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Energy Potentials and Carbon Intensity for Bio-natural Gas from Livestock Manure in China

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Bio-natural Gas (BNG) from livestock manure (BNGLM) is a potential alternative energy source that can yield significant resource and environmental benefits. Energy potentials and carbon intensity differences in livestock manure utilization may exist in provincial areas. The spatial and temporal distribution characteristics for the BNG potentials are analyzed. A life-cycle carbon emission accounting model for carbon intensity was proposed. The results show that with the increase of scale and intensification of animal husbandry, the BNG potential is increasing. The potentials vary greatly among provinces. The annual carbon emission reduction potential from BNGLM reached 1.25 Gt. The proposed energy potential, its spatial characteristics, and carbon emission reduction measurement are expected to provide better support for enhancing specific regional plans for waste manure utilization and development.

1. Introduction

The demand for natural gas as a fuel has been growing rapidly in China for both industrial and residential consumers. The share of imported natural gas has increased from 30 % in 2015 and is expected to reach nearly 40 % by 2035 (NDRC, 2016). One of the options to reduce dependence on fossil fuels is the production of Bio-natural Gas (BNG) from renewable energy sources (Skorek-Osikowska et al., 2020). Mohtar et al. (2021) developed a mathematical model to determine the optimal process pathway of biogas, covering from the purification technology to mode of transportation and utilization. The exploitation of BNG has significant environmental benefits in addition to energy replenishment (Serra et al., 2019). Livestock manure is a major environmental pollutant in rural areas and at the same time an important resource for BNG production. It is important to quantitatively assess the energy potential and carbon reduction potential of biomass energy reserves. The different stages of biomass utilization have different impacts on the environment. For the biogas purification process to prepare biogas, the unit with the greatest impact on environmental emissions is the purification process of biogas (Wu, 2020). Pyrolysis carbon gas co-production and large-scale biogas/biogas technologies have the largest contribution to GHG emission reduction (Huo et al., 2021). The addition of biochar during anaerobic fermentation in renewable natural gas production can reduce GHG emissions by 32 % (Uddin et al., 2022). The production of biogas can be increased by co-digesting food waste and glycerol. The elimination rates for TS and COD can reach 32.6 % and 35.8 % when the ratio is 3:1 (Muhammad et al., 2021). From the perspective of the life cycle, this work presents specific accounting of the energy potential of BNGLM. A methodological system for measuring the carbon emission reduction of BNGLM is constructed to comprehensively evaluate the carbon emission reduction effect of the BNGLM system.

2. Methods and models

Based on data from livestock farming in China from 2011 to 2020 (NBSC, 2021), this study conducted a comprehensive techno-economic analysis. The entire amount of livestock manure resources, the amount that can be collected, the amount that can be used, and the potential to reduce emissions were investigated using

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a mix of model creation and literature study. Energy potential and carbon emission reduction potential models were developed. The carbon intensity of the BNGLM manufacturing process was investigated using the Life Cycle Assessment (LCA) approach.

2.1 Life cycle modeling framework

The goal of this study was to determine BNGLM's life-cycle energy potential (represented as biogas generation) and carbon intensity (expressed as reduced carbon emissions). This research was carried out on large-scale farms in China that raised pigs, beef cattle, dairy cows, broilers, chicken, laying hens, and sheep. It is expected that the farms have an anaerobic fermentation plant and a purification plant and that any livestock manure that can be collected is used to make BNG. Figure 1 depicts the life-cycle system boundaries in relation to the entire process of livestock manure utilization. It is made up of three modules: (a) feedstock production (includes livestock farming and the manure creation process), (b) process gas production (including anaerobic digestion and biogas purification), and (c) user consumption (including motor fuel, heating, and power generation).

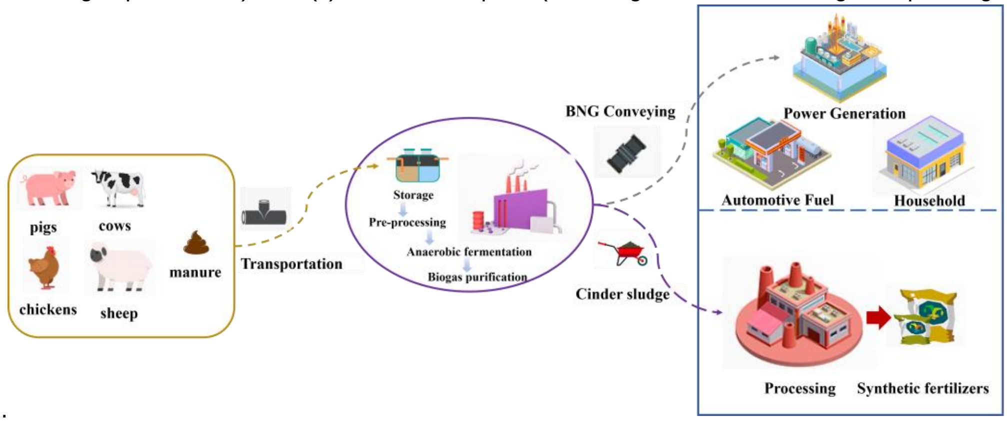

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Figure 1: The life cycle boundary of BNGLM system

Table 1 depicts the major carbon emission sources inside the BNGLM system's border. When livestock manure is not employed to make BNG, they naturally store and emit carbon dioxide. The emissions in this scenario are the baseline scenario's carbon emissions. The difference between the total carbon emissions of the BNGLM system and the baseline carbon emissions during its lifecycle represents the BNGLM system's emissions reduction.

Table 1: Boundaries of the BNGLM system and the primary sources of greenhouse gas emissions

Scenario		Emission sources	Gas type
Baseline scenario	Source	Natural decomposition of manure piles	CH_4, NO_2
	Terminal	Fossil gas extraction, transportation, production, use	CO_2
life cycle of manure BNG systems	Livestock farming	Gastrointestinal fermentation	CH_4
		Feedlot power generation and heating	CO_2
	BNG production process	Process gas production	CO_2
		Purification and purification	CO_2
	BNG use process	Electricity generation, heating, vehicle fuel	CO_2

2.2 Energy potential assessment

The energy potential of livestock manure was obtained based on three levels: the theoretical reserve of fresh mass (Q^f) (the theoretical amount of livestock manure directly produced by each type of livestock), the theoretical reserve of dry matter (Q^d) (the amount of dry matter contained in fresh livestock manure), and the collectable volume ($Q^d{}_c$) (the amount of livestock manure that can be collected from large-scale farms).The reserves and energy potential of each substance are calculated using Eq(1)-Eq(5).

$$Q^f = \sum_{i}^{n} W_i * K_i * T_i \quad (1)$$

$$Q^d = \sum_i^n Q_i^f * D_i \tag{2}$$

$$Q_c^d = \sum_i^n Q_i^d * \varepsilon_i * \lambda_i \tag{3}$$

$$F_{bio} = \sum_i^n Q_{ci}^d * \beta_i \tag{4}$$

$$F_{BNG} = \sum_i^n F_{bio} * \alpha = \sum_i^n W_i * K_i * T_i * D_i * \varepsilon_i * \lambda_i * \beta_i * \alpha \tag{5}$$

2.3 Establishment of emission reduction methodology

The total carbon reduction of the BNGLM system can be obtained from Eq(6). The production and utilization process of BNGLM engineering follows material conservation, and there is essentially no effect of carbon fixation and reduction. However, whether it be through natural decomposition or incineration, if livestock manure resources are not properly utilized, carbon emissions will eventually be produced. Therefore, the collection and utilization of livestock manure resources belongs to source emission reduction ((Eq(7)). The carbon emissions caused by the process from livestock breeding to BNGLM generation are called production process carbon emissions (Eq(8)-Eq(10)). Carbon emissions may be produced during the whole fossil natural gas production and consumption process, including coal mining, coal transportation, and coal to natural gas production. Utilizing BNGLM can lower the amount of fossil fuels consumed, avoiding this kind of emissions reduction known as terminal substitution emission reduction (Eq(11)). BNGLM and fossil natural gas both produce the same amount of carbon emissions when in use, hence they can both be excluded from the calculation of reduced emissions. Deducting the emissions from the manufacturing process by the sum of the source emission reduction and the terminal substitution emission reduction allows us to get the total emission reduction of the BNGLM system.

$$RE_{total} = E_{Manure\ management} - \left(E_{raise_{heating}} + E_{raise_{electricity}} + E_{fermentation} + E_{factory}\right) + E_{replace} \tag{6}$$

$$E_{Manure\ management} = \sum_i^n W_i * ef_{i2} * GWP_{\mathrm{NO2}} + \sum_i^n W_i * ef_{i3} * GWP_{\mathrm{CH4}} \tag{7}$$

$$E_{raise_{heating}} + E_{raise_{electricity}} = \sum_{i=1}^n W_i * \frac{\mathrm{cost}_{ie}}{price_e} * ef_e + \sum_{i=1}^n W_i * \frac{\mathrm{cost}_{ic}}{price_c} * ef_c \tag{8}$$

$$E_{fermentation} = E_{\mathrm{CH4}} * GWP_{\mathrm{CH4}} = \sum_{i=1}^n W_i * ef_{i1} * GWP_{\mathrm{CH4}} \tag{9}$$

$$E_{factory} = F_{BNG} * C_e * ef_e \tag{10}$$

$$E_{replace} = E_{transport}^{CNG} + E_{exploit}^{CNG} + E_{product}^{CNG} = (E_{CO2}^{CNG} + 21E_{CH4}^{CNG})/F_{CNG} * F_{BNG} \tag{11}$$

3. Results

3.1 Theoretical yield of livestock manure

The regional theoretical reserves of livestock manure in China were obtained. The theoretical reserves of livestock manure have mostly stabilized as animal husbandry has advanced. The feces of beef cattle and pigs make up the majority of the theoretical reserve structure, as illustrated in Figure 2, accounting for an average of around 30 % over a ten-year period. The annual production of livestock manure is significantly impacted by the number of animals with high feeding capacity and high manure production coefficients, such as pigs and beef cattle. The change in total amount is proportional to the production of livestock manure.

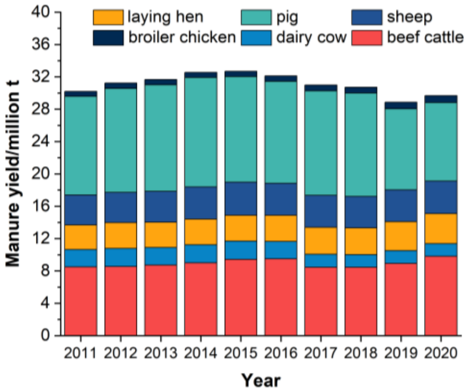

Figure 2: Manure generation over time from 2011 to 2020

Figure 3 displays the geographic distribution of theoretical livestock manure generation for 30 areas in 2017. In terms of regional distribution, Sichuan Province produces the most livestock manure, followed by Yunnan, Henan, Inner Mongolia, Shandong, and Hunan, all of which produce more than 1.5×10^8 t, 18 other regions produce between 5×10^7 t and 1.5×10^8 t, 7 additional regions produce less than 5×10^7 t, and Tianjin, Shanghai, and Beijing produce the least livestock manure. The structure and volume of livestock rearing directly affect the amount of manure resources. The differences in farming structure make the amount of livestock manure produced and the BNGLM potential of the produced material appear variability with spatial distribution. A significant amount of manure is stored in China's northwest, southwest, central, and east areas, which also offer the best geographic circumstances for developing livestock breeding, complete breeding species, and greater breeding scales, leading to high manure production.

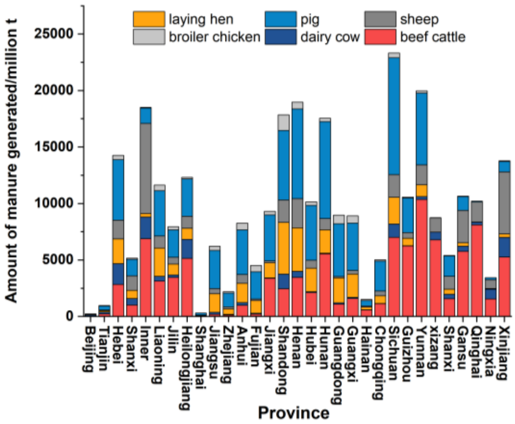

Figure 3: Manure generation by provinces

3.2 Energy potential

By measuring the amount of livestock manure resources, as shown in Figure 4(a), the energy potential model was able to produce the graph of BNGLM over time for the decade of 2011-2020. It is clear that there is a rising tendency in the overall production of BNGLM. Due to their high livestock rearing volume and high manure production coefficient, laying hens and sheep account for a significant share of the total BNGLM produced. According to 2020, each Chinese province provided data on the spatial distribution characteristics of its livestock manure resources, as seen in Figure 4(b). It is evident that regions with extensive livestock breeding sectors, such as Inner Mongolia, Sichuan, Shandong, and others, produce a significant amount of BNGLM and have significant energy potential. It is evident that the spatial distribution makes the volume of livestock manure production and the potential for BNGLM production appear obviously variable.

3.3 Carbon reduction potential of natural gas systems for livestock manure generation

The carbon emission reduction potential is determined based on the whole life cycle model, taking into account the output within the life cycle boundary, in order to emphasize the benefits of using livestock manure. As shown in figure 5, the theoretical net emission reduction of China's BNGLM system reaches 1.25 Gt of CO_2, which has a good GHG reduction potential. For each m^3 of BNGLM produced and utilized, 13 kg of CO_2 emissions will be reduced. It can be seen that the BNGLM system can effectively reduce the carbon emissions caused by the original fossil energy.

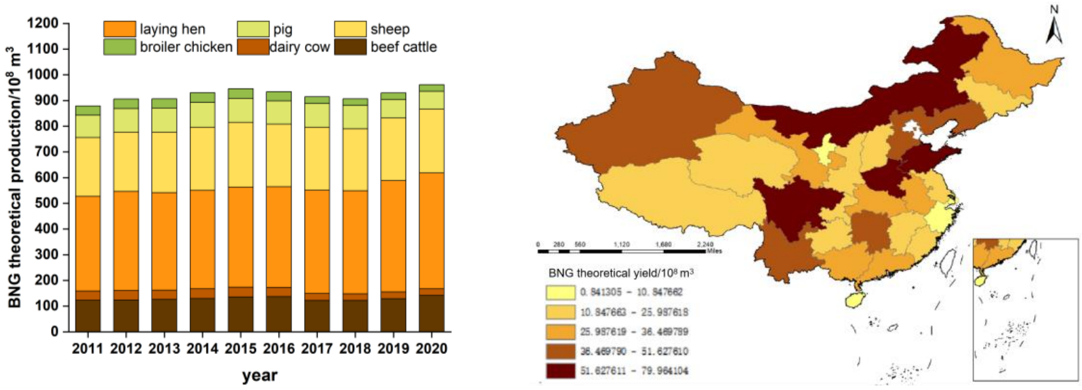

Figure 4: (a) BNGLM production over time from 2011 to 2020 (b) Theoretical BNG production by province

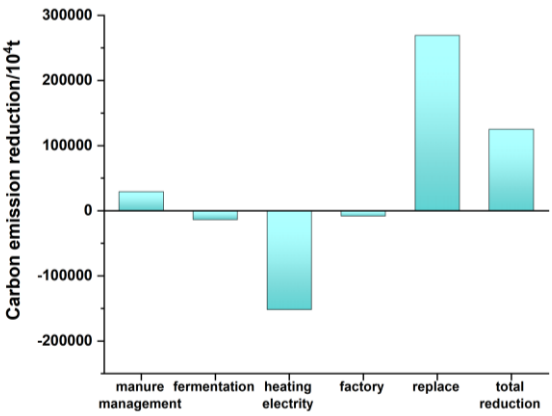

Figure 5: Emission reduction in each stage

4. Conclusions

A thorough assessment model was built in this work based on the life cycle of using livestock manure for energy conversion. The model was used to analyze the spatial characteristics of 30 provincial regions in China and highlight their potential for integrated energy and carbon reduction using manure. The scientific development of BNG from China's resources of livestock manure, which total 92.16 Gm^3, can close the country's present annual net natural gas import imbalance. From 2011 through 2020, the BNGLM energy potential exhibits a general trend of growth. The highest theoretical output among them is in Sichuan, which is followed by Inner Mongolia, Shandong, and Henan. Applying the BNGLM system developed in this study's GHG emission reduction measurement technique, the yearly GHG emission reduction (in terms of CO_2) from this project was estimated, reaching 1.25 Gt, using livestock farms in China as an example. This indicates that the production of BNGLM can significantly reduce carbon emissions

Nomenclature

W_i – the number of livestock and poultry feeding, million pieces

ef_{i1} – CO_2 emission factors of gastrointestinal fermentation, Kg/(piece*y)

$cost_{ie}$ – expenditures on electricity for livestock and poultry, Yuan/hundred pieces

$price_e$ – unit price of electricity for livestock farming, yuan/kWh

ef_e – CO_2 emission factor for electricity consumption, t/MWh

$cost_{ic}$ – expenditures on coal for livestock and poultry, Yuan/hundred pieces

$price_c$ – unit price of coal for livestock farming, yuan/t

C_e – electricity consumption for the production of a unit volume of BNG, kWh/m^3

ef_{i2} – NO_2 emission factor from manure management, Kg/(piece*y)

ef_{i3} – CH_4 emission factor from manure management, Kg/(piece*y)

Q_f – theoretical amount of manure directly produced by various types of livestock and poultry, billion t
Q_d – mass of dry matter contained in fresh manure, billion t
Q_d^c – the amount of manure that can be collected from large-scale farms, billion t
GWP – warming potential
ef_c – CO_2 emission factor of coal consumption, t/t
F_{BNG} – total annual production of BNG, billion m^3
F_{bio} – theoretical biogas production, billion m^3
K_i – fecal production factor, Kg/d
D_i – feeding cycle, d
ε_i – collection factor, %
β_i – gas production coefficient, %
α – purification factor, %
λ_i – Business Size Factor, %
R_E – Carbon reduction, billion t
E – Carbon emissions, billion t

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