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RESEARCH

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Value creation of straw-based biogas in China

Yingmu Chang[1*], Walter Stinner[3] and Daniela Thraen[1,2]

Abstract

Background Value creation is a common concept in business, and the core purpose of economic activity. "Value creation" of biogas refers to how much biogas value can be created when it is used for different purposes. The fact that 1 m^3 of biogas contains enough value as an energy carrier to replace coal, liquefied petroleum gas (LPG), and natural gas in the power and heat sector, as well as gasoline and diesel as a vehicle fuel, receives too little attention in China. The use of agricultural residues and waste is not only a key element for the reduction of resource demand and climate gas emissions, but also offers the potential for value creation. Biogas provision, which is being promoted more and more in China, could be the key to unlocking this potential.

Results To assess the potential of value creation for straw-based biogas in China, we calculated the value created by substituting fossil fuels by biogas in different provinces. Likewise, we calculated the collectable straw potential between 2011 and 2020 by using data regarding methane yield, the official biogas electricity price and rate of subsidy by province, as well as market prices of fossil fuels issued by the *National Bureau of Statistics* as unit price. Furthermore, the amount of value that 1 m^3 methane creates in different applications is compared in Chinese yuan, euro and dollar.

Conclusions The results showed that value creation for vehicle use is the highest, which reached 5.52/6.57/8.16 yuan/m^3 methane (0.789/0.939/1.166 USD/m^3) as a gasoline replacement, and 5.17/5.81/7.07 yuan/m^3 methane (0.699/0.785/0.955 USD/m^3) as a diesel replacement; followed by substitution of natural gas, and LPG; the current most common use, electricity generated by the CHP plant showed a relatively low value, which reached 1.08/1.90 yuan/m^3 methane (0.154/0.271 USD/m^3); and the heat supply showed the lowest with only 0.56 yuan/m^3 methane (0.08 USD/m^3). This scientific calculation method of the value of biogas as an energy carrier provides a basis for further development of the biogas industry. This paper initially raises this research question in China.

Keywords Biomethane, Energy carrier, Fossil fuel replacement, Calorific value, Energy price, Subsidy

*Correspondence:
Yingmu Chang
yingmu_chang@hotmail.com
[1] Faculty of Economic Sciences, University of Leipzig, Grimmaische Street 12, 04109 Leipzig, Germany
[2] Department of Bioenergy, Helmholtz Centre for Environmental Research, Torgauer Street 116, 04247 Leipzig, Germany
[3] DBFZ German Biomass Research Centre, Torgauer Street 116, 04347 Leipzig, Germany

Background

As the second largest economy and the carbon emitter in the world, China is faced with the need for better solutions in renewable energy development, pollution control and related social and economic benefits. China has set the goal of reaching carbon peak by 2030 and carbon neutrality by 2060 [1], at which point the development of renewable energy will need to have been largely achieved. The quantity of available wind and solar power plays an important role here. Compared with wind and solar energy, biogas is less abundant and more expensive. However, biogas has an irreplaceable advantage, which functions as a "joker" (in this context, 'joker' denotes an all-purpose, adaptable element) in the renewable energy system [2]. One the other hand, China, as a large agricultural country, provides a good basis for biogas development. As the world's main grain producer, China is rich in straw resources and thus has a relatively high amount of available collectable straw. From 2011 to 2020, the total crop residue yield increased from 8.56×10^{11} to 9.85×10^{11} kg. Chinese government vigorously supports the biogas industry. However, given the large advances in research and breakthroughs in biogas technical feasibility, research focusing on value creation of biogas as an energy carrier in China is seldom reported. According to the author's literature review, the research topic of biogas is still in its initial phase in China. In countries with leading biogas development, like Germany and northern Europe, discussion of value creation of biogas is already in process. This helps to show stakeholders a more complete picture of the biogas industry.

Biogas has a long history in China starting from the 1970s, beginning with household biogas, an important energy source in rural area in China. This progressed to medium- and large-sized combined heat and power (CHP) biogas plants, and has now reached the current state of large- and very large-scale plants for biogas engineering and bio-natural gas engineering. Biogas plants have developed quickly in recent years (Fig. 1). In 2008, there were 39,842 biogas plants in China; there were 109,976 biogas plants in 2017, which is 2.76 times more than in 2008 [3].

In China, biogas is mainly produced by bioconversion of agricultural residues. In 2017, the contribution of biogas plants drastically increased to 21.09%, where biogas plants, based on agricultural residues, accounted for 19.17%, and those based on industrial residues for 1.92%. The quantity of biogas plants based on agricultural residues and their processing capacity has drastically increased in the last 10 years [3].

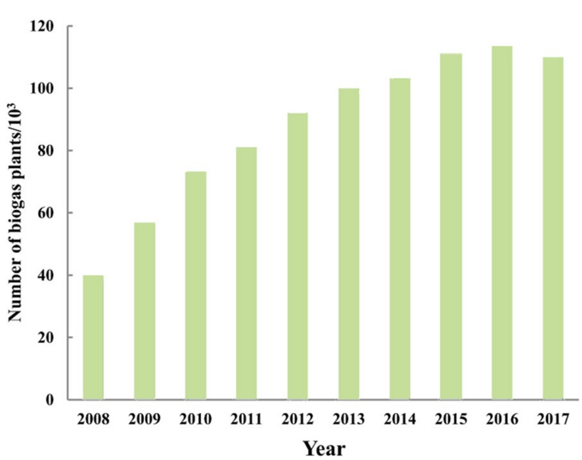

Fig. 1 Number of biogas plants in China from 2008 to 2017 [3]

Based on the data in *National Rural Renewable Energy Statistics* of 2017 [4], at the end of 2017, there were a total of 109,976 biogas projects nationwide, with an annual gas output of 2,607,877,600 m^3 and an annual power generation of 758,923,900 kWh. Among them, there are 109,732 projects dealing with agricultural waste [4]. Table 1 lists the states of biogas projects and agricultural biogas projects in China for 2017.

Based on the authors´ results from 2011 to 2020, the total crop residue yield increases from 8.56×10^{11} to 9.85×10^{11} kg. Among 34 provinces in mainland China, the top 3 provinces with the largest amount of crop residues are always Heilongjiang, Henan and Shandong; whereas, provinces Tibet, Beijing and Shanghai have the lowest yield.

China is the world's largest carbon emitter, and the largest energy sources are still fossil fuels. Figure 2 lists the detailed energy structure for China in 2020. At the same time, import of coal, liquefied petroleum gas (LPG) and gasoline continuously increased.

Coal import: According to the *National Bureau of Statistics*, in 2020, national coal consumption increased by 0.6%, and coal consumption accounted for 56.8% of total energy consumption, with a 0.9% decrease from 2019. From 2010 to 2020, the proportion of coal in primary energy consumption structure dropped from 69.2 to 56.8%, but still accounted for more than half. In 2020, coal import was 303.99 million tons [6].

Table 1 State of biogas projects and agricultural waste biogas projects in China [4]

1	Total biogas projects	109,976
2	Annual gas output	2,607,877,600 m^3
3	Installed capacity	291,794 kW
4	Annual generation capacity	758,923,900 kWh
5	Raw material consumption	Industrial waste: 2,806,600 ton
		Livestock Manure: 185,599,600 ton
		Crop straw: 5,608,500 ton
		Other organic waste: 4,231,700 ton
6	Agricultural biogas projects	109,732
7	Annual gas output	2,370,605,200 m^3
8	Installed capacity	281,707 kW
9	Annual power generation	751,351,500 kWh
10	Very large biogas projects	65 (Daily biogas production ≥ 5000 m^3/day), of which 15 biomethane projects
11	Large biogas projects	7565 ($5000 > Q \geq 500$)
12	Middle-sized biogas projects	10,516 ($500 > Q \geq 150$)
13	Small-sized biogas projects	91,585 ($150 > Q \geq 5$)

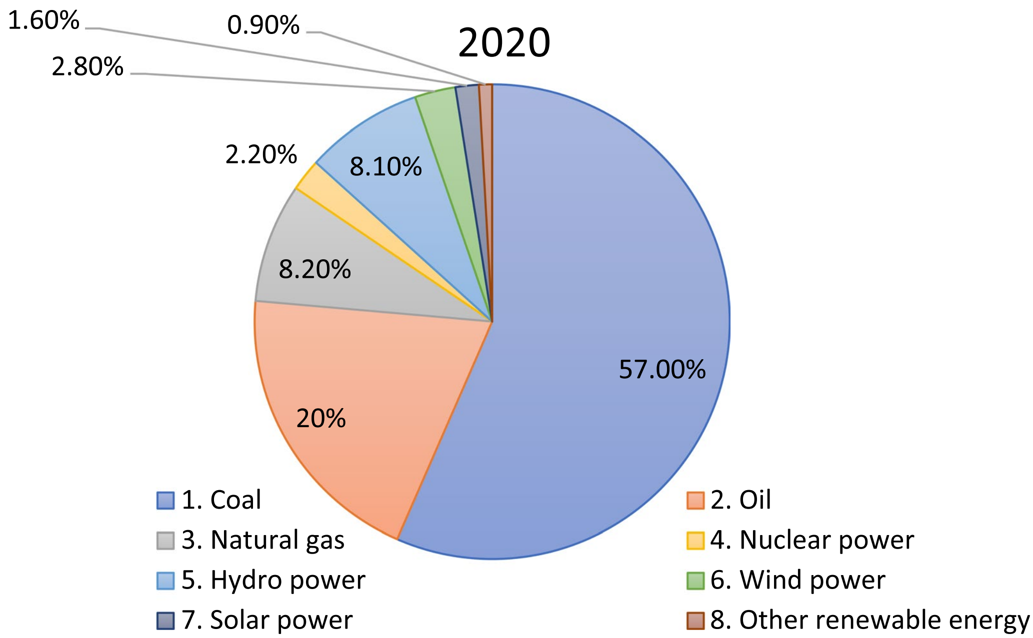

Fig. 2 Energy structure in China in 2020 [5]

Oil import: According to data from the *National Bureau of Statistics*, China's crude oil production is 195 million tons in 2020, with a year-on-year increase of 1.6%. According to data from the General Administration of Customs, in 2020, China imported 540 million tons of crude oil, a year-on-year increase of 7.3%. The growth rate of China's crude oil imports continued to be higher than the growth rate of domestic crude oil production. Oil dependence on import increases to 73.5%, which is 1% higher than in 2019. [7]

Natural gas import: In 2020, China's natural gas production reaches 192.5 billion m^3, with a 9.8% year-on-year increase of 16.326 billion m^3. According to data from the General Administration of Customs, in 2020, China's imports of 101.66 million tons of natural gas (about 140.3 billion cubic meters), increased by 5.3% compared to 2019. The external dependence on natural gas is about 43%, which is about 2% lower than that in 2019 [8].

It is estimated that biogas yield potential by 2060 will reach 371 billion m^3 in China, which is equivalent to replacing 68% of natural gas consumption from 2020, or more than 1.5 times the natural gas import volume of 2020. When all is used for power generation, it is equivalent to nearly 10% of the national electricity consumption in 2020. When all is converted into energy consumption, it is equivalent to nearly 6% of the national energy consumption of 2020 [9].

With the goal of carbon peak in 2030 and carbon neutrality in 2060, biogas industry has been given more importance. Biogas in China urgently needs industrial transformation with sustainable and profitable economic models. A common problem is that many established biogas projects are abandoned because they are not profitable. However, while there are research and achievements on technical feasibility, most academic papers focus on specific technology topics or analyze agricultural residues and methane potential of agricultural residues (which are used as a very good basis and reference for this research); see for example, Biogas: *"Potential, challenges, and perspectives in a changing* China" by Lu J and Gao X, *"Biogas Technology and the Application for Agricultural and Food Waste Treatment"* by Qiao W, Dong RJ et al. showing and discussing the development status and technology application of biogas in China, which is a good reference as background. *"Potential biomethane production from crop residues in China: Contributions to carbon neutrality"* by Sun H, Wang E et al.; *"Straw Utilization in China-Status and Recommendations"* from Ren J, Yu P and Xu X; *"Method Handbook—Material flow-oriented assessment of greenhouse gas effects"* by Daniela Thrän, Philipp Adler, Walter Stinner et al. provide a good basis for the technical-related calculation and methodology of this paper.

In recent years, biogas has rapidly developed in China, especially within the context of achieving peak carbon and carbon neutrality. The development of biogas projects is a crucial means for realizing agricultural carbon neutrality. Many scholars in China have conducted extensive research on biogas technology and policy planning. However, compared to the achievements of various scholars and predecessors in the technical field, research on the economic aspects of biogas operations in China is still very limited. The author has received unanimous feedback from several senior experts in the Chinese biogas field during discussions, highlighting this as a critical issue that urgently needs to be addressed for the industrialization of biogas in China. Industrial development needs theoretical support of scientific research. Based on the authors´ literature review, this paper initially raises the research topic of value creation of biogas in China and the following research questions:

– How much value and unit value can straw-based biogas create as an energy carrier in different energy usage options in China? It is necessary to investigate the economic potential and regional value creation of straw-based biogas in China. It is specifically necessary to assess how different usage forms of biogas (e.g. electricity production, transportation fuel, natural gas replacement) contribute to its economic value in various provinces, as well as to identify the most effective strategies for biogas implementation in order to maximize economic benefits and support decision-making in the biogas industry.

The aim of this study is:

1) To assess the potential of value creation based on agricultural residues in China at the regional level to support decision-makers in biogas implementation strategies. Therefore, the potential of agricultural residues and the related potential for biogas provision in China could be calculated on a regional scale. For the estimation of the potential contribution of biomethane, value creation calculation is the unanimous alternative choice based on the current energy price and subsidy when biogas substitutes fossil fuels in different energy sectors;
2) To show the whole picture of potential biogas value creation in each province in China for the past 10 years, and replacement of other energy forms, such as coal, LPG, natural gas, gasoline and diesel;
3) To compare unit value creation (1 m^3 methane creates how much value) of different usage forms, which would be helpful for the future development of biogas in different energy sectors;
4) The article demonstrates the value creation of different usage options of biogas or biomethane (electricity production, biomethane for traffic sector and for replacing natural gas or LPG, heat provision). There are big differences of up to 7.6 CNY/1.068 USD in the value creation per m^3 of methane. Hence, the results have a big impact on (a) the biogas industry, which could base feasible business strategies on it; (b) on the value creation for rural regions, which could create additional value from the current unused residue; (c) for policy makers, who can see the preferable usage and options for adjustment, if there is a higher need for biogas/biomethane energy in a special sector of energy use.

This paper raises value creation of biogas in China, and scientific methods as a reference for the first time. In the following research study that this paper is based upon, the authors go deeper and make comparisons between China and Germany in order to provide more discussion and references for the biogas industry development in China and other countries.

Methods

Agricultural regions and provinces of mainland China

Regions are divided geographically, politically, agriculturally, etc., in China based on agricultural division, which is more reasonable for assessing the usage of crop residues and value creation from this part. Different agricultural regions have different natural conditions, characteristics of grain cultivation, and grain/crop ratio.

The quantity of crop residues depends on crop type and the agronomic system. Due to official introduction, mainland China (Hong Kong, Macon and Taiwan) are not included in this division), 31 provinces are divided into six agricultural regions (Fig. 3) as follows from [11–13]:

- Northeast: Heilongjiang, Jilin, and Liaoning.
- North China: Beijing, Tianjin, Hebei, Inner Mongolia, Shanxi, Shandong, and Henan.
- Middle-lower Yangtze: Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, and Hunan.
- Northwest: Shaanxi, Ningxia, Gansu, Qinghai, and Xinjiang.
- Southwest: Chongqing, Sichuan, Guizhou, Yunnan, and Tibet.
- South China: Fujian, Guangxi, and Hainan.

Overall methodology

Calculation steps for value creation of biogas from crop residues:

Step 1: to calculate the crop residue potential and the available collectable crop residues at provincial and national levels from 2011 to 2020 based on crop production in *China's Rural Statistical Yearbook* from year 2012 to 2021 and the spatial grain–straw ratio in six agricultural regions [10–12];

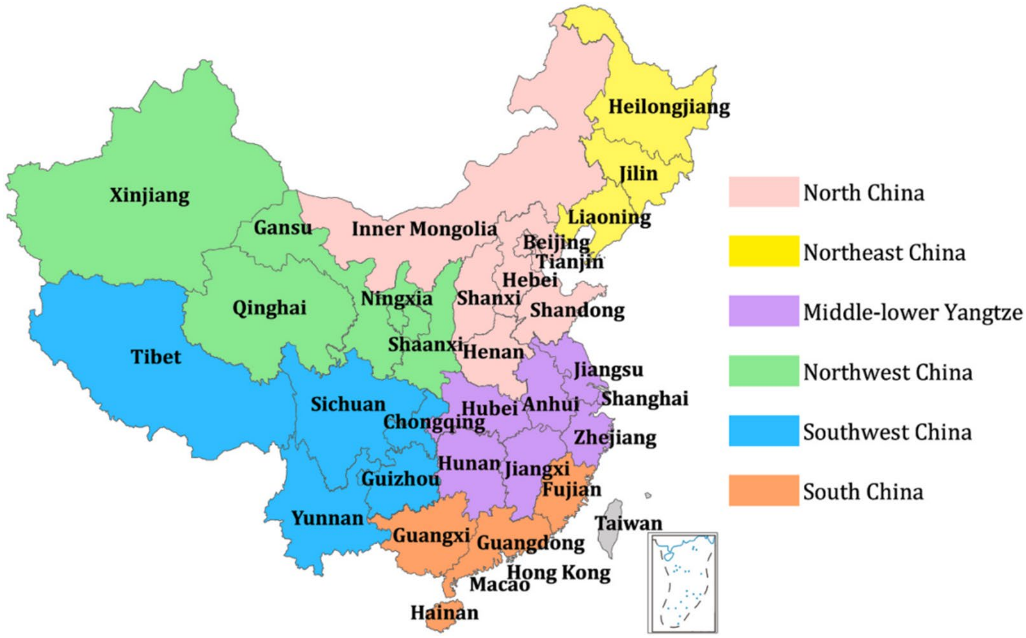

Fig. 3 Spatial distribution of six agricultural regions in mainland China [13]

Step 2: to calculate the biomethane potential from the available collectable agricultural residues at provincial and national level;

Step 3: to calculate the energy potential from biomethane considering the self-sufficient biogas production;

Step 4: to evaluate the substitution potential for coal, LPG, natural gas, gasoline and diesel;

Step 5: to assess the value creation potential for the different energy carriers;

Step 6: to compare the unit value creation (1 m^3 methane creates how much value) in different energy usage options.

Data source and methodology for calculating the crop residue potential and the available collectable crop residues

The methodology in 2.3. and 2.4. follows the study of Hui S, Enzhen W et al. [13].

Crop residue potential

Crop residue yield depends on crop yield and *grain–straw ratio*. Data of crop yield are taken from *China's Rural Statistical Yearbook* from year 2012 to 2021, which covers the data of 2011 to 2020. According to this literature, the crop production of early rice, middle-season rice and one-season late rice, double crop late rice, winter wheat, spring wheat, corn, beans, tubers, peanuts, and rapeseed by provinces in China in the past 10 years are used.

The grain–straw ratio (field residue index, FRI) [11, 12] in six agricultural regions of mainland China is listed in Table 2. The grain–straw ratio was used from the *Notice on the final assessment of planning for comprehensive utilization of crop straw*, which issued by *China's National Development and Reform Commission* [11].

$$Y_{cr} = Y_c \times I_{FR}, \tag{1}$$

where Y_{cr} = crop residue yield, Y_c= crop yield, I_{FR} = field residue index (Table 2).

Available straw potential

The theoretical crop residue yield cannot be directly used as an estimation for methane production. There is a certain amount of stubble when crop residues are harvested, and some crop residues are used as fodder and industrial materials, for example. Based on these two considerations, the available straw potential (technical potential) is calculated using the following Eq. 2, which is further used as the basis for methane calculation [13, 14]:

$$Y_{acr} = Y_{cr} \times F_C \times F_U, \tag{2}$$

where Y_{acr}= available crop residue yield, Y_{cr} = crop residue yield, F_C = collection factor of crop residue, F_U= utilization factor.

F_C is the crop residue collection factor of the official recommended values (see Table 2). F_U is set as 65% in the present study based on the assumption that the current reported share of the direct return as fertilizer (around 50%) and waste (around 15%) in China would be considered for anaerobic digestion to recover biomethane and apply the digestate as a fertilizer.

Table 2 Grain–straw ratio [11–13]

Region	North agricultural region	Northeast agricultural region	Agricultural region in middle and lower reaches of Yangtze River	Northwest agricultural region	Southwest agricultural region	Southern agricultural region
Early rice (HI)[1]	0.93	0.97	1.28	0.93	1.00	1.06
Mid-season rice and one-season late rice	0.93	0.97	1.28	0.93	1.00	1.06
Double crop late rice	0.93	0.97	1.28	0.93	1.00	1.06
Winter wheat	1.34	0.93	1.38	1.23	1.31	1.38
Corn	1.73	1.86	2.05	1.52	1.29	1.32
Beans	1.57	1.70	1.68	1.07	1.05	1.08
Tubers	1.00	0.71	1.16	1.22	0.60	1.41
Peanut	1.22	1.22	1.50	1.22	1.65	1.65
Rapeseed	2.05	2.05	2.05	2.00	2.00	2.00

HI = harvest index, related amount of straw per ton of harvested grain. Table 2 lists the grain–straw ratio of major crops in China in different agricultural regions

Data source and methodology for the calculation of biomethane and biogas yield

The available straw potential from the result in 2.3 and all the other indices for biomethane calculation were taken from official issued documents and the scientific paper which is listed in Table 2 and in the respective reference.

The potential of biomethane yield is calculated using Eq. 3 [13]:

$$Y_{\text{acr}} = Y_{\text{cr}} \times 0.85 \times Y_{\text{exb}}, \tag{3}$$

where Y_{acr}= the available crop residue yield, Y_{cr}=the crop residue yield, 0.85 is the dry matter content of crop residues, Y_{exb}= the expected specific biomethane yield.

In the above Eq. 3, the expected specific biomethane yield is the unit of biomethane yield from 1 kg dry matter of specific crop residues. It is calculated based on the following Eq. 4:

$$Y^{i}_{\text{esb}} = C^{i}_{\text{oc}} \times 50\% \times 22.41\ (\text{L/mol}) \times \text{coeff}, \tag{4}$$

where Y^{i}_{esb}= the expected specific biomethane yield $_{\text{i}}$ (m^3 /kg dry matter), C^{i}_{oc} = the organic carbon content $_{\text{i}}$ (% dry matter)/12.01 (g / mol), coeff = the degradation rate coefficient (%).

The organic carbon content (% dry matter) was set according to an extensive investigation reported by the National Agro-Tech Extension and Service Center [15] (Table 2); 12.01 g/mol is the molar mass of carbon; 50% is the assumed CH_4 content of biogas; and 22.41 L/mol is the molar volume of gas under standard conditions (273.15 K, 101.33 kPa). A degradation rate coefficient of 50% was applied in the present study in consideration of the refractory properties of crop residues [16–19] and based on a recent government announcement [20] that encouraged the development of technology and equipment for anaerobic digestion with an organic matter degradation rate of 50–75%.

The expected specific biomethane yield range of main crop residues was taken from the relevant literature, in the past case from Sun H, Wang E et al.'s summary mentioned in 2.3.

Methodology of energy substitution and value creation

Biogas is a multi-purpose fuel and can replace many other energies. Different usage options result in different value creation. In this paper, the methodology for energy substitution and value creation refers to and is based on energy content/calorific value of methane and each other fossil fuel (coal, LPG, gasoline and diesel), i.e. how much coal/LPG/gasoline/diesel can be theoretically replaced by methane. The calculations are based on following steps:

Step 1, to calculate *the amount of biomethane that can be used to replace other energy sources.*

Not all biomethane (the result is based on the methodology from 2.4.) yield can be used to replace other energy sources. In all cases without CHP, heat and electricity demand for self-use also ought to be integrated as the same in the calculation for the CHP plant. Based on the experts' experience in Germany, it is defined that 45% of electricity, and 10% among this, is only thought to be for own electricity demand; 45% of heat, and 1/3 of it for self-use heating, for a huge plant, 1 MW for the single engines or larger; for a small plant, 30 to 40%; 1 m^3 methane contains a 10-kWh heating value. The amount of biomethane which could replace another energy form is calculated using the following equation:

$$\begin{aligned} B^{p}_{R} &= B^{p} \times 90\% - B^{p} \\ &\times 45\% \times 10\% - B^{p} \times 45\%\ (\text{self - use electricity}) \\ &\times 0.333\ (\text{self - use heat}) = 0.705B^{p} \end{aligned} \tag{5}$$

where B_R^p = the amount of biomethane which could be used to replace fossil fuel in province p, B^p = the biomethane amount in province p, 45% is the self-use electricity and 0.333 is self-use heat.

In step 2, based on the calorific value/energy content, the unit energy replacement is calculated, which means 1 m^3 methane could replace how much other energy:

$$R_{\mathrm{ue}}^{f} = \mathrm{CV_m}(\mathrm{MJ/m^3})/\mathrm{CV_f}(\mathrm{MJ/Kg}) = X, \tag{6}$$

where R_{ue}^{f} = the unit energy replacement of fossil fuel f, CV_{m} = the calorific value of methane (MJ / m^3), CV_{f}= the calorific value of fossil fuel f (MJ/kg), X = result (1 m^3 methane could replace X kg f).

In step 3 how much energy could be replaced by biomethane is calculated in each type in total and for in each province

$$R_f^p = R_M \times X, \tag{7}$$

where R_f^p = the amount of fossil fuel f which is replaced by biomethane in province p, R_M = the replacement amount by biomethane, X = the results from Eq. 6.

Step 4, to calculate value creation

$$\mathrm{VC}_{f1,2,3}^{p} = R_f^p \times \mathrm{UP}_{f1,2,3}\ (\mathrm{yuan/kg}), \tag{8}$$

where p refers to which province, f 1,2,3 refers to the lowest, average and highest unit price of fossil fuel. VC = value creation, R = replacement, the result derived from step 3, UP = unit price.

For the unit price of fossil fuels (f), it changes frequently in a stable range before corona. Because of pandemic, the prices largely increased and were not stable in 2020 and 2021. In order to have a more objective analysis, in this paper, prices of LPG, natural gas, gasoline and diesel from 2018 and 2019 (before pandemic) are taken as a reference. *National Bureau of Statistics* issued *Changes in Market Prices of Important Means of Production in Circulation* three times every month, which covers the unit price at the beginning, in the middle and at the end of each month. The lowest, highest and average price among them (prices in 2018 and 2019; Appendix A) are taken as a reference for the calculation in this paper. The price in each province is not available.

Step 5, to calculate the unit value creation

$$\mathrm{UVC}_{f1,2,3} = \mathrm{VC}_{f1,2,3}/\mathrm{TM} \tag{9}$$

where $\mathrm{UVC}_{f1,2,3}$ = unit value creation of fossil fuel f in its lowest, average and highest unit price, $\mathrm{VC}_{f1,2,3}$ = maximal, average and minimal value creation of fossil fuel f, TM = total amount of biomethane.

In coal replacement by biogas for electricity and heat supply, the methodology is slightly different; unit price and subsidy are regulated by state and vary from province to province. This calculation is listed in detail in part Coal replacement by biogas and value creation and Heat supply from the combined heat and power plant (CHP).

Coal replacement by biogas and value creation

Biogas can replace coal for providing electricity and heat. The most commonly used biogas plant is the CHP plant. Based on the current biogas power operation, the electricity efficiency of biogas amounted from 38 to 40% in direct electricity production. In CHP plants, electricity efficiency is around 40%, and heat efficiency is around 40% to 42%. In this paper, electricity efficiency is defined as 40%, and heat efficiency is also defined as 40%. The self-energy use is normally between 6 and 15%, in this paper it is defined as 10%:

$$\mathrm{EG_p} = Y_{\mathrm{B}}^{p} \times \mathrm{EC_m} \times 40\%, \tag{10}$$

where $\mathrm{EG_p}$= electricity gross in province p, Y_B^p= the biomethane yield in province p, $\mathrm{EC_m}$ = the energy content of methane (9.97 kWh/m^3), 40% is the biogas electricity efficiency:

$$\mathrm{EN_p} = Y_{\mathrm{B}}^{p} \times \mathrm{EC_m} \times 40\% \times 90\%, \tag{11}$$

where $\mathrm{EN_p}$ = the electricity net in province p; $\mathrm{EC_m}$= the energy content of methane; 40% is the biogas electricity efficiency, and 90% represents the net electricity (minus 10% self-use).

The unit price of biogas-based electricity consists of two parts: basic price + subsidy (Appendix B). Basic price is set by each province, which is the same price as the desulfurization coal-fired-based electricity price in 2005 per province. Subsidy is set by the national standard, which is 0.25 yuan/kWh (3.57 cent/kWh). Hebei and Zhejiang provide more subsidy besides these two parts. The unit price in Hebei amounted to 0.75 yuan/kWh (0.107 USD/kWh), and the unit price in Zhejiang to 0.8 yuan/kWh (0.114 USD/kWh).

Basic value creation is only carried out from the unit price of the desulfurization coal-fired-based electricity price, and value creation is calculated from the current provincial price with subsidy:

$$\mathrm{BVC} = \mathrm{EN} \times \mathrm{BP}, \tag{12}$$

where BVC = basic value creation, EN = electricity net, BP= basic price

$$\mathrm{VC} = \mathrm{EN} \times (\mathrm{BP} + S), \tag{13}$$

where VC = value creation, BP=basic price, S= subsidy, for which, basic price and subsidy are listed in Appendix B.

$$\mathrm{UVC} = \mathrm{TVC}/\mathrm{TB}, \tag{14}$$

where UVC = value creation of biogas, TVC = total value creation, TB = total biomethane.

Coal replacement Electricity from biogas replaces part of coal-based electricity. How much coal it replaces is also part of biogas' value creation. In China, on average 1 kWh electricity consumes 308 g of standard coal. Coal replacement equals the total electricity gross multiple 308 g coal [21]:

$$R_\mathrm{c} = \mathrm{TEG} \times 308(g)\ \mathrm{coal}, \tag{15}$$

where R_c = coal replacement, TEG=total electricity gross.

Heat supply from the combined heat and power plant (CHP)

Based on the experience of German experts, for CHP biogas plants, heat efficiency is around 40 to 42%. In this paper, the heat efficiency is defined as being 40%. In the operation of biogas plants, self-using heat normally accounts for 20–80%, whereas in this paper, it is defined as being 50% in calculation. The part for outside supply or market sold for biogas production is around 20% (40%×50%) of total biogas production by each region. However, this definition in this paper is quite theoretical; in practical application, heat supply would be very different and much lower. Heat use is strongly bound to time, season and place. On the other hand, heat storage over longer time and heat transport are also expensive [22].

Heat sold from the CHP plant in the energy market is still quite small in China. There are only a few cases which could be taken as a reference. For example, Beijing Deqingyuan Agriculture Technology Co. Ltd (Deqingyuan Agriculture) is an ecological agribusiness, which is the best example of a large-scale biogas plant in China. Deqingyuan is located in Yanqing District, Beijing. It is an integrated ecological enterprise running chicken farm, high-quality egg production, and biomass energy. It is the biggest chicken farmhouse in Asia, and the biggest chicken manure-based biogas plant in China, with 3 million chickens, producing 220 tons of manure and 170 tons of wastewater each day. Deqingyuan sells electricity and fertilizer as income, and provides heat for free to inhabitants nearby [23].

In Hebei Province, the unit selling price is around 2.2 yuan/m^3 (0.314 USD/kWh) [24]. In this paper, this unit price is used as a reference nationally (which is also quite theoretical, since the options of using biogas heat greatly vary among the different provinces). The value creation from biogas heat supply and coal replacement per region are calculated from following formulae:

$$A_\mathrm{h} = \mathrm{TM} \times 55(\mathrm{MJ/kg}) \times 20\%, \tag{16}$$

where A_h= amount of heat supply from biogas, 55 MJ/kg is the energy content of methane, 20% is defined as exhaust heat in the CHP plant.

In China, 1 kWh electricity consumes 308 g coal

$$R_\mathrm{c} = A_\mathrm{h} \times 308(\mathrm{g})\ \mathrm{coal}, \tag{17}$$

where R_c = coal replacement, A_h = amount of heat (kWh).

Since heat sold from biogas plants is still small, and in most cases, the heating price depends on the size of the room, the unit price of heating given per cubic meter of the room size cannot be used. The unit price of standard coal is available, so that total value creation from biogas heat could also be calculated via coal replacement. The unit price of standard coal in China is:

$$\mathrm{TVC} = R_\mathrm{tc} \times \mathrm{UP}_\mathrm{sc}, \tag{18}$$

where TVC=total coal replacement, UP_sc = unit price of standard coal.

Biogas as a liquefied petroleum gas replacement

Energy content of methane is defined to be 55 MJ/kg, energy content of LPG as being 46 MJ/kg. Based on Eq. 6, 1 m^3 methane can replace 1.196 kg LPG; the lowest, average and highest unit price of LPG is 1.4 yuan/kg, 1.73 yuan/kg and 2.34 yuan/kg (0.2/0.25/0.33 USD/kg), respectively [25, 26]; the amount of biomethane which can replace LPG is 0.705 of biomethane yield in each province. Equations 7–9 allow the minimal, average and maximal value creation of LPG replacement per province in China from 2011 to 2020, and the related unit value creation to be calculated.

Biomethane as natural gas replacement

Biomethane can directly replace natural gas. The current domestic price of bio-natural gas is around 4–5 yuan/m^3, the domestic residential natural gas price is 2–3 yuan/m^3; the industrial gas price is 3–5 yuan/m^3 [27]. In this paper, the lowest price, 2 yuan /m^3 (0.286 USD/m^3) was taken as the unit price for minimal value creation, and the highest price, 5 yuan/m^3 (0,714 USD/m^3) is taken as the unit price for maximal value creation, where 4.5 /m^3 (0.643 USD/m^3) is the average price. Based on Eqs. 7–9, unit value creation of natural gas replacement was calculated.

Biogas as vehicle fuel replacement

Biogas as gasoline replacement The energy content of methane is defined as being 55 MJ/kg, the energy content of gasoline amounts to 43.4 MJ/kg. 1 m^3 methane can replace 1.267 kg gasoline (Eq. 6); the amount of biomethane which can replace gasoline is 0.705 of biomethane yield in each province (Eq. 5). The lowest, average and highest unit price of gasoline amounted to 6.18 yuan/kg, 7.35 yuan/kg, 9.14 yuan/kg (0.883/1.05/1.306 USD/kg). Equations 7–9 allow minimal, average and maximal value creation of gasoline replacement per province in China from 2011 to 2020, and the related unit value creation to be calculated.

Biogas as diesel replacement The energy content of methane is defined as being 55 MJ/kg, the energy content of diesel amounts to 42.6 MJ/kg. Based on the methodology in 2.5., 1 m^3 methane can replace 1.291 kg gasoline (Eq. 6); the amount of biomethane which can replace gasoline is 0.705 of biomethane yield in each province (Eq. 5). The lowest, average and highest unit price of gasoline amounts to 5.68 yuan/kg, 6.38 yuan/kg and 7.77 yuan/kg (0.811/0.911/1.11 USD/kg), respectively [25, 26]. Equations 7–9 allow minimal, average, and maximal value creation of gasoline replacement per province in China from 2011 to 2020, and the related unit value creation to be calculated.

Results

Biomethane potential from straw per province

From 2011 to 2020, the total methane potential from straw in China reached from 6.98×10^{10} to 8.19×10^{10} m^3. Below in Fig. 4 the biomethane potentials from straw per province in China are shown from 2011 to 2020. Major food producing provinces like Heilongjiang, Henan and Shandong rank top, while Tibet, Beijing, Hainan and Shanghai are provinces with the lowest methane potential. Based on the results for methane production compared to straw production using statistical data, there is a positive correlation between methane production and straw production evident.

Value creation and coal replacement for biogas-based electricity

From 2011 to 2020, total value creation of biogas to electricity is continuously increased due to the increasing yield of crop residues. The basic value creation (without subsidy) from biogas electricity in China reached from 7.479×10^{10} yuan, (1.068×10^{10} USD) yuan to 1.335×10^{11} yuan (1.907×10^{10} USD), and the value creation with subsidy from 1.3×10^{11} yuan (1.857×10^{10} USD) to 1.564×10^{11} yuan (2.234×10^{10} USD). Value creation in province Heilongjiang yielded the highest and in Beijing is lowest value which has also a positive correlation with methane yield/straw production. Basis value creation and value creation with subsidy per province in China from 2011 to 2020 is listed in Appendix C1.

The electricity part reflected that the value creation depends not only on provincial biogas electricity production, but also largely on the unit electricity price which is set provincially and varies. Higher prices promote better development of biogas-based electricity and also higher value creation in the energy market, such as Zhejiang province.

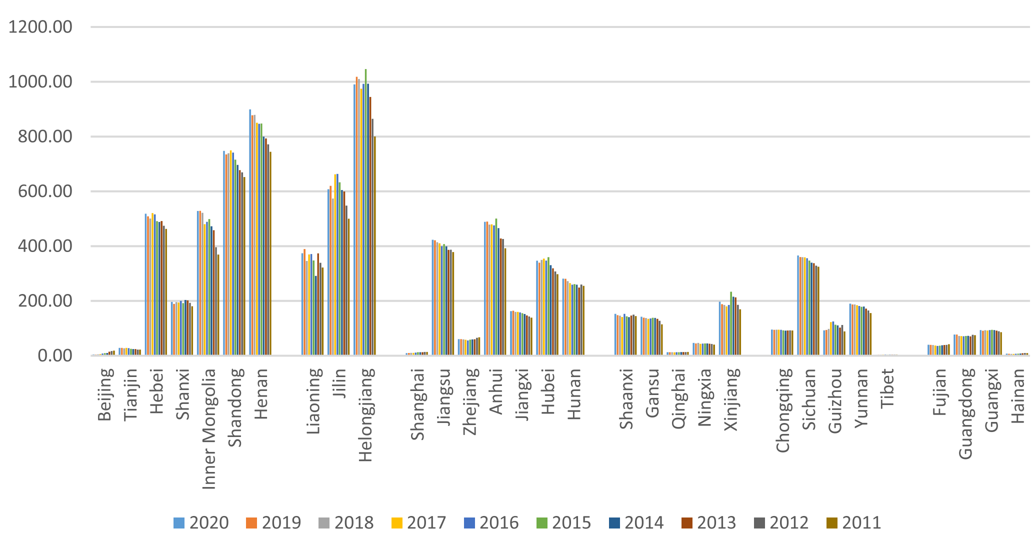

Fig. 4 Methane potential from straw per province in China from 2011 to 2020 (10^7 m^3)

For coal replacement, from 2011 to 2020, biogas replaces 7.715×10^{10} kg to 9.052×10^{10} kg coal. Heilongjiang, Henan and Shandong show the highest and Tibet, Beijing, Hainan and Shanghai the lowest values in 2020.

Value creation and coal replacement in heat supply by the combined power and heat plant

As mentioned in the methodology, heat supply from biogas is still quite small in China, then there is insufficient reference of heat price. Value creation in the heat supply part is calculated from coal replacement and the unit price of standard coal in China. From 2011 to 2020, biogas could replace 4.286×10^{10} to 5.029×10^{10} kg coal. Value creation of biogas heat supply in each province in China from 2011 to 2020 is listed in Appendix C2, in which province Heilongjiang showed the highest, while Tibet indicated the lowest.

Value creation in liquefied petroleum gas replacement

From 2011 to 2020, biogas replaces 5.884×10^{10} to 6.904×10^{10} kg LPG. Based on the replaceable methane yield and the unit price of LPG, 1.4/1.73/2.34 yuan/kg (0.2/0.25/0.33 USD/kg), the lowest value creation reached from 8.238×10^{10} yuan (1.177×10^{10} USD) to 9.666×10^{10} yuan (1.381×10^{10} USD); the average value creation from 1.018×10^{11} yuan (1.454×10^{10} USD) to 1.195×10^{11} yuan (1.707×10^{10} USD); and the highest value creation from 1.377×10^{11} yuan (1.967×10^{10} USD) to 1.616×10^{11} yuan (2.309×10^{10} USD). Potential LPG replacement and minimal, average and maximal value creation for LPG replacement is listed for each province in China from 2011 to 2020 in Appendix C3.

Value creation in vehicle fuel replacement

Value creation in vehicle fuel replacement of gasoline

From 2011 to 2020, biomethane can replace 6.234×10^{10} to 7.314×10^{10} kg gasoline. Based on the unit price of gasoline, 6.18/7.35/9.14 yuan/kg, (0.883/1.05/1.306 USD/kg), the lowest value creation of biogas to gasoline reached from 3.852×10^{11} yuan (5.503×10^{10} USD) to 4.52×10^{11} yuan (6.457×10^{10} USD); the average from 4.582×10^{11} yuan (6.546×10^{10} USD) to 5.376×10^{11} yuan (7.68×10^{10} USD); and the highest value creation of biogas to gasoline from 5.679×10^{11} yuan (8.113×10^{10} USD) to 6.685×10^{11} yuan (9.55×10^{10} USD). In Appendix C4, the lowest, average and highest value creation of gasoline replacement is listed per province from 2011 to 2020.

Value creation in vehicle fuel replacement of diesel

From 2011 to 2020, biomethane can replace 6.352×10^{10} kg to 7.453×10^{10} kg diesel. Based on the unit price of diesel (5.68/6.38/7.77 yuan/kg, 0.811/0.911/1.11 USD/kg), the lowest value creation of biogas to diesel reached from 3.608×10^{11} yuan (5.154×10^{10} USD) to 4.233×10^{11} yuan (6.047×10^{10} USD); the average from 4.052×10^{11} yuan (5.789×10^{10} USD) to 4.755×10^{11} yuan (6.793×10^{10} USD); and the highest value creation of biogas to diesel from 4.935×10^{11} yuan (7.05×10^{10} USD) to 5.791×10^{11} yuan (8.273×10^{10} USD). In Appendix C5, the lowest, average and highest value creation of diesel replacement is listed per province from 2011 to 2020.

Discussion

Comparison of value creation

In the above chapters, value creation and energy substitution nationally and provincially have been analyzed and discussed, which helps to address the picture of value creation of biogas. The question is now "in which form of usage" does biogas create the highest value. The ratio of energy content between other energy replacements and methane is fixed. Hence, the unit value creation is the same in every year. In this part, the unit value creation

Table 3 Comparison of the unit value creation of biomethane

Unit value creation (CNY/m^3 methane)	Biogas-based electricity (basic/with subsidy)	Biogas-based heat	LPG replacement	Natural gas replacement	Gasoline replacement	Diesel replacement
Unit value creation (CNY/m^3)	1.08/1.90	0.56	1.18/1.46/1.97	1.41/3.17/3.53	5.52/6.57/8.16	5.17/5.81/7.07
Unit value creation (Euro/m^3)	0.146/0.257	0,076	0.159/0.197/0.266	0.191/0.428/0.477	0.746/0.888/1.103	0.699/0.785/0.955
Unit value creation (USD/m^3)	0.154/0.271	0.08	0.169/0.209/0.281	0.201/0.453/0.504	0.789/0.939/1.166	0.739/0.83/1.01

Based on the currency in December 2022, 1 euro = 7.40 CNY/yuan; 1 dollar = 7.00 CNY/yuan of biogas to electricity, of the heat supply from biogas, of biogas for replacing LPG, of biogas for replacing natural gas, of biogas for replacing gasoline and diesel as a vehicle fuel is presented. It is also shown in which form of usage it created the highest value, and which energy form allowed for creating the lowest value.

The results listed in Table 3 indicated that:

1) The available straw potential has positive correlation with food production. The province with the highest amount of food production also has the highest technical straw potential and methane potential, such as China's famous agricultural provinces, Heilongjiang, Henan, Shandong, for example. When the same price is used as a reference, the value it created is also the largest. In the electricity part, a higher provincial bonus also plays an important role for a higher value creation (Supplementary B, *Desulfurization electricity price and subsidy by province*; Supplementary C, Value creation of biogas by province as electricity, heat, LPG, gasoline and diesel).
2) Under the current framework conditions, the value creation by using biogas from straw as traffic fuel is higher than using biogas for electricity generation, heat supply, or for natural gas and LPG replacement. Using biogas as gasoline replacement showed a higher value as diesel replacement (Table 3 *Comparison of the unit value creation of biomethane*; Supplementary C, Value creation of biogas per province in the form of electricity, heat, LPG, gasoline and diesel).
3) Based on this result, we can conclude that for an average biogas plant, the value creation of vehicle fuel would mean more than electricity and heat for the CHP. It hence represents a micro-economic analysis under the given framework conditions.
4) This comparison does not consider the technological options in the different energy sectors and the priorities of the governmental politics. For example, the government could set GHG-emissions reduction as a first priority or also a reduction of dependency on imports to reduce vulnerability of the country in energy imports, or a reduction of air pollution or lowest cost strategies or smooth adjustments, or also the pushing of technology in energy efficiency (EE) and renewable energy (RE).
5) The priority setting will have consequences on the best use of biogas. With the given results, it is possible to adjust the framework conditions to lead the biogas to the preferred pathways, however, to do this in the best way needs a very good understanding of the energy sectors and its interactions, regarding technology, framework conditions, spatial and time related restrictions.
6) Based on the Chinese experts´ opinions, biogas engineering becomes a main tool for achieving agricultural carbon neutrality. However, the biogas industry in China is not sufficiently marketed, and a large number of projects do not have a viable economic model with significant benefits. This paper raises the importance of value creation of biogas as an energy carrier for the first time and helps to show a more complete picture for stakeholders, and, last not least, it aims to build a good bridge between research and industry development [7, 8, 13].
7) When the biogas industry in China is discussed, it is in most cases with regard to its technical feasibility. An update of framework conditions is also in progress, however, the value creation of biogas as an energy carrier has been long under-evaluated or not been considered explicitly. In consequence, this blind spot has led to short-comings in assessments and decision-making in the past. With this study, the authors recommend to provide and use additional biogas from residues to unlock the additional potential for value creation. Evaluation, analysis and comparison of value creation of biogas in China is not only an important insight for China, but also could be a reference to other countries, particularly to developing countries.

Indirect value creation

The gap between urban and rural areas in China is still large. Therefore, biogas development not only relates to energy supply and pollution control, but also to *rural vitalization*, which is an important topic in China, like the related food security and rural youth employment, for example. This paper points to and discusses the importance of biogas in the social-economic part, which could be a reference for policy makers and local industry. Besides direct value creation in the energy market and fossil fuel replacement, it provides work opportunities for both well-educated and less-educated people. For example, in the biogas plant management part, it provides jobs for well-educated people with specific background. However, in agricultural residue collection, transportation, etc., it provides jobs for less-educated people which helps to encourage more young people to remain in the countryside. Development of the countryside could also support food security [28].

Conclusions

The novelty of the research is that this paper initially raises the research topic, calculation methodology and discussion of value creation of biogas in China, addresses an important but long-neglected topic by building on data from the past 10 years to conduct a detailed analysis and comparison of the value creation of straw-based biogas in various energy sectors in China. The results show that value creation for vehicle use is the highest, which reached 5.52/6.57/8.16 yuan/m^3 methane (0.789/0.939/1.166 USD/m^3) as gasoline replacement, and 5.17/5.81/7.07 yuan/m^3 methane (0.699/0.785/0.955 USD/m^3) as diesel replacement; followed by the substitution of natural gas, and LPG; the current most common use, electricity generated by the CHP plant has a relatively low value, which amounted to 1.08/1.90 yuan/m^3 methane (0.154/0.271 USD/m^3); the heat supply, however, showed the lowest value, which amounted to only 0.56 yuan/m^3 methane (0.08 USD/m^3). This also leads to the discussion of biogas as an energy carrier in different usage options. The study presented concretely and vividly, how much value is contained in one unit of methane. It not only provides a reference for scientific research, but also for the business model of the biogas industry. The research results showed that value creation in vehicle use has the highest, and in electricity and heat supply is relatively low value. Additionally, the paper provides essential data for further research and serves as a robust methodological reference for biogas development not only in China but also in other developing countries. By highlighting these aspects, the paper greatly contributes to the understanding of the potential and challenges of biogas as a renewable energy source, which has irreplaceable features and advantages.

In the context of China's carbon neutrality goal and rural revitalization initiatives, this work offers a comprehensive overview of the biogas industry for researchers and stakeholders. It is particularly valuable for those involved in industry development and the formulation of business models. Biogas has a long history in China, and its scale has gradually expanded. Especially in the past 15 years, with the support of policies and the joint efforts of the industry, it has achieved rapid development. However, the industrialization of biogas is still in its early stages. China's biogas industry has experienced ups and downs over the past two decades, with various challenges pointing to misplaced expectations that biogas technology is overly focused on energy production. With the promotion of China's low-carbon strategy, a more rational and sustainable transformation strategy is crucial for the development of the biogas industry [29]. According to the conclusions of this article, especially in the field of creating higher value biogas to replace oil and diesel as a fuel, it is still quite small in the Chinese energy market. Accurate policy subsidies and business models are also very important for the development of the biogas industry, the study's new findings on the value of biogas are of significance to both the policy subsidies and business models of the biogas industry. The author will further discuss this in the following research paper [30–35].

Abbreviations

LPG	Liquefied petroleum gas
CHP	Combined heat and power plants
CNY	Chinese yuan renminbi
USD	The United States dollar
EE	Energy efficiency
RE	Renewable energy

Supplementary Information

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Supplementary Material 1

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Author contributions

YMC and WS conceived the presented ideas and all developed the research idea. WS and DT supervised the whole research. YMC contributes to manuscript writing, data collection and analysis. DT contributes to paper structure. All contribute to methodology, manuscript modification. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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