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Article

A Site Selection Model for a Straw-Based Power Generation Plant with CO_2 Emissions

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Abstract: The decision on the location of a straw-based power generation plant has a great influence on the plant's operation and performance. This study explores traditional theories for site selection. Using integer programming, the study optimizes the economic and carbon emission outcomes of straw-based power generation as two objectives, with the supply and demand of straw as constraints. It provides a multi-objective mixed-integer programming model to solve the site selection problem for a straw-based power generation plant. It then provides a case study to demonstrate the application of the model in the decision on the site selection for a straw-based power generation plant with a Chinese region. Finally, the paper discusses the result of the model in the context of the wider aspect of straw-based power generation.

Keywords: straw-based power generation; carbon emissions; project location; mixed-integer programming

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1. Introduction

Straw-based power generation is a kind of stable and reliable method to utilize co-product energy sources. Bioenergy now makes up most part of the total renewable energy consumption in the world [1]. The total electricity generated from renewable energy in 2012 was 992 TWh (except hydro-power); the electricity generated from biomass was 424 TWh, and it accounts for nearly 9.5% of the whole electricity generated [2].

In China, biomass resources from agriculture and the forestry are quite rich. The total production of straw crop in 2010 was about 720 million tons. It is expected to reach 800 million tons by 2020. The research and appliance of technologies related to biomass utilization are listed as the key scientific research projects continuously in the recent four Five-year Plans of China. By the end of 2013, the cumulative capacity of biomass power generation checked and approved by the Chinese government (checked and approved capacity) was 12,226.21 MW, and the capacity of straw-based power generation connected to the grid (on-grid capacity) reached 7790.01 MW, which accounts for about 63.72% of the total checked and approved capacity. Among the on-grid capacity, agricultural and forestry biomass-based power generation accounted for 53.85%, whose installed capacity was 4195.3 MW [3].

Straw-based power generation is a kind of resource-oriented power generation form, which means that the resource has a great influence on the operation and performance. In richer areas for agriculture and forestry biomass resources, the electricity generation cost could be less, because of economies of scale. Operation is also affected by factors related to the resource endowment and production characteristics of different areas. At present, the total installed capacity in Eastern China is 3514.84 MW, accounting for 45.12% of the whole country. The installed capacities in Central China and the southern area of China are 1438 MW and 1096 MW, respectively [3].

In the operation process of straw-based power generation, the fuel cost takes up more than 60% of the total electricity cost [4]. Compared with traditional energy, the fuel purchasing cost, warehousing cost and transportation expense, which dominate straw-based power generation plants' fuel cost, are all influenced by the location of the plant. However, currently, most of the studies on straw-based power generation have been concentrated on assessing the technologies and related public policies, and research studies on the location problems are lacking, especially in China. Liuqin Chen discussed the current problems for biomass power generation in China, including the technology problems, the policy problems, and so on [5]. Tianyu Qi *et al.* adopted the optimized cost calculating methods to analyze the electricity costs of biomass power generation in different provinces and areas in China. They identified the provinces and areas whose electricity costs are less than others [6]. Lin Zhao applied fuzzy synthetic evaluation techniques in her analysis of planning and site selection for straw-based power generation plants to compare the characteristics of different regions and introduced the concept of regional suitability [7].

The site selection of the project has two phases: region and site selection. The first phase usually considers the straw resources and different policies on straw-based power generation plants in different regions, the economic levels and social environments of the regions. In the second phase, the problem is which site in the chosen region is the best choice for the plant. It usually concentrates on the total cost of the plant and its environmental performance. The straw-based power generation's regional choice has effects on its investment, fuel purchasing cost, incentives, and so on. Site selection affects the fuel's transporting cost greatly. Zhimei Guo *et al.* used a conditional logit model (CLM) to make a straw-based power generation plant's location decision. They assumed that each firm screens locations based on a latent profit function that is dependent on a variety of state attributes where it plans to locate. They use the function $\pi_{ij} = \beta' X_j + \mu_{ij}$ as the latent profit function, where π_{ij} are the expected profits of firm i if locating the new plant in state j, X_j is a vector of the observable characteristics of state j, β' is a vector of estimated coefficients and μ_{ij} is the random disturbance term. According to the model, the economic benefit of biomass power generation is determined by the decision of the location problem [8].

Traditional solutions of site selection problems include the iterative gravity method and the linear programming method [7–13]. Matt Kocoloski *et al.* used a mixed-integer program (MIP) to locate ethanol refineries and connected these refineries to biomass supplies and ethanol demands in a way that minimizes the total cost [11]. Cong Dong *et al.* and Cong Chen *et al.* introduced the concept of uncertainty into the program method and use a mixed-integer interval program model to solve the location decision for biomass power generation. They replaced the imprecise integer number with the interval to deal with the uncertainties [12,13]. Lin Zhao analyzed the cost of the electricity generated from biomass resources [7]. She used an iterative gravity method for biomass power generation that has no candidate sites to obtain the optimal location with the least total cost for a straw-based power generation plant to generate electricity over the whole life cycle.

All of the studies discussed above take the economic benefit optimization as the objective. Based on the traditional theory of project site selection, most of them are conducted by dealing with the optimization of the total electricity cost. Some of them considered the uncertainties of the system and combined methods to deal with these uncertainties with the traditional linear program method to obtain a location model that accords with reality. On the basis of current research, this paper further talks about the objectives of the model. It introduces the objective of the minimization of carbon emissions during the whole life of the project, which is of equal importance to the economic benefit. It gives a multi-objective mixed-integer linear programming model to solve the site selection problem for a straw-based power generation plant and considers the model's application.

2. The Regional Distribution of Biomass Power Generation in China

The first straw-based power generation plant in China was built in 2006. Since then, straw-based power generation has been growing at a rapid speed. From the end of 2013, the regional distribution of agricultural and forestry biomass power generation is shown in Table 1.

From the perspective of the resource distribution among the regions, the cumulative straw resources of the nine province areas in Table 1 account for nearly 56.49% of China's total straw resources. Meanwhile, the straw-based power generation in the nine provinces takes up nearly 75.99% of the whole country. It can be observed that the distribution of the straw-based power generation does not accord with the distribution of straw resources. Take Henan Province as an example, the installed capacity of straw-based power generation in Shandong Province is 45.97%, more than that of Henan Province, but its straw resources are almost the same as that of Henan Province; the straw resources of Heilongjiang Province are much less than those of Henan Province, but it has a larger installed capacity than Henan Province. We can conclude that the distribution of straw-based power generation is not in accordance with the resource supply.

From the perspective of the regional electricity demand distribution, the cumulative annual electricity consumption of the nine provinces takes up about 45.3% of China's annual electricity consumption. However, the percentage of the nine provinces' accumulative installed capacity with respect to the whole country is far more than that. Then, it will also cost money to transport electricity from the plant to the whole country. Therefore, we can observe that the biomass power generation's regional distribution is not in accordance with the regional demand distribution of the electricity.

In Table 1, the regional straw-based power generation's annual equivalent full load operation hours reflect the utilization efficiency of a straw-based power generation plant's production ability: the more hours the straw-based power generation can operate annually, the more efficiently the generation's capacity is used. On the perspective of site selection, the project's annual equivalent full load operation hours are mostly influenced by the straw fuel's supply and collection. If the supply of straw is sufficient, the straw-based power generation is expected to operate for many hours, and the utilization of equipment is great. As a result, we can take straw-based power generation's annual equivalent full load operation hours as an indicator to assess the regional biomass resource supply ability.

Table 1. The agricultural and forestry biomass resource distribution in some regions of China.

Province	Electricity consumption (100 million kWh)	Annual equivalent full load operation hours (h)	Total installed capacity (MW)	Percentage that this province's straw resource makes up in China (%)
Henan	2988	4940	422	10.24%
Shandong	4083	6018	616	9.98%
Heilongjiang	845	4987	465	8.44%
Hebei	3251	5436	218	7.53%
Jiangsu	4956	-	380	5%
Anhui	1528	6166	406	4.76%
Hunan	1423	5396	242	4.63%
Hubei	1629	5157	374	4.27%
Zhejiang	3453	5897	65	1.46%
Others	29,067	-	1007.3	43.51%
Cumulative	53,223	-	4195.3	1

Data resources: National Bureau of Statistics of China, renewable energy database [14], Science and technology education department of Ministry of Agriculture of the People's Republic of China, 2010. The report on national straw crop resource survey and assessment.

3. Methodology

3.1. Candidate Sites Selection for Straw-Based Power Generation

During the candidate site selection for straw-based power generation, some important factors need to be considered. They are general site requirements, community impacts, environmental impacts, economic impacts and land use impacts.

Firstly, the location of straw-based power generation should comply with the overall urban planning and the national government's regulations. Secondly, the straw-based power generation plant should be located near rivers, as it will consume large amounts of water in its operation. The selected site for straw-based power generation should have access to municipal service facilities, such as fire-fighting service and road service, because of the storage and transportation of straw. These are all the general site requirements.

During the site selection, the straw-based power generation plant's community impacts have to be taken into consideration. Located in areas where people's attitudes toward straw-based power generation are friendly, the plant's construction and operation will be smooth. Otherwise, it would come up against many impediments from local residents [7].

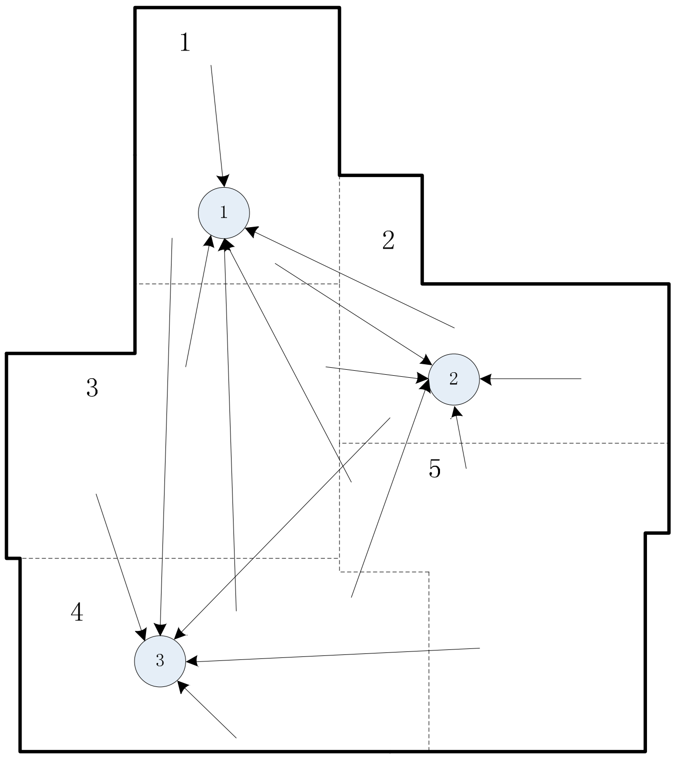
The environmental impacts of straw-based power generation plants include the carbon emissions, water pollution and ash [7]. The water pollution and ash can be controlled by specific methods and technologies; while carbon emissions can be minimized during the site selection period of the plant. The straw-based power generation plant should be located in places where the price of straw and the labor costs are both low, to reduce the construction and operation costs. The transportation cost for straw can also be minimized with a reasonable location decision. These economic factors are the most frequently used ones in recent research studies [6–13].

Land occupation is a specific characteristic of straw-based power generation, for it needs large amounts of land to store straw resources. In the location decision of straw-based power generation plants, the land cost would be an important factor. The plants should be located in places with low land costs. Meanwhile, the selected sites need to be open spaces without construction or residences, so that the construction and operation of the plants will not cause the removal and relocation of residents. Another requirement is that straw-based power generation plants should try not to occupy farmland or to take up as little as possible; because the occupation of farmland may influence the farmers' production, which could causes community impacts.

3.2. Mathematical Model

To take both optimizations of the economic benefit and environmental influences of straw-based power generation into consideration simultaneously, this paper uses a two-objective integer linear programming model to get the optimal location for the straw-based power generation plant from a set of candidate sites. The two objectives here are minimizing the total cost and total carbon emissions of the biomass power generation plant, respectively. The model presented in this paper is based on the mixed-integer programming model of Matt Kocoloski *et al.*, which only has one objective: the economic benefit [11]. The model here recognizes the carbon emissions to be one of the key factors that will have an impact on the real performance of straw-based power generation. During the whole life cycle of the power generation system, the total carbon emissions may be more than expected without reasonable planning and scheduling of the system. By including the carbon emissions as one of the model's objectives, this paper tries to obtain the optimal operation performance with respect to carbon emissions. In the original model, the project's operation cost is the main optimization objective of the MIP model. According to the authors, the plant's operation cost consists of the biomass resources' and the ethanol's transportation fees, the investment of purchasing the equipment and the operation and maintenance costs of the equipment. The constraints of the original model are the size of the facilities and the supply of the resources. In this paper, it is assumed that the straw-based power generation's location will be selected from the candidate sites in a chosen region. The given region is divided into some sub-regions (see Figure 1). Every sub-region is a straw supplier for straw-based power generation. It then translates the location decision problem of the biomass power generation into a transportation planning problem.

Figure 1. The candidate sites of the biomass power generation and the division of the region.



Note: the number 1 to 5 represents the five sub-regions.

As show in Figure 1, there are three candidate sites for the biomass power generation from which to select. The region can be divided into five sub-regions, and the straw crop collection is in the five sub-regions independently. However, the straw resources can be translated across different sub-regions to a large degree. During the collection process of straw resource in sub-regions, the acquisition range is limited to less than 10 kilometers for the economic benefits. The transportation machines include small-sized agricultural trucks and electro-tricycles. When the straw is transported across the sub-regions, the machines used are usually trucks, whose full load is between 20 tons and 25 tons to minimize the transportation cost.

Here, it is defined that xij (i = 1,2,3…, j = 1,2,3…) is the number of straw resources transported from sub-region i to site j. $y_j = \begin{cases} 0 \\ 1 & j = 1,2,3\ldots \end{cases}$. When $y_i = 0$, this means that straw-based power generation will not be located in site j. In this scenario, other sub-regions seem not to transport their straw resources to this site and this sub-region ($x_{.j} = 0$). When $y_i = 1$, this means that in site j, there will be straw-based power generation, so that other sub-regions can transport the straw resources to this site.

The objectives of this model are the optimization of the economic benefit of the straw-based power generation and the carbon emissions of the whole system.

Objective 1: optimizing the economic benefit of straw-based power generation. The scale of the plant is given. Here, we assume that in the selected region, the on-grid price of the electricity is determined. Therefore, the optimization of the economic benefit is the same as the minimization of the total cost of the generation.

Mohammad Asadullah assessed the economic benefit of biomass gasification power generation. In the assessment, he pointed out that the cost of biomass gasification power generation contains the initial investment of the plant and the operation and maintenance costs [15]. The operation and maintenance costs of the plant are calculated by summing up the biomass fuel cost, the labor cost and the fossil fuel cost. Daniel G. Wright *et al.* said that the total cost of biomass power generation is calculated by using the sum of the initial investment, the operation and maintenance cost and the fuel cost minus the sum of the economic incentives and the benefits from supplying heat [16]. Then, they made a mathematical model to calculate the levelized cost of electricity generated from biomass resource. Almost 60% of the unit cost of the electricity generated in the biomass power generation is the biomass fuel cost, including the purchasing price of the straw in the field, the transportation cost, the pre-processing cost and the storage cost [17–21]. Lihuan Chen *et al.* adopted the activity-based cost method to calculate the straw resources' transportation cost. They took the straw purchase center belonging to the biomass power generation as the activity center in the study and analyzed the transportation cost of different straw crops in Jiangsu, Henan, Hebei, *etc*. According to the research, the total transportation cost for the rice straw is 226 RMB yuan/ton, and the total transportation costs for the wheat straw, the corn straw and the cotton straw are 228 RMB yuan/ton, 217 RMB yuan/ton and 192 RMB yuan/ton, respectively [22].

Rogers, J.G. and Brammer, J.G. claimed to set pre-disposing points in the collection field of the biomass resource when analyzing the electricity cost of the biomass gasification power generation [23]. They made a model to estimate the average logistic cost per GJ for a given plant to calculate the total transportation cost of the biomass resources.

As described by Ruiz, J.A. *et al.*, 75% of the transportation cost of the biomass from the temporary acquisition points to the plant is the cost of the trucks, including their purchasing cost, their operation and maintenance costs, the fossil fuel cost, the drivers' salary, and so on [24]. At the same time, the two key factors that influence the straw's total transportation cost are the travel distances and the travel durations for the trucks. The travel distance mainly affects the fossil fuel consumption of the truck. Therefore, this has effects on the total transportation cost. Meanwhile, travel duration has a greater influence on the total transportation cost, as it determines the salary paid to the drivers. It seems to be true that the labor cost is the most important factor of the biomass resource's total transportation cost [25].

We give the empirical function of the total cost of the biomass power generation as Equation (1).

$$TC = C_{investment} + C_{O\&M} + C_F - R_{incentive} \quad (1)$$

where TC is the total cost of the biomass power generation, $C_{investment}$ is the initial investment of the project, $C_{O\&M}$ is the operation and maintenance costs of the plant, C_F is the total cost of the biomass resource and $R_{incentive}$ is the economic incentives from the government. As we have discussed in Section 1, in a certain region, the initial investment, the operation and maintenance costs and the economic incentives are almost the same in different sub-regions and different candidate sites for the plant. The cost of the biomass resource consists of the purchase price of the straw, the disposal cost of the straw and the transportation cost. Among these three parts, the purchase cost of the straw is determined by the economic level of the selected region and the technology level of the agricultural crops' harvest. The differences in purchase costs among different sub-regions are so small, that they can be ignored. Therefore, we can reduce the objective of minimizing the total cost of the biomass power generation into the minimization of the total transportation cost of the straw.

The total transportation cost of the biomass power generation contains the cost to transport the straw in the sub-region and the cost to transport the straw from the supplying sub-region to the selected site. The first part of the total transportation cost can be calculated by Equation (2).

$$C_{\text{transporting,i}} = \lambda \sum_{j} x_{ij} \quad (2)$$

where λ is the collection cost ratio on the supply side (RMB yuan/ton).

The cost to transport the straw from the supply side to the selected site can be calculated by Equation (3).

$$C_{transport,ij} = \alpha_{ij} \times x_{ij} \quad (3)$$

where α_{ij} is the cost to transport per ton of straw from sub-region *i* to selected site *j* (RMB yuan/ton).

Objective 1 is then described by Equation (4).

Objective 1:

$$\min z_1 = \sum_{i}\sum_{j} \lambda x_{ij} + \sum_{i}\sum_{j} \alpha_{ij} x_{ij} \quad (4)$$

Objective 2: minimizing the total carbon emission during the whole life cycle of straw-based power generation. Biomass power generation is famous for its characteristic of having "few carbon emissions or zero carbon emission". In fact, however, during the operation of the straw-based power generation plant, there will be some carbon emissions produced. Most of the carbon emission produced is in the collection and transportation processes of the straw. All of the pre-processing, collecting and transporting of straw consume fossil fuels and then emit carbon into the atmosphere. Those carbon emissions will influence the performance of biomass power generation. Guoliang Cao *et al*. estimated by experiment that the carbon emission ratio of the straw crop's burning in the field is between 1400 g/kg and 1800 g/kg. It is discovered that the amount of straw burned in the field in China has a great and obvious effect on the whole carbon emissions of the country [26]. Zhen He *et al*. utilized a simplified full life cycle model (FLCM) to estimate the total carbon emissions of the biomass power generation. They divided the whole life cycle of biomass power generation into three parts, which are the growing process of biomass crops, the collecting, storage and transporting process of straw and the straw utilization and electricity production process. They then calculated the carbon emissions during these three parts independently by their activities and their links to the environment of the system. It is pointed out in the study that the carbon emissions of the straw-based direct burning power generation is associated with the straw fuel it burns. During the burning process in a straw-based direct burning power generation with a capacity of 25 MW, the carbon emission coefficients for different kinds of straw are: 377.1 kgC/ton for rice straw, 395.8 kgC/ton for corn straw and 389.9 kgC/ton for wheat straw; the carbon emission coefficients for different kinds of straw during the transporting process are, respectively: 0.1435 kgC/(ton·km) for rice straw, 0.1270 kgC/(ton·km) for corn straw and 0.3403 kgC/(ton·km) for wheat straw [27].

According to Chao Feng and Xiaoxi Ma, burning 100 kg of rice straw directly to generate electricity will emit 164.24 kg CO_2, during the transportation of the straw, consume about 0.07 L diesel and emit nearly 1.7 g CO and 0.03 kg CO_2 during the burning process of the straw; it will emit almost 136.77 kg CO_2 [28]. Yin Li and Jing Li analyzed the appliance of the CDM (Clean Development Mechanism) method's ACM0006 technique, which is designed to calculate the projects' real carbon emissions [29]. Amit Thakur *et al.* listed the energy consumption of related machines when analyzing the total carbon emissions during the full life cycle of forestry biomass power generation. In that study, a truck with a load capacity of 25 tons is the main transportation machine for the biomass resource [30].

The total carbon emissions during the whole life cycle of the biomass power generation mostly comes from the consumption of fossil fuels. Fossil fuels' consumption usually happens in the straw resource transportation process. Most of the fossil fuels are consumed by the transportation machines and some of the pre-processing machines. The total fossil energy consumption during the whole life cycle of the biomass power generation can be calculated by Equation (5).

$$Total\_Energy = Energy_{processing} + Energy_{transporting} \quad (5)$$

where $Energy_{processing}$ is the fossil energy consumed to pre-process the straw, which is mainly determined by the amount of biomass resources demanded by the plant and the biomass resources' characteristics. $Energy_{transporting}$ is the fossil energy consumed during the transportation of the biomass resources, and it is mainly related to the straw fuel's travel distance. We can calculate the total carbon emissions by multiplying the total energy consumption with the corresponding emission coefficients of the fossil fuels. Therefore, Objective 2 can be described as Equation (6).

Objective 2:

$$\min z_1 = \sum_i \sum_j \eta x_{ij} + \sum_i \sum_j \beta_{ij} x_{ij} \quad (6)$$

where η is the carbon emission coefficient during the collecting process of the biomass in the sub-regions. β_{ij} is the carbon emission coefficient for transporting the biomass resources between different sub-regions; it can be described as the carbon emissions from transportation per ton of biomass per kilometer from sub-region i to selected site j.

The constraints of the model include:

(1) Straw fuels collected from the whole region and transported to the selected site of the biomass power generation are sufficient to meet the demand of the straw-based power generation plant to generate the electricity planned. It can be described as Equation (7).

$$\sum_i x_{ij} = D \times y_j \quad (7)$$

where D is the annual demand of the straw-based power generation plant, which is only related to the capacity of the plant.

(2) The total amount of the crop straw collected in the sub-region cannot be more than what the sub-region itself can really supply as a kind of energy resources. This means that only part of the total straw in the sub-region can be collected and utilized as the energy resource. It can be described as Equation (8).

$$\sum_j x_{ij} \le R_i \tag{8}$$

where R_i is the amount of biomass resources that can be utilized as the energy resource and that can be collected in sub-region *i*. It can be calculated by multiplying the total production of straw crop with the use ratio of biomass as energy.

(3) The plant can only choose one site from the candidate sites as its location, and there must be one site to be selected as the result. This can be described as Equation (9).

$$\sum_j y_j = 1 \tag{9}$$

In conclusion, we present Equation (10) as the whole model.

$$\begin{aligned} &\min \quad w = \varphi z_1 + (1-\varphi) z_2 \\ &z_1 = \sum_i \sum_j \lambda x_{ij} + \sum_i \sum_j \alpha_{ij} x_{ij} \\ &z2 = \sum_i \sum_j \eta x_{ij} + \sum_i \sum_j \beta_{ij} x_{ij} \\ &\sum_i x_{ij} = D \times y_i \\ &\sum_j x_{ij} \le R_i \\ &\sum_j y_j = 1 \\ &0 < \varphi < 1 \end{aligned} \tag{10}$$

where φ is the weight of Objective 1. When φ is larger than 0.5, the weight of Objective 1 is larger than Objective 2, *vice versa*. Through solving this model, we can get the optimal location of the straw-based power generation plant.

4. Case Study and Discussion

An electric power group has decided to develop a 25-MW straw-based power generation plant in Nantong, Jiangsu Province, China. The total demand of the straw is estimated to be about 270 thousand tons. Nantong consists of Chongchuan District, Gangzha District, Tongzhou District, Hai'an County, Rudong County, Rugao County and Haimen County. The first three districts together form the municipal district. The whole area of Nantong is nearly 8544 square kilometers. Its total straw production is almost 4.7 million tons [31]. The production of crop straw in the sub-regions in Nantong is shown in Table 2. We find that Rudong County has the most biomass straw production in Nantong. Rugao County has the second largest amount of straw production, and Hai'an has the third largest amount of straw production in Nantong. To efficiently reduce the amount of straw transported between different sub-regions, three candidate sites were chosen in Rudong, Rugao and Hai'an, respectively. The three candidate sites are labeled 1, 2 and 3. The cumulative straw production of these three sub-regions is equal to 3.224 million tons. According to Zhang *et al.*, by the end of 2012, the utilization of straw as energy is expected to reach 26% [4]. Take the completion of other straw-based power generation plants and other uses for straw, where it is hypothesized that the real utilization of straw as energy is about 10%. Therefore, the total supply ability of these three sub-regions is about 320 thousand tons. Rudong County can supply nearly

129 thousand tons every year. Rugao County can supply about 102 thousand tons every year, and Hai'an County can supply about 90 thousand tons of straw every year. Meanwhile, because there are two counties that are next to these three sub-regions, but outside Nantong (these two counties are Dongtai and Taixing), the total straw production for them is 1.33 million tons and 0.98 million tons, respectively. Their straw supply ability is, respectively, 133 thousand tons and 98 thousand tons. The distances between the sub-regions and the other coefficients related to the system can be found in Table 3.

Assume that crop straw is collected and transported in the sub-region mainly by small agricultural machines whose load abilities are less than 10 tons; the machines used to transport the straw from the sub-regions to the biomass power generation plant are trucks with load abilities between 20 tons and 25 tons. During the collecting process of the straw in the sub-regions, the cost coefficient for the transportation is about 1.5 RMB yuan/(ton·km), and the energy consumption coefficient and carbon emission coefficient for the transportation are almost 0.15 L/(ton km) and 0.24 kgC/(ton km), respectively. When the straw is transported from the sub-regions to the plant side, the cost coefficient for the transportation is nearly 1 RMB yuan/(ton km); the fossil energy consumption coefficient and carbon emission coefficient for the transportation are nearly 0.02 L/(ton km) and 0.03 kgC/(ton km), respectively [4,27,32].

Table 2. The cultivated area and crop production in the sub-regions of Nantong.

Sub-region	The grain plantation area (1000 ha)	The production of the crops (10,000 tons)	The cotton plantation area (1000 ha)	The production of cotton (tons)	The total production of biomass straw （10,000 tons）
Municipal area	92.2	59.53	6.78	7535	84.6
Hai'an County	79.19	64.43	0.14	171	90.4
Rugao County	110.53	72.81	0.21	200	102.2
Rudong County	131.87	90.8	12.55	17,281	129.8
Haimen County	40.97	17.83	11.43	12,859	26.8
Qidong County	70.85	24.09	14.73	16,349	36.2
Cumulative	525.61	329.49	45.84	54,395	470

Table 3. The parameters related to this case.

	Candidate Site 1 (y_1)			**Candidate Site 2 (y_2)**			**Candidate Site 3 (y_3)**		
	Travel distance of straw (km)	**Cost coefficient for transportation (RMB yuan/ton)**	**Carbon emission coefficient for transportation (kgC/ton)**	**Travel distance of straw (km)**	**Travel distance of straw (km)**	**Carbon emission coefficient for transportation (kgC/ton)**	**Travel distance for straw (km)**	**Travel distance for straw (km)**	**Carbon emit coefficient for transportation (kgC/ton)**
Dongtai	35	50	5.05	80	95	6.4	100	115	7
Hai'an	0	15	2.16	45	60	3.51	75	90	4.41
Rugao	45	60	4.46	0	15	3.11	55	70	4.76
Rudong	75	90	6.01	55	70	5.41	0	15	3.76
Taixing	55	70	3.84	40	55	3.39	90	105	4.89
Municipal district	85	100	5.11	50	65	4.06	20	35	3.16
Haimen	111	126	4.33	75	90	3.25	50	65	2.5

Note: both the cost coefficient for transportation and the carbon emission coefficient for transportation contain the collection of straw in the sub-region and transporting the straw from the sub-regions to the plant site.

According to the assumptions presented above and the model given in this paper, we present results as shown in Table 3, making the number of φ 0.5. The minimum transportation cost of the plant is estimated to be about 8735 thousand RMB yuan. The price of straw at the plant is nearly 200 RMB yuan/ton. The total carbon emission during the transportation is about 963.04 ton C (carbon). Candidate Site 3 is the best choice for the straw-based power generation plant to be built. Therefore, the electric power group should build the straw-based power generation plant at the candidate site in Rudong County to get the best economic benefits and the least carbon emissions.

Table 4. The result of the model for the case study (units: 10,000 tons).

	Candidate Site 1 (y1 = 0)	**Candidate Site 2 (y2 = 0)**	**Candidate Site 3 (y3 = 1)**
Dongtai	x11 = 0	x12 = 0	x13 = 0
Hai'an	x21 = 0	x22 = 0	x23 = 0
Rugao	x31 = 0	x32 = 0	x33 = 3.1
Rudong	x41 = 0	x42 = 0	x43 = 12.9
Taixing	x51 = 0	x52 = 0	x53 = 0
Municipal District	x61 = 0	x62 = 0	x63 = 8.4
Haimen	x71 = 0	x72 = 0	x73 = 2.6
The demand of the site	D1 = 0	D2 = 0	D3 = 27

Compared with the model given by Matt Kocoloski *et al.*, in which the optimal site for the straw-based power generation plant in this case is also Site 3, the model presented in this paper considers the impacts of carbon emissions. In these two models' results, Site 1 is preferable to Site 2. However, if taking Objective 2 as the only objective of the model, we would choose Site 2 as the optimal selection for the plant. When the weight of Objective 1 (φ) is less than 0.4 in this case, Site 2 would be preferable to Site 1 by the results of our model.

One of the key parameters having an influence on the total cost of the straw-based power generation plant is the price of straw. Take the municipal district as an example. The price of straw could be higher than other sub-regions. When the price of straw in the municipal district is 25 RMB yuan/ton higher than those in other sub-regions, the optimal site will remain as Site 3. When the price of straw in the municipal district is 26 RMB yuan/ton higher than in other sub-regions, the optimal site will be Site 1.

It can be recognized from the results of the case study that Rudong County has the most biomass straw production in Nantong. It is also the best choice of the three candidate sites for the straw-based power generation to be located. Taking both the economic benefit and carbon emissions of the plant into consideration, we can infer that the total transportation cost and carbon emissions of the straw's transportation and collection are usually determined by the transportation process of straw between sub-regions. It also proves that the acquisition range of straw has a great influence on both the straw-based power generation's economic benefit and total carbon emission. The straw-based power generation technology is a kind of resource-oriented technology. In the location decision for the biomass power generation, the supply abilities of the sub-regions should be adequately considered.

5. Conclusions

Biomass power generation is currently a mature and reliable technology for utilizing this renewable energy source. A biomass power generation plant's economic benefit and carbon emission are both influenced by the supply of straw fuel. Without sufficient straw supply, the plant's performance may be quite poor, the economic benefit may be negative and the carbon emissions may be larger than expected. This problem can be avoided by the location decision of the plant. This paper studied a solution to site selection for a biomass power generation plant. It introduces the objective of minimizing the total carbon emissions into the traditional site selection model. A linear multi-objective integer program model was then developed to get the best location for the plant. Through the case study, an example shows how to apply the model to make the location decision. We find that when the weight of the carbon emission optimization objective is large enough, the results of our model will be different from those of models considering only economic benefits. This further demonstrates that carbon emissions really have a great influence on the site selection of the straw-based power generation plant. We also find from the results that the transportation of straw between sub-regions has more influence on the straw-based power generation total cost and total carbon emissions than the straw's collection and transportation in sub-regions. This conclusion also demonstrates that the straw acquisition range is a determining factor for the straw-based power generation plant's performance. During the location decision, we need to take full consideration of the straw fuel supply abilities of the sub-regions.

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Author Contributions

All of the authors made contributions to the work in this paper. Hao Lv proposed the idea and partly contributed to the model development. Hao Ding contributed to model development, data collection and analysis. Dequn Zhou contributed to policy analysis and formulation. Peng Zhou provided guidance for writing this paper. Hao Lv and Hao Ding were the main authors for the writing of this paper.

Conflicts of Interest

The authors declare no conflict of interest.

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