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Economic and Technical Efficiency of the Biomass Industry in China: A Network Data Envelopment Analysis Model Involving Externalities

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Abstract: This paper proposes the network data envelopment analysis (DEA) model accounting for negative externalities and applies it for decomposition of profit inefficiency in the biomass-agriculture circular system (Bio-AG system). A circular structure of the Bio-AG system which is different from the previously applied network structures is assumed. Since the negative externalities (i.e., pollutant emissions from the biomass industry) occur in the Bio-AG system, the property rights are taken into consideration to model the externalities-adjusted profits. Therefore, the changes in profits due to changes in the property rights (assuming no property rights, allocating property rights to agricultural sector, and allocating property rights to biomass power generation sector) are quantified. Further, the decomposition shows that the biomass power generation sector is less affected by technical inefficiency if contrasted to allocative inefficiency in terms of the profit loss. The findings suggest that the biomass power generation technology influences the profits of the biomass industry. What is more, the inefficient allocation of resources is now the key factor undermining performance of the biomass industry. Therefore, the government should adopt measures to improve the allocation of resources and prevent excessive investments or development of less efficient technologies.

Keywords: data envelopment analysis; biomass industry; negative externalities; efficiency decomposition

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1. Introduction

Since the Kyoto Protocol was put forward in 1997, much effort has been paid to tackle the environmental problems along with ensuring economic development worldwide. Accordingly, research on climate change and climate policies has attempted to identify the consequences of climate change along with effective means for climate change mitigation (Watson [1]; Walther et al. [2]; Kumar et al. [3]; Wei et al. [4]; Stocker [5]). Such concepts as sustainability, environmental culture, economic development, and social civilization have been considered simulatenously (General Assembly of United Nations [6], Dirzyte, Rakauskiene [7]; Fuinhas et al. [8]; Liobikiene et al. [9]). In this context, sustainable development of energy and electric power has also become an important issue as represented by the environment and energy (E&E) concept (see Noori and Chen [10]; Hwang et al. [11]; Zhou et al. [12]; Chen et al. [13]). The traditional energy generation relies on the fossil fuels, with the thermal power generation being the main option for generating electricity. Besides, the renewable and sustainable energy sources (such as wind energy, hydroelectric energy, biomass energy, solar energy) have been utilized to generate electric power.

As regards China, the industry of the renewable energy power generation has experienced a rapid development there since 2000 with an upturn in the number of hydropower stations, wind power plants, biomass power generation plants constructed (Zhang et al. [14]; Chang et al. [15]; Yang et al. [16]). Biomass energy constitutes one of the recently developed sources of the renewable energy. According to China Statistical Yearbook 2013, before 2005, the development of Chinese biomass power industry was rather limited. Later on, with the introduction and implementation of the Renewable Energy Law [17] as well as other regulations on subsidies for renewable energy, the investment in biomass power industry was on the rise. However, Chinese biomass energy industry still has some potential to increase its scale and scope of application [18]. The energy output of biomass accounted for 14.7% of the total renewable energy in 2005 [18]. The development of biomass energy is subject to competition of other renewable energy sources. Currently, the major constraining factors for development of the Chinese biomass industry are the electric power generating cost and the material supplies.

There have been some studies on the development of the biomass industry in China. Lin [19] pointed out the biomass energy resources are quite abundant in China and China has a great potential to develop the biomass power generation industry by switching to low-carbon energy sources. Kahrl et al. [20] suggested that China's forest bioenergy policy should address rural energy challenges, and discussed the prerequisites for a modern, biomass-based energy infrastructure in rural China. Li et al. [21] pointed out that less fertile land utilization has great prospects of supplying bio-energy resources in China, and thus a win-win situation for the eco-society and bio-energy development could be realized in the future. Zhou et al. [22] discussed the possible capacity of biomass energy production from agricultural residues, forest residues, and municipal solid waste. Zhao et al. [23] discussed the development of the biomass sector in China from perspective of the five driving forces as defined by the Porter's Five Forces model.

Energy production and use efficiency is one of the key issues for energy policy. Zhou et al. [24] and Sueyoshi et al. [25] presented surveys on energy efficiency studies. According to Zhou et al. [24], 38% of the studies dealing with energy and environment (E&E) issues are focused on electricity industry. Moreover, they found that, prior to 1990, the relevant literature had mainly focused on the electricity generation plants (see Färe et al. [26,27]), whereas the focus was placed on the efficiency of electricity distribution utilities after 1990 (see Edvardsen et al. [28]; Forsund, Kittelsen [29]). Modeling the environmental performance has widely attracted the attention of researchers, and about 25% of E&E studies that were carried out from 1990 to 2008 focused on this area (see Färe et al. [30]). From 2010 to 2014, the research on E&E has reached a new peak. For instance, Chang et al. [31] used the slack-based measure (SBM) to analyze the environmental efficiency of China's transportation sector. Song et al. [32] used the bootstrap-DEA approach to analyze the energy efficiency in China. Bi et al. [33] proposed a SBM approach to investigate the relationship between fossil fuel consumption and the environmental regulation of China's thermal power generation. However, the biomass industry in China has received little attention in the efficiency analysis literature. Therefore, in order to avoid arbitrary investments and subsequent inefficient resource allocation, one should consider the operational efficiency of the biomass industry.

Methodologically, DEA is widely applied to derive relative measures of performance of decision making units (DMUs). DEA, proposed by Charnes et al. [34], is based on a linear program and implements the Debreu-Farrell measure. In its early stage, DEA assumed the production technology as a black box without modeling its inner structure; see surveys by Emrouznejad et al. [35] and Cook and Seiford [36]. Later on, research on network DEA emerged to account for the underlying network structure of DMUs. For example, Seiford and Zhu [37] used the two-stage DEA model to measure the profitability and marketability of US commercial banks. Zhu [38] applied the same two-stage DEA model to Fortune Global 500 companies. Cook et al. [39] delivered a review on the models of the basic two-stage system. The network DEA models have been extended to allow different types of internal structure. Kao [40] classified the network DEA models into nine types, i.e., the independent model by Zhu [38], the system distance measure model by Chen et al. [41], the process distance measure model by Chen et al. [42], the factor distance measure model by Chen [43], the slacks-based measure model by Tone and Tsutsui [44], the ratio-form system efficiency model by Chen [45], the ratio-form process efficiency model (Chen et al. [36], Cook et al. [41]), the game theoretic model by Du et al. [46] and the value-based model by Wei and Chang [47]. Besides, Kao [40] differentiated five types of the internal structure of the network DEA model, including the basic two-stage structure, the general two-stage structure, the series structure, the parallel structure, and the dynamic structure. The basic two-stage structure is the simplest network structure where all exogenous inputs are supplied to the first process to produce intermediate products for the second process to produce the final outputs (Chen and Zhu [42]). The general two-stage structure is a generalization of the basic two-stage structure, which allows both stages to consume exogenous inputs supplied from outside and to produce final outputs (Premachandra [48]). The series structure consists of a series of process connected in a sequence (Park et al. [49]). Considering the parallel structure, the most distinctive feature is that all process in the parallel structure operate independently (Färe et al. [50]). The dynamic structure is used to solve the multi-period problems, and it connects several single-period systems together by carry-overs (Färe and Grosskopf [51]).

The network DEA is important when looking into performance of the Chinese biomass sector as the latter is not only dependent on itself, but is also related to the upstream and downstream industries, such as agriculture, forestry, the light industry etc. Specifically, the biomass energy generation industry can provide the power for the related industries and the related industries can provide the some inputs to the biomass power generation industry. Therefore, the biomass energy generation industry and the related ones can form up the series structure. In addition, pollution is generated by the biomass power plants during the process of power (and heat) generation even though it has long been recognized as a clean energy source. The pollutants might affect the related industries. Accordingly, the production process should include undesirable outputs to ensure proper benchmarking. As a result, the network DEA model with undesirable outputs in the profit efficiency framework is applied.

This paper develops a network DEA model for analysis of the efficiency of a Bio-AG system in the presence of desirable and undesirable outputs. The directional distance functions are employed to estimate the economic inefficiency. Such a setting allows decomposing the economic inefficiency into technical and allocative inefficiencies. Furthermore, the concept of property rights is employed to estimate the gains in profits due to imposition or re-allocation of property rights. The proposed model is then applied to the case of China at the province level.

The paper is organized as follows: Section 2 describes the development of the biomass industry in China; Section 3 constructs the production technology for the Bio-AG system and discusses the methods employed in this paper; Section 4 analyses performance of the Chinese Bio-AG system with respect to different assumptions on resource management and efficiency decomposition; Finally, Section 5 presents the conclusions.

2. Development of Biomass Energy Generation in China

China is a large agricultural country with abundant biomass resources which makes the development of biomass power industry rather promising. On the one hand, the arable land area is 2.02 billion mu (135 million hectares) and the annual crop production is almost 700 million tons, which is equal to 350 million tons of standard coal. Besides, agricultural residues are also important biomass resources, including rice husk, corncob, peanut shell, bagasse and cottonseed hull, etc. On the other hand, forests cover about 195 million hectares in China and the rate of forest coverage is 20.36%. Annually, there is 0.8–1 billion tons of biomass resources that can be produced [52,53].

The development of Chinese biomass power industry gained momentum in 2004, which is later than it was the case in the developed countries. Until 2005, the development scale of Chinese biomass power industry was limited. As of 2005, the total installed capacity of the biomass was about 2 million kW. The main resource of biomass is the waste generated in the agriculture products processing, especially the bagasse, which produced 1.7 million kW energy in total. With the introduction and implementation of the Renewable Energy Law [17] as well as other regulations on subsidies for renewable energy tariff, the investment in biomass power industry was on the rise and a various of power generation projects were launched allowing for the use of agricultural waste. In 2013, the total installed capacity of the biomass in China reached 8360 MW with grid-connected capacity of 7790 MW [52,53].

Table 1 shows the installed generating capacity and generated energy of the top ten provinces of the Chinese biomass power industry. Chinese biomass power industries are mainly located in the eastern part, especially in Jiangsu and Shandong. Until 2013, the total installed capacity of energy generated by biomass in the eastern part was 3514.84 MW, which accounted for 49% of the total energy generation and ranked the region as the first one in China. The central and northeast part of China ranked as the second and third ones with the total generated energy of 1438 MW and 1096 MW respectively.

Table 1. Installed capacity in the top ten provinces of the Chinese biomass power industry as of 2013 [54].

Province	Installed Capacity (MW)	Province	Installed Capacity (MW)
Shandong	1089	Guangdong	442
Henan	640	Anhui	388
Jiangsu	554	Hebei	367
Heilongjiang	524	Inner Mongolia	320
Hubei	475	Zhejiang	290

By the year 2013, the total installed capacity of power plants based on combustion of biomass from agriculture and forestry was 4195.3 MW, accounting for 53.85% of the total capacity of biomass power generation; based on that of municipal solid waste (MSW) was 3400.29 MW, accounting for 43.65%; based on other technologies was 194.42 MW, accounting for 2.5%.

The pollutants produced by biomass power plants include SO_2, NO_X, CO, CO_2, waste water among others, which lead to air pollution, water pollution and solid waste pollution. Therefore, the negative externalities caused by biomass power industry towards environment should be taken into consideration.

3. Methodology

3.1. Biomass-Agriculture System

In this paper, the research is confined to the interaction between the biomass power generation industry and agriculture. As outlined in Section 2, the biomass industry and agriculture are related in a number of ways. Agricultural residues constitute inputs for biomass power generation, whereas the residues of the biomass power plants can be used as fertilizers in agriculture. In addition, the process of electricity generation in the biomass power plants renders pollutant emissions. To illustrate this interaction, let us assume that there are only two technologies (i.e., biomass power generation industry and agriculture) that are being modeled. The following exogenous inputs are considered for the biomass power generation industry: capital costs, forest residues, and MSW. Meanwhile the inputs provided by agriculture are agricultural residues. The exogenous outputs of the biomass power generation industry are the power for commercial and residential utilities, while the outputs supplied to agriculture are the production of rural power, straw residues and pollutants. As regards to agriculture, the exogenous inputs are the production of rural power by other sources, fertilizers, and agricultural machinery, while the inputs provided by biomass power generation industry are all the carry-overs as mentioned above. The exogenous output of agriculture is agricultural output, whereas the output carried over to the biomass power generation industry is agricultural residues. In this sense, the biomass power generation industry and agriculture constitute a cycle system.

As biomass and agricultural sectors are linked in a number of ways, the use of the common resource pool impacts the activities of these sectors. Therefore, the regulations imposed on the resource use would affect the performance of the two sectors. In this paper, the shifts in production possibilities for each sector are modeled by considering the changes in property rights. According to Coase [55], property rights also serve as a solution to externality problem. Based on the theory of Coase and the framework linking the property rights and profit (Färe, Grosskopf [56]), the analysis considers the impact of property rights on profit of the biomass industry and agriculture in the Bio-AG system. Indeed, a preferential policy towards a certain sector governing the use of resources (e.g., taxes or subsidies) might be considered as an instance of imposition of property rights even if no actual property right changes are imposed in the strict sense.

3.2. Biomass Production Technology

Based on the principles discussed in the previous sub-section, the biomass production technology can be defined to model the production possibilities. Specifically, let us assume that the vectors of exogenous inputs for agriculture and the biomass power generation industry are represented by $\vec{x}_A \in \mathbb{R}^3$ and $\vec{x}_B \in \mathbb{R}^3$, respectively, while the vectors of exogenous outputs for them are represented by $y_A \in \mathbb{R}$ and $y_B \in \mathbb{R}$, respectively. Similarly, the desirable and undesirable carry-overs from the biomass power generation industry to agriculture are represented by $\vec{d}_{BA} \in \mathbb{R}^2$ and $u_{BA} \in \mathbb{R}$, respectively, while the vector of carry-overs from agriculture to the biomass power generation industry are represented by $d_{AB} \in \mathbb{R}$. In addition, let us assume that there are N decision making units (DMU) indexed by $j = 1, 2, \ldots, N$. According to Färe and Grosskopf [56], a technology which transforms inputs into outputs can be represented in three ways: (1) by graph sets; (2) by output correspondence sets; (3) by input correspondence sets. The graph technology consists of all feasible combinations of input vectors and output vectors, and the graph technologies that are used in agriculture and the biomass power generation industry are:

$$T_A = \{(\vec{x}_A, \vec{d}_{BA}, u_{BA}, y_A, d_{AB}) | (\vec{x}_A, \vec{d}_{BA}, u_{BA}) \text{ can produce } (y_A, d_{AB})\}, \quad (1)$$

$$T_B = \{(\vec{x}_B, d_{AB}, y_B, \vec{d}_{BA}, u_{BA}) | (\vec{x}_B, d_{AB}) \text{ can produce } (y_B, \vec{d}_{BA}, u_{BA})\}, \quad (2)$$

The output correspondence sets consists of all the possible output vectors that can be produced by a given input vector, and the output correspondence sets for agriculture and biomass power generation industry are:

$$P_A(\vec{x}_A, \vec{d}_{BA}, u_{BA}) = \{(y_A, d_{AB}) | (\vec{x}_A, \vec{d}_{BA}, u_{BA}, y_A, d_{AB}) \in T_A\}, \quad (3)$$

$$P_B(\vec{x}_B, d_{AB}) = \{(y_B, \vec{d}_{BA}, u_{BA}) | (\vec{x}_B, d_{AB}, y_B, \vec{d}_{BA}, u_{BA}) \in T_B\}. \quad (4)$$

The input correspondence set consists of all the possible input vectors that can produce a given output vector:

$$L_A(y_A, d_{AB}) = \{(\vec{x}, \vec{d}_{BA}, u_{BA}) | (\vec{x}_A, \vec{d}_{BA}, u_{BA}, y_A, d_{AB}) \in T_A\} \quad (5)$$

$$L_B(y_B, \vec{d}_{BA}, u_{BA}) = \{(\vec{x}_B, d_{AB}) | (\vec{x}_B, d_{AB}, y_B, \vec{d}_{BA}, u_{BA}) \in T_B\} \quad (6)$$

Note that the definitions of the graph technologies, the output correspondence and the input correspondence sets are equivalent to each other [56]. Following Färe [57], the following assumptions underlie the technology set:

- A1 (inactivity): $\vec{0} \in P_A(\vec{x}_A, \vec{d}_{BA}, u_{BA}), \forall(\vec{x}_A, \vec{d}_{BA}, u_{BA})$ and $\vec{0} \in P_B(\vec{x}_B, d_{AB}), \forall(\vec{x}_B, d_{AB})$ (note that the zero vectors have respective dimensions here and in further notations);
- A2 (null-jointness): $(y_A, d_{AB}) \notin P_A(\vec{0}), (y_A, d_{AB}) \geq \vec{0}$ and $(y_B, \vec{d}_{BA}, u_{BA}) \notin P_B(\vec{0})$, $(y_B, \vec{d}_{BA}, u_{BA}) \geq \vec{0}$;
- A3 (strong disposability): if $(\vec{x}', \vec{d}'_{BA}, u'_{BA}) \geq (\vec{x}_A, \vec{d}_{BA}, u_{BA})$, and $(\vec{x}_A, \vec{d}_{BA}, u_{BA}) \in L_A(y_A, d_{AB})$, then $(\vec{x}'_A, \vec{d}'_{BA}, u'_{BA}) \in L_A(y_A, d_{AB})$ (similar strong disposability assumptions for output vectors are also imposed on biomass power generation industry technology as well);

- A4 (weak disposability): if $(y_A, d_{AB}) \in P_A(\vec{x}, \vec{d}_{BA}, \vec{u_{BA}})$, $0 \leq \theta \leq 1$, then $\theta(y_A, d_{AB}) \in P_A(\vec{x}_A, \vec{d}_{BA}, u_{BA})$ (Similar weak disposability assumptions for input vectors are also imposed on biomass power generation industry technology as well);
- A5: both $P_A(\vec{x}_A, \vec{d}_{BA}, u_{BA})$ and $P_B(\vec{x}_B, d_{AB})$ are bounded;
- A6: both T_A and T_B are convex and closed.

Assumption A1 shows that inactivity is always possible, and A2 shows that it is impossible to generate outputs such as electricity power without consuming any inputs. Also, an equivalent representation of A2 further indicates the the undesirable output can be fully avoided only by halting the production, i.e., if $(y_A, d_{AB}) \in P_A(\vec{x}_A, \vec{d}_{BA}, u_{BA})$, $d_{AB} = 0$, then $y_A = 0$. A3 is the strong disposability assumption which allows for an increase in inputs for the frontier input level. A4 is the weak disposability assumption for the output correspondence, under which, if desirable carry-overs are to be decreased proportionally by θ, then exogenous outputs must also be decreased at the same proportion. Assumption A5 shows that only finite amount of outputs can be produced by using finite amounts of inputs.

Based on the definition and assumptions on the technology, one can non-parametrically approximate the biomass power generation industry technology as follows:

$$\hat{T}_B = \left\{ \begin{array}{l} (\vec{x}_B, d_{AB}, y_B, \vec{d}_{BA}, u_{BA}) : \\ \delta_1 y_B \leq \sum\limits_{j=1}^{N} \lambda_j^B y_{Bj}, \\ \delta_1 d_{BA}^i = \sum\limits_{j=1}^{N} \lambda_j^B d_{BAj}^i, i = 1, 2, \\ \delta_1 u_{BA} = \sum\limits_{j=1}^{N} \lambda_j^B u_{BAj}, \\ \delta_2 x_B^r \geq \sum\limits_{j=1}^{N} \lambda_j^B x_{Bj}^r, r = 1, 2, 3, \\ \delta_2 d_{AB} = \sum\limits_{j=1}^{N} \lambda_j^B d_{ABj}, \\ \lambda_j^B \geq 0, j = 1, \ldots, N, \\ \sum\limits_{j=1}^{N} \lambda_j^B \leq 1, \delta_1 \geq 1, 0 \leq \lambda_2 \leq 1. \end{array} \right. \tag{7}$$

Here, it is assumed the biomass power generation industry technology in Equation (7) satisfies non-increasing returns to scale due to restriction on the intensity variables $\lambda_j^B, j = 1, \ldots, N$, which, indeed, implies nonnegative profit. Scalars δ_1 and δ_2 applied in Equation (7) are used to assure the outputs $(y_B, \vec{d}_{BA}, u_{BA})$ and inputs $(\vec{x}_B, d_{AB})$ are weakly disposable under the assumption of non-increasing returns to scale. In addition, exogenous inputs and outputs in Equation (7) are freely (strongly) disposable.

Similarly to the biomass power generation industry technology, one can approximate the agricultural technology as follows:

$$\hat{T}_A = \begin{cases} (\vec{x}_A, \vec{d}_{BA}, u_{BA}, y_A, d_{AB}) : \\ r_1 y_A \leq \sum_{j=1}^{N} \lambda_j^A y_{Aj}, \\ r_1 d_{AB} = \sum_{j=1}^{N} \lambda_j^A d_{ABj}, \\ r_2 x_A^i = \sum_{j=1}^{N} \lambda_j^A x_{Aj}^i, i = 1,2,3, \\ r_2 d_{BA}^r \geq \sum_{j=1}^{N} \lambda_j^A d_{BAj}^r, r = 1,2, \\ r_2 u_{BA} = \sum_{j=1}^{N} \lambda_j^A u_{BAj}, \\ \lambda_j^A \geq 0, j = 1, \ldots, N, \\ \sum_{j=1}^{N} \lambda_j^A \leq 1, r_1 \geq 1, 0 \leq r_2 \leq 1. \end{cases} \quad (8)$$

Here exogenous inputs $\vec{x}_A$ and outputs y_A are freely (strongly) disposable as is shown by the corresponding inequalities in their constraints. Scalars r_1 and r_2 involved in Equation (8) are used to assure the outputs (y_A, d_{AB}) and inputs $(\vec{x}_A, \vec{d}_{BA}, u_{BA})$ are weakly disposable under the assumption of non-increasing returns to scale.

3.3. Relationship between Property Rights and the Profitability in the Bio-AG System

As is mentioned previously, negative externalities (pollutants produced by the biomass power generation) had long been neglected in the literature. In this paper, the property rights are considered to analyze the relationship between access to resources and profitability in the Bio-AG system. According to Grosskopf [56], the three cases are considered when modeling the externalities: (1) the property right is absent in the Bio-AG system; (2) the biomass power generation industry is given with the property right; (3) agriculture is given with the property right.

First, the profit maximization in the absence of regulation in the Bio-AG system (i.e., the current situation in China) is presented. In this case, the two sectors optimize their production independently with respect to input and output prices. In this setting, carry-over factors are ignored. Therefore, the obtained profits can be referred to as "unrestricted" ones. For the biomass industry, the "unrestricted" maximal profit is obtained as

$$\Pi_1^U(p_B, \vec{\omega}_B) = \max\left(p_B y'_B - \sum_{r=1}^{3} \omega_{Br} x'^r_B\right),$$

$$s.t. \begin{cases} y'_B \leq \sum_{j=1}^{N} \lambda_j^B y'_{Bj}, \\ x'^r_B \geq \sum_{j=1}^{N} \lambda_j^B x'^r_{Bj}, r = 1,2,3, \\ \lambda_j^B \geq 0, j = 1, \cdots, N, \\ \sum_{j=1}^{N} \lambda_j^B \leq 1. \end{cases} \quad (9)$$

Similarly, the maximal profit for the agricultural sector under no property rights can be obtained via

$$\Pi_2^U(p_A, \vec{\omega}_A) = \max\left(p_A y'_A - \sum_{i=1}^{3} \omega_{Ai} x'^i_A\right),$$

$$s.t.\begin{cases} y'_A \le \sum_{j=1}^{N} \lambda_j^A y'_{Aj}, \\ x'^i_A \ge \sum_{j=1}^{N} \lambda_j^A x'^i_{Aj}, i = 1,2,3, \\ \lambda_j^A \ge 0, j = 1, \cdots, N, \\ \sum_{j=1}^{N} \lambda_j^A \le 1. \end{cases} \tag{10}$$

The next setting is the case where the biomass power generation has the property rights. In this manner, the biomass industry can maximize its profits with no constraints on the production of the bad carry-over u_{BA}, yet the agricultural sector needs to adapt to the resulting optimal solution. Let us assume that the prices for inputs and outputs of the biomass industry are $\vec{\omega}_B \in \mathbb{R}^3_+$ and $p_B \in \mathbb{R}_+$ and the prices for inputs and outputs of the agriculture industry are $\vec{\omega}_A \in \mathbb{R}^3_+$ and $p_A \in \mathbb{R}_+$ respectively. In the first step, profit of the biomass power generation industry is maximized thereby obtaining the maximal profit and the optimal quantities $(\vec{d}^*_{BA}, u^*_{BA}, d^*_{AB})$. This carry-over vector is then taken as the exogenous input vector for the agriculture industry, which, in the next step, maximizes the profits considering $(\vec{d}^*_{BA}, u^*_{BA}, d^*_{AB})$. The profit maximization problem for the biomass power generation industry under property right restrictions is

$$\Pi_1^R(p_B, \vec{\omega}_B) = \max \left(p_B y'_B - \sum_{r=1}^{3} \omega_{Br} x'^r_B \right),$$

$$s.t.\begin{cases} \delta_1 y'_B \le \sum_{j=1}^{N} \lambda_j^B y'_{Bj}, \\ \delta_1 d^i_{BA} = \sum_{j=1}^{N} \lambda_j^B d^i_{BAj}, i = 1,2, \\ \delta_1 u_{BA} = \sum_{j=1}^{N} \lambda_j^B u_{BAj}, \\ \delta_2 x'^r_B \ge \sum_{j=1}^{N} \lambda_j^B x'^r_{Bj}, r = 1,2,3, \\ \delta_2 d_{AB} = \sum_{j=1}^{N} \lambda_j^B d_{ABj}, \\ \lambda_j^B \ge 0, j = 1, \cdots, N, \\ \sum_{j=1}^{N} \lambda_j^B \le 1, \delta_1 \ge 1, 0 \le \delta_2 \le 1. \end{cases} \tag{11}$$

The solution to this problem gives the maximal profit when the biomass power generation industry has the property rights. The solution also yields a vector of optimal carry-overs $(\vec{d}^*_{BA}, u^*_{BA}, d^*_{AB})$. By inserting them into the corresponding problem for the agricultural industry, one can estimate the maximal profit for agricultural industry under property rights restrictions:

$$\Pi_2^R(p_A, \vec{\omega}_A) = \max \left(p_A y'_A - \sum_{i=1}^{3} \omega_{Ai} x'^i_A \right),$$

$$s.t.\begin{cases} r_1 y'_A \leq \sum_{j=1}^{N} \lambda_j^A y'_{Aj}, \\ r_1 d^*_{AB} = \sum_{j=1}^{N} \lambda_j^A d_{ABj}, \\ r_2 x'^i_A \geq \sum_{j=1}^{N} \lambda_j^A x'^i_{Aj}, i = 1,2,3, \\ r_2 d^{r*}_{BA} = \sum_{j=1}^{N} \lambda_j^A d^r_{BAj}, r = 1,2, \\ r_2 u^*_{BA} = \sum_{j=1}^{N} \lambda_j^A u_{BAj}, \\ \lambda_j^A \geq 0, j = 1,\cdots,N, \\ \sum_{j=1}^{N} \lambda_j^A \leq 1, r_1 \geq 1, 0 \leq r_2 \leq 1. \end{cases} \tag{12}$$

Suppose the observed profits for the biomass power generation industry and agriculture industry are $\prod_1$ and $\prod_2$. Then, the sum of $\left(\prod_1^R(p_B, \vec{\omega}_B) - \prod_1\right)$ and $\left(\prod_2^R(p_A, \vec{\omega}_A) - \prod_2\right)$ is the total profit change in the Bio-AG system in case the biomass power generation industry is provided with the property rights. Note that the total profit change in the bio-AG system (PI) is composed of the two parts. One is due to the improvement of the technology or management (TMI), i.e., $\prod_1^U(p_B, \vec{\omega}_B) - \prod_1$ and $\prod_2^U(p_A, \vec{\omega}_A) - \prod_2$, and the other is due to the transfer of the property rights to the biomass industry (PRI), i.e., $\prod_1^R(p_B, \vec{\omega}_B) - \prod_1^U(p_B, \vec{\omega}_B)$ and $\prod_2^R(p_A, \vec{\omega}_A) - \prod_2^U(p_A, \vec{\omega}_A)$. In this sense, the profit change decomposes as follows:

$$\begin{aligned} &PI = TMI + PRI, \\ &PI = \sum_{i=1}^{2} \left[\prod_i^R(p_B, \vec{\omega}_B) - \prod_i\right], \\ &PRI = \sum_{i=1}^{2} \left[\prod_i^R(p_B, \vec{\omega}_B) - \prod_i^U(p_A, \vec{\omega}_A)\right], \\ &TMI = \sum_{i=1}^{2} \left[\prod_i^U(p_A, \vec{\omega}_A) - \prod_i\right]. \end{aligned} \tag{13}$$

Third case of the property right attribution can be briefly presented by the way of analogy. In this case, the agricultural industry is given the property rights. First, the agricultural industry maximizes its profit. This solution yields the maximal profit and the optimal quantities $(\vec{d}^{**}_{BA}, u^{**}_{BA}, d^{**}_{AB})$. Then, the latter carry-over vector is taken as exogenous output vector for the biomass power generation industry, which, in the next step, maximizes its profit given $(\vec{d}^{**}_{BA}, u^{**}_{BA}, d^{**}_{AB})$. The profit change decomposition can then be facilitated as described above. Note that the prices of inputs and outputs may vary across the DMUs, yet the corresponding notations are suppressed for sake of readability.

3.4. Efficiency Decomposition

The technical efficiency concept was first proposed by Koopmans [58], and Debreu [59] was the first to develop a method (i.e., the coefficient of resource utilization measure) to measure the technical efficiency. Farrell [60] extended the aforementioned approaches and proposed Debreu-Farrell measure of technical efficiency, which became an important part of efficiency analysis theory. Later on, different models to implement the Debreu-Farrell measure have been proposed, e.g., the econometric approach (Forsund et al. [61]) and the linear programming approach (Charnes et al. [34]).

While the measures of technical efficiency require no price information, the wider concept of economic efficiency is related to price information. Farrell [60] and Nerlove [62] proposed decomposing the total (economic) inefficiency into technical inefficiency and allocative inefficiency. Subsequently, a number of approaches have been developed to measure and decompose the economic efficiency: the approach based on the geometric distance function measurement proposed by Portela and Thanassoulis [63], the two-stage network model by Saboo et al. [64], the weighted additive model by Cooper [65], the pro-efficiency model by Park [49]. Note that the economic efficiency might be approached by considering cost minimization, revenue maximization and profit maximization. Shephard [66,67] proposed that input distance function and output distance function could be used to represent technology, and then discovered the duality relationship between the distance and value functions. More precisely, the input/output distance function provides a lower bound of the cost/revenue function, so that the total inefficiency represented by the cost/revenue function can be decomposed into the technical inefficiency, which is represented by distance functions, while the allocative inefficiency is represented by the residual. Chambers [68] proposed the directional distance function (DDF) and proved the duality relationship between DDF and the profit function. Specifically, DDF is the lower bound of the profit inefficiency (Mahler inequality) and the total inefficiency (profit inefficiency) can be decomposed into the technical part (represented by DDF) and the allocative efficiency (residual). As DDF is dual to the profit function, one can exploit the DDF to decompose the profit efficiency. Therefore, the technical inefficiency of DMU_0 (a province engaged in the biomass industry) can be computed by setting up the following DDF-based measure:

$$\vec{D}_r^1(\vec{x}_0, \vec{y}_0; \vec{g}_1^x, \vec{g}_1^y) = \max\beta,$$

$$s.t. \begin{cases} y'_{B0} + \beta g_1^y \leq \sum\limits_{j=1}^{N} \lambda_j^B x'_{Bj}, \\ x'^r_{B0} - \beta g_{1r}^x \geq \sum\limits_{j=1}^{N} \lambda_j^B x'^r_{Bj}, r = 1,2,3, \\ \lambda_j^B \geq 0, j = 1, \cdots, N, \\ \sum\limits_{j=1}^{N} \lambda_j^B = 1, \end{cases} \tag{14}$$

where $(\vec{g}_1^x, \vec{g}_1^y)$ is the non-negative directional input-output vector of the biomass industry and subscript "0" denotes the values of the variables observed for DMU under evaluation, namely DMU_0.

Similarly, the technical inefficiency of DMU_0 of agriculture can be computed by setting up the following DDF-based measure:

$$\vec{D}_r^2(\vec{x}_0, \vec{y}_0; \vec{g}_2^x, \vec{g}_2^y) = \max\alpha,$$

$$s.t. \begin{cases} y'_{A0} + \alpha g_2^y \leq \sum\limits_{j=1}^{N} \lambda_j^A y'_{Aj}, \\ x'^i_{A0} - \alpha g_{2i}^x \geq \sum\limits_{j=1}^{N} \lambda_j^A x'^i_{Aj}, i = 1,2,3, \\ \lambda_j^A \geq 0, j = 1, \cdots, N, \\ \sum\limits_{j=1}^{N} \lambda_j^A = 1. \end{cases} \tag{15}$$

where $(\vec{g}_2^x, \vec{g}_2^y)$ is the non-negative directional input-output vector of the biomass industry and subscript "0" denotes the values of the variables observed for DMU under evaluation, namely DMU_0.

The maximum profits of the biomass industry and agriculture can be computed using models (9) and (10), with y'_A and y'_B replaced by y_A and y_B. In this sense, the profit inefficiency (PE), the technical inefficiency (TE) and the allocative inefficiency (AE) of each industry can be obtained as follows:

$$\begin{aligned} PE &= \frac{\prod_i^U(p_i, \vec{\omega}_i) - \prod_i}{p_i g_i^y + \sum\limits_{r=1}^{3} \omega_r g_r^x}, \\ TE &= \vec{D}_r'(\vec{x}_0, \vec{y}_0; \vec{g}_i^x, \vec{g}_i^y), \\ AE &= PE - TE, \end{aligned} \tag{16}$$

where $i = 1$ is associated with the biomass industry and $i = 2$ is related to agriculture. Based on the Mahler inequality, it can be easily proved that $0 \leq \mathrm{TE} \leq \mathrm{PE}$ and, as a result, $\mathrm{AE} \geq 0$.

4. Empirical Analysis

4.1. Data

The approach outlined in Section 3.3 is employed to examine the relationship between property rights and profitability in the Bio-AG system. The data on biomass power generation industry and agriculture in Chinese 31 provinces cover year 2012. Table 2 provides an overview of three types of variables in the Bio-AG system, namely exogenous inputs, exogenous outputs and carry-overs.

Table 2. Inputs, outputs and carry-overs for the network DEA the model.

Type of Variable	Industry	Variable	Description (Dimension)
Inputs (exogenous)	Biomass power generation	Operation cost (OC)	Capital costs for building biomass power plants, wages, financial costs and management costs (RMB)
		Forest residues (FR)	Residues released together with wood production and processing (t)
		Organic waste (OW)	Biomass released after human material use (t)
	Agriculture	Rural power produced by other resources (RPO)	Rural power produced by coal, hydropower, wind, nuclear power, photovoltaic power etc. (biomass power is excluded) (kWh)
		Fertilizers (F)	Fertilizers used in agriculture (t)
		Agricultural machinery (AM)	Agricultural machinery used in agriculture, such as agricultural tractors, agricultural diesel engines (kWh)
Outputs (exogenous)	Biomass power generation	Commercial and residential power (CRP)	Electric power generated by biomass power plants for commercial use and residential use (kWh)
	Agriculture	Agricultural production (AP)	Agricultural products include rice, wheat, corn, grains, beans, tubers, oil crops, cotton, hemp etc. (RMB)
Carry-overs	From biomass power generation to agriculture	Rural power produced by biomass resources (RPB)	Rural power produced by biomass resources (kWh)
		Straw residues (SR)	Residues released during the process of biomass power generation (t)
		Pollutants (P)	Pollutants produced by biomass power plants, such as SO2, NOX, CO, CO2, cinder, waste water etc. (t)
	From agriculture to biomass power generation	Agricultural residues (AR)	Residues released together with food production and processing (t)

With respect to the biomass power generation industry, the exogenous inputs are operation costs (OC), forest residues (FR) and organic waste (OW), while the exogenous output is commercial and residential power (CRP). The carry-overs from biomass power generation industry to agriculture can be divided into two parts. One is desirable (including rural power produced by biomass resources (RPB) and straw residues (SR)). The other is undesirable (pollutants (P)). As for agriculture, the exogenous inputs are rural power produced by other resources (RPO), fertilizers (F) and agricultural machinery (AM), while the exogenous outputs are agricultural production (AP). The carry-overs from agriculture to the biomass power generation industry are agricultural resides (AR).

The data for OC, RPB, RPO, CRP come from the China Electric Power Yearbook 2013, while the data of F and AM come from the Statistics yearbook of China in 2013, and the data for SR come from the China Renewable Energy Industry Development Report 2013. However, the data of FR, OW, P and AR cannot be obtained directly from other reports or references, and they were calculated according to the principles outlined by Zhou et al. [22].

The prices of FR and OW were obtained from the China Renewable Energy Industry Development Report 2013; the prices of CRP and RPB were obtained from the Regulation on Adjusting the Price of Biomass in Agriculture and Forest released by the National Development and Reform Commission; the price of RPO was obtained from China Electric Power Yearbook 2013; the price of F was obtained from the China Agricultural Development Report 2013.

4.2. Empirical Results and Discussion

According to models (9)–(12), one can calculate the maximum profit of the biomass power generation industry and agriculture in three cases (i.e., no property rights were given, property rights were given to the biomass power generation industry, and property rights were given to the agriculture). Table 3 shows the maximal profits of the biomass power generation industry and agriculture in three cases.

Table 3. Maximal profits for the biomass power generation industry and agriculture in the three cases (million RMB).

Sector	Case 1	Case 2	Case 3
Biomass industry	3597.1	4000.3	2120.5
Agriculture	218,224.42	247,890	251,980

Notes: Under Case 1, no property rights are allocated; under Case 2, property rights are given for the biomass industry; and, under Case 3, property rights are given for agriculture. 1 USD equalled 6.33 RMB as of 1 January 2012.

As it can be seen in Table 3, the maximum profits of the biomass power generation industry and agriculture are 3.5971 billion RMB and 218.2244 billion RMB respectively when there are no property rights; the maximum profits of the two industries are 4.0003 billion RMB and 247.89 billion RMB respectively when property rights are given to the biomass power generation industry; the maximum profits of the two industries are 2.1205 billion RMB and 251.98 billion RMB respectively when property rights are given to agriculture. Note that 1 USD equalled 6.33 RMB as of 1 January 2012. Table 4 shows the gaps among the observed and maximum profits of the two industries in each province in three cases. Note that the observed profit is based on certain assumptions as outlined in Sections 3.1 and 4.1.

Case 1 defines a situation in which no property rights are present. In this setting, as it is shown in Table 4, Jiangsu is the only province where the observed profits are equal to the maximum profits of the biomass power generation industry and agriculture which indicates that the Bio-AG system in Jiangsu performed the best performing one among the 31 provinces in China. Indeed, most of biomass power plants in Jiangsu use the straw combustion power generation technology as the highly-developed agriculture in Jiangsu provides good opportunities for further development of the biomass industry. However, some experts have noted that the market of biomass industry in Jiangsu has been saturated, and the raw materials for biomass industry are in short supply. Therefore the government should be more cautious as concerns this problem and guide the market to operate more efficiently. Second, there are two provinces where observed biomass profits exceed 200,000 RMB (i.e., Jiangsu and Shandong), and there are 10 provinces who are facing negative biomass profits (i.e., Xinjiang, Qinghai, Guizhou, Shanxi, Gansu, Guangxi, Sichuan, Xizang, Inner Mongolia, and Yunan). Indeed, most of these 10 provinces are located in the western part of China, which is consistent with the current situation of the development of the biomass industry in China. Table 5 lists ten most efficient provinces ranked in terms of the gap between their observed profit and maximum profit in biomass industry. As is shown in Table 5, most of these 10 provinces are located in the southeast of

China, which is consistent with the current situation of the development of biomass industry in China. Note that 7 of these 10 provinces are using the straw combustion power generation technology (except Guangdong, Zhejiang and Hebei for MSW incineration technology), thus one can conclude that the straw combustion power generation technology performs better than the other technologies. Figure 1 depicts the geographical location of the most efficient provinces.

Table 4. Profit gaps between the observed profit and maximum profit for the two industries in three cases of property right imposition across provinces (million RMB).

Province	Observed Profit		Case 1		Case 2		Case 3	
	Profit (Bio)	Profit (AG)	Difference (Bio)	Difference (AG)	Difference (Bio)	Difference (AG)	Difference (Bio)	Difference (AG)
Beijing	121.73	12,434.99	3475.37	205,725.01	3878.57	235,455.01	1998.77	239,545.01
Tianjin	148.92	10,098.68	3448.18	208,061.32	3851.38	237,791.32	1971.58	241,881.32
Hebei	485.32	136,924.93	3111.78	81,235.08	3514.98	110,965.07	1635.18	115,055.07
Shanxi	−165.95	34,593.85	3763.05	183,566.15	4166.25	213,296.15	2286.45	217,386.15
Inner Mongolia	−679.68	62,302.29	4276.78	155,857.71	4679.98	185,587.71	2800.18	189,677.71
Liaoning	424.42	110,400.94	3172.68	107,759.06	3575.88	137,489.06	1696.08	141,579.06
Jilin	1173.09	72,707.24	2424.01	145,452.76	2827.21	175,182.76	947.41	179,272.76
Heilongjiang	1086.72	155,865.68	2510.38	62,294.33	2913.58	92,024.33	1033.78	96,114.33
Shanghai	59.06	14,386.8	3538.04	203,773.2	3941.24	233,503.2	2061.44	237,593.2
Jiangsu	3597.13	218,224.42	0	0	403.17	29,665.58	−1476.63	33,755.58
Zhejiang	1437.5	79,167.42	2159.6	138,992.58	2562.8	168,722.58	683	172,812.58
Anhui	1611.94	88,010.71	1985.16	130,149.29	2388.36	159,879.29	508.56	163,969.29
Fujian	443.84	102,800.2	3153.26	115,359.8	3556.46	145,089.8	1676.66	149,179.8
Jiangxi	429.08	25,800.39	3168.02	192,359.61	3571.22	222,089.61	1691.42	226,179.61
Shandong	2940.84	192,049.74	656.26	26,110.26	1059.46	55,840.26	−820.34	59,930.26
Henan	1905.13	212,392.42	1691.97	5767.58	2095.17	35,497.58	215.37	39,587.58
Hubei	1143.09	181,663.43	2454.01	36,496.57	2857.21	66,226.57	977.41	70,316.57
Hunan	61.15	179,246.03	3535.95	38,913.97	3939.15	68,643.97	2059.35	72,733.97
Guangdong	1171.48	174,777.61	2425.62	43,382.39	2828.82	73,112.39	949.02	77,202.39
Guangxi	−392.37	117,587.2	3989.47	100,572.8	4392.67	130,302.8	2512.87	134,392.8
Hainan	41.12	37,685.53	3555.98	180,474.47	3959.18	210,204.47	2079.38	214,294.47
Chongqing	98.15	63,949.74	3498.95	154,210.26	3902.15	183,940.26	2022.35	188,030.26
Sichuan	−452.17	213,517.17	4049.27	4642.83	4452.47	34,372.83	2572.67	38,462.83
Guizhou	−153.92	51,626.73	3751.02	166,533.27	4154.22	196,263.27	2274.42	200,353.27
Yunnan	−776.64	90,730.87	4373.74	127,429.13	4776.94	157,159.13	2897.14	161,249.13
Xizang	−472.55	−1979.77	4069.65	220,139.77	4472.85	249,869.77	2593.05	253,959.77
Shaanxi	37.27	111,004.03	3559.83	107,155.97	3963.03	136,885.97	2083.23	140,975.97
Gansu	−180.53	61,035.34	3777.63	157,124.66	4180.83	186,854.66	2301.03	190,944.66
Qinghai	−78.66	4756	3675.76	213,404	4078.96	243,134	2199.16	247,224
Ningxia	81.44	10,992.94	3515.66	207,167.06	3918.86	236,897.06	2039.06	240,987.06
Xinjiang	−69.52	132,806.33	3666.62	85,353.68	4069.82	115,083.68	2190.02	119,173.68

Notes: *Bio* stands for Biomass and *AG* stands for Agriculture. 1 USD equalled 6.33 RMB as of 1 January 2012.

Table 5. Ten most efficient provinces ranked in regards to the gap between the observed profit and maximum profit in biomass industry.

Province	Difference (Bio), Million RMB	Technology	Location
Jiangsu	0	Straw combustion	Southeast
Shandong	656.26	Straw combustion	East
Henan	1691.97	Straw combustion	Middle
Anhui	1985.16	Straw combustion	Southeast
Zhejiang	2159.6	MSW incineration	Southeast
Jilin	2424.01	Straw combustion	Northeast
Guangdong	2425.62	MSW incineration	South
Hubei	2454.01	Straw combustion	Southeast
Heilongjiang	2510.38	Straw combustion	North
Hebei	3111.78	MSW incineration	Middle

Note: 1 USD equalled 6.33 RMB as of 1 January 2012.

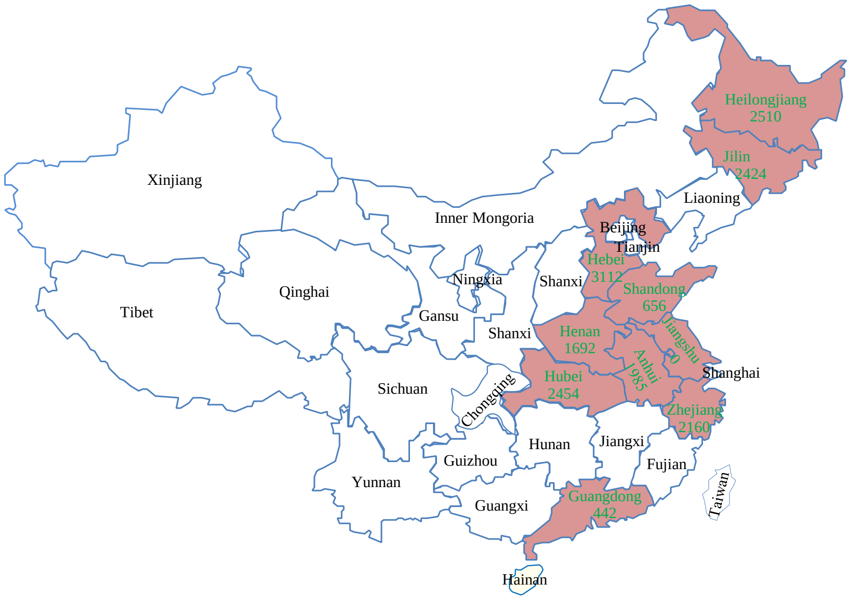

Figure 1. The provinces of China considered in the analysis with the ten most efficient ones shaded in red. Numbers indicate the gains in biomass sector profits if economic efficiency is maintained without property rights.

Further on, Cases 2 and 3 assume that the property rights are given to biomass industry and agriculture respectively. According to Section 3, the exogenous outputs of the biomass industry and agriculture are both maximized. First, under Case 2, the maximal profits for these two industries increase if compared to Case 1, which indicates that the overall profits go up when the government implements the regulation on controlling the negative externalities. The results indicate that the maximal (optimized) profit for the biomass industry under Case 2 is the highest one if compared to Cases 1 and 3, which indicates that when property rights are given to the biomass industry, there are no constraints on the emission of pollutants and maximization of the profits is less restrictive. In this case, agriculture suffered from heavier pressure of environmental protection. However, with the assumption of weak disposability, the supply of rural power and quantity of straw residues for agriculture also increased with increasing pollutant emission, thus the maximal profits for agriculture still increased. Second, with respect to Case 3, the maximal profits for agriculture were the highest ones if compared to Cases 1 and 2, while the maximal profits for the biomass industry were the lowest ones. This shows that the biomass industry was influenced greatly when the property rights were given to agriculture. In this case, in order to maximize their profits, agricultural plants minimize the pollutant emission to the highest possible extent. With the assumption of weak disposability on pollutants and exogenous outputs of the biomass industry, the decrease in pollutant emissions would result in the decrease in of commercial power and residential power generated from the biomass power plants. Therefore, the profits for the biomass industry declined sharply. It is noted that the maximal profits for the biomass industry in Case 3 were lower than the observed profits of Jiangsu and Shandong (as is shown in Table 4, the change in profits for Jiangsu and Shandong in the 8th column are negative). Thus, it would cause great damage to the biomass industry when agriculture was given with the property rights, especially judging from the current situation of the development of the biomass industry in China.

As is mentioned previously, in both of the two industries of most provinces, there was a gap between their observed profits and maximum profits. In order to ascertain the sources for the profit inefficiencies, i.e., technical inefficiency or allocative inefficiency, one needs to further decompose the profit inefficiencies into technology inefficiencies and allocative inefficiencies. One can find the results of the inefficiency decomposition in Table 6.

Table 6. Inefficiency decomposition for the biomass industry and agriculture in China (million RMB).

Province	Biomass industry			Agriculture		
	PE	TE	AE	PE	TE	AE
Beijing	21.59	0.95	20.64	205,725.01	0	205,725.01
Tianjin	21.42	0	21.42	208,061.32	0.19	208,061.13
Hebei	19.33	1.44	17.89	81,235.07	3.24	81,231.83
Shanxi	23.37	0.07	23.3	183,566.15	1.13	183,565.01
Inner Mongolia	26.56	0.28	26.29	155,857.71	1.84	155,855.87
Liaoning	19.71	0.56	19.15	107,759.06	1.42	107,757.65
Jilin	15.06	1.15	13.91	145,452.76	2.02	145,450.74
Heilongjiang	15.59	0.54	15.05	62,294.32	2.35	62,291.97
Shanghai	21.98	0	21.98	203,773.2	0	203,773.2
Jiangsu	0	0	0	0	0	0
Zhejiang	13.41	5.86	7.55	138,992.58	0.87	138,991.71
Anhui	12.33	0.95	11.38	130,149.29	3.29	130,146.01
Fujian	19.59	2.21	17.38	115,359.8	1.16	115,358.64
Jiangxi	19.68	0.09	19.59	192,359.61	1.36	192,358.25
Shandong	4.08	2.86	1.22	26,110.26	4.71	26,105.55
Henan	10.51	1.05	9.46	5767.58	6.79	5760.79
Hubei	15.24	2.17	13.07	36,496.57	3.5	36,493.07
Hunan	21.96	0.24	21.72	38,913.97	2.44	38,911.53
Guangdong	15.07	5.52	9.55	43,382.39	2.4	43,379.98
Guangxi	24.78	0	24.78	100,572.8	2.44	100,570.36
Hainan	22.09	0	22.09	180,474.47	0.41	180,474.07
Chongqing	21.73	1.12	20.61	154,210.26	0.91	154,209.35
Sichuan	25.15	0.27	24.88	4642.83	2.48	4640.35
Guizhou	23.3	0	23.3	166,533.27	0.93	166,532.34
Yunnan	27.17	0.27	26.9	127,429.13	2.05	127,427.08
Xizang	25.28	0	25.28	220,139.77	0	220,139.77
Shaanxi	22.11	0.08	22.03	107,155.97	2.35	107,153.62
Gansu	23.46	0.17	23.3	157,124.66	0.87	157,123.78
Qinghai	22.83	0	22.83	213,404	0	213,404
Ningxia	21.84	0	21.84	207,167.06	0.34	207,166.72
Xinjiang	22.77	0.01	22.76	85,353.68	1.88	85,351.8

Note: 1 USD equalled 6.33 RMB as of 1 January 2012.

With respect to the biomass industry, the average profit inefficiency is 19.3215 million RMB, while the average technical inefficiency and allocative inefficiency are 0.8984 million RMB and 18.4232 million RMB respectively. This indicates that the allocation of resources has greater influence on the performance of the biomass industry in each province than the level of technology. However, it is noted that the technical inefficiency of Guangdong and Zhejiang was the highest among all of the 31 provinces, and the biomass technology adopted by these two provinces was mainly the MSW incineration technology. In this sense, one can conclude that the biomass power generation technology indeed influences biomass profitability. Especially, the straw combustion power generation technology performed better than the MSW incineration technology.

However, the carried out analysis suggests technology (as represented by technical inefficiency) is not the main factor contributing to the economic inefficiency of biomass power production in China. Instead, it is the inefficient allocation of resources that is the main factor that strongly influences the performance of the biomass industry. Therefore, the government should pay more attention to the allocation of resources, and prevent excessive or blind investments. Similarly, in the biomass industry, the most influential factor for the profit in agriculture is also the allocation of resources. As China is an agricultural country with an undergoing development processes in agriculture, the technical inefficiency of the agricultural sector remains rather uniform across the provinces.

5. Conclusions

This study focused on the biomass power generation industry in China by establishing the Bio-AG model. The proposed approach was then applied to analyze the relationships between the biomass industry and agriculture. In particular, the analysis covered the negative externalities in the form of pollutant emissions resulting from activities of the biomass industry. Then, the DDF was employed to decompose the profit inefficiency of each province.

The Bio-AG system in Jiangsu appeared as the best performing one among the 31 provinces in China. The main reasons for this might be the developed network of biomass power plants and implementation of advanced technology in biomass power generation. However, the market of biomass industry in Jiangsu has been saturated, and the raw materials for biomass industry are in short supply. Therefore the government should be more cautious to this problem and introduce appropriate incentives to ensure smooth operation of the biomass power generation sector in the region.

Geographically, the development of the biomass industry is rather uneven. Specifically, the western part of China lags behind that of the other districts in terms of the profit, whereas the biomass industry is fairly well developed in southeast of China. Therefore, the government should seek to balance of the biomass industry development among different provinces in the future.

The profits of both the biomass industry and agriculture would increase in case property rights were given to the biomass industry in order to address the negative externalities, while the profits of the biomass industry would decline sharply when property rights were given to agriculture. Therefore, with the rapid development of the biomass industry in China, government should pay more attention to the negative externalities caused by the biomass industry and take appropriate measures to address this issue, for example. The results also show that additional support measures are needed to address the demand of the biomass industry. Without such measures, agricultural sector would not ensure the highest possible level of development of the biomass power sector due to property rights.

The biomass power generation technology does have the influence on the profits of the biomass industry. Specifically, the straw combustion power generation technology performed better than the MSW incineration technology. However, in China, the inefficient allocation of resources has appeared as the major factor reducing performance of the biomass industry. Therefore, the government should pay more attention to the allocation of resources, and prevent excessive or blind investments. Systematic benchmarking is an important tool in this regard.

The biomass industry in China is facing multiple difficulties in its developing process, such as the lack of materials, high costs of biomass power generation, as well as the biomass feed-in tariff. In the long run, the negative externalities caused by the biomass industry should also be accounted for. Although, in this paper, we only modeled the relationship between the biomass industry and agriculture, the negative externalities associated with the other sectors cannot be neglected in the Bio-AG system and the profits should be adjusted accordingly. Therefore, future research should focus on the following directions. First, the time span can be extended to cover a longer period of time, thereby providing more information to support decision making in regards to the negative externalities of biomass power production. Second, more industries could be taken into account (such as forestry, fishery, the light industry etc.) thus extending the network DEA system. In particular, because of the lack of materials and supply issues pertinent to the biomass industry, the analysis involving upstream and downstream industries is important. All in all, two-stage DEA models and network DEA models could be adopted to obtain more information and analyze this sector in a more comprehensive way.

In any case, the competing energy generation technologies need to be considered in the analysis as the costs and benefits associated with biomass and the other renewable energy sources tend to diverge. Given China's growing demand for electricity, the biomass sector might be appealing in terms of improving energy security through energy-mix diversification. Therefore, the optimization of energy generation should account for multiple economic and strategic factors.

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References

1. Watson, R.T. Climate change: The political situation. *Science* **2003**, *302*, 1925–1926.
2. Walther G.R.; Post, E.; Convey, P.; Menzel, A.; Parmesan, C.; Beebee, T.J.C.; Fromentin, J.M.; Hoegh-Guldberg, O.; Bairlein, F. Ecological responses to recent climate change. *Nature* **2002**, *416*, 389–395.
3. Kumar, A.; Jain, V.; Kumar, S. A comprehensive environment friendly approach for supplier selection. *Omega* **2014**, *42*, 109–123.
4. Wei, Y.M.; Mi, Z.F.; Huang, Z. Climate policy modeling: An online SCI-e and SSCI based literature review. *Omega* **2014**, *57*, 70–84.
5. Stocker, T.F. Climate change: Models change their tune. *Nature* **2004**, *430*, 737–738.
6. United Nations. Development and International Cooperation: Environment. In *Report of the World Commission on Environment and Development: Our Common Future*; Distr. General. A/42/427, Forty-Second Session; The United Nations: New York, NY, USA, 1987.
7. Dirzyte, A.; Rakauskiene, O.G. Green Consumption: The gap between attitudes and behaviours. *Transform. Bus. Econ.* **2016**, *15*, 523–538.
8. Fuinhas, J.A.; Marques, A.C.; Almeida, P.; Nogueira, D.; Branco, T. Two centuries of economic growth: international evidence on deepness and steepness. *Transform. Bus. Econ.* **2016**, *15*, 192–206.
9. Liobikiene, G.; Mandravickaite, J.; Krepstuliene, D.; Bernatoniene, J.; Savickas, A. Lithuanian achievements in terms of CO_2 emissions based on production side in the context of the EU-27. *Technol. Econ. Dev. Econ.* **2017**, *23*, 483–503.
10. Noori, H.; Chen, C. Applying scenario-driven strategy to integrate environmental management and product design. *Prod. Oper. Manag.* **2003**, *12*, 353–368.
11. Hwang, S.-N.; Chen, C.; Chen, Y.; Lee, H.-S.; Shen, P.-D. Sustainable design performance evaluation with applications in the automobile industry: Focusing on inefficiency by undesirable factors. *Omega* **2013**, *41*, 553–558.
12. Zhou, P.; Ang, B.W.; Poh, K.L. Slacks-based efficiency measures for modeling environmental performance. *J. Econ.* **2006**, *60*, 111–118.
13. Chen, C. Design for the environment: A quality-based model for green product development. *Manag. Sci.* **2001**, *47*, 250–263.
14. Zhang, D.; Wang, J.; Lin, Y.; Si, Y.; Huang, C. Present situation and future prospect of renewable energy in China. *Renew. Sustain. Energy Rev.* **2017**, *76*, 865–871.
15. Chang, Y.C.; Wang, N. Legal system for the development of marine renewable energy in China. *Renew. Sustain. Energy Rev.* **2017**, *75*, 192–196.
16. Yang, X.J.; Hu, H.; Tan, T.; Li, J. China's renewable energy goals by 2050. *Environ. Dev.* **2016**, *20*, 83–90.
17. Renewable Energy Law of the People's Republic of China. Available online: http://english.mofcom.gov.cn/article/policyrelease/questions/201312/20131200432160.shtml (accessed on 13 September 2017).
18. Zhang, P.D.; Yang, Y.L.; Shi, J.; Zheng, Y.H.; Wang, L.S.; Li, X.R. Opportunities and challenges for renewable energy policy in China. *Renew. Sustain. Energy Rev.* **2009**, *13*, 439–449.
19. Lin, D. The development and prospective of bioenergy technology in China. *Biomass Bioenergy* **1998**, *15*, 181–186.
20. Kahrl, F.; Su, Y.; Tennigkeit, T.; Yang, Y.; Xu, J. Large or small? Rethinking China's forest bioenergy policies. *Biomass Bioenergy* **2013**, *59*, 84–91.
21. Li, X.; Huang, Y.; Gong, J.; Zhang, X. A study of the development of bio-energy resources and the status of eco-society in China. *Energy* **2010**, *35*, 4451–4456.

22. Zhou, X.; Fang, W.; Hu, H.; Yang, L.; Guo, P.; Bo, X. Assessment of sustainable biomass resource for energy use in China. *Biomass Bioenergy* **2011**, *35*, 1–11.
23. Zhao, Z.Y.; Zuo, J.; Wu, P.H.; Yan, H.; Zillante, G. Competitiveness assessment of the biomass power generation industry in China: A five forces model study. *Renew. Energy* **2016**, *89*, 144–153.
24. Zhou, P.; Ang, B.W.; Poh, K.L. A survey of data envelopment analysis in energy and environmental study. *Eur. J. Oper. Res.* **2008**, *189*, 1–18.
25. Sueyoshi, T.; Yuan, Y.; Goto, M. A literature study for DEA applied to energy and environment. *Energy Econ.* **2017**, *62*, 104–124.
26. Färe, R.; Grosskopf, S.; Logan, J. The relative performance of publicly-owned and privately-owned electric utilities. *J. Public Econ.* **1985**, *26*, 89–106.
27. Färe, R.; Grosskopf, S.; Logan, J. The relative efficiency of Illinois electric utilities. *Resour. Energy* **1983**, *5*, 349–367.
28. Edvardsen, D.F.; Førsund, F.R. International benchmarking of electricity distribution utilities. *Resour. Energy Econ.* **2003**, *25*, 353–371.
29. Førsund, F.R.; Kittelsen, S. Productivity development of Norwegian electricity distribution utilities. *Resour. Energy Econ.* **1998**, *20*, 207–224.
30. Färe, R.; Grosskopf, S.; Hernandez-Sancho, F. Environmental performance: an index number approach. *Ecol. Econ.* **2004**, *26*, 343–352.
31. Chang, Y.T.; Zhang, N.; Danao, D.; Zhang, N. Environmental efficiency analysis of transportation system in China: A non-radial DEA approach. *Energy Policy* **2013**, *58*, 277–283.
32. Song, M.; Yang, L.; Wu, J.; Wendong Lv. Energy saving in China: Analysis on the energy efficiency via bootstrap-DEA approach. *Energy Policy* **2013**, *57*, 1–6.
33. Bi, G.B.; Song, W.; Zhou, P.; Liang, L. Does environmental regulation affect energy efficiency in China's thermal power generation? Empirical evidence from a slacks-based DEA model. *Energy Policy* **2014**, *66*, 537–546.
34. Charnes, A.; Cooper, W.W.; Rhodes, E. Measuring the efficiency of decision making units. *Eur. J. Oper. Res.* **1978**, *2*, 429–444.
35. Emrouznejad, A.; Parker, B.R.; Tavares, G. Evaluation of research in efficiency and productivity: A survey and analysis of the first 30 years of scholarly literature in DEA. *Soc.-Econ. Plan. Sci.* **2008**, *42*, 151–157.
36. Cook, W.D.; Seiford, L.M. Data envelopment analysis DEA—Thirty years on. *Eur. J. Oper. Res.* **2009**, *192*, 1–17.
37. Seiford, L.M.; Zhu, J. Profitability and marketability of the top 55 U.S. commercial banks. *Manag. Sci.* **1999**, *45*, 1270–1288.
38. Zhu, J. Multi-factor performance measure model with an application to fortune 500 companies. *Eur. J. Oper. Res.* **2000**, *123*, 105–124.
39. Cook, W.D.; Liang, L.; Zhu, J. Measuring performance of two-stage network structures by dea: A review and future perspective. *Omega* **2010**, *38*, 423–430.
40. Kao, C. Network data envelopment analysis: A review. *J. Oper. Res.* **2014**, *239*, 1–16.
41. Chen, Y.; Cook, W.D.; Zhu, J. Deriving the dea frontier for two-stage processes. *Eur. J. Oper. Res.* **2010**, *202*, 138–142.
42. Chen, Y.; Zhu, J. Measuring information technology's indirect impact on firm performance. *Inf. Technol. Manag.* **2001**, *5*, 9–22.
43. Chen, Y.; Cook, W.D.; Kao, C.; Zhu, J. Network DEA pitfalls: Divisional efficiency and frontier projection under general network structures. *Eur. J. Oper. Res.* **2013**, *226*, 507–515.
44. Tone, K.; Tsutsui, M. Network DEA: A slacks-based measure approach. *Eur. J. Oper. Res.* **2007**, *7*, 243–252.
45. Chen, C.; Zhu, J.; Yu, J.-Y.; Noori, H. A new methodology for evaluating sustainable product design performance with two-stage network data envelopment analysis. *Eur. J. Oper. Res.* **2012**, *221*, 348–359.
46. Du, J.; Liang, L.; Chen, Y.; Cook, W.D.; Zhu, J. A bargaining game model for measuring performance of two-stage network structures. *Eur. J. Oper. Res.* **2011**, *210*, 390–397.
47. Wei, Q.L.; Chang, T.S. Optimal system design series-network DEA models. *J. Oper. Res. Soc.* **2011**, *62*, 1109–1119.

48. Premachandra, I.M.; Zhu, J.; Watson, J.; Galagedera, D.U.A. Best-performing us mutual fund families from 1993 to 2008: Evidence from a novel two-stage dea model for efficiency decomposition. *J. Bank. Financ.* **2012**, *36*, 3302–3317.
49. Park K.S.; Park, K. Measurement of multiperiod aggregative efficiency. *Eur. J. Oper. Res.* **2009**, *193*, 567–580.
50. Färe, R.; Grabowski, R.; Grosskopf, S.; Kraft, S. Efficiency of a fixed but allocatable input: A non-parametric approach. *Econ. Lett.* **1997**, *56*, 187–193.
51. Färe, R.; Grosskopf, S. Intertemporal production frontiers: With dynamic DEA. *J. Oper. Res. Soc.* **1997**, *48*, 656.
52. National Bureau of Statistics of China. *China Statistical Yearbook*; China Statistics Press: Beijing, China, 2013.
53. National Bureau of Statistics of China. *China Energy Statistical Yearbook*; China Statistics Press: Beijing, China, 2013.
54. Chinese Renewable Energy Society. *Chinese New Energy and Renewable Energy Almanac 2013*; Chinese Renewable Energy Society: Beijing, China, 2014.
55. Coase, R. The problem of social cost. *J. Law Econ.* **1960**, *3*, 1–44.
56. Färe, R.; Grosskopf, S. New directions: Efficiency and productivity. *Stud. Product. Effic.* **2003**, *17*, 979–995.
57. Färe, R. *Fundamentals of Production Theory*; Springer: Geneva, Switzerland, 1988.
58. Koopmans, T.C. Analysis of production as an efficient combination of activities. *Org. Agric.* **1951**, *13*, 33–37.
59. Debreu, G. The coefficient of resource utilization. *Econ. J. Econ. Soc.* **1951**, *19*, 273–292.
60. Farrell, M.J. The measurement of productive efficiency. *J. R. Stat. Soc. Ser. A (Gen.)* **1957**, *120*, 253–290.
61. Førsund, F.R.; Lovell, C.A. Knox and Schmidt, Peter A survey of frontier production functions and of their relationship to efficiency measurement. *J. Econ.* **1980**, *13*, 5–25.
62. Nerlove, M. *Estimation and Identification of Cobb-Douglas Production Functions*; Rand McNally Company: Skokie, IL, USA, 1965.
63. Portela, M.C.A.S.; Thanassoulis, E. Developing a decomposable measure of profit efficiency using DEA. *J. Oper. Res. Soc.* **2006**, *58*, 481–490.
64. Sahoo, B.K.; Zhu, J.; Tone, K.; Klemen, B.M. Decomposing technical efficiency and scale elasticity in two-stage network DEA. *Eur. J. Oper. Res.* **2014**, *233*, 584–594.
65. Cooper, W.W.; Pastor, J.T.; Aparicio, J.; Borras, F. Decomposing profit inefficiency in DEA through the weighted additive model. *Eur. J. Oper. Res.* **2011**, *212*, 411–416.
66. Shephard, R.W. *Cost and Production Functions*; Princeton University Press: Princeton, NJ, USA, 1953.
67. Shephard, R.W. *Theory of Cost and Production Functions*; Princeton University Press: Princeton, NJ, USA, 1970.
68. Chambers, R.G.; Chung, Y.; Färe, R. Profit, directional distance functions, and Nerlovian efficiency. *J. Optim. Theory Appl.* **1998**, *98*, 351–364.