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Optimization on straw logistics radius of the biogas manure co-generation

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Abstract. This paper proposed a straw logistics radius optimization model on the base of analyzing the cost and profit of the biogas and manure co-generation, to obtain the maximized per-unit scale profit. Through mathematical differential method, the relationship between the optimal straw logistics radius and the factors is obtained. Combining with the data from Dengzhou, the influences of the straw logistics radius on the per-unit straw total cost and per-unit scale profit, and the influences of factors on the optimal straw logistics radius is analyzed. The analytical result shows that with the increase of scale factor, the optimal straw logistics radius increases first and then starts to drop. And it increases with the decrease in straw spatial distribute density, tortuosity factor, transportation rate and payback period, while the straw conversion rate increases. When the production scale is small, the fixed investment cost plays a leading role in the total cost. Furthermore, the larger scale of production, the higher transportation rate will has a greatest influence on the optimal straw logistics radius.

Introduction

Renewable energy is an effective way to solve the energy shortage and environmental pollution. The straw biogas and manure co-generation has been a broad consensus in the field of scientific research and engineering application [1] [2]. However, the production of biogas and manure is constantly limited by the high price of straw logistics [3]. It is generally believed that the profit and loss of project is largely determined by the straw logistics radius. On the macro level, the straw logistics radius determined should be based on the production plant and reasonable layout. Micro level, it is closely related to the factors such as the distribution of straw, straw spatial distribute density, crop species, conversion technology, roads condition of collection area, and so on. So, it is an important work for biogas manure production layout to determine the reasonable straw logistics radius.

Primary work mainly focused on minimum straw collection cost and optimal plant size. Hu Yanxia [4] researched biomass reasonable collection radius with the sum of the collection cost of per unit mass of wood residues and the production costs of the biomass gas less than the sum of coal price and state subsidies. D'Ovidio [5] studied the collection radius with biomass corporate obtained maximum profit index. Gan [6] proposed the optimal straw collection radius based on the demand amount of biomass plant is equal to straw yield of the collection area. Diep [7] researched straw collection radius through minimize the straw collection costs. Preceding researches have been done to estimate straw collection costs as well as optimized plant size and straw logistics radius without considering conversion, and failed to propose targeted analytical methods with biomass production process characteristics. The radius optimization without energy conversion do not represent overall optima, but only suboptimal at best.

The paper built an analytical framework for determining the optimal straw logistics radius. The method minimizes biogas and manure co-generation costs. The work is expected to provide useful information to assist managers of the biogas and manure co-generation, and facilitate development of the engineering in China.

Estimation of the costs and incomes for the biogas and manure co-generation

The straw recoverable quantity for biogas and manure co-generation is estimated from collection amount, which remove the amount of other utilization types. Estimating straw quantity correctly is the premise and foundation of straw utilization. The available density of straw M was calculated using the following equation [8]:

$$M = \rho \cdot \lambda \cdot v_1 \cdot v_2 \cdot v_3 \quad (1)$$

Where 'ρ' is the crop production ($t \cdot km^{-2} year^{-1}$); '$\lambda$' is grass valley ratio; 'v_1'is the proportion of the land where biomass is grown in the collection area; 'v_2'is the available collection coefficient; and 'v_3' is the available coefficient of straw.

The equation of the straw available quantity of the collection Q was given by the following:

$$Q = M \cdot \pi R^2 \quad (2)$$

Where 'R' is the radius of the collection area and optimal straw logistics radius, km.

Whether artificial collection or mechanical collection, collection cost is proportional to the straw collection amount [9]. The collection cost C_p, can be expressed as the following:

$$C_P = Q \times F_0 \quad (3)$$

Where 'F_0' is the unit price of straw, yuan t^{-1}.

Transportation cost depends on road transportation cost and treatment cost. Road transportation cost is proportional to the collection amount, transportation fee rate, including fuel cost, transportation vehicle depreciation cost, artificial cost, maintenance cost, and transportation distance [10]. Treatment cost A is proportional to the collection amount. Straw transportation cost has nothing to do with a single volume. So, the transportation cost C_t was given by the following [11]:

$$C_t = Q \cdot (\mu \cdot d + A) \quad (4)$$

Where 'μ' is transportation rate, yuan $t^{-1} \cdot km^{-1}$; 'd' is average transportation distance, km; 'A' is treatment cost yuan t^{-1}. However, in the real world transportation distance is not a straight line and dictated by the tortuosity. Therefore average transportation distance can be given by [12]:

$$d = \frac{2}{3} R\tau \quad (5)$$

Straw collection with strong seasonality, to ensure a steady supply of straw resources, here we introduced safety inventory. So, the straw safety proportion can be expressed as:

$$\varepsilon = b / B \quad (6)$$

The storage cost relevant to unit straw storage cost F_s. The straw consumption for biogas and manure production is uniform and continuous, therefore the storage cost C_s, was calculated using the following equation [10]:

$$C_s = [Q \cdot \varepsilon + \frac{1}{2} Q \cdot (1 - \varepsilon)] \cdot F_S \quad (7)$$

Biogas and manure production cost includes the fixed investment cost and the conversion cost. The fixed investment cost refers to the money to purchase fixed assets, such as land, buildings, equipment costs and other construction investment costs. The fixed investment cost has an exponential relationship with conversion plant size [13]. The paper assumed a payback period T of 15 years for a base case. The predicted equation of fixed cost C_f was as follows:

$$C_f = a \cdot \frac{X^e}{T} \quad (8)$$

Where 'X' is the production scale, and $X = Q \cdot k_1$, 'k_1' is the conversion rate ($m^3 t^{-1}$); 'e' is the conversion scale factor, which usually takes value between 0.6 and 0.9; 'a' is engineering scale coefficient.

Straw convert into biogas and manure including straw fermentation, biogas purification and manure treatment. Conversion cost involves artificial cost, equipment operations and maintenance costs, and biogas and manure treatment cost. The conversion cost has an exponential relationship with conversion plant size [14]. So, the conversion cost C_c was given by the following:

$$C_c = C_0 \times \left(\frac{X}{X_0} \right)^e \tag{9}$$

Where 'C_0' is the conversion cost from straw at a base scale X_0 of the conversion plant.

Purified residue fluid and sludge are new type of green manures with comprehensive nutrition and abundant organic matter, which has the good economic value. Supplying manure for surrounding farmland to realize the step utilization of energy. The income can be determined by

$$I = Q \cdot k_1 \cdot p_1 + Q \cdot k_2 \cdot p_2 \tag{10}$$

Where 'p_1' is the price of biogas; 'k_1' is the straw-manure conversion rate; and 'p_2' is the price of manure.

Development of the straw optimal logistics optimization model

Optimal logistics radius is the radius of the straw collection area when the unit production scale benefit achieves optimum. The ultimate goal of corporate decision-makers is to reduce the total cost of biogas and manure co-generation, improve the efficiency in the use of equipment and facilities and pursue maximized profit. The income increases with the expansion of production scale, but the total cost will be increased. The unit total cost C_u can be expressed as the following:

$$C_u = \frac{C_p + C_t + C_s + C_f + C_c}{X} \tag{11}$$

$$C_u = \frac{Q \cdot F_0 + Q \cdot (\frac{2}{3} R\tau\mu + A) + Q \cdot (1 + \frac{1}{2}\varepsilon) \cdot F_s + a \cdot \frac{X^e}{T} + C_0 \cdot \left(\frac{X}{X_0} \right)^e}{X} \tag{12}$$

Simply pursuit profit maximization doesn't reflect the economics of different production scale for the biogas and manure co-generation. Collection and utilization of straw is interlinked, individually optimize the part of the cost is only suboptimal best. With the goal of obtaining unit scale profit maximum, to ensure that the material and equipment have been used at the greatest extent in biogas and manure co-generation, the solved straw optimal logistics radius is more reasonable. Unit production scale profit equation Y was given by the following:

$$Y = \frac{I - (C_p + C_t + C_s + C_f + C_c)}{X} \tag{13}$$

$$Y = \frac{Q \cdot (k_1 p_1 + k_2 p_2) - [Q \cdot F_0 + Q \cdot (\frac{2}{3} R\tau\mu + A) + Q \cdot (1 + \frac{1}{2}\varepsilon) + a \cdot \frac{X^e}{T} + C_0 \cdot \left(\frac{X}{X_0} \right)^e]}{X} \tag{14}$$

The straw logistics radius optimization problem can be mathematically described that when the unit production scale profit of the biogas and manure engineering for the first derivative of the straw logistics radius equal to zero, to obtain the maximum unit scale profit, then the radius is the optimal straw logistics radius. Hence, Y derivative of the R obtained the following:

$$dY / dR = 2\tau\mu / 3k_1 + 2(C_0 / X_0^e + a / T) \cdot (e-1) \cdot (\pi M k_1)^{e-1} \cdot R^{2e-3} = 0 \tag{15}$$

$$R = \{[3(1-e)k_1^e (C_0 / X_0^e + a / T)] / [\tau\mu(\pi M)^{1-e}]\}^{[1/(3-2e)]} \quad (0<e<1) \tag{16}$$

Results and discussion

To study the factors of the optimal straw logistics radius on the optimal straw logistics radius and predict the changes in the optimal radius of the collection area in the future, the paper analyzed wheat straw collection and conversion for biogas and manure co-generation from China Dengzhou.

Table.1-The values of coefficients used in the biogas manure co-generation [15] [16] [17]

Parameters	Unit/Symbol	Value	Source
Cultivated land rate	v_1	0.72	literature
Straw collection efficiency	v_2	0.8	literature
Available coefficient	v_3	0.7	Field investigation
Grassy alley proportion	λ	1.1	literature
Harvest price	F_0/（yuan t^{-1}）	70	Field investigation
Transportation rate	μ /（yuan t^{-1} km^{-1}）	4	Field investigation
Other cost	A/（yuan t^{-1}）	10	Field investigation
The unit storage cost	F_s/（yuan t-1）	70	Field investigation
Scale factor	e	0.75	literature
Engineering factor	a	25.4	literature
straw safety proportion	ε	0.1	Field investigation
Biogas conversion rate	k_1/（m^3 t^{-1}）	260	Field investigation
Manure	k_2	4.5	Field investigation
Biogas price	P_1/（yuan m^{-3}）	1.5	Field investigation
Manure price	P_2/（yuan t^{-1}）	3	Field investigation
Base scale	X_0/（m^3 a^{-1}）	15000	Field investigation
Base dealing costs	C_0/yuan	50000	Field investigation

According to equation (16), for $0.5<e<1$, the optimal straw logistics radius increase with the scale factor increase, and the increased rate gradually slow. When the scale factor reach around 0.88, the optimal straw logistics radius reaches the maximum, then decreases rapidly. This indicates production scale increase while the straw logistics and the fixed investment cost increase, leading profits to drop.

The optimal straw logistics radius decreases dramatically with an increase in transportation rate and straw spatial density. It decreases at an increasing rate with the conversion rate, straw spatial density and payback period. But the optimal logistics radius increases with increasing conversion rate at an increasing rate, and decreases with increasing tortuosity factor at a decreasing rate in different scale factors. The transportation rate is the most sensitive factor to the optimal straw logistics radius, the payback period is the least all of the factors.

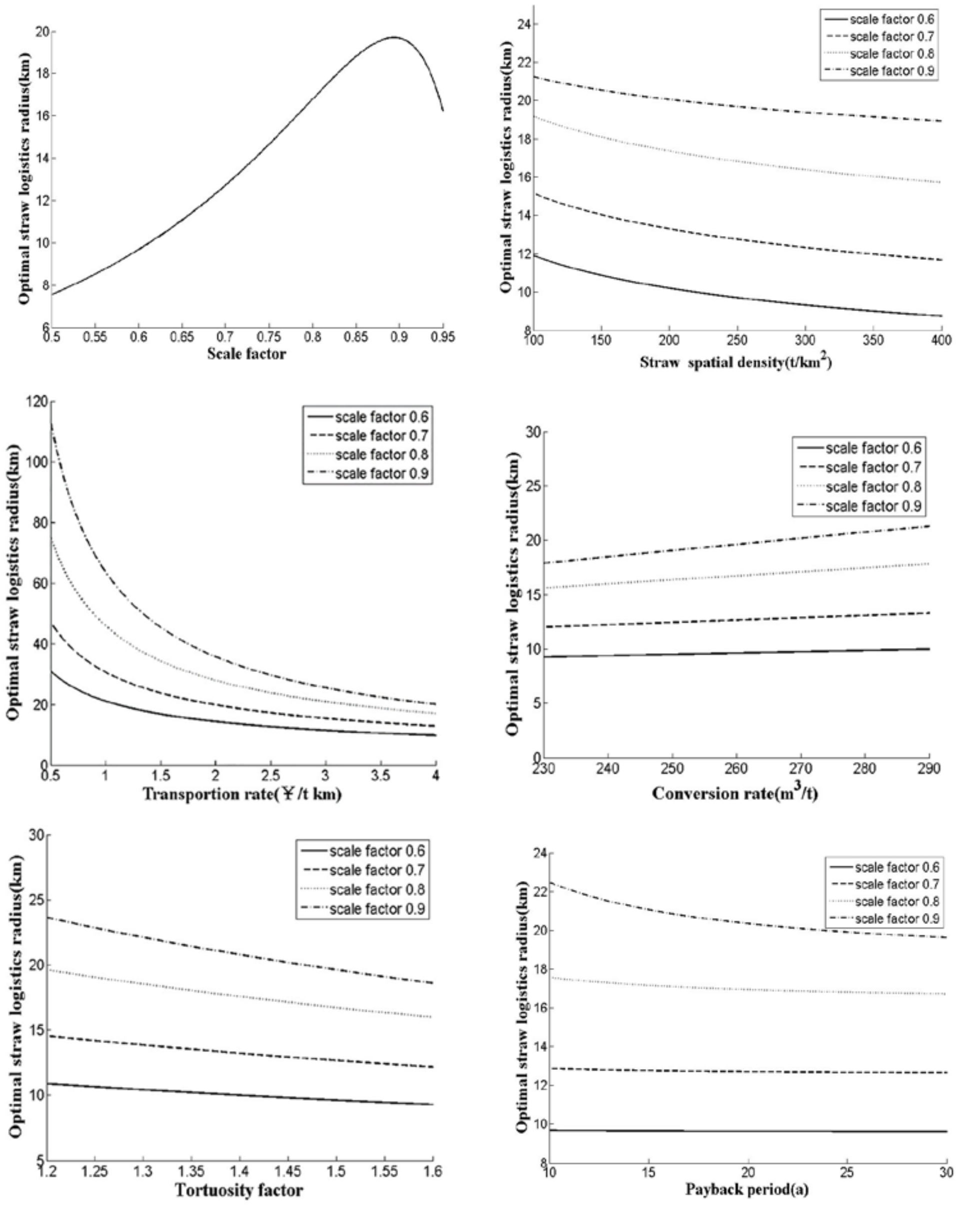

Fig 1 Optimal straw logistics radius for biogas manure co-generation vs. various factor

To explore the effect of changes in the unit total cost and unit profit, using equation (12), (14), and the data from Table 1 map Fig 2. At first, the unit production cost is high and unit profit is low, this is because the unit straw total cost is composed of the variable cost and the fixed cost, the impact of fixed cost is much greater than the variable cost. So, the fixed investment cost plays a dominant role in the unit production cost. With the expanding of the production scale, the unit cost increases and the unit profit decreases severely, due to the fixed cost and variable cost of the unit mass straw decline and sales revenue increase. As the radius of logistics continues to expand, the unit cost increases and unit profit decreases mildly, for the unit cost reduce progressively caused by scale. The fixed cost increases due to the economy of scale, whereas the cost of the straw collection increases due to the increasing transportation distance.

It is obviously that the unit total cost and unit profit increase with the production scale increases. The unit cost curve for biogas and manure co-generation above 286 Yuan per ton is relatively flat across a wide range. By equation (16), we can get the optimal logistics radius of 14.8 km when the maximum profits.

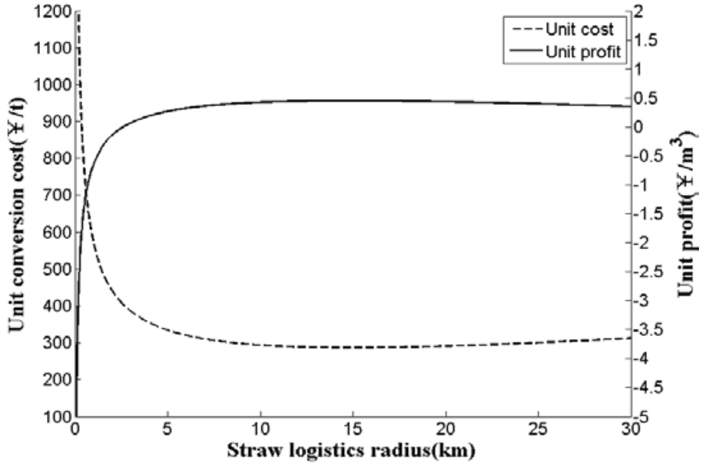

Fig.2. Straw logistics radius impacts on the unit cost and profit

Conclusions

Based on the analysis of the costs and incomes of biogas manure co-generation, the paper established straw logistics radius optimization model, and analyzed the influences of radius on the unit cost and profit, and research on the factors of the optimal straw logistics radius affect the optimal straw logistics. The theoretical simulation results can provide useful information to the managers to make decision in biogas manure co-generation development and deployment. The analytical results indicate:

(1) The paper proposed the concept of unit production scale profit maximization, and established straw logistics radius optimization model with the aim to obtain the mix unit scale profit.

(2) The optimal straw logistics radius increases with scale factor first and then decreases dramatically. The optimal straw logistics radius increases with a decrease in straw spatial density, tortuosity factor, transportation rate and payback period, or an increase in conversion rate, and with the increase of scale factor.

(3) The fixed investment cost plays a leading role in the total cost when the production scale is small. And when the scale of production becomes large, the transportation rate has a greatest influence on the optimal logistics radius.

Our method and main analytical results can be applied to multiple straw sources from other regions and used to determine the optimal straw logistics of new biogas and manure co-generation plants or resize optimal logistics radius of existing plant based on factors changing. Future works can research the aspects of collection area which is not limited by the area's border.

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