. japonica.2	Yingtan. japonica.2	Ganzhou. japonica.2	Yichun. japonica.2
1990	1155	5183	20,338	9041
1991	952	4806	20,107	8915
1992	619	3097	18,908	8645
1993	427	2852	18,312	8265
1994	352	1815	16,402	7945
1995	243	1139	16,931	7865
1996	193	1000	16,213	7647
1997	196	783	17,355	7502
1998	119	110	16,518	7322
1999	103	289	14,543	6920
2000	80	161	12,420	6176
2001	68	32	11,504	6022
2002	48	27	8315	4612
2003	27	1	5118	3477

+

	Jian. japonica.2	Xinyu. japonica.2	Shangrao. japonica.2	Jingdezhen. japonica.2
1990	13,230	20,308	33,925	5541
1991	11,890	20,203	32,896	5750
1992	11,602	19,533	32,041	4567
1993	10,807	18,880	31,018	4051
1994	10,516	18,263	29,312	3923
1995	10,501	17,613	28,397	3512
1996	9838	17,100	28,416	2984
1997	10,102	16,949	27,778	2916
1998	9571	16,543	26,731	2734
1999	9301	16,222	27,143	2849
2000	7992	16,174	25,792	2314
2001	7116	15,650	26,596	2533
2002	6873	14,967	25,149	2376
2003	5677	13,901	22,154	2220

+

	Jiujiang.japonica.2	Nanchang.japonica.2	Fuzhou.japonica.2
1990	23,252	19,610	20,486
1991	22,085	18,687	19,008
1992	21,658	18,421	16,344
1993	22,640	18,076	14,250
1994	20,907	17,636	14,093

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(*continued*)

1995	20,690	17,287	13,801
1996	23,166	16,579	13,059
1997	19,714	16,791	13,949
1998	19,427	17,194	13,366
1999	19,316	17,761	13,513
2000	17,833	16,845	12,296
2001	19,030	17,109	11,992
2002	17,017	16,250	10,707
2003	14,733	14,265	9122

A.4. Energy and GHG prices

Year	Quarter	93 Gasoline ($ liter)	Global thermal coal ($ short ton)	GHG price ($ ton)
2015	1	0.82	52.00	0.14
2014	4	0.96	50.00	0.14
	3	1.11	55.00	0.14
	2	1.14	60.00	0.14
	1	1.14	65.00	0.14
2013	4	1.13	59.00	0.14
	3	1.14	55.00	0.14
	2	1.11	58.00	0.14
	1	1.14	60.00	0.14
2012	4	1.13	62.00	0.05
	3	1.13	54.00	0.10
	2	1.10	58.00	0.39
	1	1.04	62.00	0.10
2011	4	1.02	70.00	0.07
	3	1.02	73.00	0.50
	2	1.05	77.00	1.25
	1	1.04	72.00	0.05
2010	4	0.99	65.00	3.62
	3	0.95	60.00	1.38
	2	0.96	56.00	0.75
	1	0.96	55.00	0.77
2009	4	0.97	52.00	0.69
	3	0.93	49.00	1.14
	2	0.86	47.00	1.33
	1	0.75	45.00	1.92
2008	4	0.76	60.00	1.48
	3	1.05	80.00	3.40
	2	1.12	100.00	5.52
	1	1.05	138.00	4.42
2007	4	0.98	100.00	2.01
	3	0.94	80.00	3.32
	2	0.89	60.00	3.55
	1	0.85	43.00	3.80
2006	4	0.87	40.00	4.08
	3	0.89	46.00	4.25
	2	0.91	50.00	3.91
	1	0.83	57.00	2.01
2005	4	0.79	59.00	1.98
	3	0.82	59.00	2.18
	2	0.80	58.00	1.35
	1	0.77	58.00	1.72
2004	4	0.74	60.00	1.55
	3	0.74	61.00	0.96
	2	0.72	51.00	0.85
	1	0.71	45.00	0.90
2003	4	0.65	37.00	0.97

*Sources come from US Energy Information Administration (http://www.eia.gov/coal/reports.cfm) and Chicago Climate Exchange (https://www.theice.com/ccx).

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