Review of biogas models and key challenges in the further development in China

Lihong Chen 1*, Pia Frederiksen 2*, Xin Li 1, Bangrong Shu 1

1 School of Geography, Geomatics and Planning, Jiangsu Normal University, Xuzhou, 221116, China
2 Department of Environmental Science, Aarhus University, DK-4000 Roskilde, Denmark

*Corresponding and Co-corresponding author’s e-mail: chenlihong505@hotmail.com; pfr@envs.au.dk

Abstract: This paper provides an overview of biogas models and key challenges of further biogas development in China. A review of the biogas models aim to highlight the complexity of biogas development in China, and thereby draw attention to some easily neglected issues in China's biogas development. China's biogas development had stagnated in recent years, and while household biogas projects have always been the leading force of biogas production in China, their proportion declines year on year. “3 in 1”, “4 in 1” and “5 in 1” models are the most common models used in China, but Medium and Large-scale Biogas Projects (MLBPs) increasingly play a significant role. By comparison, MLBPs perform better than household biogas projects in some aspects. On the other hand, household projects have their advantages and are essential aspects of energy system development, particularly in more remote rural areas. This paper strongly recommends paying more attention to the practical application of household biogas models and providing the necessary support to skill development and digester maintenance. Moreover, this paper argues that biogas policies need to be based on scientific evidence.

1. Introduction

With the increasingly severe global problems related to climate change and the decrease in the storage of fossil energy[1], renewable energy has become one of the leading choices to address these problems. The governments of many countries have committed to decreasing their emissions and respond actively through increased use of renewable energy[2]. Especially in the European Union, the use of renewable energy is expected to account for 20% of final energy consumption by 2020 and the renewable energy contribution is further projected to increase to 55–75% of gross final energy consumption in 2050[3]. Bioenergy is one of humanity's earliest renewable energy sources, and it is often the only accessible and affordable source of energy in rural areas[4]. Bioenergy has numerous benefits for the energy systems and sustainable development, including increasing energy security[5], environment and health improvements[6], contributing to rural development[7] and significantly contributing to reducing greenhouse gas emissions[8]. Presently China's energy structure is too simple to support the sustainable development of the economy, as coal is still the primary energy carrier used[9]. China has abundant biomass resources, but its development and rate of utilization are presently very low. It is imperative to change the structure of the energy system in China for the
further development of renewable energy. In turn, this may lead to substantial environmental co-benefits[10]. However, the overall consequences of biofuel production for society should be considered, as bioenergy may also have critical disadvantages[11]. Biofuels, for example, has been discussed intensively for its potential consequences for food production[12] and, in China fuelwood collection and associated deforestation is reported[13].

Biogas is a clean renewable energy carrier, and it has been identified as one of the leading renewable energy sources capable of mitigating environmental emissions in rural areas[14]. In rural China, more than 1200 million tons of crop residue and manure could be used as substrates for biogas production, and only about 19% of the biogas potential is utilized[15,16]. China has devoted enormous resources to promote the dissemination of household biogas plants (typically ranging from 8 to 10 m³) [17] and estimated data show that annual biogas potential from agricultural waste is approximately $(335.06 \pm 66.93) \times 10^9$ m³ (equal to 239.22 ± 47.78 million tons of equivalent standard coal) in China[18]. However, biogas accounts for merely 1% of energy consumption in rural China[19]. Biogas could be an essential means to convert agricultural wastes to clean and safe energy, thereby reducing the need for fossil fuels and alleviating environmental pollution[18].

Integrated biogas engineering implies that biogas technology is integrated with what Chinese-based scientific literature calls “eco-agriculture”[20]. Different from the conventional agricultural production mode of one-way flow, from “resources–agricultural products–wastes” to “resources–agricultural products–renewable resources” the eco-agriculture means low-cost, high resource efficiency and low waste emission[21]. These models are now widely distributed in China and contribute to expanding the circular resource flow in rural areas and thereby a circular economy. The latter refers to an economical production model in which the resource or feedstock used for production gains value through practices such as circulation or regeneration that enable the utilization of recycled materials while reducing waste disposal. A circular economy may be able to achieve a “win-win-win” situation by linking ecological improvement, and structural optimization with economic development[22] and this model is implemented as a national policy of sustainable development in China[23].

This paper attempts to show a variety of local designs of household biogas projects, compare the performances of household biogas and Medium and Large-scale Biogas Projects (MLBPs) and list some easily neglected issues in China’s biogas development. Some constructive advice is given in the conclusions and recommendations.

2. Status of Chinese biogas development
China has abundant agricultural waste and thus a high potential for rural biogas production[18]. In 2016 the total annual production of biogas in China reached $14.49 \times 10^9$ m³. From 2001 to 2016, the growth rate of China’s biogas production declined and even demonstrated negative growth during 2014-2016 (Fig. 1). Chen et al. [24] claimed that China’s biomass energy development has been very slow in recent years and seems to be marginalized when compared with other types of renewable energy systems in China.
Along with the development of livestock operations in China and the application of biogas projects to agricultural waste disposal, agricultural biogas projects have developed tremendously not only in terms of the total quantity of the product but also in terms of the percentage of biogas production[26]. According to China’s statistical yearbook, there are three main categories of biogas projects in China: household biogas, agricultural waste, and industrial waste biogas projects. By the end of 2016, there were about 41.61 million household biogas digesters in rural China, accounting for 30% of the suitable households[9]. The total biogas production of household biogas digesters reached $11.79 \times 10^9$ m$^3$, with an annual average household production of 3.68 m$^3$; 113,182 agricultural waste disposal projects produced $2.43 \times 10^9$ m$^3$ of biogas, and 258 industrial waste disposal projects produced $0.27 \times 10^9$ m$^3$ of biogas[25]. Additionally, some small biogas projects scattered among schools and hospitals. Total biogas production from agricultural biogas plants increased from $35 \times 10^6$ m$^3$ in 2001 to $2428 \times 10^6$ m$^3$ in 2016, approximately a 69-fold increase. The percentage of agricultural biogas project against total biogas production in China has increased from 1.11% in 2001 to 16.76% in 2016. The household biogas project is still the leading force of biogas production in China, but its proportion declines year by year. (Fig.2).

![Figure 1. Biogas production in China from 2000–2016 ($10^8$ m$^3$)][25]

![Figure 2. The proportion of biogas types in China from 2001–2016 (%)][25]
The utilization rate of household biogas is approximately 85% in China[27], and the utilization rate usually refers to the biogas digesters used for eight months a year in the southern region, or half a year in the north of the country or in high elevation areas[6]. In some provinces of China, the average utilization rate of household biogas is low, such as 62.03% in Guizhou Province, 30-70% in Shanxi Province[28] and about 65-70% in the northwest of China[29].

The development of biogas as a strategy for building new socialist countryside and sustainable agriculture in rural China is an essential means to convert agricultural wastes to clean and safe energy [18]. Song et al. [30] argued that the Chinese government should give more attention to biogas use in rural areas and provide financial support to rural biogas development in order to achieve sustainable development.

3. Major biogas models in China

In the countryside of China, biogas production comes mainly from two primary sources: household biogas and MLBPs[28,30]. MLBPs usually refer to livestock and poultry farm biogas projects in China, and BLBPs is an essential part of agricultural biogas projects. Household biogas has become the largest biomass energy industry in China[31].

3.1. Household biogas models

3.1.1. Types and concepts

Development of household biogas digesters in rural areas and integrated use of agricultural wastes has changed the structure of rural household energy consumption and significantly increased the application of highly efficient organic fertilizer, improved soil fertility and promoted sustainable farming development[32]. As such, rural household biogas expansion is a vital program of the renewable energy system in China[33].

Most household biogas systems are variations of the biogas-linked eco-agricultural model in rural China. The biogas-linked eco-agricultural model has a long utilization chain for agricultural wastes, which takes in non-renewable resources and outputs renewable resources. Therefore, the household biogas-linked eco-agricultural model is a useful measure in relieving energy shortages, reducing environmental pollution, and realizing sustainable agriculture in rural areas[34]. The “3 in 1”, “4 in 1” and “5 in 1” are three prevalent models in China. The “3 in 1” is widely used in southern China and the biogas digester is combined with a pigpen and toilet; the “4 in 1” is popular in northern China and always combines a biogas digester with a pigpen, greenhouse and toilet; the “5 in 1” is popular in northwest China and combines a biogas digester with a solar-powered pigpen, a water cellar and a rainwater collecting pool[30]. Compared with the conventional animal husbandry system, the integrated biogas eco-agricultural system, in general, proves more sustainable[35].

Table 1. Different types of household biogas-linked eco-agriculture in China.

| Model | Types |
|-------|-------|
| 3 in 1 | biogas-pigpen-toilet[18]; pig-biogas-fruit[30,36]; pig-biogas-fish[37]; pig-biogas-vegetable[38]; pig-biogas-vegetable greenhouse system[39]; pear-biogas-pig[40]; pig-biogas-grain[19]; pig-biogas-paddy[41]; pig-biogas-orange[42]; pig-biogas-energy[43]; pig-biogas-orchard[44] |
| 4 in 1 | biogas-pigpen-solar greenhouse-and toilet[18,30]; pig-biogas-fruit-fish [45]; fresh eatable maize-sheep(pig)-biogas-forage grass[46]; cattle-biogas-pig-grain[47]; pig-biogas-dockwee-cassava[48]; fruit–amaranth–pig–biogas[49] |
| 5 in 1 | biogas-solar powered barns-water saving irrigation system-water cellar-toilet [18,30]; Biogas-solar powered pigpen-water cellar-rainwater collecting pool-a suit of drip irrigation system[30]; pig-biogas-rice-lamp-fish[50]; fruit–amaranth–pig–biogas–fruit[51]; apple-grass-pig-biogas-rainwater[52] |

Note: the models in Table 1 only refers to the number of objects on one model chain.
Regional variations are considerably between north and south China, as well as east and west. As such, there are many different types of household biogas-linked eco-agriculture in China[53]. (see Table 1 for an overview of published systems). Overall, resource utilization and biogas production are limited by geographical characteristics and regional differences[54].

3.1.2. Technical performance
The Chinese household biogas digesters usually have a volume of 8–10 m³[21] and are designed to last for 20 years[6]. Animal manure, crop straws, and processing residues of agricultural products are essential sources of fermentation materials for biogas production, and the household biogas produced is used for cooking and lighting[28]. In 2016, the average yearly yield of biogas in each household was only 368 m³[25] because of the environment and technology. There are significant differences between the microbial community structures of the biogas digesters in different climatic regions, which implies that the energy efficiency is affected by the environment[55]. Moreover, the efficiency of the household biogas will still need to be improved by addressing the current limiting technology[34]. Meanwhile, the owners of household biogas digesters often lack management and technology skills, which also results in low efficiency in a large proportion of household biogas digesters[56]. Besides, household biogas technical services are also essential and most county-level rural (hundreds of thousands or more than one million people, usually) energy offices only have three to seven staff members, who cannot meet the rapidly growing demand for the follow-up services of rural household biogas digesters[57]. In the future, the straw will replace animal manure as the primary raw material of biogas in rural China[56]. Also, technical solutions for tackling the low productivity of biogas digesters in cold regions may need to be further considered[35], and more attention should be paid to efficiency and accelerants to promote digestion process performance[58].

3.1.3. Economic performance
Chen et al. [59] document that household biogas systems have brought enormous economic benefits to the local people. The installation of a household biogas digester could increase crop yields and thereby economic performance by 25%[17], based on fertilizer substitution, or increase household income considerably, due to its substitution for cooking coal and electricity[59]. Wang et al. showed that the energy consumption of every household possessing biogas digesters was about 337 kg, while those without used 451 kg[32], implying a significant reduction in energy expenditure by households using biogas digesters. Especially in northwestern China, an 8 m³ biogas digester annually provides an amount of biogas manure that is equivalent to 50 kg of ammonium sulfate, 40 kg of calcium phosphate and 15 kg potassium chloride and could save about $60 from cooking and lighting[29]. A typical household biogas project in Gongcheng County showed a net substitution benefit of estimated $6520 for the best 10-year operation period[53]. Conversely, other research claimed that the economic performance of household biogas might not be satisfactory[60].

3.1.4. Environmental performance
Household biogas digestion has several environmental benefits. The Chinese government’s promotion of biogas technology can address soil degradation, which results from the full application of inorganic fertilizers[6] and can avoid eutrophication from nutrient release from the discharge of livestock and poultry manure directly into the water[26]. Human and animal excreta can be appropriately collected and fermented, which reduces the spread of germs[53]. In addition, the household biogas project has a significant effect of SO₂ emission reduction, which is necessary to reduce the formation of acid rain and pollutants in the atmosphere in general[33]. A household biogas project in Gongcheng County showed that 4120 kg of CO₂ and 34.7 kg of SO₂ emissions were effectively reduced during the 10-year operation period[53]. China's household biogas project also has a decisive role in forest protection. In the northwest of China, a household biogas project can decrease the proportion of straw and firewood fuel by 60–88% and protect about 0.03–0.20 ha of the forest land area[29]. Due to the high number of
household biogas digesters distributed in China's rural areas, the use of household biogas digesters will protect a significant amount of forest resources.

Of course, potential environmental risks should be taken seriously by society. Biogas slurry, as a quality organic fertilizer[61] and microbial biomass in biogas residues, may be a significant contributor to soil organic matter formation[62] but there is still a health risk from food crops contaminated with heavy metals through the intake of cereals and vegetables grown from biogas slurry-irrigated sites[63].

3.1.5. Climate mitigation performance
The greenhouse gas emission reduction of household biogas projects is widely studied. Reducing the emission of CO$_2$ and CH$_4$ represents an essential contribution of household biogas digesters to climate mitigation[56]. Several studies agree that a household biogas project with a volume of 8 m$^3$ can produce a total CO$_2$ emission reduction of 2–3 tons during its whole life cycle[59,64] and an annual CO$_2$ emission reduction potential of 1–1.5 tons[29,64]. In total, its net emission reduction benefit is reached within 2–3 years[64,65].

3.2. MLBPs models

3.2.1. Types and concepts
MLBPs often refers to systems where the total digester volume is more than 50m$^3$[66]. Most of the MLBPs are constructed based on medium or large livestock and poultry farms and usually the biogas from MLBPs is used for cooking, heating, and lighting within the farm regions, as well as for power generation[28]. The popularization rate of MLBPs in livestock farms has formerly been low but developed rapidly with the average annual increasing rate of 13.94% from 2001 to 2010 and high differentiation existed in popularization rate and growth trends, as about 98.63% of MLBPs were located in southern areas, such as Liaoning, Hebei, Shanxi, Shaanxi, Gansu, and Sichuan[67]. The characteristics of some typical large-scale biogas plants that have been developed in recent years in China are listed in Table 2.
Table 2. Large-scale biogas projects in China[68-70]

| Biogas project                                      | Completion Time (year) | The capacity of raw material handling | Scale | Biogas production and utilization |
|-----------------------------------------------------|------------------------|--------------------------------------|-------|----------------------------------|
| Mengniu Austasia Demonstration Pasture biogas project| 2007                   | 10,000 cows, 280 t/d of cow dung, 54 t/d of cow urine, 360 t/d of flushing water | 2,500 m$^3 \times 4$ | Power generation: 20000 kW·h/d |
| Shandong Minhe Animal husbandry biogas project       | 2008                   | 800 t/d of chicken farm manure       | 3200 m$^3 \times 8$ | Power generation: 60000 kW·h/d |
| Henan Yexian Group biogas project                   | 2009                   | 200,000 pig manure: 300 t / d        | 13000 m$^3$ | Power generation                  |
| Guangxi Wuming Anning starch company biogas Demonstration Project | 2011                   | Cassava residue, tapioca starch, alcohol wastewater: 6000 m$^3$ /d | 34000 m$^3$/d | CNG for vehicle: 60000 m$^3$/d |
| Saibei of Modern animal husbandry biogas project     | 2011                   | 15,000 cows                          | 9500 m$^3$ | Power generation                  |
| Biogas project of Tianshan town, Chifeng City        | 2013                   | Straw, animal manure and garbage and other mixed material: 120 t TS / d | 5000 m$^3 \times 12$ | CNG: 60000 m$^3$/d            |
| Qingyuan biogas project                             | 2017                   | 219 t/d of chicken manure, 274 t/d of sewage | 3000 m$^3 \times 4$ | Power generation: 40,000 kW·h/d |

Note: Units of “capacity of raw material handling” are not uniform and there is no specific data in “biogas production and utilization” because of available references.

3.2.2. Technical performance

According to the Technical Code for MLBPs Biogas Engineering (GB/T 51063 -2014), the raw materials of the MLBPs include agricultural organic waste, high concentration industrial organic wastewater, industrial organic residue and sludge. MLBPs for civilian use, power generation, purification, and compression must not be lower than 500 m$^3$, 1200 m$^3$ or 10000 m$^3$ per day, respectively. The above technical code does not mention the lifetime of the MLBPs. In the Code for Process Design of Straw Biogas Project (NY/T 2142-2012), the lifetime of MLBPs based on straw is more than 25 years. The livestock operation portion of the biogas systems refers to a production facility that performs anaerobic digestion of the livestock manure and sewage, enabling biogas production and pollution reduction. Dry methane fermentation will become an important method for the large-scale production of biogas from agricultural wastes[57]. As a typical representative of MLBPs, the technological process of the De Qing Yuan (DQY) biogas project consists of five main components: pre-treatment of the raw material, biological desulphurization, the power grid, biogas for household use and biogas residues as fertilizer. Monitoring the management of biogas production is performed during the entire process[69]. Usually, MLBPs are better than household biogas projects in terms of several technical indicators, due to the utilization of more advanced technology.

3.2.3. Economic performance

Usually, the economic benefits of MLBPs are remarkable. The DQY biogas project generates $14 \times 10^6$ KW·h of power from biogas annually, with a unit price of approximately RMB 0.6 yuan/kw; the profit from power generation is RMB 8.4 million yuan each year[70]. The annual yield of biogas fertilizer is
6600 tons, and the sales profit is RMB 2 million yuan. By improving the quality of discharged water, a poultry farm can reduce the number of their discharge penalties (RMB 2 yuan/ton) and save RMB 200,000 yuan each year. As a result, the total economic benefits of the DQY biogas project are valued at RMB 10.6 million yuan per year[26]. Zhang et al.[8] evaluated that the economic value of reducing the emission of CO$_2$ from the MLBPs in China was $1.16 \times 10^5$ – $2.69 \times 10^5$ Yuan (RMB), according to the price of the international carbon market. Chang et al. evaluated the economic benefits of the Mengniu Australia Demonstration Pasture (see Tab.2) in detail and revealed that MLBPs may bring the following economic benefits: (i) reduction of the pollutant emission fees, (ii) reduction of fuel costs, saving the cost of fertiliser and pesticide and creation of income by selling organic fertiliser made from biogas slurry and residue, (iii) reduction of utility bills and increase in incomes by uploading generated electricity to power grids, (iv) creating incomes through CDM, etc. Other studies showed that small-scale biogas might perform better economically, even if the energy efficiency of the large plants is better[71].

3.2.4. Environmental performance
Comparing the Technical Code for MLBPs Biogas Engineering (GB/T 51063 - 2014) with the Specifications of Household Biogas Digester Operation and Maintenance (NY/T 2451 - 2013), MLBPs have special requirements in terms of biogas project site selection to avoid water and soil pollution and more stringent requirements to remove harmful gases than household projects. Biogas slurry and biogas residue can increase soil organic matter quality, available phosphorus, and soil enzyme activity. This reduces crop diseases, along with the use of pesticides 77.5%[72]. Producing commercial fertilizer from biogas residue and slurry can avoid heavy-metal pesticide residues and pathogenic bacteria that pollute the water and farmland[57]. Take DQY biogas project as an example: the 80,000 tons of chicken manure and 100,000 tons of sewage produced each year would seriously pollute the environment if not properly treated. The initial COD concentration of the manure-sewage-mixture was 18,000 – 24,000 mg/l and the BOD concentration was 4,600 mg/l. Using advanced technology, DQY achieves COD and BOD removal rates of 64% and 70%, respectively. The annual removal quantity of gravel in manure is 2600 tons, with a removal rate of 89%[69]. MLBPs with the eco-agricultural model can effectively use agricultural waste, reduce environmental pollution significantly and, furthermore, avoid chemical pollution resulting from overuse of fertilizer in the long term[73].

3.2.5. Climate mitigation performance
The greenhouse gas emission reduction potential of MLBPs was also widely studied. Zhang et al. [8] found that a typical MLBPs can reduce the discharge of CO$_2$ by $0.54 \times 10^6$ – $1.51 \times 10^6$ t and CH$_4$ by $1.53 \times 10^5$ t (CO$_2$ equivalent). Similar results from a large-scale farm in Northwest China showed the total greenhouse gas emission mitigation of an eco-agricultural integrated production system of cattle, biogas, and greenhouse vegetables was 185,054.43 kg CO$_2$ per year[21]. A CO$_2$ emission reduction of about 25,000 tons per year was found in the Mengniu Australia Demonstration Pasture biogas project with 10,000 cows, which successfully applied for the CDM project in 2006 according to the relevant provisions of the Kyoto protocol and signed a purchase agreement with a Dutch carbon trading company[22].

4. Key challenges for further development of biogas in China
4.1. Household biogas and MLBPs cannot replace each other
According to performances of household biogas projects and MLBPs, these two types of biogas projects display both outstanding performance and drawbacks. Household biogas project applications are more widely distributed because China has vast and remote rural areas. Household biogas involves lower investment but can effectively reduce water pollution, prevent soil degradation, and reduce greenhouse gas emissions. The drawbacks of household biogas include insufficient raw materials and lack of operational guidance and operator skills. These factors result in low efficiency.
For the MLBPs, their comparatively better energy efficiency performance is derived from large-scale production and high-tech applications that produce high efficiency and reduce pollution and greenhouse gas emissions. There is not full consensus on the economic benefits of MLBPs: excessive investment may pose a cost-benefit risk. The apparent drawback related to MLBPs is that they are limited to areas with high livestock and poultry farm density, which is again influenced by the environment.

In summary, in the foreseeable future household biogas projects and MLBPs will both exist as essential elements in biogas development in China and cannot replace each other completely.

4.2. Household biogas development has stagnated but is still critical
According to public statistics, the utilization rate of household biogas decreased considerably as more and more digesters were discontinued. On the one hand, existing policies of household biogas projects place excessive emphasis on construction support rather than to management and maintenance. On the other hand, household biogas stagnation also comes from the development of large-scale livestock farms, agricultural modernization and urbanization, which profoundly affect the agricultural and social environment in rural China. In the future, development of biogas may allow for a transition from household models to MLBPs[28]; meanwhile, it will also be necessary to ensure a sufficient quantity of household biogas digesters in proper operation. This requires targeted policy support.

4.3. Promotion of biogas industrialization is imminent
Presently, China is importing large quantities of natural gas every year, and energy security is threatened. Biogas upgrading is attracting increasing attention and biogas can be converted to transportation fuels after cleaning procedures. Upgrading biogas to bio-compressed natural gas and liquefied biogas is an essential direction of biogas utilization. In the future, central gas supply systems in the main grain-producing areas for producing biogas and organic fertilizers can be considered a direction for future development[18]. In fact, the MLBPs are more or less similar to this central gas supply system and sometimes can be considered the same system. The central supply model, which generates electricity, will probably become the future biogas development model in rural China [57]. In summary, the promotion of further industrialization and technological development of biogas in China is imminent.

4.4. A more evidence-based biogas policy is needed
China's biogas development is dependent on policy support and the rapid development of China's biogas production in the past two decades was mainly due to economic policy incentives. Household biogas policies mainly focus on construction support and offer less consideration to management and maintenance, resulting in high scrap rates and the waste of resources. Alternative policies must be developed to balance construction and operation[60].

According to the current situation, if there are no further strong financial and policy stimuli, the Chinese government’s aims to reach the biogas development goals of Medium and Long-Term Development Plan or Development Plan of Agricultural Biomass Energy Industry 2007-2015 will not be realized. It should be a priority to explore future development models further, to revise development goals, and to develop appropriate policy instruments to pursue them. One of the potential pathways to pursue could be to consider paying for the environmental and climate benefits that these systems provide. Overall, China’s biogas policy needs to be improved and perfected, and evidence-based development of biogas policies are incredibly critical.

5. Conclusions and recommendations
(1) In recent decades, China's biogas production has undergone rapid development. Household biogas projects are the primary model for biogas production in China, but its proportion has declined year by year. The reason lies in China's rural areas, where fewer and fewer single families are willing to breed livestock, and many young men move to the city for employment. Biogas digesters are challenging for
children and seniors to operate. On the contrary, MLBPs in China has seen rapid development, due to the intensification of animal husbandry and tremendous changes in lifestyle and the social structure of rural areas.

(2) China has many types of household biogas utilization models. In general, these types belong to the “3 in 1”, “4 in 1” or “5 in 1” models. China's biogas development must be adapted to local conditions. Despite household biogas running into problems in China, these models will provide the most crucial utilization of biomass waste in rural areas of China for the foreseeable future. Hence, a valuation of the environmental benefits that household biogas delivers in China may be an essential basis for further biogas subsidies.

(3) By comparison, household biogas and MLBPs both show outstanding performances in reducing greenhouse gas emissions and pollution. Comparatively better performances of household biogas seem to include low investment and wide adaptability. The parameters of which MLBPs perform better than household models include more advanced technology and more efficient output. The biogas industry is an obvious future development direction in energy supply and resource management. It is however imperative to base development on scientific evidence.

(4) China's biogas development policies are the basis and initial impetus for the development of the Chinese biogas industry. There are, however, examples of policies that are not sufficiently supported by scientific evidence, and there are signs that the total production of biogas in China may stabilize or even decrease for a period. With the weak growth in the expansion of biogas production in China, it is necessary to pay more attention to evidence-based policy formulation and implementation in the future.

Acknowledgments
Financial support was received from the Jiangsu Social Science Foundation Project (Grant Nos. 17EYB010) and Aarhus University (DCE) strategic funds.

References
[1] Zeng M, Duan JH, Wang L, Zhang YJ, Xue S. (2015) Orderly grid connection of renewable energy generation in China: Management mode, existing problems and solutions. Renew Sust Energ Rev., 41:14-28.
[2] Hua YP, Oliphant M, Hu EJ.(2016) Development of renewable energy in Australia and China: A comparison of policies and status. Renew Energ., 85:1044-1051.
[3] Scarlat N, Dallemend JF, Monforti-Ferrario F, Banja M, Motola V.(2015) Renewable energy policy framework and bioenergy contribution in the European Union - An overview from National Renewable Energy Action Plans and Progress Reports. Renew Sust Energ Rev., 51:969-985.
[4] Demirbas A.(2004) Combustion characteristics of different biomass fuels. Progress in Energy and Combustion Science, 30(2):219-230.
[5] Borjesson M, Athanassiadis D, Lundmark R, Ahlgren EO.(2015) Bioenergy futures in Sweden - system effects of CO2 reduction and fossil fuel phase-out policies. Gcb Bioenergy., 7(5):1118-1135.
[6] Xia ZZ.(2013) Domestic biogas in a changing China: Can biogas still meet the energy needs of China's rural households? London: International Institute for Environment and Development.
[7] Gautam YB, Pelkonen P, Halder P.(2013) Perceptions of bioenergy among Nepalese foresters - Survey results and policy implications. Renew Energ., 57:533-538.
[8] Zhang P, Li X, Yang Y, Zheng Y, Wang L.(2008) Greenhouse gas mitigation benefits of large and middle-scale biogas project in China. Transactions of the CSAE., 24:239-243(in Chinese).
[9] Shen JF, Luo C.(2015) Overall review of renewable energy subsidy policies in China - Contradictions of intentions and effects. Renew Sust Energ Rev., 41:1478-1488.
[10] Long XL, Naminse EY, Du JG, Zhuang JC. (2015) Nonrenewable energy, renewable energy, carbon dioxide emissions and economic growth in China from 1952 to 2012. Renew Sust Energ Rev., 52:680-688.

[11] Moller F, Slento E, Frederiksen P. (2014) Integrated well-to-wheel assessment of biofuels combining energy and emission LCA and welfare economic Cost Benefit Analysis. Biomass Bioenerg., 60:41-49.

[12] Tilman D, Socolow R, Foley JA, Hill J, Larson E, Lynd L, et al.(2009) Beneficial biofuels—the food, energy, and environment trilemma. Science, 325(5938):270-271.

[13] Chen L, Heerink N, van den Berg M. (2006) Energy consumption in rural China: A household model for three villages in Jiangxi Province. Ecol Econ., 58(2):407-420.

[14] Yang J, Chen B. (2014) Extended exergy-based sustainability accounting of a household biogas project in rural China. Energ Policy., 68:264-72.

[15] Chen Y, Hu W, Sweeney S. (2013) Resource availability for household biogas production in rural China. Renew Sust Energ Rev., 23:655-659.

[16] Chen Y, Yang GH, Sweeney S, Feng YZ. (2010) Household biogas use in rural China: A study of opportunities and constraints. Renew Sust Energ Rev., 14(1):545-549.

[17] Ding WG, Wu Y, Li Q. Cost effectiveness analysis of household biogas plants in China. Energy Sources Part B-Economics Planning and Policy. 2013;8(4):431-8.

[18] Zhang T, Yang YH, Xie DT. (2015) Insights into the production potential and trends of China's rural biogas. International Journal of Energy Research., 39(8):1068-1082.

[19] Jian L. (2009) Socioeconomic Barriers to Biogas Development in Rural Southwest China: An Ethnographic Case Study. Hum Organ., 68(4):415-430.

[20] Wu XF, Chen GQ, Wu XD, Yang Q, Alsaeedi A, Hayat T, et al. (2015) Renewability and sustainability of biogas system: Cosmic exergy based assessment for a case in China. Renew Sust Energ Rev., 51:1509-1524.

[21] Wu XH, Wu FQ, Tong XG, Jiang B. (2013) Emergy-based sustainability assessment of an integrated production system of cattle, biogas, and greenhouse vegetables: Insight into the comprehensive utilization of wastes on a large-scale farm in Northwest China. Ecological Engineering., 61:335-344.

[22] Chang IS, Zhao J, Yin XF, Wu J, Jia ZB, Wang LX. (2011) Comprehensive utilizations of biogas in Inner Mongolia, China. Renew Sust Energ Rev., 15(3):1442-1453.

[23] Geng Y, Fu J, Sarkis J, Xue B. (2012) Towards a national circular economy indicator system in China: an evaluation and critical analysis. J Clean Prod., 23(1):216-224.

[24] Chen LH, Li XB, Wen WY, Jia JD, Li GQ, Deng F. (2012) The status, predicament and countermeasures of biomass secondary energy production in China. Renew Sust Energ Rev., 16(8):6212-6219.

[25] China MoA. (2015) Chinese Agricultural Statistics. Beetong: China Agriculture Press (in Chinese).

[26] Chen LH. (2015) Spatial Distribution of Biomass Waste Resources and Its Biogas Potential in China. Beijing: China Agriculture Press (in Chinese).

[27] Feng YZ, Guo Y, Yang GH, Qin XW, Song ZL. (2012) Household biogas development in rural China: On policy support and other macro sustainable conditions. Renew Sust Energ Rev., 16(8):5617-5624.

[28] Wang XJ, Lu XG, Yang GH, Feng YZ, Ren GX, Han XH. (2016) Development process and probable future transformations of rural biogas in China. Renew Sust Energ Rev., 55:703-712.

[29] Li CJ, Liao YC, Wen XX, Wang YF, Yang F. (2015) The development and countermeasures of household biogas in northwest grain for green project areas of China. Renew Sust Energ Rev., 44:835-846.

[30] Song ZL, Zhang C, Yang GH, Feng YZ, Ren GX, Han XH. (2014) Comparison of biogas development from households and medium and large-scale biogas plants in rural China. Renew Sust Energ Rev., 33:204-213.
[31] Zhang TT, Tan YF, Zhang XD.(2016) Using a hybrid heating system to increase the biogas production of household digesters in cold areas of China: An experimental study. Applied Thermal Engineering, 103:1299-1311.

[32] Wang XH, Li JF.(2005) Influence of using household biogas digesters on household energy consumption in rural areas - a case study in Lianshui County in China. Renew Sust Energ Rev., 9(2):229-236.

[33] Zhang PD, Jia G, Wang G.(2007) Contribution to emission reduction of CO2 and SO2 by household biogas construction in rural China. Renew Sust Energ Rev., 11(8):1903-1912.

[34] Qi J, Chen B, Chen WC, Chu XL.(2012) Inventory analysis for a household biogas system. In: Yang Z, Chen B, editors. 18th Biennial Isem Conference on Ecological Modelling for Global Change and Coupled Human and Natural System. Procedia Environmental Sciences: 1902-1906.

[35] Qu W, Tu Q, Bluemling B.(2013) Which factors are effective for farmers' biogas use? Evidence from a large-scale survey in China. Energ Policy., 63:26-33.

[36] Zhou Y, Xie ZH, Liu YL.(2004) Economic evaluation on household-scaled “pig-biogas-fruit” ecological mode. Chinese Journal of Eco-Agriculture, 4:061(in Chinese).

[37] Wu XF, Wu XD, Li JS, Xia XH, Mi T, Yang Q, et al.(2014) Ecological accounting for an integrated "pig-biogas-fish" system based on energetic indicators. Ecol Indic., 47:189-197.

[38] Qi XS, Zhang SP, Wang YZ, Wang RQ.(2005) Advantages of the integrated pig-biogas-vegetable greenhouse system in North China. Ecological Engineering., 24(3):177-185.

[39] Zhou Y, Xie ZH, Liu YL.(2004) Economic evaluation on household-scaled "pig-biogas-fruit" ecological mode. Chinese Journal of Eco-Agriculture, 4:061(in Chinese).

[40] Kangwa J.(2003) Pear-biogas-pig production simulation model. Hangzhou: Collage of agriculture and biotechnology of Zhejiang University (in Chinese).

[41] Deng YJ, Liu JH, Jia RA.(2012) Study on the project for controlling pollution caused by anaerobic and aerobic digester effluent of piggery methane. Journal of Anhui Agricultural Sciences, 31:15388-15390 (in Chinese).

[42] Luo XF, Xiong W, Yang CF, Xie J, Lei SM. (2010) Characteristics of agricultural circular economy in the Three Gorges Reservoir Region of Chongqing—a case study of the ecological agriculture pattern of" pig-biogas-orange". Chinese Journal of Eco-Agriculture., 18(2):405-409 (in Chinese).

[43] Tu GP, Jia RA, Wang CX, Jia XJ, Deng QZ, Peng YQ.(2009) Theory and application research on construction of planting and livestock breeding biomass energy industry based on system dynamics. Systems Engineering-Theory & Practice., 29(3):1-9.

[44] Rahmann G, Sun Z, Sun Y, Wei X, Shi C, Cong L.(2006) Energy input and output of a rural village in China-the cas of the" Beijing Man village"/District of Beijing. Landbauforschung Völkenrode., 56(1-2):73-83.

[45] Liu MQ, Xi YG, Gong LP, Xu X, Wei Q, Li DB.(2010) Key techniques and non-point source pollution control effect of" pig-biogas-fruit-fish" eco-agriculture model in headwaters of Dongjiang river. Journal of Ecology and Rural Environment., 26:58-63 (in Chinese).

[46] Kou XM, Zhang JH, Wang SH, Zhu W, Jin YG, Han GM.(2012) High-efficient complementary technologies for circulative agriculture model of fresh eatable maize-sheep (pig)-biogas-forage grass Hunan Agricultural Sciences.,11:136-138 (in Chinese).

[47] Wu YG, Zeng GC, Zeng QP.(2004) The plenty of scope for the liquid manure of methane used in grain production. Jiangxi Energy., 4(4):43-44 (in Chinese).

[48] Foo J.(2002) Integrated Bio-systems: A global perspective. Peter Core :37.

[49] Zhang JC, DeAngelis DL, Zhuang JY.(2011) Social and Economic Benefits of Forest Reconstruction. Theory and Practice of Soil Loss Control in Eastern China: Springer, 257-276.

[50] Meng QJ, Wu WC, Rui CJ, Shi QD.(2007) Practice on building the eco-agriculture mode in paddy field. Journal of Guangxi Agriculture, 22(6):44-5 (in Chinese).
[51] Zhang J, DeAngelis D, Zhuang J.(2011) Models of Reforestation for Soil Erosion Control in the Hilly Region of the Middle and Lower Reaches of the Yangtze River. Theory and Practice of Soil Loss Control in Eastern China: Springer:161-212.
[52] Wu XH, Wu FQ, Wu J, Sun L.(2015) Emergy-Based Sustainability Assessment for a Five-in-One Integrated Production System of Apple, Grass, Pig, Biogas, and Rainwater on the Loess Plateau, Northwest China. Agroecology and Sustainable Food Systems, 39(6):666-690.
[53] Dai J, Chen B, Hayat T, Alsaeedi A, Ahmad B.(2015) Sustainability-based economic and ecological evaluation of a rural biogas-linked agro-ecosystem. Renew Sust Energ Rev., 41:347-355.
[54] Chang IS, Wu J, Zhou CB, Shi MM, Yang YX.(2014) A time-geographical approach to biogas potential analysis of China. Renew Sust Energ Rev., 37:318-333.
[55] Dong MH, Wu Y, Li QM, Tian GL, Yang B, Li YJ, et al.(2015) Investigation of Methanogenic Community Structures in Rural Biogas Digesters from Different Climatic Regions in Yunnan, Southwest China. Current Microbiology, 70(5):679-684.
[56] Chen Y, Hu W, Chen P, Ruan R.(2017) Household biogas CDM project development in rural China. Renew Sust Energ Rev., 67:184-191.
[57] Chen Y, Hu W, Feng Y, Sweeney S.(2014) Status and prospects of rural biogas development in China. Renew Sust Energ Rev., 39:679-685.
[58] Mao CL, Feng YZ, Wang XI, Ren GX.(2015) Review on research achievements of biogas from anaerobic digestion. Renew Sust Energ Rev., 45:540-555.
[59] Chen B, Chen SQ.(2013) Life cycle assessment of coupling household biogas production to agricultural industry: A case study of biogas-linked persimmon cultivation and processing system. Energ Policy., 62:707-716.
[60] Wang CB, Zhang YQ, Zhang LX, Pang MY.(2016) Alternative policies to subsidize rural household biogas digesters. Energ Policy., 93:187-195.
[61] Chen SL, Yu WW, Zhang Z, Luo SR.(2015) Soil properties and enzyme activities as affected by biogas slurry irrigation in the Three Gorges Reservoir areas of China. Journal of Environmental Biology.,36(2):513-520.
[62] Coban H, Miltner A, Kastner M.(2015) Fate of fatty acids derived from biogas residues in arable soil. Soil Biology & Biochemistry, 91:58-64.
[63] Bian B, Wu HS, Lv L, Fan YM, Lu HM.(2015) Health risk assessment of metals in food crops and related soils amended with biogas slurry in Taihu Basin: perspective from field experiment. Environmental Science and Pollution Research., 22(18):14358-14366.
[64] Zhang LX, Wang CB, Song B.(2013) Carbon emission reduction potential of a typical household biogas system in rural China. J Clean Prod., 47:415-421.
[65] Wang CB, Zhang LX. (2012) Life cycle assessment of carbon emission from a household biogas digester: Implications for policy. In: Yang Z, Chen B, editors. 18th Biennial Isem Conference on Ecological Modelling for Global Change and Coupled Human and Natural System. Procedia Environmental Sciences: 778-789.
[66] Jiang XY, Sommer SG, Christensen KV.(2011) A review of the biogas industry in China. Energ Policy., 39(10):6073-6081.
[67] Yang YL, Zhang PD, Li GQ.(2012) Regional differentiation of biogas industrial development in China. Renew Sust Energ Rev., 16(9):6686-6693.
[68] Li Y, Sun Y, Li D, Yuan Z, Kong X, Xu J, et al.(2014) Analysis of biogas industrial policy in China and foreign countries. Advances in New and Renewable Energy., 2:413-422.
[69] Chen LH.(2013) Research on Development of Biogas and Reduction of Greenhouse Gas Emission in China. Beijing: Beijing Normal University.
[70] Chen LH, Cong RG, Shu BR, Mi ZF.(2017) A sustainable biogas model in China: The case study of Beijing Deqingyuan biogas project. Renew Sust Energ Rev., 78:773-779.
[71] Wang XL, Chen YQ, Sui P, Gao WS, Qin F, Wu X, et al. (2014) Efficiency and sustainability analysis of biogas and electricity production from a large-scale biogas project in China: an emergy evaluation based on LCA. J Clean Prod., 65:234-245.

[72] Pan WZ. (2008) Analysis of the large farms biogas projects—take the Beijing Deqingyuan Biogas Project as an example. Engineering Sciences., 24(9):239-243 (in Chinese).

[73] Zhou SY, Zhang B, Cai ZF. (2010) Emergy analysis of a farm biogas project in China: A biophysical perspective of agricultural ecological engineering. Communications in Nonlinear Science and Numerical Simulation, 15(5):1408-1418.