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Bi-Objective Optimization for Straw-Based Bio-Natural Gas Supply Chain

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The development of Bio-Natural Gas (BNG) is of great strategic significance in alleviating the shortage of fossil natural gas and fostering low-carbon energy transition. This work shows the economic and environmental analysis of the straw-based BNG supply chain using a Mixed Integer Linear Programming (MILP) model. Considering a sustainable supply chain framework, including straw collection, transportation, pre-treatment and product, and technologies (e.g., Anaerobic Digestion and Gasification), the optimal alternative is determined. Different straw harvesting rates and carbon emission reduction targets are designed to evaluate the cost and carbon emissions of each routine. The proposed model is applied to a country case study in China to illustrate the optimization of a regional straw-based BNG supply chain. The results show that the minimal cost ranges from 6.02 to 8.55 RMB/$m^{3,}$ and the emission reduction potential is from 9.82 to 12.74 kg/m^3. The use of straw-based BNG can generate environmental benefits and estimate costs.

1. Introduction

Biomass is a valuable renewable source of energy as an alternative to fossil fuels. As a typical biomass raw material, straw has great potential for Bio-Natural Gas (BNG), and its greenhouse gas emissions of the BNG production processes is reduced by 82 % compared with natural gas (Adelt et al.,2011). It can not only reduce the environmental burden, alleviate the aggravation of greenhouse effect, but provide local employment opportunities and promote the development of agricultural economy. Due to the high raw material cost, lack of reliable supply, and the uncertainty of process integration, the straw-based BNG project has been shut down. BNG supply chain optimization is significant. Mao et al. (2021) proposed a dual-objective planning model and cost and carbon emission metrics to plan the sites of straw-based collection and storage facilities. Zhang et al. (2017) designed the two-stage fuzzy method for biofuel supply chains to maximize the profit of the entire supply chain and minimize the total carbon emission in transportation, production, and inventory. Zahraee et al. (2020) proposed a multi-objective model considering sustainability criteria involving cultivating, harvesting, preprocessing, transporting, handling, and storing. Zhao and Li (2016) developed a bi-objective integer programming model for location optimization and feedstock supply chain design of biomass power plants. Ravina and Genon (2015) show that anaerobic digestion of agricultural products is the most frequently employed bioenergy technology. Rusín et al. (2022) conducted research on the safety of biogas plant operation during anaerobic digestion. Relative research shows that anaerobic digestion technology is relatively mature, while gasification technology is suitable for large-scale utilization. Singh et al. (2019) applied LCA tool to different processing technologies for rice straw. In this paper, considering different technologies, anaerobic digestion, and gasification, a bi-objective fuzzy optimization supply chain model is proposed. Costs and carbon emissions were assessed through LCA.

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2. Problem statement

Straw-based BNG supply chain involves four stages, including raw material collection, transportation, storage for pretreatment, and BNG production. This supply chain considers **I** collection points, **n** storage stations, **j** plants, and *k* BNG technologies. Each **i, n, j** has a given location, straw-based yield, and technical parameters, and each n, j can be assigned to any location that may exist. Due to the number, scale, and location of i, n, j and BNG technologies are uncertain, the problem is to determine the distribution of straw-based and locations at different harvesting rates based on costs and emission reduction targets to achieve the optimization of the supply chain. The straw-based BNG supply chain network representation with uncertainty is illustrated in Figure 1.

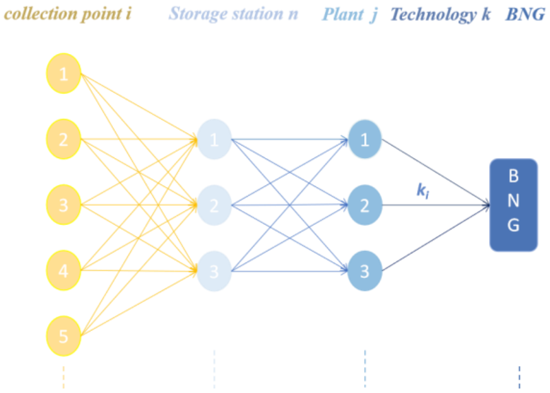


Figure 1: Network representation for the straw-based BNG supply chain process with uncertainty

3. MILP model formulation

This study aims to identify the optimal locations of storage stations and BNG plants under different straw-based harvesting rates and technologies. The objective functions of this model are to minimize annual production cost Z and maximize annual carbon emission E, as shown in Eq.(1) and Eq.(2). The MILP model considers the technology (Anaerobic Digestion/Gasification) k_i of the BNG plants. To improve the purity of biogas upgrading and purification for BNG, it is necessary to remove some impurities, such as H_2S and CO_2 (Ramos et al., 2023). The cost model includes straw-based collection $Z_i^{collection}$, transportation $Z_i^{transportation}$, pretreatment $Z_i^{pretreatment}$, and BNG production $Z_i^{product}$. In addition, different technologies produce different by-products, and the by-products of anaerobic digestion technology are organic fertilizers composed of biogas residue and biogas slurry, while gasification technology includes organic fertilizers, wood vinegar, straw charcoal, and wood tar. Organic fertilizers replace chemical fertilizer, and wood vinegar replace pesticides. This paper does not consider straw charcoal returning to the field and wood tar used as fuel or chemical raw materials. The by-product profits $Z_i^{by\text{-}product}$ are also considered. Based on the baseline of natural decomposition of straw-based, clean development mechanism methodology and emission factor method were used to construct the measurement methods. The carbon emission model of entire supply chain includes straw-based baseline emission BE_i, project operation emission PE_i. The baseline emissions involve the emissions generated by straw-based natural decomposition BE_i^{straw}, the replacement of fossil fuels by BNG BE_i^{fuel}, the replacement of chemical fertilizers and pesticides by by-products $BE_i^{fertilizer}$.Project operation emission generated by transportation $PE_i^{transportation}$ and energy consumption $PE_i^{electric}$. The economic and carbon emission of BNG utilization have not been considered.

$$Z = \sum_i Z_i^{collection} + Z_i^{transportation} + Z_i^{pretreatment} + Z_i^{product} - Z_i^{by\text{-}product} \tag{1}$$

$$= \sum_i F_i \cdot cost^{feedstock} \cdot \varepsilon \cdot k_i + \sum_i \sum_n \sum_j 2\, F_i \cdot R \cdot DL \cdot cost^{diesel} \cdot \varepsilon \cdot k_i$$

$$+ \sum_i F_i \cdot ML \cdot cost^{material} \cdot \varepsilon \cdot k_i + \sum_i (F_i \cdot costa_i \cdot \varepsilon \cdot k_1 + biomass_{gasification} \cdot costb_i \cdot k_2)$$

$$- \sum_i (F_i \cdot \varepsilon \cdot k_1 + biomass_{gasification} \cdot k_2) \cdot cost_i^{fertilizer}$$

$$E = \sum_i \mathrm{BE_i} - \mathrm{PE_i} \tag{2}$$

$$= \left(\sum_i \mathrm{BE}_i^{straw} + \mathrm{BE}_i^{fuel} + \mathrm{BE}_i^{fertilizer}\right) - \left(\sum_i \mathrm{PE}_i^{transportation} + \mathrm{PE}_i^{electric}\right)$$

$$= \left(\begin{array}{c} \sum_i \mathrm{F_i} \cdot k^{straw} + \sum_i \left(biomass_{AD} \cdot NCVB^{fuel} \cdot EB \cdot \mathrm{k_1} + \mathrm{F_i} \cdot k^{fuel} \cdot \mathrm{k_2}\right) \\ + \sum_i \left(\begin{array}{c} \left((4.84C_N + 0.71C_P + 0.36C_K) \cdot 10^{-3} + 1.43\mathrm{F_i} \cdot \varepsilon\right) \cdot \mathrm{k_1} \\ +(\mathrm{F_i} \cdot \varepsilon \cdot 90\,\% \cdot k^{fertilizer}) \cdot \mathrm{k_2} \end{array}\right) \end{array}\right)$$

$$- \left(k^{trans} \cdot NCVB^{trans} \cdot C^{diesel} \cdot 10^{-3} \cdot \mathrm{k_1} + \left(\begin{array}{c} \mathrm{F_i} \cdot c^{elec1} \cdot 10^{-3} \\ + biomass_{gasification} \cdot c^{elec2} \cdot 10^{-3} \end{array}\right) \cdot k^{elec} \cdot \mathrm{k_2}\right)$$

In Eq(3), variable e is introduced to represent the degree of satisfaction under all objectives. Each fuzzy goal increases linearly from 0 to 1, where 0 represents the minimum satisfaction and 1 represents the complete satisfaction. Bi-objective fuzzy optimization is carried out based on the degree of satisfaction, and economical and environmental objectives are considered to achieve the optimization of supply chain system.

$$e = e(Z) + e(E) \tag{3}$$

$$e(Z) \le \frac{Z_i^M - Z_i}{Z_i^M - Z_i^m} \tag{4}$$

$$e(E) \le \frac{E_i - E_i^m}{E_i^M - E_i^m} \tag{5}$$

$$0 \le e(Z) \le 1 \tag{6}$$

$$0 \le e(E) \le 1 \tag{7}$$

4. Case study

The straw-based BNG supply chain system model was applied to a county in Shandong Province, which the output yield of straw-based is 91.38×10^4 approximately. The model considered 11 towns, 3 storage stations, and 2 technological routines (anaerobic digestion and gasification). All plants are assumed to operate 7,200 h/y, and the equipment life is 15 y. Equipment depreciation mainly adopts the straight-line depreciation method, and the net residual rate of fixed assets is 5 %. The annual total cost is determined by the amount of straw-based collected each year. The gas production rate of anaerobic digestion is assumed to be 150 m^3/t and the cost of organic fertilizers is 0.15 RMB/m^3 (Yang et al.,2020), while the gas production rate, the cost of organic fertilizers and wood vinegar of gasification is 126.67 m^3/t, 25.9 RMB/t and 77.65 RMB/t. The distances between each town are given (Li et al. 2016). The cost and carbon emission parameters of each technology are given as Table 1.

Table 1: Technical parameter of economy and environment

parameters		Anaerobic Digestion	Unit	Gasification	Unit
Economy	Equipment depreciation	0.6	RMB/m^3	2	RMB/m^3
	Salary	50	RMB/t	0.75	RMB/m^3
	Running	0.08	RMB/m^3	0.3	RMB/m^3
	Electric	85.2	RMB/t	45	RMB/t
	Energy consumption	0.15	RMB/m^3		
	Material	19.6	RMB/t		
Environment	BE^{straw}	0.57	kg/kg	0.57	kg/kg
	BE^{fuel}	0.56×10^{-1}	t/GJ	0.68	kg/kg
	$BE^{fertilizer}$	4.85	t/t_N	0.53	kg/kg
		0.71	t/t_P		
		0.36	t/t_K		
	$PE^{transportation}$	0.74×10^{-1}	t/GJ	0.74×10^{-1}	t/GJ
	$PE^{electric}$	1.07	kg/kwh	1.07	kg/kwh

5. Results and discussions

The results showed that with the increase of straw-based harvesting rates, the overall satisfaction tended to increase (Figure 2). When the economic cost is 0, the maximum degree of satisfaction is 1, while with the constant increase of straw-based harvesting rates, the total cost will continue to increase, leading to a gradual decline in the trend of satisfaction. As the harvesting rates keeps increasing, the satisfaction of net emission reduction gradually approaches 1. When the harvesting rates reaches 100 %, the satisfaction e(Z) of economic target is 0.23, the satisfaction e(E) of carbon emission reduction target is 0.89 and e has the highest satisfaction,1.12. Under the same harvesting rates, although the cost of gasification is slightly higher than that of anaerobic digestion, the carbon emission reduction benefit is better than that of anaerobic digestion. So when the straw-based collection rates is below 68.8 %, the technology route is gasification. As the straw-based harvesting rates exceeds 68.8 %, the technology route is anaerobic digestion. The reason is the net emission reduction increases with the harvesting rates, which is gradually constant with the net emission reduction of gasification technology. The cost of anaerobic digestion is lower than that of gasification technology. Shown as Figure 3, the BNG output is 1,041.76×10^4 m³ and when straw-based is fully utilized, the BNG yield is 12,161.49×10^4 m³. The minimal cost ranges from 6.02 to 8.55 RMB/m³ in this project, while BNG projects have a minimum cost of 2.5 RMB/m³ (Ecepc, 2016). The maximal BNG emission reduction of straw-based is 1.45 t/t, so straw-based BNG can reduce the amount of greenhouse gases emitted into the atmosphere in relieving global warming. The results show straw-based harvesting rates affects the unit price of BNG and emission reduction benefits, and this project has to rely on government subsidies to operate.

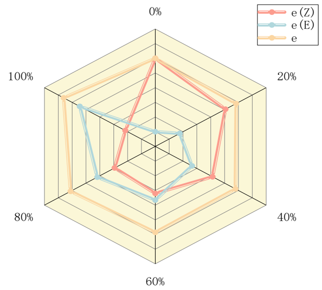
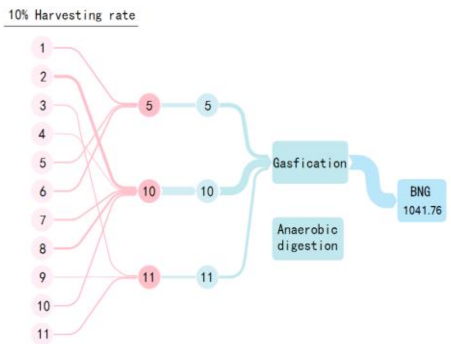
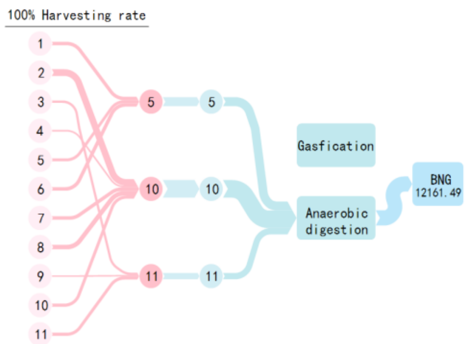


Figure 2: Multi-objective solution results



a.10 % Harvesting rate



b.100 % Harvesting rate

Figure 3: Straw-based BNG supply chain integration process under different straw-based harvesting rates

5.1 Changes in harvesting rates of straw-based

In general, the optimal structure of a straw-based supply chain system is strongly influenced by the straw-based harvesting rates and the transport distance, the cost of the associated technology, and the benefit of carbon emission reduction. The results show that the cost and carbon emission are associated with the harvesting rates, and the growth of emission reduction target is more obvious compared with the economical target with increasing harvesting rates. When the straw-based is completely utilized, the total cost is 732.09 million RMB. After deducting the income from by-products, the cost is 732.08 million RMB, and the net emission reduction is 133.52 × 10^4 t. The largest of total costs is pretreatment costs from 25.6 % to 50.0 %, the second is BNG processing costs, and transportation costs for a minimum proportion, accounted for 0.02 %

to 0.04 %. Due to lower processing costs and higher by-product incomes, anaerobic digestion is more cost-effective than gasification. In terms of carbon emission reduction, the emission reduction potential is from 9.82 to 12.74 kg/m³. When the harvesting rate is 100 %, it reaches 133.52 × 10^4 t. The baseline carbon emission reduction of gasification technology is higher than that of anaerobic digestion technology, the net emission generated by the replacement of fossil fuels and chemical fertilizers is larger, and the power consumption generated during the project operation is less than that of anaerobic digestion. Therefore, gasification technology is superior to anaerobic digestion in carbon emission reduction benefits.

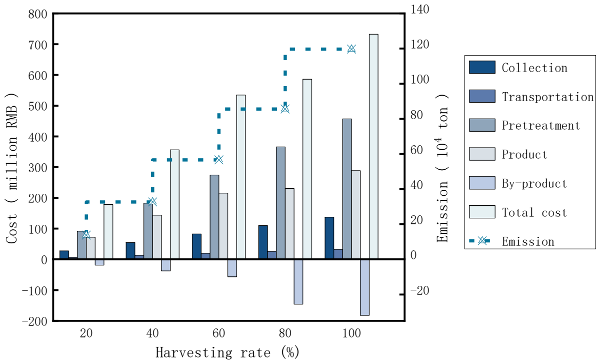


Figure 4: Costs and carbon emission under different straw-based harvesting rates

5.2 Changes in emission reduction targets

For the given case study, the changes of economy were studied to obtain the distribution of the supply chain network when the emission reduction targets are 20 %, 40 %, 60 % 80 % and 100 %. The results show costs of different components vary with carbon emission reduction targets. It can be seen that the impact of the emission reduction targets on the costs of pretreatment, product, collection, by-product and transportation decreases gradually. With the continuous improvement of emission reduction targets, the amount of straw-based distributed at different sites has changed, so the unit emission reduction cost gradually decreases with the reduction of transportation cost. When the carbon emission reduction target is 100 %, the straw-based harvesting rates reached 100 %. The largest cost is still the pretreatment, accounting for 46.4 %. Unit emission reduction cost is from 593.48 to 756.79 RMB/t. In spite of this, the cost at this harvesting rate is even higher than the total cost when the straw-based is fully utilized under anaerobic digestion. While improving the efficiency of BNG emission reduction, it will also improve the total costs. Since the carbon reduction efficiency of gasification is better than that of anaerobic digestion, gasification is preferred as a process technology when considering the economic impact of different emission reduction targets, despite its higher cost.

6. Conclusions

The straw-based BNG supply chain system model is built to evaluate the economic and environmental target optimization and realize the process integration of supply chain system. By considering different factors, the economic impact of straw-based harvesting rates and emission reduction target are studied. It provides a reference for bringing agricultural waste into the regional planning. The results show that the minimal cost ranges from 6.02 to 8.55 RMB/m³ and the emission reduction potential is from 9.82 to 12.74 kg/m³. For efficient distribution of produced BNG, the existing natural gas networks can be utilized with end applications in electricity, thermal, and transportation energy generation, and future work needs to involve the end use of straw-based to ensure that BNG becomes a practical option. Multi-objective optimization models can be developed that consider both the economic and inherent safety of supply chain.

Nomenclature

Parameters

F_i – straw-based output, t
R – distance of transportation, km
DL –diesel consumption per unit, L/t/km
ML – unit consumption of material, t/t
$costa_i$ – unit price of process, RMB/t
$costb_i$ – unit price of process, RMB/m^3
BL – biogas production of unit straw-based, m^3/t

k^{straw} – carbon emission factor from natural burning of straw-based, kg/kg
$NCVB^{fuel}$ – net calorific value of BNG, GJ/m^3
EB – fossil fuel emission factor, t/GJ
k^{fuel} – carbon emission factor of replacement fuel (gasification), kg/kg
C_N – nitrogen fertilizer content in organic fertilizers, kg
C_P – phosphorus fertilizer content in organic fertilizers, kg
C_K – potassium fertilizer content in organic fertilizers, kg
$k^{fertilizers}$ – carbon emission factor of fertilizers, kg/kg
$NCVB^{trans}$ – net calorific value of transport fuel, GJ/t
k^{trans} – carbon emission factors of transport fuels, t/GJ
c^{diesel} – diesel fuel consumption in transportation, t
k^{elec} – electric emission factor, kg/kwh
c^{elec1} – electricity consumed of anaerobic digestion process, kwh/t
c^{elec2} – electricity consumed of gasification process, kwh/m^3
Z_i^M – maximum cost based on the degree of satisfaction
Z_i^m – minimum cost based on the degree of satisfaction
E_i^M – maximum carbon emission based on the degree of satisfaction
E_i^m – minimum carbon emission on the degree of satisfaction

Variable

ε – harvesting rate, %
k_i – technology routines

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