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ORIGINAL PAPER

Where is the future of China's biogas? Review, forecast, and policy implications

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Abstract This paper discusses the history and present status of different categories of biogas production in China, most of which are classified into rural household production, agriculture-based engineering production, and industry-based engineering production. To evaluate the future biogas production of China, five models including the Hubbert model, the Weibull model, the generalized Weng model, the H–C–Z model, and the Grey model are applied to analyze and forecast the biogas production of each province and the entire country. It is proved that those models which originated from oil research can also be applied to other energy sources. The simulation results reveal that China's total biogas production is unlikely to keep on a fast-growing trend in the next few years, mainly due to a recent decrease in rural household production, and this greatly differs from the previous goal set by the official department. In addition, China's biogas production will present a more uneven pattern among regions in the future. This paper will give preliminary explanation for the regional difference of the three biogas sectors and propose some recommendations for instituting corresponding policies and strategies to promote the development of the biogas industry in China.

Keywords Biogas production · China · Temporal–spatial · Forecast · Policy

1 Introduction

When faced with a global energy crisis, we have seen considerable efforts and progress in exploring effective and sustainable energy during recent years. Among different types of energy, biogas is regarded as an important and versatile one that not only is a sustainable fuel source for producing electricity, heat, or driving power, but it also has multiple advantages in environment improvement, greenhouse gas reduction, carbon capture, and fertilizer production, even social benefits like cost and labor saving in some cases (Cheng et al. 2011; Barnhart 2013; Gosens et al. 2013; Zhang et al. 2013). Therefore, biogas is widely used in both developed and developing countries nowadays.

Due to different natural resource endowments, climate conditions, technologies and industrialization development levels, and socioeconomic status, the production of biogas varies among different cases. According to the statistical data by the International Energy Agency (IEA), the entire biogas production of the world was about 42 Giga cubic meters in 2008 (IEA 2010). In detail, the countries of the Organization for Economic Co-operation and Development

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(OECD) have an annual production of 27 Giga cubic meters; non-OECD countries produce approximately 15 Giga cubic meters biogas a year. Some European countries like Germany represent the advanced level of biogas production in the world, not only in production amount, but also in technology and policy frameworks (Poeschl et al. 2010). The utilization of biogas shows a number of diverged functions and has achieved a high level of industrialization and commercialization in OECD countries (GARR 2012; U.S.EPA 2015; Couture and Gagnon 2010; FIT 2012), such as electricity production, biogas vehicles, and other transport systems (SEA 2012; Fallde and Eklund 2015; Olsen et al. 2013; NIFU 2015; Gildas 2010; Bojesen et al. 2014). Recently, some crucial changes have happened in biogas production among those countries: some Central or East European countries including Poland, Hungary, Slovakia have made fast progress in biogas development; the number of biogas power stations continues to grow in a steady rate in Sweden, UK, and Denmark, but the biogas industries in Germany, Austria, and Italy have gradually stagnated in the past few years. As the biggest contributor in Europe, the stagnation of Germany's biogas industry may have a strong influence on Europe as a whole. Thus, the European Biogas Association believes that the future is not bright for biogas development in Europe (EBA 2014).

Biogas production in developing countries varies greatly. The data from the IEA show that only 36 % of the total biogas is produced by non-OECD countries. China produces 98.4 % of biogas among the non-OECD countries in 2008 (IEA 2010). Most of developing countries have just accelerated their pace to develop their biogas industries in recent years. Factors such as industry structure and socioeconomic status have direct influence on biogas production and its dissemination. As a result, in such countries as China, India, Nepal, and Bangladesh, small-scale and economic domestic biogas plants have become the mainstream of biogas technology and are widely used by people in rural areas in the household mode (Tomar 1995; Bhat et al. 2001; Singh and Maharjan 2003; Alam 2008; Gautam et al. 2009; Chen et al. 2010; Dimpl 2010). The main materials for household biogas plants are livestock manure, human excreta and agriculture residues, among which livestock manure (pig or cow) plays a crucial part in biogas generation (Bond and Templeton 2011; Kabir et al. 2013). Some research indicates that there are many potential resources for creating biogas in developing nations, but with hurdles such as socioeconomic factors, climate conditions, technology, and institutional frameworks (Jiang et al. 2011; Mwirigi et al. 2014). A traditional domestic biogas plant primarily creates cooking fuel and fertilizers for farmers, but seldom generates electricity or fuel for market use. However, in recent years, medium- or large-scale multi-purposes biogas plants have been introduced and developed in countries such as China, Brazil, and India (Jiang et al. 2011; Coimbra-Araújo et al. 2014; Singh and Jash 2015), and have gradually closed the gap with developed countries in biogas productivity in the past few years.

2 Overview of biogas development in China

2.1 History of China's biogas development

China is one of the earliest countries that has developed and utilized biogas for almost a century. By the end of the nineteenth century, simple biogas digesters had appeared in the coastal areas of Southern China. In the 1920s, Luo Guorui in Taiwan has created the first water-pressure biogas digester (He et al. 2013). It was not until the 1970s that millions of household biogas tanks were installed in rural areas, when China's government first set up measures to extend biogas use to overcome the energy shortage in rural areas. Since the 1980s, the development of biogas infrastructure had been included into the national long-term development program by the central government of China (Jiang et al. 2011).

After the 1990s, due to the deep implementation of open and reform policy, China has experienced fast acceleration in industrialization and urbanization, accompanied by environmental deterioration and sharply rising energy demand. As a consequence, China has become one of the world's top energy-consuming countries, together with a rapidly degrading eco-environment (China's National Energy Administration, NEA 2012).

From 2003, the national debt aid program has supported a new round of biogas promotion, especially for rural biogas implementation by the Ministry of Agriculture (MOA) of China (MOA 2002, 2003). The central government of China paid much more attention to biogas development by offering direct financial support, from 1000 million CNY (China Yuan) in 2003–2005 to 2500 million CNY in 2006–2007 with increasing focus on biogas engineering projects after the "Renewal Energy Law" implemented in 2006 (NPC 2005; MOA 2007). The support and aid reached to 5000 million CNY in 2010, leading to a drastic rise of biogas users in the first decade of twenty-first century: from 11 million family users in 2003 to 43 million in 2013, and from 2300 biogas engineering projects in 2003 to nearly 10,000 projects in 2013 (calculated from data reported by MOA; several years used). Production capacity by household biogas digesters increased from only 4.5 Giga cubic meters in 2003 to 16 Giga cubic meters in 2013, amounting to 8000 Ktoe oil equivalent; total biogas production of large-scale biogas projects increased from 0.2 Giga to 2 Giga cubic meters during the 10 years, accounting for 12.4 % of natural gas consumption and 1000 Ktoe oil equivalent in 2013 (calculated from data reported by MOA 2013). After 2009, China has enhanced its support for biogas engineering projects by offering subsidies from 25 % to 45 % of the whole cost of projects, especially allocating more aid to Mid-Western areas and innovative projects, setting up policies similar to feed-in tariffs to promote power generation through biogas plants. Meanwhile, local biogas service systems were established by for improving the efficiency of biogas production and utilization. In 2014, central and local government still invested more than 2500 million CNY, of which the total biogas engineering construction accounting for 40 %, higher than the 18.4 % in 2008.

A long-term goal planned by China's National Development and Reform Commission (NDRC) claims that the available biogas production in 2020 will be 44 Giga cubic meters, from which 30 Giga cubic meters biogas will be produced by household users and 14 Giga cubic meters biogas will be generated from biogas engineering projects (NDRC 2007). Another short-term goal on biogas development has been set up by China's National Energy Administration (NEA): By 2015, the number of the biogas household users will reach 50 million with total biogas production of 19 Giga cubic meters. Large-scale biogas projects focused on agricultural and industrial (including municipal) wastes will produce 2.5 Giga and 0.5 Giga cubic meters of biogas, respectively, with more biogas being used to produce electricity production (NEA 2012).

As shown in Fig. 1, in general, biogas from rural household biogas digesters comprises the major proportion of total biogas production and shows a long and steady growth. However, according the updated data by the Ministry of Agriculture of China, in recent years, household biogas generation seems to have slowed down to a pre-2011 level,

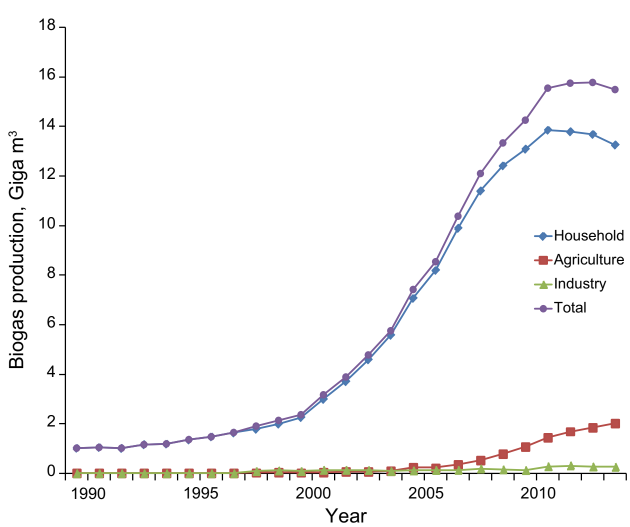

Fig. 1 Biogas production of different sectors from 1989 to 2014

and probably has reached a peak in many provinces (calculated from MOA 1989–2014). In contrast, biogas from agriculture-based biogas engineering projects shows a dramatic growth trend with increasing proportion, and starts to play a more important role in the biogas production of China. Furthermore, biogas from industry-based biogas engineering projects rises gradually with some slight fluctuations, exceeded by agriculture sector after 2004 (calculated from MOA 1989–2014). In the past few decades, China has accelerated its reform pace in urbanization, industrialization, and even energy and agriculture transformation. Therefore, China's biogas production is undertaking a dynamic and complicated transition, quite different from those of developed countries, and also different from those countries which rely on traditional agriculture or livestock husbandry.

2.2 Details of biogas sectors in China

During past years, Chinese people have introduced, modified, or created various models for biogas of different sectors according to local circumstances.

Firstly, rural household biogas plants are the largest contributor to biogas production in China. As the earliest form of biogas digester, the round-shaped water-pressure biogas plant was once popular among farmers in China (He et al. 2013), and also welcomed by many developing countries with a name of "China-mode biogas" digester (Zeng et al. 2007). Recently other types of technology have been developed in various areas of China. Strong back-flow biogas digesters have been introduced in Jiangxi province. The meandering-distribution biogas digester is a major type of digester in Yunnan province. The biogas digesters in Hunan province have separated gas storage with a floating cover. In the northwest region, biogas digesters with circumflex technology are applied to solve problems in resource updating and production efficiency (LSA 2010). Household biogas-based systems in different areas also vary from each other, such as newly developed biogas-kitchen-farm-toilet model (MOA 2008), pig-biogas-fruit model in South China (Chen 1997; MOA 2001a, b), 4-in-1 biogas system in Northern China with a greenhouse (MOA 2001a, b), and 5-in-1 model in Northwest China with water and solar infrastructures (Yue 1997; MOA 2006, 2013).

Secondly, agriculture-based biogas engineering projects have been promoted in China since late 1990s by local and central governments, and the basic technology was introduced and fixed. As Fig. 2 presents, the system of agriculture-based biogas engineering consists of a fermentation tank, gas storage room, bioliquid storage room, gas purification system, biogas electricity generator, biogas transportation system and other related parts (MOA 2006). Most of these biogas engineering projects use either the upflow solid reactor (USR) or the continuous stirred tank reactor (CSTR) as reactor

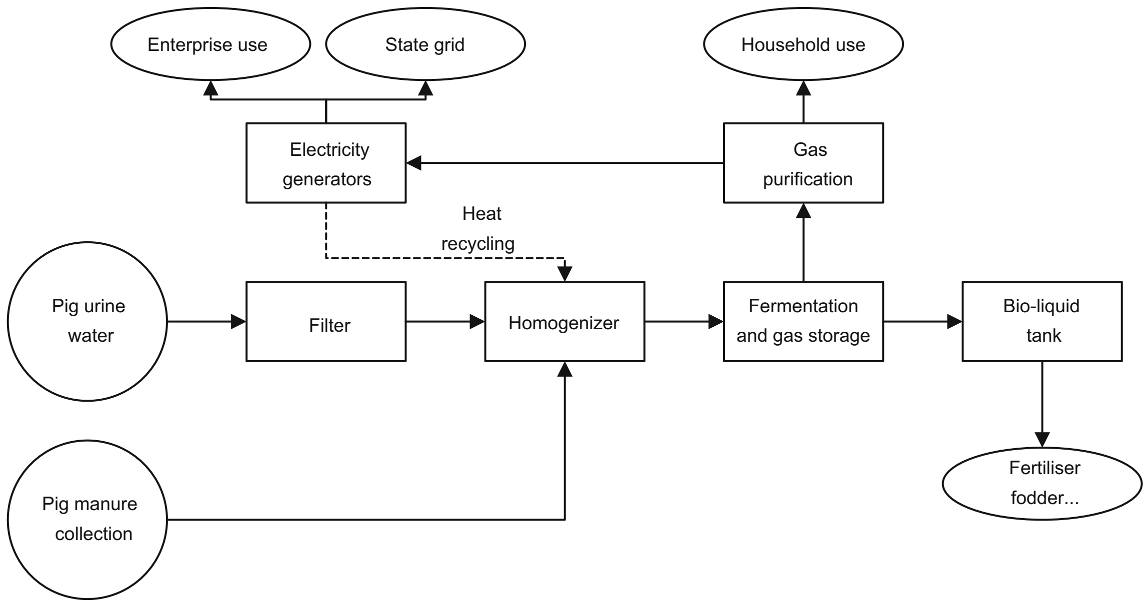

Fig. 2 Entire system of biogas engineering project with a pig farm

technology, and these technologies have been used for more than 20 years (HWEEC 2011). For these engineering projects, though climate condition is no longer the most important, enough raw materials should be guaranteed, and the project should be well maintained both technologically and financially. Biogas production involves many different stakeholders in this market-oriented model, far different from the model of the household biogas plant for families' use.

Thirdly, China's industrial biogas sector ranks the third largest biogas contributor. China's industry-based biogas project started in Henan province in the 1960s, dealing with the wastewater of an alcohol factory (Zhang et al. 2008). There are increasing numbers of industry-based biogas projects in China that tackle rising industrial liquid and solid waste in paper making, food or liquor manufacturing, printing and dyeing, among other challenges. With regard to core regeneration technology of biogas production, the upflow anaerobic sludge blanket (UASB) technology is used in more than half of all biogas plants, followed by CSTR and USR (HWEEC 2011). In addition, municipal sewage-cleaning biogas projects, landfill gas projects, and other biogas plants are small but non-neglected parts of the biogas industry in China, and part of biogas they produce is often reported together with the industry-based engineering projects (NEA 2012).

3 Literature review

Undoubtedly, biogas production is a comprehensive process with complex relationships between nature and humans. So with regard to the issues of biogas in China, there are various perspectives: not only about resource, climate and technology, but also with social, economic, cultural, and political considerations.

Many studies on China's biogas are from just one microperspective. Some focus on the introduction of new biogas technology. During its long history, China has developed a variety of household-based biogas technologies (Cheng et al. 2013): glass fiber-reinforced plastic digesters, plastic soft/hard digesters, and solar fiberglass reinforced plastic (FRP) biogas digester (Shi et al. 2008), as well as different comprehensive biogas systems as mentioned above. However, studies related to technological innovations of large-scale biogas engineering projects are rarely reported in China. In fact, most of the high-level biogas engineering technology in China is introduced from developed countries.

It is evident that the biogas systems mentioned above have benefits for energy consumption, environment improvement, labor and cost saving, fertilizer production, etc., compared to many non-renewable energy forms, so many studies analyze efficiency, sustainability or performance of biogas plants. Some studies are focused on the carbon emission reduction by using the life cycle analysis method and energy analysis, demonstrating that biogas systems are effective for reducing the emission of greenhouse gases and other waste gases (Wang et al. 2014; Zhang and Wang 2005; Yang and Chen 2014). Some studies evaluate the performance of biogas plants in field studies including the interview and questionnaire method, which is more realistic and helpful according to the local situation. He and coworkers has made a survey in

Shandong province and found that bioenergy systems should be selected based on the local circumstances (He et al. 2013). Although biogas has many advantages, it is still controversial whether these advantages can be fully explored due to different environments.

Recently, more researchers have expressed interests in comprehensive factors that influence biogas development, especially social and political reasons. According to a questionnaire survey in five provinces, Qu et al. (2013) believes that besides government promotion, other social factors also have significant effects on households' decision of biogas use. Another study suggests that the net effect of the current subsidy policy on rural household biogas use is nearly negligible (Sun et al. 2014). Frankly speaking, these studies have already posed challenges to the current policy on biogas in China. Is it necessary to change China's current biogas policy and plan?

From a macroperspective, most of the studies related to China's biogas are of qualitative, with consideration to introduction, overview and experiences (Wang et al. 2012; Li and Xue 2010; Jiang et al. 2011; Chen et al. 2012). However, only a few of the studies are quantitatively based with a macroperspective. According to some studies, China has abundant natural resources to produce biogas, but with low utilization rate and significant regional differences (Yang et al. 2012, Chang et al. 2014); Some other research paid attention not only to the regional differences, but also to the regional policy and strategy level (Deng et al. 2014). These studies can provide guidance to decision-making in a more accurate and thorough way. With a new temporal–spatial perspective, this paper aims to investigate the status of China's biogas production with respect to all sectors, and to predict its development in the foreseeable future through mathematical models. Then, according to the results associated with the current background and conclusions from the literature, this paper will discuss the possible reasons and explanations for temporal–spatial transformation in biogas production, and also give corresponding policy implications and strategies in the final part of the paper. Hopefully, this study could provide valuable insight into the future of China's biogas industry, and also give guidance to those developing countries with similar circumstances.

4 Methodologies

4.1 Time-dependent approach and technology diffusion

In this study, a time-dependent approach and time series methods were employed to investigate and forecast the trend of biogas production. On one hand, biogas production tends to be a grey box system that is not entirely and accurately understood by scientists, because it is difficult to explore all natural and social factors that influence the transformation of biogas production; in addition, data on influencing factors are either qualitative or quantitative, and sometimes insufficient too. On the other hand, based on observed data, time-dependent approaches and time series methods have their own advantages: focusing on the inter-relation and consistency of existing data series, and taking time as its only independent variable without consideration of other factors temporarily. The time-dependent approach does not provide long-term forecasts, and is proved to be successful only for short period prediction, when conditions do not change dramatically.

The time-dependent approach to technology diffusion was first introduced and applied by Mansfield (1961) in industrial and high technology fields with a logistic model. However, the real situation in the society is actually more complex than the original version of the logistic model. Due to a variety of situations, the facts can vary sometimes, for example, the trend may decline after reaching a peak, or the curve has multiple cycles. Later, to cope with different situations of transformation, researchers introduced some derivative logistic models with more complex features (including flexible growth or decline, symmetric bell-shaped, asymmetric bell-shaped and multiple cycled): Floyd model, Gompertz curve, Sharif–Kabir model, nonsymmetric responding logistic model, nonuniform influence model, Stanford Research Institute model (Mahajan et al. 1990), Hubbert model (Hubbert 1982; Bartlett 2000; Tao and Li 2007; Maggio and Cacciola 2009; Mohr and Evans 2009), Weibull model, generalized Weng model (Weng 1991; Chen and Hu 1996), H–C–Z model (Hu et al. 1995), Boltzmann model, GHB model, and multi-cycle Hubbert model (Lynch 2002; Guseo et al. 2007; Reynolds and Kolodziej 2008; Mohr and Evans 2010). It is proved to be credible that these modified logistic-like models have been adopted by researchers in many fields to simulate and forecast not only the process of innovation diffusion, but also resource transformation, such as water, fish, population, and energy sources including oil, gas and coal (Mahajan et al. 1990; Laherrère 1997, 2000; Bardi and Yaxley 2005; Palaniappan and Gleick 2008; Brandt 2010; Sorrell 2010; Hook et al. 2011).

With regards to biogas production, it can be seen as a type of resource production through a process of technology diffusion. A general process of technology diffusion is illustrated in Fig. 3. Some studies also indicate that technology diffusion has its own life cycle, including ascent phase, maturity phase, and descent phase, showing a bell-shaped curve that looks similar to some logistic-like models (Mansfield 1961; Mahajan et al. 1990). Similar to a bell-shaped curve, some research on technology adoption life cycle draws a conclusion of five stages: innovators, early adopters, early majority, late majority, and laggards

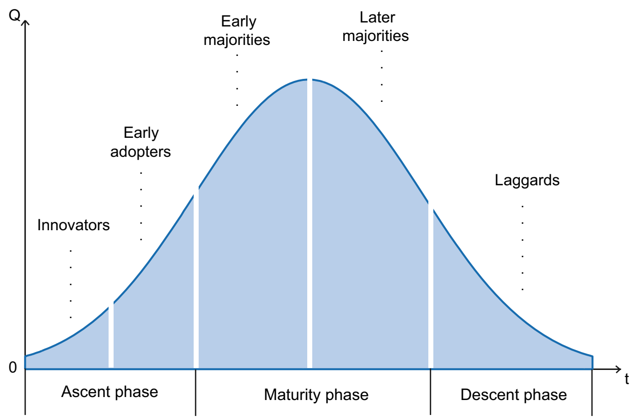

Fig. 3 Process and stages of technology diffusion (modified from Rogers 2003). *Notes* t represents time and Q represents the degree of technology evolution

(Rogers 2003). With regards to China's biogas production, according to the data reported by MOA (2013, 2014), the total biogas production has achieved the first peak in 2013 (15.8 Giga cubic meters), then decreased in 2014 (Fig. 1). In terms of household biogas production, the first peak value appeared in 2012 (13.8 Giga cubic meters) and then production declined. In detail, 22 out of 31 provinces directly revealed a bell-shaped curve, showing a declining trend after reaching the peak from 2011 to 2013; 6 of 31 provinces slowed down their growth rate and were about to achieve their peak value, probably located at the early maturity phase. For agriculture-based engineering projects, although they have shown a growth trend during the past decades, the annual growth rate actually became smaller than ever in recent years (from 45 % in 2008 to 9 % in 2014), which means it is probably reaching the early stage of the maturity phase of a bell-shaped curve (Fig. 3). Moreover, the industry-based projects present a form of multiple bell-shaped curves. As historical data demonstrates, in many cases, the trend of biogas production is related to bell-shaped curve(s) or part of a bell-shaped curve, so it is reasonable to consider the temporal change of biogas production as a technology diffusion process that fits some logistic-like curve in a certain period. Thus, some of modified logistic-like models will be applied to forecast the biogas production of China in the short term.

4.2 Forecast models

We take N_{p} as the accumulative production from the first year to the tth year and $Q(t)$ as the production at t year, which satisfies:

$$N_{\mathrm{p}}(t) = \int_0^t Q(t)\,\mathrm{d}t. \tag{1}$$

On the case that the production of biogas is finite, when $t \to +\infty$, that is, $Q(t) \to 0$, the total production of biogas is defined as:

$$N_{\mathrm{R}} = N_{\mathrm{p}}(t)_{t\to+\infty} = \int_0^{+\infty} Q(t)\,\mathrm{d}t. \tag{2}$$

If $f(t)$ and $F(t)$ are the probability density function (PDF) and accumulative density function (CDF) of the sample data respectively, then

$$F(t)_{t\to+\infty} = \frac{N_{\mathrm{p}}(t)_{t\to+\infty}}{N_{\mathrm{R}}} = \int_0^{+\infty} \frac{Q(t)}{N_{\mathrm{R}}}\mathrm{d}t = 1 \tag{3}$$

and

$$f(t) = \frac{Q(t)}{N_{\mathrm{R}}}. \tag{4}$$

Here we will discuss four different modified models: the Hubbert model, the generalized Weng model, the H–C–Z model and the Weibull model, showing different types of bell-shaped transformation. The specific description of each model is displayed in Table 1.

To determine the value of a, b and c, conduct the division of annual production to accumulative production, then we can get:

$$\frac{Q}{N_{\mathrm{p}}} = \frac{abN_{\mathrm{R}}e^{-bt}}{N_{\mathrm{R}}(1+ae^{-bt})} = \frac{abN_{\mathrm{p}}e^{-bt}}{N_{\mathrm{R}}} = \frac{bN_{\mathrm{p}}\left(1+ae^{-bt}\right)}{N_{\mathrm{R}}} - \frac{bN_{\mathrm{p}}}{N_{\mathrm{R}}} \tag{5}$$

and then we can get: $N_{\mathrm{R}} = \alpha/\beta$ and $b = \beta N_{\mathrm{R}}$.

Besides, with $N_{\mathrm{R}} = \alpha/\beta$, $\log\left((N_{\mathrm{R}} - N_{\mathrm{p}})/N_{\mathrm{p}}\right) = A - Bt$.

Therefore, the parameter a and b can be given by $a = 10^A$ and $b = 2.303B$.

The parameters in the Weibull model, generalized Weng model, and H–C–Z model can be calculated in a similar way.

Considering the uncertainty of some cases, we use the Grey model as a supplementary. Grey theory is a study containing the known and unknown information at the same time, constructing a Grey model to forecast from a limited, discrete data. The modeling process is as follows:

The original sequence, $\{x_t,\ t = 1, 2, \ldots, n\}$, is done with the accumulative generation operation (AGO). As a result, we get $\{x_t^{(1)},\ t = 1, 2, \ldots, n\}$, and $x_t^{(1)} = \sum_{i=1}^{t} x_i, t = 1, 2, \ldots, n$.

$$\frac{\mathrm{d}x^{(1)}}{\mathrm{d}t} + ax^{(1)} = b. \tag{6}$$

Equation (6) presents the differential equation based on the AGO sequence. Correspondingly, the discrete form of GM (1, 1) is given by Eq. (7)

Table 1 Description of different models

Models	Hubbert	Weibull	Generalized Weng	H–C–Z	GM (1, 1)
Annual production	$Q = \frac{abN_{\mathrm{R}}e^{-bt}}{(1+ae^{-bt})^2}$	$Q = at^b e^{-\left(t^{b+1}/c\right)}$	$Q(t) = at^b e^{-(t/c)}$	$Q = aN_{\mathrm{R}} \exp[-(a/b)\exp(-bt) - bt]$	$\hat{x}^{(0)}(t) = (x^{(0)}(0) - \frac{b}{a})(1 - e^{-at})e^{-at}$
Maximum annual production	$Q_{\max} = 0.25bN_{\mathrm{R}}$	$Q_{\max} = a\left[\frac{bc}{2.718(b+1)}\right]^{b/(b+1)}$	$Q_{\max} = a\left(bc/2.718\right)^b$	$Q_{\max} = 0.3679bN_{\mathrm{R}}$	–
Accumulative production	$N_{\mathrm{p}} = \frac{N_{\mathrm{R}}}{1+ae^{-bt}}$	$N_{\mathrm{p}} = N_{\mathrm{R}}\left[1 - e^{-\left(t^{b+1}/c\right)}\right]$	$N_{\mathrm{R}} = ac^{b+1}\Gamma(b+1)$	$N_{\mathrm{p}} = N_{\mathrm{R}} \exp[-(a/b)\exp(-bt)]$	$\hat{x}^{(1)}(t) = (x^{(0)}(0) - \frac{b}{a})e^{-at} + \frac{b}{a}$
Accumulative production at peak time	$N_{\mathrm{pm}} = 0.5N_{\mathrm{R}}$	$N_{\mathrm{pm}} = 0.3679N_{\mathrm{R}}$	–	$N_{\mathrm{pm}} = 0.3679N_{\mathrm{R}}$	–
Peak time	$t_{\mathrm{m}} = \frac{1}{b}\ln a$	$t_{\mathrm{m}} = \left(\frac{bc}{b+1}\right)^{1/(b+1)}$	$t_{\mathrm{m}} = bc$	$t_{\mathrm{m}} = \frac{\ln(a/b)}{b}$	–

– means the item of the model is nonexistent

$$x^{(1)}(t) + az^{(1)}(t) = b \tag{7}$$

where $z^{(1)}(t) = \frac{x^{(1)}(t)+x^{(1)}(t-1)}{2}$.

With least square method (LSM), the solution of the difference Eq. (6) is given by:

$$\hat{x}^{(1)}(t) = \left(x^{(0)}(0) - \frac{b}{a}\right)e^{-at} + \frac{b}{a} \tag{8}$$

Therefore, the simulated values of the original sequence are:

$$\hat{x}^{(0)}(t) = \left(x^{(0)}(0) - \frac{b}{a}\right)(1 - e^{-at})e^{-at} \tag{9}$$

In the above process, GM (1, 1) contains three mainly basic parts: accumulative generation operation (AGO), inverse accumulative generation operation (IAGO) and forecast model GM (1, 1). AGO can deal with the stochastic and chaos of the data, which can transfer the discrete and irregular time series data to the strict monotone increasing smoothed time series. Then the difference equation is established with the AGO series, whose results will be conducted with the IAGO. Based on the above two steps, the GM (1, 1) is ultimately constructed.

4.3 Optimization algorithm

The cuckoo search algorithm is inspired by the breeding behavior of cuckoos in combination with Lévy flight distribution. A Lévy flight is a random walk with step-lengths drawn from the Lévy distribution with a heavy-tailed probability, which was featured by Yang and Deb who worked to improve the search efficiency of the cuckoos (Yang and Deb 2010).

According to Yang and Deb (2010), for multi-objective optimization, three idealized rules in the Cuckoo Search Algorithm are declared below: (1) N eggs (the solutions of n objectives) are laid by each cuckoo at a time, and placed in a randomly chosen nest; (2) the best nests that carried high-quality eggs (solutions) from each generation are kept for the next generation; (3) the number of available host nests is fixed and those nests in which a host can discover alien eggs with probability $p_\alpha \in [0, 1]$ are discarded and removed from further calculations.

Therefore, in the searching process, specifically, when generating new solutions $\left(x_{t+1}^{(i)}\right)$, the local random walk can be expressed as:

$$x_{t+1}^{(i)} = x_t^{(i)} + \beta s \oplus H(p_\alpha - \varepsilon) \oplus \left(x_t^{(j)} - x_t^{(k)}\right) \tag{10}$$

where $x_{t+1}^{(i)}$ and $x_t^{(i)}$ represent the location of the ith host nest at tth generation, while $x_t^{(j)}$ and $x_t^{(k)}$ are two random different solutions at tth generation. $\beta > 0$ is the size scaling factor, $H(\cdot)$ is a Heaviside function, and s is the

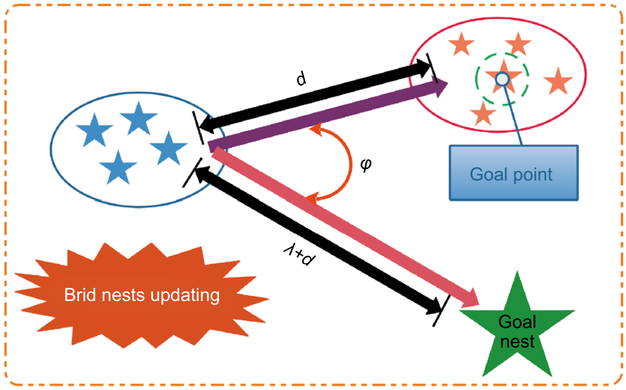

Fig. 4 Searching mechanism of the cuckoo search algorithm

step size. The product $\oplus$ indicates entry-wise multiplications.

The global random walk is performed by Lévy flights and the searching mechanism is illustrated in Fig. 4.

$$x_{t+1}^{(i)} = x_t^{(i)} + \beta \oplus \text{Lévy}\,(\lambda) \tag{11}$$

where the value of Lévy (λ) is calculated from the following Lévy distribution.

$$\text{Lévy}\,(\lambda) = \frac{\lambda\Gamma(\lambda)\sin(\pi\lambda/2)}{\pi s^{1+\lambda}} \tag{12}$$

with the Gamma function $\Gamma(z) = \int_0^{+\infty} t^{z-1}e^{-t}\mathrm{d}t$.

With the cuckoo search algorithm, the parameter b and parameter a in the generalized Weng model and Weibull model, respectively, can be calculated more efficiently and accurately, but originally calculated through trial and error.

4.4 Grey relational analysis

Grey relational analysis is widely used for testing the closeness of different sequences of number by comparing with their curve shapes. In this study, it will be used to analyze the relationship between local biogas production and its factors. At first, the original data are processed via normalization.

The reference sequence is expressed as $X_0 = \{x_0(k)|\,k = 1, 2, \ldots, n\}$, and the factor sequence is expressed as $X_i = \{x_i(k)|\,k = 1, 2, \ldots, n\}$, $i = 1, 2, \ldots, N$.

The Grey relational degree between X_i and X_0 is defined as:

$$r_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k), k = 1, 2, \ldots, n \tag{13}$$

where

$$\xi_i(k) = \frac{\min\limits_i \min\limits_k |x_0(k) - x_i(k)| + \rho \max\limits_i \max\limits_k |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \rho \max\limits_i \max\limits_k |x_0(k) - x_i(k)|} \tag{14}$$

Finally, a comparison is made among the values of $r_i\,(i = 1, 2, \ldots, N)$, in order to identify the importance of each factor.

5 The simulation analysis and forecast of biogas production in China

China's biogas production is currently undergoing a process of drastic transformation, with significant regional differences and sector disparities. Therefore, it is essential to make a thorough assessment and prediction on the biogas production in China from both temporal and spatial perspectives.

5.1 Data sets and preliminary analysis

The data sets contain three sectors, including biogas capacity from household biogas digesters (1989–2014), agriculture-based biogas projects (1996–2014) and industry-based biogas projects (1996–2014) in 31 provinces in China. The data are reported officially by the MOA of China. The missing part, the value of the biogas production in the year of 2000, is addressed using the piecewise cubic hermite interpolating polynomial (PCHIP), which is also called contact difference. In order to keep the derived function as close to the original function as possible, it requires the derived function not only to have the same values, but also the same derivative values on the inserted nodes.

In cubic polynomial $P_3(x) = y_0\varphi_0(x) + y_1\varphi_1(x) + hy_0'\phi_0(x) + hy_1'\phi_1(x)$, $\varphi_0, \varphi_1, \phi_0, \phi_1$ are the cubic polynomials needed to be determined which satisfy:

$$\begin{aligned}
&\varphi_0(0) = 1, \varphi_0(1) = \varphi_0'(0) = \varphi_0'(1) = 0\\
&\varphi_1(1) = 1,\ \ \varphi_1(0) = \varphi_1'(0) = \varphi_1'(1) = 0\\
&\phi_0'(0) = 1,\ \ \phi_0(0) = \phi_0(1) = \phi_0'(1) = 0\\
&\phi_1'(1) = 1,\ \ \ \phi_1(0) = \phi_1(1) = \phi_1'(0) = 0
\end{aligned} \tag{15}$$

Then the cubic polynomial can be written as:

$$\begin{aligned}
P_3(x) = {} & y_0\varphi_0\left(\frac{x - x_0}{h}\right) + y_1\varphi_1\left(\frac{x - x_0}{h}\right) + hy_0'\phi_0\left(\frac{x - x_0}{h}\right)\\
& + hy_1'\phi_1\left(\frac{x - x_0}{h}\right)
\end{aligned} \tag{16}$$

where $h = x_1 - x_0$, x_0, x_1 are two random numbers.

From the perspectives of regional data trends, the value of household biogas digesters of different provinces shows great diversity in transformation dynamics. Though fluctuation sometimes occurred, it is generally divided into three forms: upward, bell-shaped, and downward. In fact, according to technology diffusion laws, the upward trend can be considered as the ascent phase of the technological life cycle, and the downward ones are actually the descent phase of technological cycle. With regard to engineering projects, biogas production of agriculture-based projects appears with an analogous upward trend in most provinces; while biogas production of industry-based project varies among different provinces, showing unsmooth growth or decline trends with fluctuations in most places, probably because of uncertain life cycle of industry-based projects.

5.2 Evaluation criteria

Since the forecast results affect the model itself directly, it is necessary to evaluate the performance of each model. In this paper, three indicators: mean absolute error (MAE), mean absolute percentage error (MAPE) and root-mean square error (RMSE) are adopted to assess the forecast accuracy of each model, respectively.

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}\left|\hat{y}_i - y_i\right| \tag{17}$$

$$\mathrm{MAPE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{\hat{y}_i - y_i}{y_i} \times 100\right| \tag{18}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\hat{y}_i - y_i\right)^2} \tag{19}$$

where y_i and $\hat{y}_i$ represent the observed value and simulated value of the ith data point for the performance evaluation, and n is the total number of data points used for the performance evaluation and comparison.

Besides, to evaluate the performance of each model consistently, the criteria of MAPE are listed in Table 2.

Table 2 Criteria of MAPE

MAPE, %	Forecast performance
<20	Excellent
20–30	Good
30–50	Reasonable
>50	Incorrect

5.3 Result and analysis

5.3.1 *Household biogas production with temporal–spatial analyses*

Since the production of biogas per household in China and each province almost demonstrates the characteristics that the shape of the production curve is the left side of a bell-shaped curve, five models, namely the Hubbert model, the generalized Weng model, the Weibull model, the H–C–Z model, and the Grey model, are adopted to study the biogas production. The comparison of five models is demonstrated in Fig. 5, where Fig. 5a illustrates the MAE, MAPE, and RMSE of five models with the radar map and Fig. 5b shows the simulated values of the generalized Weng model which has the minimum error and the errors between them. For simulating national biogas production, this model fits the data series with an R-squared value of 0.9942.

The results of five models listed in Tables 3, 4 and 5 reveal that for most of provinces in China, the four models (the Hubbert model, the generalized Weng model, the Weibull model, and the H–C–Z model) with smaller errors are much plausible to the present status of China, compared to GM (1, 1). For the exceptional cases, such as Guangdong, Sichuan, and Xinjiang provinces, the simulated accuracy of the Grey model is much higher than other four models, which mainly results from the fluctuation and the current growth of the production data.

For most provinces in China, especially in the household biogas production of the whole nation shown in Fig. 5b, the generalized Weng model can portray the trend more precise than other four models in terms of the MAPEs listed in Table 4. According to Table 2, the MAPEs of different provinces indicate that the generalized Weng model offers excellent forecast results for nearly half the cases and its results are also authentic overall. The H–C–Z Model also has some excellent performances and good performance for most cases. The Hubbert model and Weibull model conduct good and reasonable results in about half the different provinces, while GM (1, 1) is inappropriate for some provinces due to the fact that the MAPE is over 50 %. Therefore, we choose the prediction value calculated by generalized Weng model, and the forecast of household biogas production is shown in Fig. 5b, which indicates that the total household biogas production will be about 10 Giga cubic meters.

When considering both time dynamics and regional difference, Fig. 6 shows that the spatial diffusion process can be described by four cross sections which have some correlations with spatial factors. In Fig. 6, the relative productivity, referring to the ratio of local value to the maximum value, is used as a mapping index. In all the four periods, Sichuan (the darkest brown color in Fig. 6) has always been the most productive province of the whole nation. In the early 1990s, Jiangsu from the coastal area, as well as Hunan and Hubei from central China also had plenty of household biogas production. It was not until 2000 that household biogas production diffused toward adjacent southwestern and central areas, such as Yunnan, Guangxi, and Jiangxi (relatively dark brown color in Fig. 6b), which probably have the most suitable climate

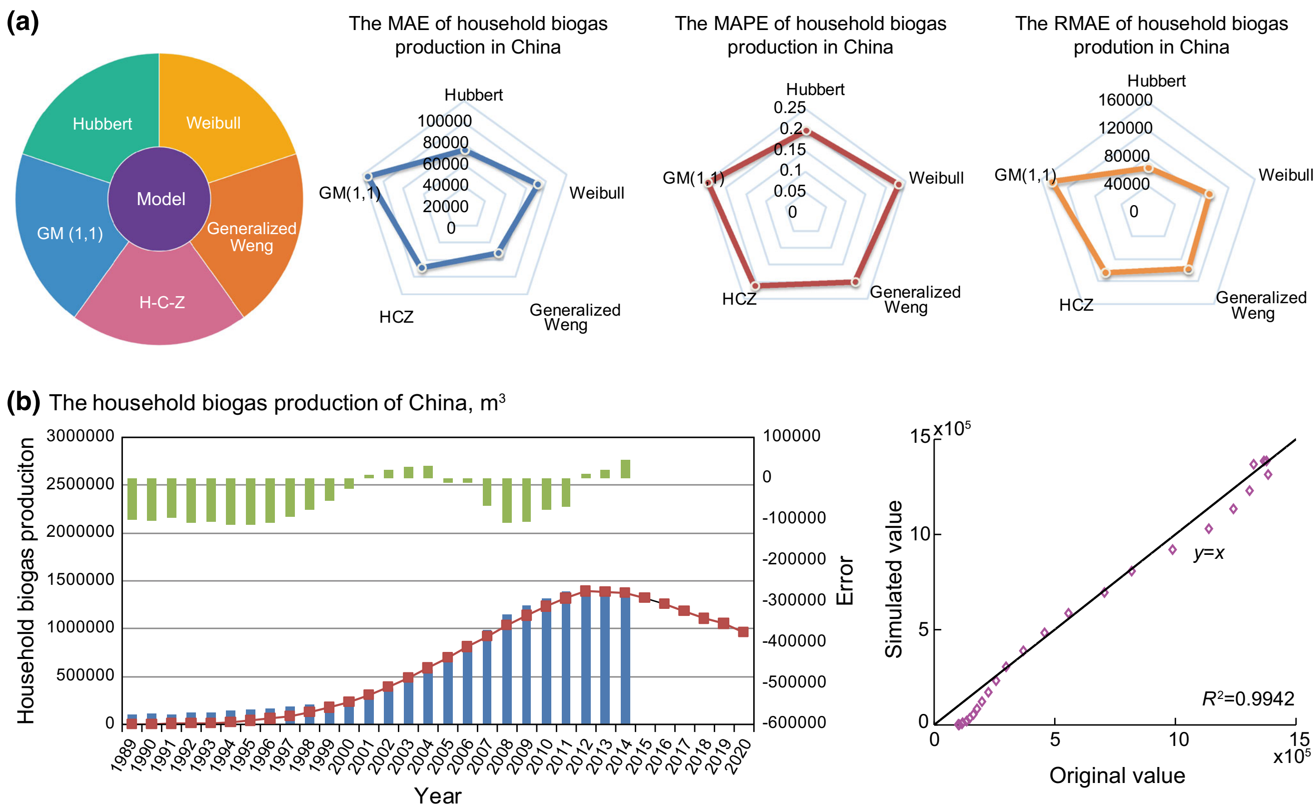

Fig. 5 Results of five models on the household biogas production in China. **a** The MAE, MAPE, RMSE of five models. **b** The actual values are displayed by the *blue histogram*, and simulated values of generalized Weng model which has the minimum error are displayed by the *red line* and the errors between them are displayed by the *green histogram*

conditions for household biogas production. On the other hand, people who use household biogas digesters in the east coast regions make up a lower proportion than before. After 10 years of promotion by government and the progress of technology, a considerable number of household biogas plants have been built and used for biogas production. It has spread north to more places, such as Henan, Hebei, and Shandong (medium brown color in the central China of Fig. 6c) and these have become important regions of biogas production; even in Tibet, there are also a number of family-sized biogas plants, however, household biogas is no longer produced in Shanghai. In contrast, Sichuan, Guangxi, and Yunnan (relatively dark brown color in Fig. 6c) were still the regions where household biogas production was the highest in the early years of 2010s. But in around 2012, most provinces started to decelerate their speed of increase of biogas production, and some of them had already reached their peaks. According to the result of forecasts, household biogas will decrease in most provinces in the early 2020s, and be not as widely used as before, and finally show an agglomeration effect in southwest regions (in Fig. 6d) that have more suitable climate condition for all year biogas use, and more small-sized or family-sized livestock raising than any other region in China.

In the Chinese context, there might be diverse reasons related to these phenomena which have occurred over the last few years: the decrease in small-scale agriculture/livestock production (large-scale agriculture/livestock breeding rising), the rural population reduction, the more centralized rural residential patterns, the increased choices for other types of energy, etc. (Wang et al. 2012). It is obvious that these processes seem too hard to reverse in contemporary China under the fast pace of urbanization, industrialization as well as other reforms. Meanwhile, regional differences in agro-climate, resources, socioeconomic status and policy also make considerable diversity in household biogas production (Yang et al. 2012).

In order to analyze the reasons for regional household biogas development during recent years, further analysis is made by using various natural and socioeconomic indexes: climate condition (months above 10 °C in a year), the scale of livestock breeding fit for household (number of existing pigs in less than 50 scale farms), rural household energy demand (the proportion of alternative energy sources: coal, oil, wood, electricity, etc.), rural population level (the proportion of local rural population), local rural economic condition (rural income per person), government support (the investment from central to local government for

Table 3 MAE of five models of household biogas production

Province	Hubbert	Weibull	Generalized Weng	H–C–Z	GM (1, 1)
China	5.43E+04	7.12E+04	5.23E+04	6.92E+04	9.53E+04
Anhui	1.11E+03	1.17E+03	9.45E+02	1.01E+03	1.30E+03
Chongqing	3.68E+03	3.98E+03	2.83E+03	2.86E+03	7.73E+03
Fujian	1.60E+03	1.95E+03	1.46E+03	1.49E+03	2.42E+03
Gansu	9.81E+02	1.09E+03	8.91E+02	4.23E+03	4.23E+03
Guangdong	2.34E+03	1.76E+03	9.14E+02	1.14E+03	8.99E+02
Guangxi	1.65E+04	1.97E+04	1.65E+04	1.65E+04	2.92E+03
Guizhou	1.97E+03	2.07E+03	1.79E+03	1.82E+03	5.05E+03
Hainan	6.50E+02	9.14E+02	6.31E+02	6.75E+02	1.84E+03
Hebei	4.14E+03	5.07E+03	4.14E+03	4.14E+03	1.05E+04
Heilongjiang	7.21E+02	1.10E+03	7.21E+02	7.21E+02	2.62E+03
Henan	4.72E+03	5.14E+03	4.72E+03	4.72E+03	9.77E+03
Hubei	6.46E+03	7.48E+03	5.33E+03	6.46E+03	7.08E+03
Hunan	4.94E+03	4.94E+03	4.94E+03	4.94E+03	1.14E+04
Jiangsu	2.26E+03	3.16E+03	1.81E+03	1.52E+03	2.45E+03
Jiangxi	4.76E+03	7.40E+03	3.29E+03	3.68E+03	5.29E+03
Jilin	1.93E+02	4.94E+03	2.03E+02	2.88E+02	2.88E+02
Liaoning	9.39E+02	1.12E+03	7.68E+02	6.31E+02	5.29E+03
Inner Mongolia	5.24E+02	5.62E+02	5.16E+02	5.39E+02	2.28E+03
Ningxia	5.20E+02	6.10E+02	4.50E+02	3.97E+02	5.55E+02
Qinghai	2.74E+02	5.22E+02	2.74E+02	2.74E+02	6.45E+02
Shandong	7.12E+03	7.95E+03	6.59E+03	5.82E+03	7.14E+03
Shanxi1	1.83E+03	2.00E+03	1.80E+03	1.65E+03	3.35E+03
Shanxi2	1.63E+03	1.88E+03	1.39E+03	1.51E+03	3.34E+03
Sichuan	1.77E+04	1.78E+04	1.74E+04	1.12E+04	9.89E+03
Tianjin	1.67E+02	1.75E+02	1.72E+02	8.19E+01	1.65E+02
Tibet	8.95E+02	1.15E+03	7.43E+02	6.45E+02	1.76E+03
Xinjiang	1.07E+03	1.42E+03	1.03E+03	7.64E+02	3.37E+02
Yunnan	4.87E+03	1.11E+04	3.17E+03	5.02E+03	5.88E+03
Zhejiang	1.34E+03	1.09E+03	5.08E+02	9.07E+02	1.07E+03

building biogas digesters). By calculating the Grey relational degree to local household biogas production, the importance of factors are as below: government support (0.781) > rural population level (0.763) > energy demand (0.757) > climate condition (0.752) > local rural economic condition (0.750) > scale of livestock breeding (0.741). Hence, government support is the major factor that has impacted on rural household biogas development, which indicates that rural household biogas development is mainly from government promotion. Policy promotion is from both central and local governments. After 2003, the central government enhanced the support for rural biogas construction by offering subsidies: from 800/1000/1200 CNY per household before 2008 and then up to 1000/1200/1500 CNY per household after 2008 (for east/middle/west region, respectively). The financial support from central government in a certain period can be calculated by the number of newly built biogas units of every province and the local subsidy standard. Also improvement of biogas service systems is another way of policy support: after 2009, the number of local service centers increased and the central government provided 20,000/35,000/45,000 CNY per year for every service center (in east/middle/west region) (MOA 2008). Moreover, some local policies also take many solutions including providing direct investment and encouraging international cooperation: in some cases in Sichuan province, household biogas production is introduced into the international carbon trade system due to local policy support. However, new policies from central government have re-oriented its priority to large-scale biogas engineering projects (MOA 2015), so household biogas production is unlikely to grow as fast as before, but could be still useful in some part of China. Besides, the rural population level and energy demand are important reasons for rural household biogas usage. Climate conditions, local rural economic conditions, and scale of

Table 4 MAPE of five models of household biogas production

Province	Hubbert	Weibull	Generalized Weng	H–C–Z	GM (1, 1)
China	0.2013	0.2312	0.1986	0.2084	0.2466
Anhui	0.2423	0.2932	0.2234	0.2303	0.2536
Chongqing	0.2092	0.2312	0.1712	0.2021	0.3686
Fujian	0.2259	0.2592	0.1995	0.2033	0.4236
Gansu	0.2865	0.3312	0.2712	0.2864	0.4386
Guangdong	0.1249	0.1249	0.1249	0.1249	0.1249
Guangxi	0.2524	0.2924	0.2343	0.2245	0.6271
Guizhou	0.3532	0.3753	0.2932	0.3227	0.4803
Hainan	0.2814	0.3325	0.2214	0.2799	0.4737
Hebei	0.2604	0.3262	0.2044	0.2488	0.4921
Heilongjiang	0.3315	0.3908	0.2853	0.2915	0.5389
Henan	0.2711	0.3215	0.2137	0.2517	0.6064
Hubei	0.2055	0.2380	0.1744	0.2055	0.2114
Hunan	0.1982	0.2928	0.1852	0.1982	0.5145
Jiangsu	0.2141	0.2687	0.1868	0.1579	0.2291
Jiangxi	0.2229	0.2509	0.1940	0.1821	0.5252
Jilin	0.3238	0.3382	0.2329	0.3382	0.3174
Liaoning	0.2401	0.2600	0.2303	0.2212	0.5252
Inner Mongolia	0.4463	0.3634	0.3446	0.4036	0.8100
Ningxia	0.2576	0.3184	0.2067	0.2257	0.3562
Qinghai	0.2918	0.3443	0.2918	0.2918	0.4423
Shandong	0.3241	0.3546	0.2752	0.2572	0.3286
Shanxi1	0.3594	0.3806	0.3413	0.3204	0.3167
Shanxi2	0.3177	0.3504	0.2941	0.2791	0.3825
Sichuan	0.2680	0.2807	0.2402	0.1683	0.1368
Tianjin	0.2753	0.2909	0.2827	0.2340	0.3572
Tibet	0.2159	0.2521	0.2131	0.2251	0.3931
Xinjiang	0.2345	0.2734	0.2329	0.2068	0.1204
Yunnan	0.2063	0.1947	0.1802	0.1723	0.2939
Zhejiang	0.2713	0.2534	0.1712	0.2704	0.3732

livestock breeding are also relevant to rural household biogas production.

5.3.2 *Biogas production of engineering projects with temporal–spatial analyses*

Data for biogas engineering projects have been reported since the late 1990s by MOA (1996–2004); and the feature of these data series in different regions shows different patterns in comparison with household ones: Some are monotonously changed, while others have obvious fluctuations, thus forecast models should be more diverse according to circumstances. Considering the fluctuation of the some biogas engineering projects, it is essential to apply a multi-curve model to forecast the production of industry-based biogas. The biogas production of agriculture- and industry-based engineering projects of China is illustrated in Fig. 7a, b. By using the same approach in simulating household biogas production, we find that generalized Weng model is still a good choice for simulating agriculture-based engineering biogas production, with the best value of MAE (7.04E+03), MAPE (0.1913), RMSE (1.26E+04), and *R*-squared (0.9922) when calculating total biogas production; likewise, the (multi-cycle) Hubbert model is most suitable to simulate industry-based engineering biogas production, with the most satisfactory values of MAE (6.15E+03), MAPE (0.3137), RMSE (8.65E+03), and *R*-squared (0.7516) for evaluating national biogas production. For some provinces with unstable fluctuations which the five models cannot fit well, the least square method is used to estimate the future value. The regional difference is shown in Fig. 8, round shape of colors represents the biogas relative productivity of agriculture-based engineering projects, while the blue color from light to dark refer to relative biogas productivity of industry-based engineering projects.

Table 5 RMSE of five models of household biogas production

Province	Hubbert	Weibull	Generalized Weng	H–C–Z	GM (1, 1)
China	6.60E+04	9.18E+04	9.76E+04	1.04E+05	1.46E+05
Anhui	1.38E+03	1.38E+03	1.38E+03	1.38E+03	1.80E+03
Chongqing	4.31E+03	4.31E+03	4.31E+03	4.31E+03	1.16E+04
Fujian	2.14E+03	2.37E+03	2.14E+03	2.14E+03	3.43E+03
Gansu	1.45E+03	2.14E+03	1.02E+03	8.76E+03	8.76E+03
Guangdong	1.68E+03	1.68E+03	1.68E+03	1.68E+03	1.68E+03
Guangxi	2.94E+04	3.30E+04	2.94E+04	2.94E+04	3.87E+03
Guizhou	2.99E+03	3.19E+03	2.99E+03	2.99E+03	7.07E+03
Hainan	9.58E+02	1.41E+03	9.26E+02	1.10E+03	2.31E+03
Hebei	6.33E+03	8.44E+03	6.33E+03	6.33E+03	2.80E+05
Heilongjiang	1.04E+03	1.35E+03	1.04E+03	1.04E+03	3.97E+03
Henan	6.79E+03	7.31E+03	6.27E+03	6.39E+03	1.43E+04
Hubei	7.75E+03	8.32E+03	6.42E+03	7.75E+03	1.10E+04
Hunan	6.50E+03	6.50E+03	6.50E+03	6.50E+03	1.38E+04
Jiangsu	2.61E+03	3.27E+03	2.48E+03	2.19E+03	2.94E+03
Jiangxi	4.44E+06	1.10E+04	4.68E+03	5.00E+03	6.92E+03
Jilin	2.46E+02	6.50E+03	3.14E+02	5.93E+02	4.51E+02
Liaoning	1.33E+03	1.56E+03	1.14E+03	1.02E+03	6.92E+03
Inner Mongolia	7.62E+02	7.62E+02	7.62E+02	7.62E+02	2.72E+03
Ningxia	6.36E+02	7.83E+02	5.24E+02	5.17E+02	6.82E+02
Qinghai	4.52E+02	7.43E+02	4.52E+02	4.52E+02	7.80E+02
Shandong	9.18E+03	1.04E+04	7.88E+03	6.34E+03	8.66E+03
Shanxi1	2.51E+03	2.57E+03	2.55E+03	2.00E+03	4.12E+03
Shanxi2	2.20E+03	2.55E+03	2.29E+03	2.09E+03	3.81E+03
Sichuan	2.01E+04	1.99E+04	2.12E+04	1.38E+04	1.19E+04
Tianjin	2.10E+02	2.52E+02	2.34E+02	1.06E+02	2.12E+02
Tibet	1.41E+03	1.81E+03	9.58E+02	6.96E+02	2.33E+03
Xinjiang	1.73E+03	2.26E+03	1.61E+03	1.14E+03	4.45E+02
Yunnan	6.23E+03	2.01E+04	4.54E+03	6.20E+03	7.40E+03
Zhejiang	1.85E+03	1.35E+03	6.06E+02	1.01E+03	1.21E+03

As shown in Fig. 7a, in the next few years, the total production of agriculture-based biogas projects will probably increase steadily with an annual growth rate of 8 %, reaching a peak of almost three Giga cubic meters in around 2020. From a spatial perspective (Fig. 8), agriculture-based engineering projects have diffused from southeast coastal regions inland to provinces such as Henan and Sichuan, and become increasingly widely used on a national scale during the last decades. In early 2000s, Fujian (red spot in Fig. 8a) played the leading role in agriculture-based biogas projects among regions; however, in early 2010s, Sichuan (red spot in Fig. 8b) generated the most abundant biogas, followed by those regions located in the eastern coast. Based on this prediction (under current policy support and situation), in 2020, the spatial pattern will not change a lot from 2010, and the current top provinces will hold the lead positions and the productivity will begin to reach a peak value, while some provinces like Heilongjiang with rich resources likely to become potential growth points.

From Fig. 7b, we can see many fluctuations with a gradual growing trend happen in industry-based biogas production. By 2020, according to forecast results, based on current status and policy, the amount of industry-based biogas production will reach about 0.3 Giga cubic meters. From a spatial perspective (Fig. 8), in the early 2000s, engineering projects of this type were built in mid and eastern areas like North China Plain, where Shandong province (the darkest blue color in Fig. 8a) ranked the first place. Recently the development of industry-based project presents an agglomeration effect in certain locations, for instance, Henan province (the darkest blue color in Fig. 8b) showed a rapid growth and became the core area of industry-based biogas production in the early 2010s, yet

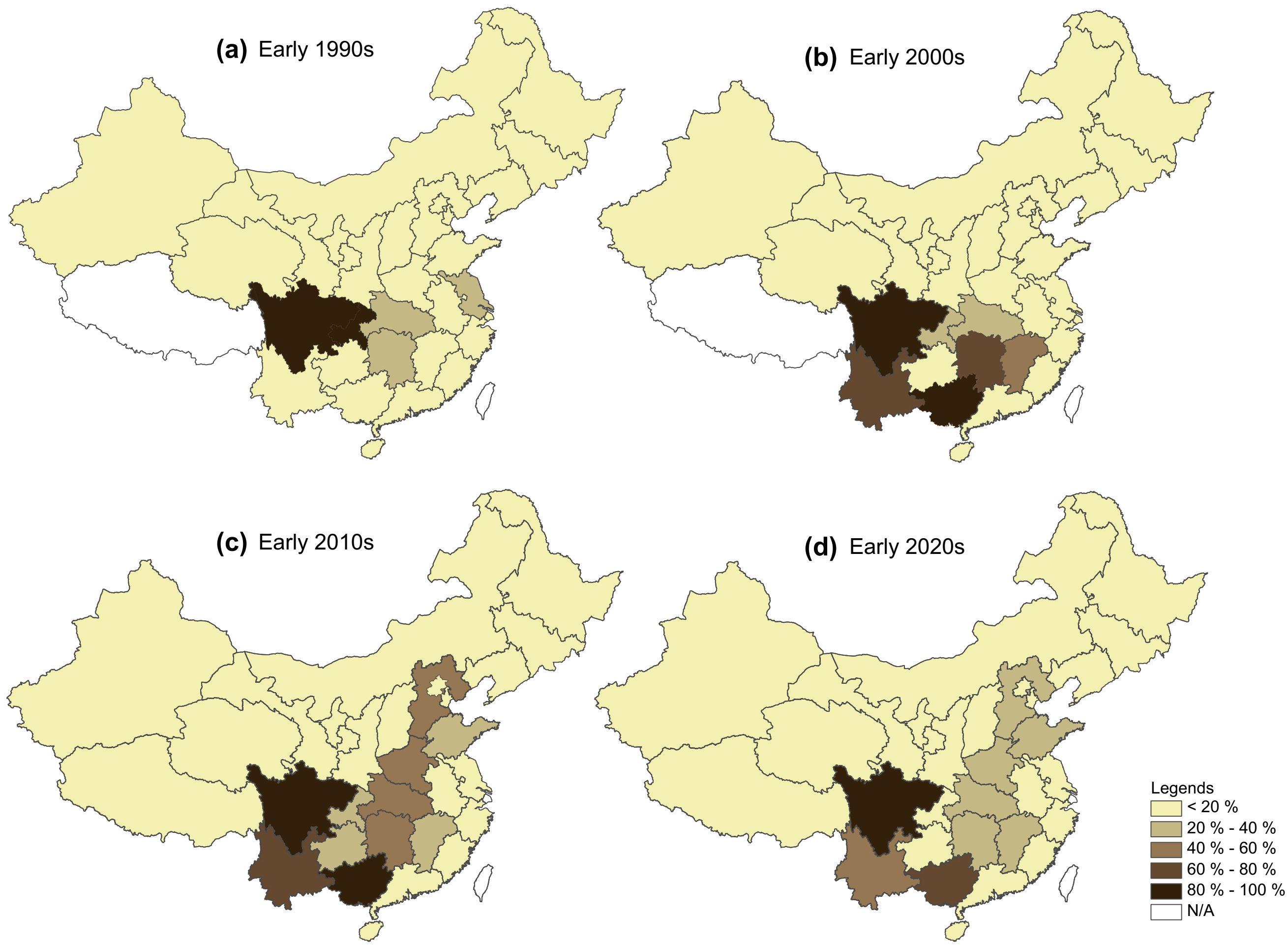

Fig. 6 Regional difference of household biogas production from 1990 to 2020

nearly half of provinces (white color in Fig. 8b) have produced little industrial-based biogas in past few years. These include Guangdong, Fujian, and Zhejiang which used to have a number of industry-based biogas plants, and this phenomenon is likely to have been caused by manufacturing industry transferring process from coastal areas to more inland areas in recent years. In the 2020s, the forecasts illustrate that the spatial pattern will not change much from 2010, which could be caused by path dependence, but there exists a slight trend from coastal area to the interior for industry-based biogas production.

Comparing between agriculture- and industry-based biogas engineering projects, we observe that agriculture-based engineering biogas production nearly follows a generalized Weng model which is an asymmetric bell shape, with a faster growing trend than declining trend (probably due to strong promotion by government), while industry-based engineering biogas production follow a (multi-cycle) symmetric bell-shaped model (Hubbert model) with almost the same rate of climbing and decreasing (possibly similar to normal technology diffusion processes). However, due to the characteristics of the two sectors, the industrial production has fluctuated more than that from the agriculture sector and thus is hard to simulate and predict, with only about an R-squared value of 0.75 compared to 0.99 for the agriculture sector.

In term of factors that drive the development of engineering projects, some studies of agriculture-based biogas projects (Li and Xue 2010; Jiang et al. 2011; Wang et al. 2012) show that the main influencing factors are slightly different from the household sector, such as raw material resources, economic conditions, technological level, and government support. The indexes selected for those factors are as follows: raw material resources (the number of livestock from large farms), economic conditions (local income per person), marketization of technology (the number of local biogas-related companies) and government support (the investment from central to local government for building engineering-scale biogas plants). By calculating the Grey relational degree to local biogas production of agriculture-based engineering projects, the factors are sorted as below: marketization of technology

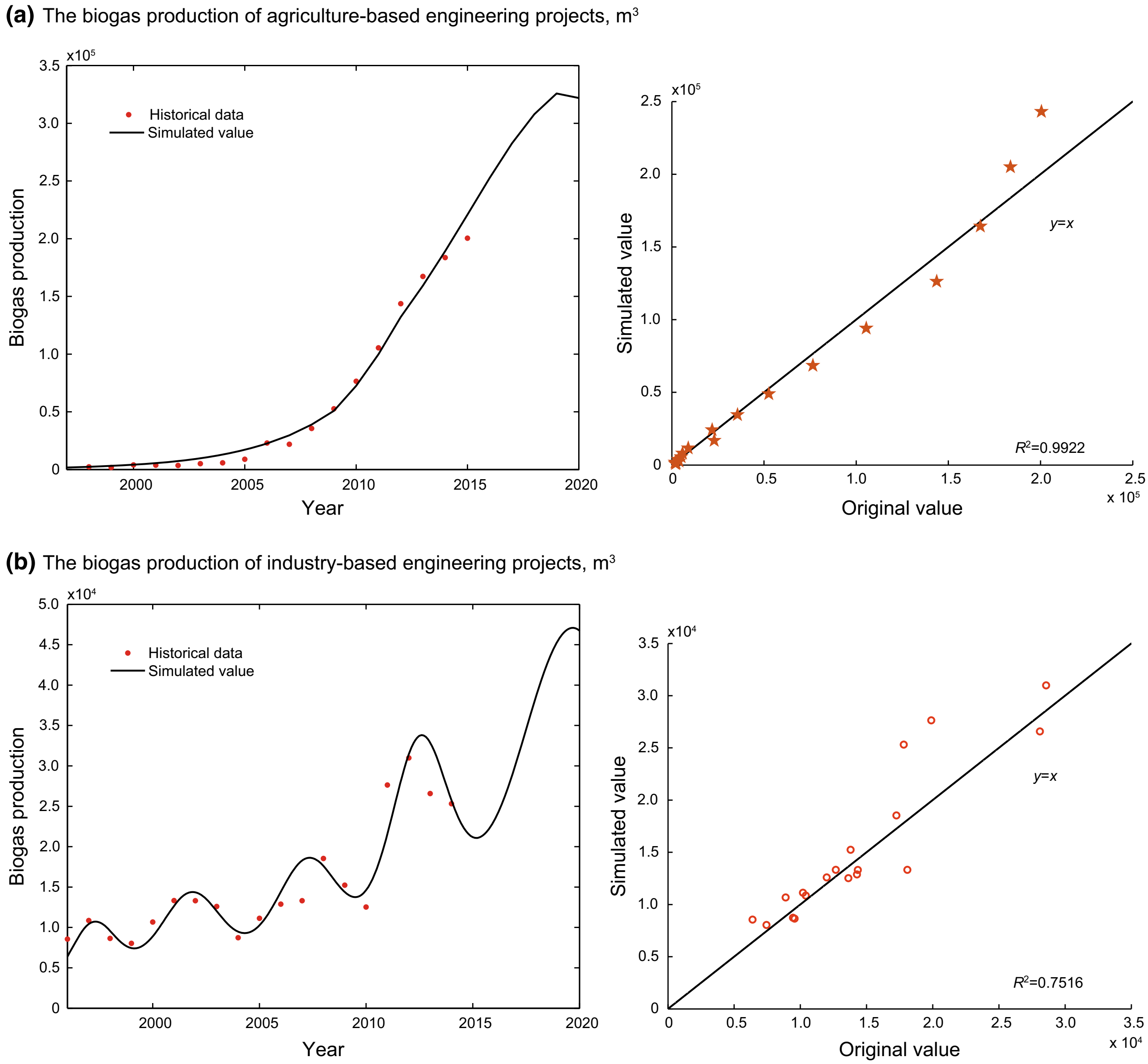

Fig. 7 Biogas production forecast of engineering projects in China. **a** The biogas production of agriculture-based engineering projects of China, **b** The biogas production of industry-based engineering projects of China

(0.758) > government support (0.736) > economic condition (0.728) > raw material resources (0.715). Therefore, marketization of technology is the most significant factor to building agriculture-based projects, for example, with the largest number of biogas companies, Sichuan province ranks the first place among all regions in engineering biogas production recently. Government support and economic conditions are also important factors, followed by raw material resources. With regard to industry-based engineering projects, this sector received much less support from government than the agricultural sector, so the productivity is relatively limited nowadays. According to data in Fig. 8, regions with a long tradition in industry-based biogas production still keep their advantage; in contrast, some provinces with low past biogas production have stopped producing biogas recently. Therefore, an obvious territorial division will gradually form due to historical path dependence. In conclusion, biogas engineering projects are much more market-oriented and technology-dependent than the household sector, and policy support from government is still a necessary factor.

From a policy perspective, for engineering-scale biogas projects, the central government offers 25 %/35 %/45 % out of total investment (up to 150/200/250 million CNY for

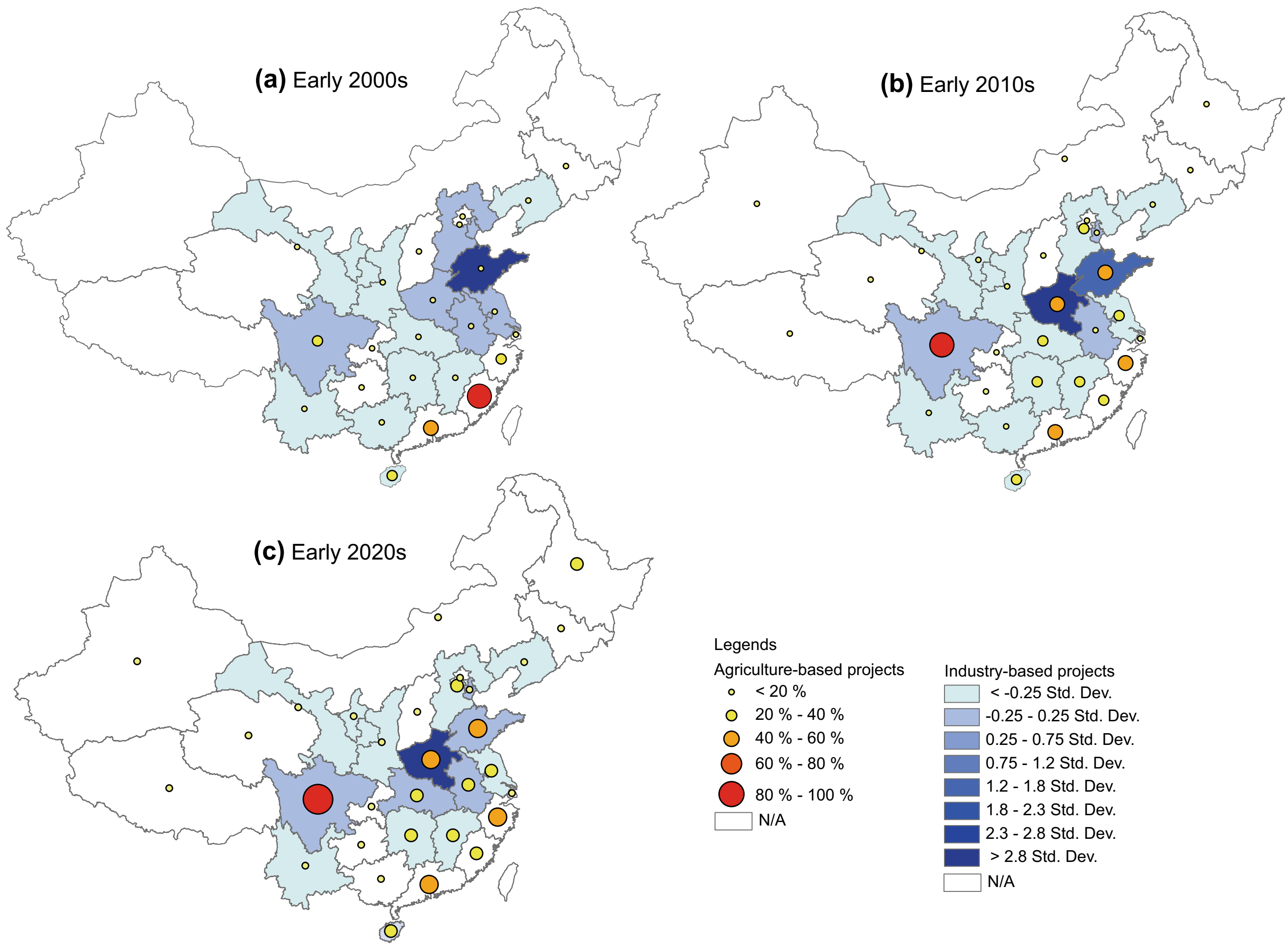

Fig. 8 Regional difference of biogas engineering projects production from 2000 to 2020

east/middle/west regions) for one newly built project since 2009 (MOA 2008). After 2015, new policies concentrate on updating existing biogas industry structure, and give priority to the development of large-scale biogas and bio-based gas projects (MOA 2015). In this context, the productivity of large-scale biogas engineering projects will probably increase to a new level; bio-based gas projects will become a new source for biogas production; yet the new policy might affect motivation of building small- and medium-scale biogas projects. In general, the biogas production from agriculture-based engineering projects will probably grow steadily under current policy promotion. Considering the expensive cost, high technology dependence and various management difficulties for building and maintaining large-scale biogas projects, future policy should not only ensure enough subsidies from government, but also pay attention to how to encourage the entrance of private capital and how to cooperate with enterprises and technical institutions, because the development of engineering projects is closely related to market and technology.

5.3.3 Uncertainty notes

The simulation and forecast results by these curve-fitting methods are on the basis of existing data under relatively stable current status, in other words, those curves can successfully be used for extrapolation of historical trends and to predict future outcomes as long as there is no significant change in underlying economic and technological conditions (Hook et al. 2011). According to this, forecasts in this study are just for the short term (until 2020), and they are not recommended for long period prediction, because of long run uncertainty in economic, technical and political aspects. For example, although the total rural household biogas production is decreasing during the past few years, it is still likely to grow and reach to another peak in the future due to technological updates and other reasons. In the industry-based engineering sector, due to complicated industry shift process, more fluctuations are likely to occur, as a result, the predicted values tend to be uncertain compared to the agricultural and household sectors, however, biogas production in the industry sector is one order of magnitude lower than the agriculture sector, between 0.1 and 0.4 Giga cubic meters and hence only a small proportion of the nation's total production (between 10 and 20 Giga cubic meters), thus uncertainty in the industry sector cannot influence the total biogas production significantly. Finally, the results in this study are just intended to give a reference based on the existing trend, which indicates that China's biogas industry is at a turning point, so it is essential to rethink the policy and planning related to China's biogas.

6 Conclusions and policy implications

6.1 General trend

As is shown with the previous data, under the current policy and status, the total amount of China's biogas production will probably continue to decrease in the next decade, which is largely a result of the declining use of rural household biogas digesters. This research implies that by the year 2020 the amount of biogas production will probably decrease to 10 Giga cubic meters for the household sector, yet grow to about three Giga cubic meters for engineering projects (in total less than 20 Giga cubic meters). Thus, the total biogas production is unlikely to grow as fast as before in next few years, even with a slight decrease in 2014. The results show a large discrepancy with the National Development and Reform Commission of China's 2007 projected long-term goal of a total of 44 Giga cubic meters biogas production in 2020 (NDRC 2007), as well as with the National Energy Administration's 2012 short-term goal of an estimated 19 Giga cubic meters of biogas produced by households in 2015 (NEA 2012), but the newest data in 2014 is 13.2 Giga cubic meters and the actual trend is still downward under the current context. Thus, the analyses detailed above demonstrate that these projections seem inaccurate.

It appears that the former planners and policy makers overestimated the growth rate of biogas production of China. This could be attributed to neglecting consideration of the technological evolution of biogas, with its cycles and peaks, as well as other factors such as rural population loss, and the decline of small livestock breeding in rural areas. Overlooking the above-mentioned factors thus resulted in far more optimistic predictions of China's biogas production, especially with regards to the household biogas sector. This type of overestimation could well cause overinvestment or miss-investment by the government, families or other agencies. Therefore, a scientific prediction of biogas production is of great significance for planners and policy makers, enabling them to set up suitable goals and regulations on biogas development that reflect reality.

6.2 Regional difference

China is a vast country with as well great variations in altitude, resulting in huge climate variations. This is one of many factors that have a profound impact on the anaerobic fermentation of rural household biogas use. This is also the reason why southwestern areas like Sichuan and Guangxi play a leading role in the production and use of household biogas. In fact, it has been demonstrated that household plants do not seem suitable in some arid and cold areas; for example many failed cases have been reported in Inner Mongolia and Heilongjiang (Cui and Ma 2009), where alternative energy sources like wind or solar power may be more effective for family use. Therefore, future policy concerning household biogas should prioritize the southwest and those regions fit for biogas development, instead of giving relatively equal support to most regions, thus avoiding unnecessary finance and resource waste. Furthermore, even within a province, there still exist large regional differences. For instance, Southeastern Gansu has better conditions for developing household biogas compared with the west of the province. Hence, local decision makers should consider a more localized and detailed policy.

Rather than household biogas production, engineering projects are more popular in those advanced regions that have better socioeconomic and technological conditions; abundant raw material is another significant factor (Li and Xue 2010). Thus, Sichuan province, a relatively developed inland region with competitive advantages in agriculture, leads in both household and engineering biogas production. As for those less developed areas with good material conditions for biogas production, local policy makers can make efforts to introduce outside capital and technology into the local biogas industry by offering subsides and other preferential treatment. The national government can also offer more political and financial support to these areas in order to help mitigate the gap in production between some regions, and avoid unnecessary waste on those regions that are not fit for certain types of biogas industry.

With regards to zoning policies on biogas, in the past policymakers set a very rough division of the "Eastern region," the "Middle–Northeastern region," and the "Western region," mainly from a geographic neighboring concept (MOA 2005, 2007). However, as biogas is a mixed sphere with natural and human factors, past zoning policies seem too simple, inflexible, and thus questionable. For example, Sichuan province should not be considered with many other western provinces when making regional policies. Thus, detailed zoning plans should be considered based on the natural environment, resources, the local economy, technology, and other criteria.

6.3 Sector disparity

In the past few decades, with strong promotion by the government, biogas from the agricultural sector including rural household biogas and agricultural engineering projects occupies the major part of China's biogas production. The policy of the first decade of the twenty-first century focused much attention on rural household biogas before shifting its focus to agricultural engineering projects, and those policies supporting biogas development were mainly set up by the Ministry of Agriculture (MOA 2005, 2007; NDRC/MOA 2008). As a result of that, biogas produced by agricultural engineering projects has steadily increased throughout the nation. According to forecasts in this study, the average annual growth rate will probably be as high as 8 % until 2020, and probably reach its first peak around that time, with even faster growth in some regions. In contrast, it has been challenging for the industry sector to develop biogas projects over the last few decades, because the Ministry of Industry and Information Technology has provided less policy support. However, as the "factory of the world," China has great potential for biogas generation within its industrial sector. In addition, biogas engineering projects also need the support of market and technology. Admittedly, in these fields, China has a long way to go to catch up with developed countries.

Consequently, on one hand, continued policy support should be given to agricultural projects in the next decade, especially for those mid-west regions which have a potential in resources; on the other hand, support for rural household construction should be given only in suitable areas. Meanwhile, more preferential policies should be given to the industry sector (prior to those advanced regions in manufacturing industry like Henan). Hence, policy makers of different sectors in China should rethink and redirect the policies according to the sector's own feature, the spatial pattern, as well as scientific forecasts. Last but not least, communication and cooperation among different official departments including energy, agriculture, industry and municipal works should be valued and encouraged in the future; also collaboration among government, enterprises and technical institutions are of great importance for future development of biogas, especially for biogas engineering projects.

6.4 Outlook for the future

Based on the predicted results, although the total productivity of biogas in China will probably become static or decrease for a period and rural household biogas plants will not be as widely used as they were in the past, it is also notable that China is making great progress in biogas production, especially through agriculture-based engineering projects. Therefore, China's biogas industry is and will continue to be in a journey of transformation. In recent years, China's government has paid more attention to the eco-environment and renewable energy issues; in recent years, it promulgated a series of new policies related to ecological civilization: the newly revised 'Environmental Protection Law' (NPC 2014), the 'Implementation plan for green industry development action,' and the 'Plan for water pollution prevention and governance'; further, the development of bio-based energy is suggested to become a priority in China's 13th Five-year Plan (Liu et al. 2015; NDRC 2015). All of the above should result in good prospects for China's biogas industry, especially for large-scale biogas engineering projects. In turn a thriving biogas industry will hopefully be beneficial to China's energy structure and environmental protection efforts.

However, there are still some disadvantages and drawbacks that hinder the development of China's biogas sector, as mentioned in previous literature (Chen et al. 2010; Jiang et al. 2011). Firstly, the technology, especially in biogas engineering projects, is still at a rudimentary level compared with the technologies of developed countries (Chen et al. 2010). In addition, a large number of biogas plants have quality problems and lack maintenance services. Therefore, it is imperative for governments and enterprises to invest more in research and development in biogas technology and develop a more educated and skilled pool of technicians and administrators. It is also important to enhance international cooperation and exchange in the sharing of best practices. Secondly, the utilization of biogas is relatively basic, and neither very commercialized nor industrialized. Thus, it is essential to provide more favorable policies that encourage the multi-utilization of biogas, for example in power or heat generation, vehicle fuel and so on; in addition, connecting biogas to the international carbon market will also result in increased profit. Thirdly, the institutional framework building should be focused on for China's biogas sector. Over the past several years, China's biogas development has excessively depended on government subsidies, and the entrepreneurial spirit of enterprises and other non-public sector actors has not been tapped into for building high-quality biogas plants. Government subsidies account for roughly 50 % of the financing for a typical biogas engineering project (NDRC/MOA 2011), often leaving room for corruption and waste, and leading to the low quality of many biogas projects. As a result, better policies such as encouraging a shareholding system, third-party monitoring, and specific legislation with strict enforcement are needed to create the appropriate institutional environment, good public–private relationships, and a tight collaborative network among governments, capitalists, enterprises, consumers, NGOs, and other stakeholders. In conclusion, future development of China's biogas is not only partly due to the changes in quantity, but also depends on the quality improvement and institutional innovation, in order to extend technological life cycle or create opportunities for the next peak. Further research is needed for detailed explanations and solutions to China's biogas development.

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