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The biomethane producing potential in China: A theoretical and practical estimation☆

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A B S T R A C T

Biomethane has been developed rapidly in many countries as a renewable energy which upgraded from biogas. China also began to pay attention to it even though we still at a initial stage, primarily, understanding the biomethane potential and development prospect, choosing appropriate biomass as the biomethane source is very important. In this work, the theoretical and practical biomethane producing potential from five main biomass resources in China were estimated with appropriate methods based on the data collected, and during calculation, two appropriate energy crops were assumed to be planted on marginal lands for biomethane production. Our estimation showed that the theoretical and practical biomethane potentials in China can reach to 888.78 and 316.30 billion m^3 per year, agricultural waste should be the preferential development biomass, and planting energy crops on marginal lands is the most promising way to enhance biomethane production in China. Finally, biomethane is compared with natural gas, and the result showed that 48.15% of the practical biomethane potential can meet the total Chinese natural gas consumption in 2013.

1. Introduction

Nowadays, the fossil fuels, especially coal, are still the main energy resources in China. In 2014, a total of 4.26 billion ton standard coal contributed 66% of the primary energy consumption. This heavy energy dependence on coal results in both serious environmental impacts [1]. Natural gas as a clean energy is an ideal substitute of coal, which can reduce dramatically environmental damage. In 2014, the amount of natural gas consumed in China was 190 billion m^3, which is only 5% of the total energy consumption. Another limitation is that, about 30% of the consumed natural gas was imported from other countries [2]. According to the Chinese energy development strategy (2014–2020), the proportion of natural gas in primary energy sector needs to be increased 10% by 2020, which corresponds to a production of 400 billion m^3 natural gas in 2020 [3]. It is of great importance to estimate the natural gas production potential in China and explore different resources to produce natural gas.

Among different natural gas resources, biomethane is considered as a very promising one and has been developed rapidly in many countries. Germany began to develop biomethane from 2006, and after years of study, there had been 107 biogas plants engaged in the biomethane production by 2011 [4]. In Sweden, there had been more than 120 biomethane gas filling stations and 40000 biomethane cars were built up, and biomethane consumption had accounted for 10% of the national nature gas consumption by 2010 [5]. The number of biomethane gas filling stations was increased from 60 to 100 in Switzerland in 2005–2008, and Swiss Gas Industry Association had signed an agreement with Biogas Association, to make some cost discount for biomethane incorporating into natural gas pipe network [6]. And the development of biomethane production also has received an increasing attention in China for the past few years [7]. Biomethane is the fuel that obtained from biogas after removal of CO_2 and H_2S, also called biological natural gas. The methane concentration in biomethane can reach up to 95%–97% and meet the Chinese natural gas standard (GB 17820-1999), so that biomethane can be used as vehicle fuel gas or incorporated into natural gas pipe network as the substitute natural gas [8,9]. Biogas is obtained from the low-grade biomass anaerobic fermentation process, and the low-grade biomass is commonly used as substrates, including livestock manure [10], straw [11], municipal solid waste [12] and sewage sludge [13,14]. Some studies already investigated the biogas potential in China. Tian [15] estimated the biogas production potential based on the amount of livestock manure from large-scale farms in China in 2009, they concluded a biogas production potential of 47.21 billion m^3 per year. Zhang *et al.* [16] estimated that the biogas production potential was 119.844 billion m^3 in China in 2009 from all excrement, among which 24 billion m^3 was from large- and medium-sized livestock and poultry breeding farms. Chang *et al.* [17] evaluated

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the biogas potential of crop straw and livestock manure through time-series and geographical approach, indicated the great regional differences in biogas potential between districts and provinces in China, and the most part of total biogas potential in China is allocated among Mid-South district, East district and South West district. And an international collaboration between China and Denmark was carried out to estimate the biogas production potential in 2011, the study considered resources such as livestock manure, municipal solid waste and sewage sludge. The biogas production potential was estimated to be 206.8 billion m^3 (124.08 billion m^3 biomethane) in 2009 [18]. However, in the above studies, the biogas potential was just estimated according to the current digestion technology in China, which was a more practical potential. When considering the development of technology, the efficiency of anaerobic digestion process can be increased, and the potential will be improved. On the other hand, many studies just considered the common low-grade biomass in China, the potential of energy crop has never been estimated. To increase the biomethane production, energy crops have been considered to be the better choice for its high biogas productivity and yield, and the broad marginal land resources are good place for energy crop planting, due to the large population and a very limited cultivated land in China [19–21].

In this work, based on the updated data collected from traditional biomethane production, the theoretical and practical biomethane potentials in China were estimated with appropriate methods (Buswell formula for the agriculture waste and energy crop, IPCC formula for the municipal solid waste and sewage sludge). And different with previous work, two appropriate energy corps were chosen from the screening process designed, and assumed to be planted on the marginal land to get the biomethane potential of energy crop in China. We hold that agricultural waste should be the preferential development biomass, planting energy crops on marginal lands is the most promising way to enhance biomethane production, developing biomethane is a promising way for energy supplement in China.

2. Estimation Methods

2.1. Theoretical and practical biochemical methane potentials

In this work, the theoretical biochemical methane potential (TBMP) represented the maximum biomethane yield per volatile solid (VS). To get the TBMP, the organic carbon in biomass was assumed to be transferred into CH_4 and CO_2 completely during the anaerobic digestion process, which were the two main composition of biogas. In this respect, a formula was firstly proposed to simulate this extreme hypothesis by Buswell and Mueller based on the element compositions of different biomass [22], and this formula was also cited in some other studies. Møller *et al.* [23] used the Buswell formula to calculate the theoretical methane potential of different specific organic components in biomass, and Li *et al.* [24] studied the methane production of three organic wastes during a batch anaerobic digestion process, and the Buswell formula was used to calculate the theoretical methane yield of organic wastes. In the Buswell formula, the distribution ratio of organic carbon in CH_4 and CO_2 was determined *via* one mole of biomass with a known elementary composition, and the theoretical production of methane was calculated according to Eqs. (1) and (2):

$$C_aH_bO_cN_d + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4}\right) H_2O \rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8}\right) CH_4 + \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8}\right) CO_2 + dNH_3 \quad (1)$$

The TBMP can be calculated by Eq. (2):

$$\mathrm{TBMP} = \frac{V_m \cdot \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8}\right)}{12.011a + 1.008b + 15.999c + 14.007d} \quad (2)$$

where V_m is the molar volume of methane at standard temperature and pressure.

When considering the actual digestion conditions, biomass can't be degraded completely by microorganism during the digestion process, so in order to get the practical biochemical methane potential (PBMP), an important factor needs to be taken into account, namely the biodegradability (BD) [25]. During the research process, Labatut *et al.* [26] thought that the extent of such an effect tends to be correlated with the composition in biomass. Triolo *et al.* [27] studied the relationship between biomethane potential and different compositions (lignin, neutral detergent fibers, acid detergent fiber, cellulose), they reported that the lignin content in volatile solid was the most important parameter for predicting biochemical methane potential of all kinds of biomass. And Li *et al.* [28] conducted a series of biomethane potential assay of many organic substrates (mesophilic digestion, VS concentration: 3 $g \cdot L^{-1}$), to study the relationship between the lignin content and the biodegradability. After a series of data analysis, they observed a good linear correlation between lignin content and the biodegradability (BD) for the lignocellulose and manure wastes, this could be used as a fast method to predict the biodegradability of fiber rich substrates. In this work, we used this linear correlation (Eq. (3)) to estimate the BD of crop residue, livestock manure and energy crop:

$$\mathrm{BD} = 80.4 - 2.7 \times C_{\mathrm{Lignin}} \quad (3)$$

where C_{Lignin} is the lignin content (wt% VS) of different biomass.

Then the PBMP can be calculated from TBMP and BD by Eq. (4):

$$\mathrm{PBMP} = \mathrm{TBMP} \times \mathrm{BD}. \quad (4)$$

2.2. Biomethane potential of crop residue

The biomethane potential of crop residue depends on their production and biochemical methane potential (BMP). The production of crop residue can be calculated based on the crop yield, straw grain ratio of different crop and the general crop residue collection rate.

In this work, the biomethane potential of crop residue was calculated by Eq. (5):

$$Y_{\mathrm{bmc}} = \sum_{i}^{n} Y_{ci} \times \mathrm{SGR}_i \times \mathrm{CR}_i \times \mathrm{VS}_i \times \mathrm{BMP}_i \quad (5)$$

where Y_{bmc} is the biomethane potential of crop residue, representing the theoretical (Y_{tbmc}) or practical (Y_{pbmc}) biomethane potential, billion m^3; Y_c is the yield of crop, 10^4 ton; SGR is the straw grain ratio; CR is the residue collection rate; and BMP can be the theoretical (TBMP) or practical (PBMP) biochemical methane potential, L $CH_4 \cdot (g\ VS)^{-1}$.

2.3. Biomethane potential of livestock manure

The biomethane potential of livestock manure was calculated based on the manure production and BMP. Different with crop residue, the production of livestock manure depends on the yield of livestock, excretion coefficient, livestock raising cycle and the general manure collection rate.

In this work, the biomethane potential of crop residue was calculated by Eq. (6):

$$Y_{\mathrm{bml}} = \sum_{i}^{n} Y_{li} \times P_i \times T_i \times \mathrm{CR}_i \times \mathrm{VS}_i \times \mathrm{BMP}_i \quad (6)$$

where Y_{bml} is the biomethane potential of livestock manure and can be the theoretical (Y_{tbml}) or practical (Y_{pbml}) biomethane potential, billion m^3; Y_l is the yield of livestock, 10^4 capita; P is the livestock excretion coefficient, $\mathrm{kg} \cdot \mathrm{capita}^{-1 \cdot \mathrm{d}}{}_{-1}$; and T is the livestock raising cycle, d.

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