

Article

Energy and GHG Analysis of Rural Household Biogas Systems in China

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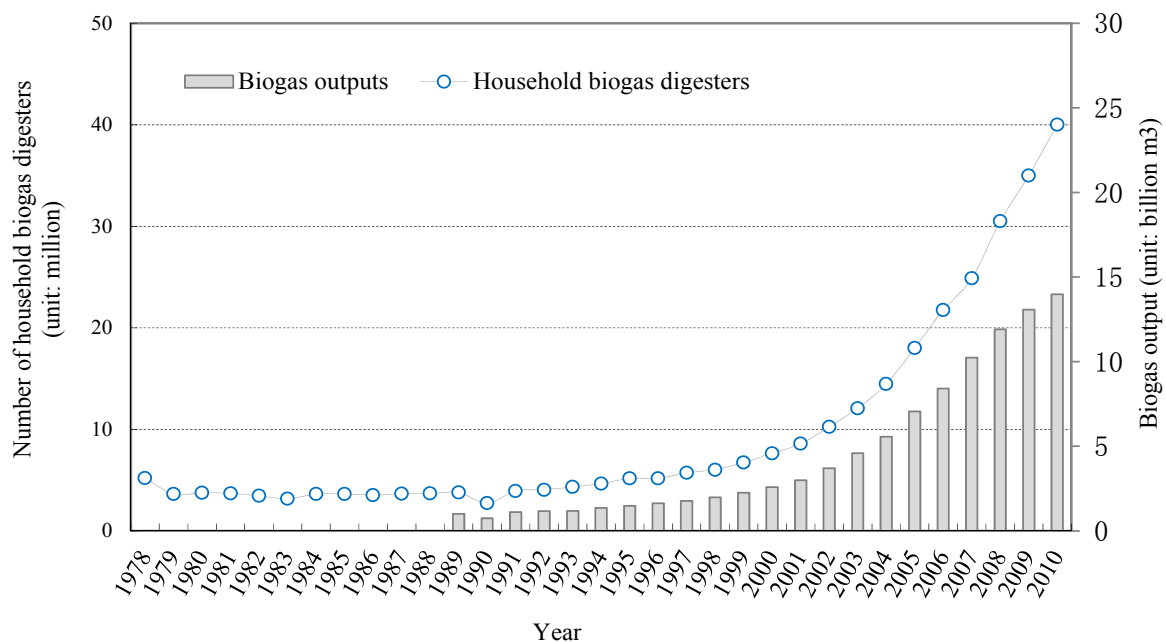
Abstract: The Chinese government has taken great efforts to popularize rural household scale biogas digesters, since they are regarded as an effective approach to address energy shortage issues in rural areas and as a potential way of reducing greenhouse gas (GHG) emissions. Focusing on a typical rural household biogas system, the aim of this study is to systematically quantify its total direct and indirect energy, concentrating on non-renewable energy and the associated GHG emission cost over the entire life cycle to understand its net dynamic benefits. The results show that the total energetic cost for biogas output is 2.19 J/J, of which 0.56 J is from non-renewable energy sources and the GHG emission cost is 4.54×10^{-5} g CO₂-equivalent (CO₂-eq), with respect to its design life cycle of 20 years. Correspondingly, a net non-renewable energy saving of 9.89×10^{10} J and GHG emission reduction of 50.45 t CO₂-eq can be obtained considering the coal substitution and manure disposal. However, it must be run for at least 10 and 3 years, to obtain positive net non-renewable energy savings and GHG emission reduction benefits, respectively. These results have policy implications for development orientation, follow-up services, program management and even national financial subsidy methods.

Keywords: household biogas digester; embodied energy; greenhouse gas (GHG) emission reduction

1. Introduction

China was one of the first countries in the world to use biogas technology early in its history and it continues to play a leading role in the development and dissemination of household biogas technology. The first unofficial test to ferment biogas was undertaken in Guangdong Province back in the 1880s [1,2]. However, it was not until the 1970s that the large-scale development of household biogas systems began in China, when the Chinese government introduced wide-scale biogas technology nationally to address energy shortages in rural areas [3]. To relieve the ever-increasing pressure as the largest GHG emitter, China is currently placing substantial focus on biogas development as a possible measure to mitigate carbon emissions [4,5]. Figure 1 shows the number of household biogas digesters and annual biogas outputs from 1978 to 2010, from which it can be found that the household biogas project in rural China has experienced its fastest growth since 2000. By the end of 2010 there were about 40 million family-sized biogas digesters in China, with a total output of 13.90 billion m³ (amounting to about 9.93 million t of standard coal), which makes China the biogas capital of the world. Consequently, household biogas digesters can be found throughout the country, mainly in the Yangtze River Basin. More than 90% of rural household scale digesters are hydraulic biogas digesters, among which the “China dome” digester constructed of clay, brick, and concrete in 6, 8 and 10 m³ volumes and mainly using livestock manure as substrate has become the standard type [2,3].

Figure 1. Development of household biogas digesters and annual biogas output in rural China from 1978 to 2010.



Like other renewable energy-based systems, rural household biogas systems seem to have no direct fossil energy inputs and related GHG emissions. However, any energy conversion system needs extra energy to deliver that energy to society [6]. With regard to renewable energy initiatives, in order to enable the delivery of energy to users, high quality, non-renewable energies are necessary and utilized to capture and concentrate the dispersed, lower quality, renewable resources [7]. As a matter of fact, the necessity for systematic analysis was emphasized in previous studies on the evaluation of some

renewable projects to estimate the total direct and indirect energy inputs and associated GHG emissions of the systems over their entire life cycle [8–11]. For example, [12–14] compared the energy return on investment and GHG emission savings between bio-ethanol and conventional petroleum and diesel over their entire life cycle. Life-cycle energy and GHG assessments of corn-ethanol production in China were conducted by [15,16], which definitely contributed to the systematic understanding of the cost-benefits of such a controversial alternative. In addition, [17,18] represented the non-renewable energy cost and GHG emission analysis of a wind power plant and a solar power tower plant in China. Similar studies have been performed for a village-level biomass gasification project and a wood pellets production plant in China to investigate from a life cycle perspective the renewability of such energy alternatives [19,20].

Considering the rapid increase in household scale biogas digester construction and the optimistic expectations about their global warming abatement potential by decision makers, a reliable and systematic account of energy and GHG emission for rural household biogas energy projects has recently become of supreme importance. Previous studies on household biogas digesters were mainly based on the processed life cycle analysis, which could only take a direct or a small part of the indirect energy demands and emissions into account [21–27]. For example, [3] estimated that in China biogas provided 832.48 PJ of energy for households and curtailed 7.32×10^7 t CO₂-eq of GHGs annually. It has been also estimated that the implementation of rural household biogas facilities could reduce China's emissions by 1.43–2.02 t CO₂-eq per digester, annually [28]. The values reported by [24,25] are 1.70 and 1.91 t CO₂ per digester per year, respectively. However, these results have been constrained by the following facts: (1) the main focus was on the anaerobic fermentation system itself, and the end use of the biogas was not included in the system boundaries when accounting for the GHG reduction benefits; (2) indirect energy inputs and GHG emissions associated with the production and transportation of materials and services necessary for the construction and maintenance of biogas systems was not considered; and (3) it is often assumed that the digester can be operated normally to the end of its full design life cycle, which rarely occurs in reality [25,29,30].

This paper aims to systematically evaluate the cost and benefit of energy and GHG emissions associated with a typical rural household biogas system with regard to different life cycle scenarios, in order to shed light on the more effective rural biogas use and to suggest appropriate rural biogas development policies. The material, energy inputs and related GHG emissions over the entire life cycle of this rural household biogas system were taken into consideration, *i.e.*, from construction, utilization, through to demolition. It is worthwhile to emphasize that dynamic analyses of GHGs emission reduction potential and energy savings were conducted for different operational lifetime scenarios, in consideration of methane emissions avoidance and substitution of fossil energy. This study helps to identify whether household biogas projects have energy saving and GHG emission reduction benefits with regard to different running times, which definitely could provide essential policy implications supportive of development orientation, follow-up services, management and even national financial subsidy methods for rural household biogas projects in China.

2. Methodology

Energy analysis of any renewable energy conversion process is a comparison of energy output with the energy needed to supply all inputs—the energy source, materials, and services [15]. One of the key indicators of such an analysis is the energy return on investment (EROI), defined as the ratio of energy extracted or delivered by a process to the energy used directly and indirectly in that process [31]. In fact, what we are really concerned with is the renewability of biogas production from household biogas system in consideration of the non-renewable energy requirements for such a project over the entire life cycle. As a reformulation of EROI, the reciprocal of EROI addressed by [32] as energy cost indicator to denote how much energy should be invested to obtain one unit of energy contained in the final product, was also used in this study. Correspondingly, the energy and non-renewable energy cost of the final product, *i.e.*, biogas, can be expressed as:

$$E_{cost} = 1/EROI = E_{con}/E_{bio} \quad (1)$$

$$NE_{cost} = NE_{con}/E_{bio} \quad (2)$$

where E_{con} and NE_{con} are the energy and non-renewable energy used directly and indirectly in the production process, including construction and maintenance of digester, as well as the energy of manure input. E_{bio} is energy content of the biogas produced. To calculate the E_{con} and NE_{con} , the inventory of all energy and materials invested in the whole process chain should be clarified first, and then the input flows are multiplied by the energy/non-renewable energy intensity coefficients of those inputs, which express the total energy needed in the production of each input. Similarly, the GHG emissions derived from the production process can be calculated as input flows multiplied by suitable conversion factors which express the unit GHG emissions in the production of each input.

With regard to the energy saving benefit, it can be calculated by the subtracting energy invested in the process from biogas energy produced or saved due to energy substitution. Similarly, the GHG emission reduction benefit is the difference between GHG reduction and GHG emitted by input flows and biogas combustion. In this study, it is assumed that the biogas produced is all used as a substitute for coal for cooking. It should be noted that the energy savings and emission reduction from fertilizer substitution are neglected in this study because of the assumption that the value of biogas fertilizer is similar to that of the initial manure [33]. Therefore, the energy saving (E_{ben}) and GHG emission mitigation benefits (GHG_{ben}) can be calculated using Equations (3) and (4):

$$E_{ben} = E_{bio} + NE_{esp} - NE_{con} \quad (3)$$

where NE_{esp} is the embodied non-renewable energy saved by energy substitution, *i.e.*, the fossil energy that should be invested in the production of coal:

$$GHG_{ben} = GHG_{esp} + GHG_{man} + GHG_{coa} - GHG_{bio} - GHG_{con} \quad (4)$$

where GHG_{esp} is the total GHG reduction by avoiding the corresponding coal production. GHG_{man} is the GHGs emission mitigated by manure disposal. GHG_{bio} and GHG_{coa} are the GHGs emitted by biogas combustion and the corresponding GHG emission reduction by avoiding coal combustion. GHG_{con} is the total GHG emission associated with resource inputs over the entire life cycle.

For systematic accounting, the energy and non-renewable energy intensities as well as GHG emission coefficients must be the embodied ones, including both direct and indirect parts. Zhou [34] performed an environmentally extended input-output analysis (EIOA) and presented a database for embodiment intensity for all the 151 kinds of typical commodities in the Chinese economy, conclusively provided as a systematic account of the embodied ecological elements in the Chinese national economy, including energy and nonrenewable energy intensities as well as GHG emission coefficients. Using this database, [17,18] estimated the total fossil energy cost and associated GHG emissions of a 1.5 MW solar power tower plant and 1.25 MW wind turbine in China, respectively. As a follow up to the above studies, this work follows the same methodology and adopts most of the energy/nonrenewable intensities and conversion coefficients of GHGs associated with the resource flows of household biogas systems from the references [17,18,34,35]. In contrast to the indirect coefficients related to the resources, the direct energy content of manure used as fermentation material and biogas, as well as the GHG emission factors of biogas and coal combustion are derived from the works of [36,37], respectively.

The calculation of CH₄ emissions avoided by manure disposal is based on the 2006 IPCC Guidelines [38], a method cited in previous research [3,28,39]. Methane mitigation was the only GHG type concerned here, since nearly no CO₂ and N₂O is emitted from manures in biogas digesters. The amount of CH₄ reduction by manure management (GHG_{man}) can be calculated as follows (using swine manure as an example):

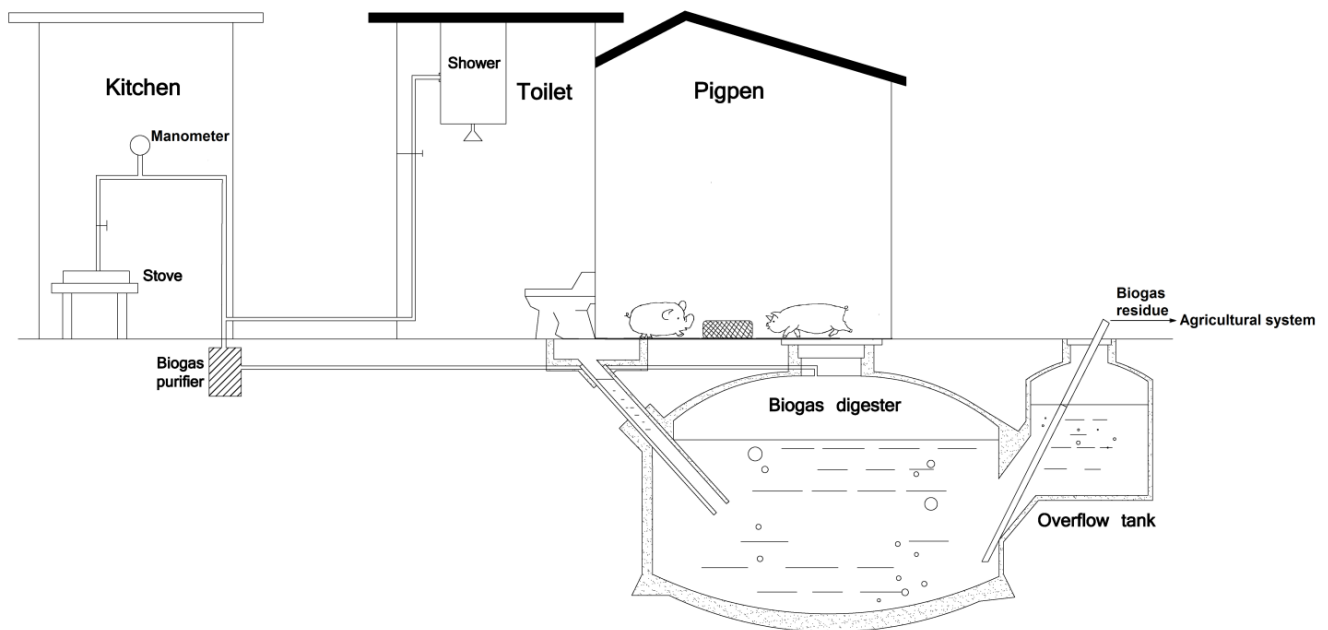
$$GHG_{man} = Manure_{dry} \left[B_0 \times 0.67(kg/m^3) \times \sum_{(S,K)} \frac{MCF_{S,K}}{100} \times MS_{(S,K)} \right] \quad (5)$$

where $Manure_{dry}$ is the annual dry swine excrement manure prepared for a digester (kg dry matter year⁻¹); B_0 the maximum CH₄ producing capacity for manure (m³ CH₄ kg⁻¹); 0.67 is the conversion factor of m³ CH₄ to kilograms CH₄; $MCF_{S,K}$ is the CH₄ conversion factor for each manure management system S by climate region K (%); $MS_{(S,K)}$ is the fraction of manure handled using manure management system S in climate region K (dimensionless). The values of all parameters can be found in the IPCC Guidelines [38].

The related data on the construction and maintenance of the typical rural household biogas project are derived from standard design sheets and our own survey of rural household biogas systems in Guizhou Province in 2010 and 2011. In addition, some assumptions are necessary to make the work easy to accomplish, namely: (1) the annual output of biogas remains constant; (2) when the digester is abandoned, the waste building materials cannot be reused in other programs.

3. Inventory of the Household Biogas System

The rural household biogas system examined in this study is very popular in South China and is known as the Three in One model, for three renovations of kitchen, toilet and livestock shed with one tank. It is usually equipped with an anaerobic biogas digester with a capacity of 8 m³, a pigpen, a toilet and related pipeline and combustion devices for the biogas (Figure 2). The entire life cycle of this system is considered from digester construction to biogas use. The demolition of the digester is not considered, in line with assumption (2) above.

Figure 2. The rural household biogas system considered in this study.

3.1. Construction

The building of an anaerobic biogas digester is usually the principal work involved in the construction of the whole system. As shown in Table 1 of Section 4, the main building materials for biogas tank construction are concrete and cement blocks. The total amount of concrete needed for an 8 m³ tank is about 3.3 t, of which 1.8 t correspond to the cement blocks made of concrete. The charging pipe is polyvinyl chloride (PVC) tubing, about 5 kg. In addition, a set of pipes, fittings and joint sealant made of synthetic rubber are necessary to transfer the biogas to combustion devices without leakage. The energy and GHGs from all the transportation processes and those due to labor and tools used in the construction process are not considered due to unavailability of suitable data.

In addition, the old and traditional latrine, livestock shed and stoves have to be renovated to work with the digester. About 4 t, 0.18 t and 6.93 t of concrete are needed for the renovations to the toilet, stove and pigpen, respectively. With regard to toilet and stove, the concrete is mainly used for plastering the walls. By comparison, more concrete is needed for the pigpen renovation due to the fact that the ground has to be cemented over for effective manure collection and digester charging. The detailed material inputs of these three renovations can also be found in Table 1. For the renovation of the stove, it is essential to install a unit which is designed for the combustion of methane and to install the auxiliary devices, such as the biogas purifier and manometer. The pigpen should be spacious enough, at least 10 square meters, to feed five or more pigs. The roof of the pigpen is usually covered by several precast hollow slabs, which weigh 0.9 t in total, including about 0.8 t concrete and 0.1 t of steel. The pigpen and toilet should be connected with the digester to make it easy to wash and sweep manure into the digester.

Table 1. Energy investment and GHGs emission associated with a typical rural household biogas system during its life cycle of 20 years.

Item	Component	Materials	Quantity	Unit	Energy intensity (J/Unit) ^a	Non-renewable energy intensity (J/Unit) ^b	GHG intensity (tCO ₂ -eq/Unit)	Energy (J)	Non-renewable energy (J)	GHG (tCO ₂ -eq)
Digester building										
	Tank	Concrete	3.30×10^0	t	6.35×10^9	6.03×10^9	5.30×10^{-1}	2.10×10^{10}	1.99×10^{10}	1.75×10^0
		Steel	2.00×10^{-2}	t	3.43×10^{10}	3.26×10^{10}	1.39×10^0	6.86×10^8	6.52×10^8	2.78×10^{-2}
	Pipe and fittings	Synthetic rubber	3.00×10^{-2}	t	3.19×10^{10}	2.66×10^{10}	1.02×10^0	9.57×10^8	7.99×10^8	3.06×10^{-2}
	Charging pipe	Plastic	5.00×10^{-3}	t	1.08×10^{11}	1.04×10^{11}	2.99×10^0	5.40×10^8	5.19×10^8	1.50×10^{-2}
	Sealants	Synthetic rubber	1.00×10^{-03}	t	3.19×10^{10}	2.66×10^{10}	1.02×10^0	3.19×10^7	2.66×10^7	1.02×10^{-3}
Subtotal								2.32×10^{10}	2.19×10^{10}	1.82×10^0
Toilet renovation										
	Wall	Concrete	4.00×10^0	t	6.35×10^9	6.03×10^9	5.30×10^{-1}	2.54×10^{10}	2.41×10^{10}	2.12×10^0
		Steel	2.50×10^{-3}	t	3.43×10^{10}	3.26×10^{10}	1.39×10^0	8.58×10^7	8.15×10^7	3.48×10^{-3}
	Urinal	Refractory	3.00×10^{-2}	t	1.37×10^{10}	1.30×10^{10}	3.00×10^{-1}	4.11×10^8	3.91×10^8	9.00×10^{-3}
	Door	Timber	2.34×10^{-1}	m ³	5.22×10^9	3.40×10^9	1.30×10^{-1}	1.22×10^9	7.95×10^8	3.04×10^{-2}
Subtotal								2.71×10^{10}	2.54×10^{10}	2.16×10^0
Stove renovation										
	Wall	Concrete	1.76×10^{-1}	t	6.35×10^9	6.03×10^9	5.30×10^{-1}	1.12×10^9	1.06×10^9	9.33×10^{-2}
		Steel	2.50×10^{-3}	t	3.43×10^{10}	3.26×10^{10}	1.39×10^0	8.58×10^7	8.15×10^7	3.48×10^{-3}
	Stove	Iron alloy	1.00×10^{-2}	t	1.04×10^{11}	9.98×10^{10}	2.96×10^0	1.04×10^9	9.98×10^8	2.96×10^{-2}
		Cast iron	5.00×10^{-4}	t	3.08×10^{10}	2.93×10^{10}	1.25×10^0	1.54×10^7	1.47×10^7	6.25×10^{-4}
	Governor and airway	Plastic	2.00×10^{-3}	t	1.08×10^{11}	1.04×10^{11}	2.99×10^0	2.16×10^8	2.07×10^8	5.98×10^{-3}
Subtotal								2.47×10^9	2.36×10^9	1.33×10^{-1}

Table 1. Cont.

Item	Component	Materials	Quantity	Unit	Energy intensity (J/Unit) ^a	Non-renewable energy intensity (J/Unit) ^b	GHG intensity (tCO ₂ -eq/Unit)	Energy (J)	Non-renewable energy (J)	GHG (tCO ₂ -eq)
Pigpen renovation										
	Wall and ground	Concrete	6.93×100	t	6.35×10^9	6.03×10^9	5.30×10^{-1}	4.40×10^{10}	4.18×10^{10}	3.67×100
	Precast hollow slab	Concrete	8.00×10^{-1}	t	6.35×10^9	6.03×10^9	5.30×10^{-1}	5.08×10^9	4.82×10^9	4.24×10^{-1}
		steel	1.00×10^{-1}	t	3.43×10^{10}	3.26×10^{10}	1.39×100	3.43×10^9	3.26×10^9	1.39×10^{-1}
Subtotal								5.25×10^{10}	4.99×10^{10}	4.23×100
Operation and maintenance										
	Pipe and fittings	Synthetic rubber	9.00×10^{-2}	t	3.19×10^{10}	2.66×10^{10}	1.02×10^0	2.87×10^9	2.40×10^9	9.18×10^{-2}
	Charging pipe	Plastic	1.50×10^{-2}	t	1.08×10^{11}	1.04×10^{11}	2.99×10^0	1.62×10^9	1.56×10^9	4.49×10^{-2}
	Governor and airway	Plastic	6.00×10^{-3}	t	1.08×10^{11}	1.04×10^{11}	2.99×10^0	6.48×10^8	6.22×10^8	1.79×10^{-2}
	Stove	Iron alloy	1.00×10^{-2}	t	1.04×10^{11}	9.98×10^{10}	2.96×10^0	1.04×10^9	9.98×10^8	2.96×10^{-2}
		Cast iron	5.00×10^{-4}	t	3.08×10^{10}	2.93×10^{10}	1.25×10^0	1.54×10^7	1.47×10^7	6.25×10^{-4}
	Fermentation material	Manure	2.40×10^1	t	1.25×10^{10}			3.01×10^{11}		
Subtotal								3.07×10^{11}	5.59×10^9	1.85×10^{-1}
Total								4.13×10^{11}	1.05×10^{11}	8.54×10^0

^{a, b} For all the resource inputs except fermentation material of manure, they refer to embodied energy or non-renewable energy intensities, *i.e.*, the energy or non-renewable energy that are required when produce these resource items. For manure, they refer to energy content of this biomass material while the energy invested to produce it is ignored, since it is the by-product of livestock farming and more importantly that energy is very minor compared to its own energy content.

3.2. Operation and Maintenance

According to local investigations and the technical instructions on rural household biogas digesters and three renovations, released by the Ministry of Agriculture (MOA), it is essential to feed at least five pigs to provide sufficient fermentation materials for the normal operation of the household digester of 8 m³, and the annual total dry excrement is about 1200 kg [40]. Additionally, it is also assumed that all tubes are replaced every five years and the biogas stoves are replaced every 10 years during its life cycle of 20 years, to maintain the normal operation of this system. The annual biogas output in this paper is assumed to be 450 m³ according to previous studies [4,24], which can provide a substitute for 0.77 t of coal in terms of equivalent effective calorific value of combustion [7].

4. Results and Discussion

4.1. Energy and GHG Emission Cost

Table 1 shows the results of the energy investment and GHG emissions associated with a typical rural household biogas system with an 8 m³ bio-digester during its life cycle. The total energy investment for a 20 year life cycle of this biogas system is 4.13×10^{11} J, of which 1.05×10^{11} J is from non-renewable sources. As mentioned in Section 3, the annual biogas output is assumed to be 450 m³, *i.e.*, 9.41×10^9 J of energy per year, and the total biogas output for 20 years is 1.88×10^{11} J. Therefore, the E_{cost} for biogas is calculated as 2.19, while more importantly, the NE_{cost} is 0.56, indicating that 0.56 J of non-renewable energy is needed to produce a unit of biogas energy. Further analysis of the energy investment for each stage shows that the construction stage (including digester building and three renovations) and operation and maintenance stage contribute differently to the total energy cost, with percentages of 25.52% and 74.48%, respectively (see Figure 3). If only the construction stage is considered, the building materials, *i.e.*, cement blocks and concrete, are the dominant energy investment sources. Correspondingly, the renovation of the pigpen accounts for the largest energy investment at this stage (13%) due to the large quantity of concrete used in wall plastering and ground treatment, while the stove renovation accounts for less than 1% of this part. In fact, the fermentation material (manure) is the largest contributor to the total energy cost, which represents 73% and 98% of the total and those in the operation and maintenance stage, respectively.

Similarly, the GHGs emission associated with the construction as well as operation and maintenance are also listed in Table 1. The total GHGs emission for a 20 year life cycle of the rural household biogas system is 8.54 t CO₂-eq, and the GHGs emission required to generate 1 J of biogas energy are 4.54×10^{-5} g CO₂-eq. As shown in Figure 4, nearly 98% of the total GHGs are derived from the construction stage mainly due to the utilization of steel and concrete, while GHGs in the operation and maintenance stage take up only 2%, due to replacement of some pipelines and stoves. As for the construction stage, the GHGs emission caused by the pigpen renovation takes up nearly half of the totals, due to the same fact that a large proportion of the concrete and steel are consumed in this part. The percentage of GHG emissions from the digester building and toilet renovation are 21% and 25%, respectively, while stove renovation accounts for a little more than 1% of the emissions from the construction stage.

Figure 3. The energy investment structure of the rural household biogas system during its life cycle of 20 years.

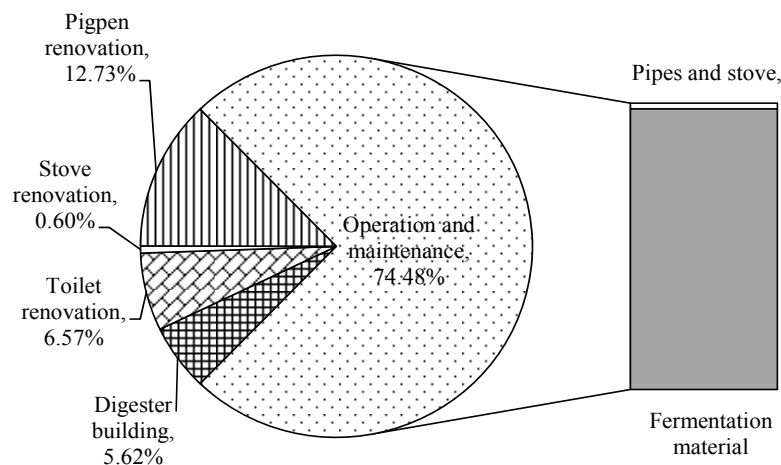
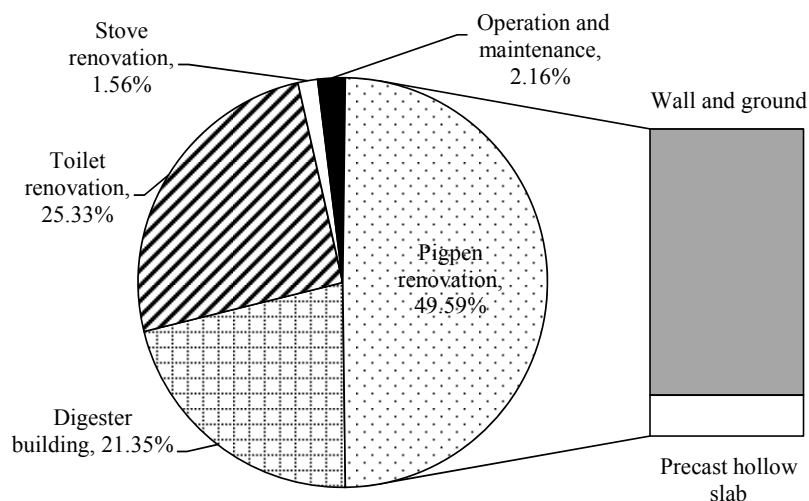


Figure 4. The GHGs emission components associated with the rural household biogas system during its life cycle of 20 years.



To evaluate the energy savings and GHGs emission reduction benefits with regard to full life cycle utilization, two further factors should be taken into account, namely disposal of the manure and energy source substitution [41]. As mentioned above, consumption of about 0.77 t of coal can be avoided annually by biogas use and the energy consumption and GHG emission intensities during the production process of coal are 1.02×10^9 J/t and 0.57 t CO₂-eq/t, as shown in [34]. The GHG emission coefficient of coal and biogas combustion is 1.92 t CO₂-eq/t and 1.17×10^{-3} t CO₂-eq/m³ [37]. The manure treated during the 20 years of the life cycle is 24.0 t in terms of dry weight and the CH₄ mitigation from manure management can be calculated to be 31.10 t CO₂-eq according to Equation (5). Therefore, according to Equations (3) and (4), the energy saving benefits (E_{ben}), and GHG emission mitigation benefits (GHG_{ben}), are evaluated as 9.89×10^{10} J and 50.45 t CO₂-eq for the rural house biogas system considered in this study.

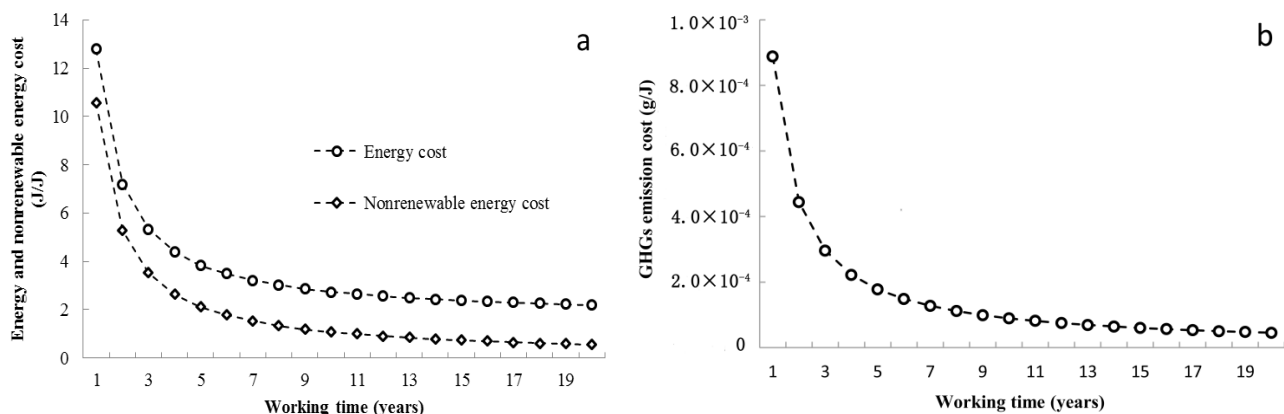
However, all these net benefits in energy savings and GHGs emission reduction of the household biogas system can only be achieved under the assumption that the system runs successfully over its

entire nominal life cycle of 20 years. Unfortunately, our local investigations in Guizhou, as well as other previous studies, show that a large proportion of household biogas projects have fallen into disuse within 3 years after their construction, as we will discuss in Section 4.2.

4.2. Scenario Analysis for Different Running Times

In light of the unstable running of the household biogas project in rural China, a scenario analysis was conducted to find variation of the energy cost, GHGs emissions, as well as appropriate benefits under different operating conditions. With regard to different scenarios of running time, both the energy and GHGs emission costs illustrated a trend of steady decrease with an increase of running time, see Figure 5a and Figure 5b. For instance, if the digester was only operated for one year, the energy and GHG emission cost for unit output will be 12.78 J and $8.88 \times 10^{-4} \text{ g CO}_2\text{-eq}$, in contrast to the values of 2.19 J and $4.54 \times 10^{-5} \text{ g CO}_2\text{-eq}$ for a 20-year life cycle. It is also found that the rate of decrease of the cost has been gradually declining, especially during the first 5 years, and the decrease rate of energy and GHG emission cost have average values of 26% and 33%, respectively. However, the average rate of decline for the last 5 years is only 2% and 5%, which indicates that it is essential to ensure the stable operation of a digester during the first several years to offset the construction cost.

Figure 5. (a) The changes of energy cost; and (b) GHG emissions under different running times.



In line with the cost, the benefit variation of energy saving and GHG emission mitigation associated with different operating life is also illustrated in Figures 6 and 7, respectively. The total energy savings and GHG emissions reduced will increase linearly with the increase in operational life, due to the hypothesis of constant values for the annual manure disposal and biogas output. The total energy saving benefit is $-8.93 \times 10^{10} \text{ J}$ under the condition of one year's operation, while it climbs to $9.89 \times 10^{10} \text{ J}$ if normally operated to its design life of 20 years. Similarly, the total GHG emission mitigation benefit increases from -5.40 to $50.45 \text{ t CO}_2\text{-eq}$ with the increase of operating life. The annual energy saving and GHG emission reduction benefit can be defined as the quotient of total benefits divided by operational life. Like the cost, these two annual benefits have also undergone a trend characterized by a gradually slowing growth rate with the variation of operational life from 1 to 20 years. The annual energy saving and GHG emission mitigation benefits increase from -8.93×10^{10} to $4.94 \times 10^9 \text{ J}$ and from -5.40 to $2.52 \text{ t CO}_2\text{-eq}$ in its entire life cycle, respectively. The most meaningful findings that need to be highlighted are that to acquire positive net energy savings and

GHG emission reduction benefits, a biogas digester must be operated for at least 10 and 3 years, respectively, according to the results shown in Figures 6 and 7.

Figure 6. The total and annual energy saving benefit of the household biogas system under different running times.

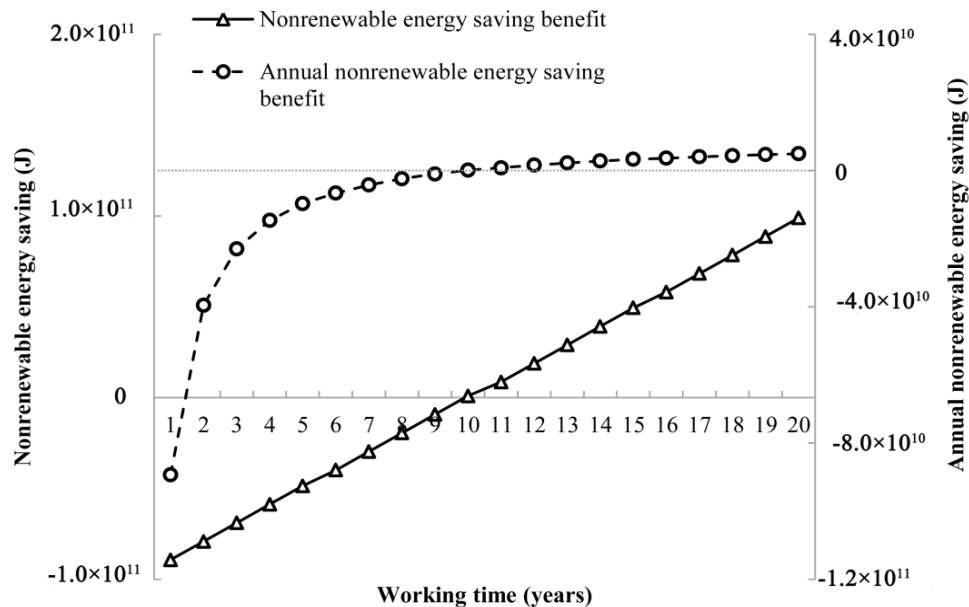
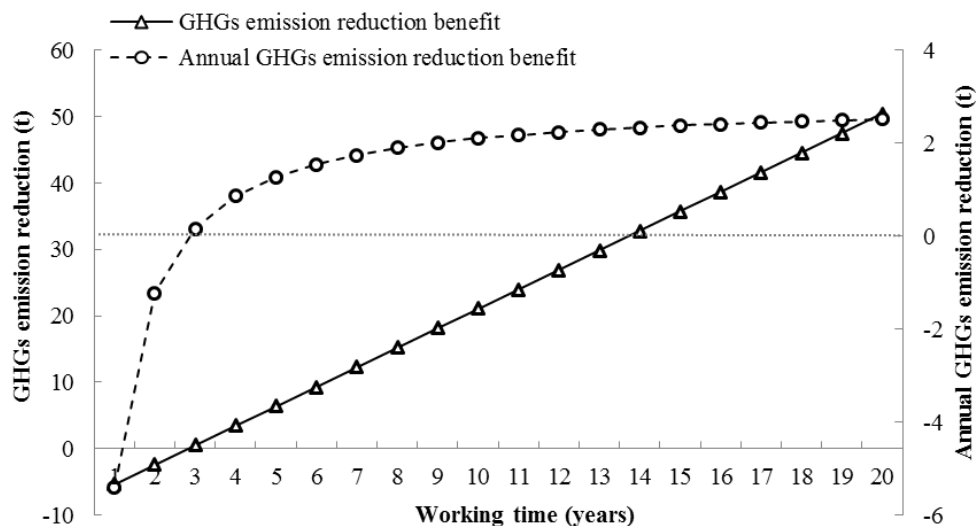


Figure 7. The total and annual GHGs emission reduction benefit of the household biogas system under different running times.



4.3. Policy Implications

Theoretically, the rural household biogas system could be in normal operation for 20 years [25]. However, our primary survey of 150 household biogas projects in Guizhou Province shows that more than 42% of bio-digesters are abandoned within 2–3 years after their construction, which is consistent with previous investigations [42]. Among those that are still in use, about 32% encounter many obstacles such as unavailability of fermentation materials, leakage, and unstable biogas production. In

rural areas, household biogas projects are often justified on the basis of the private benefits and cost accruing to the individual households [43]. In normal case, the payback period of a household biogas digester ranges from 3 to 5 years [44]. The disappointing operation of bio-digesters is detrimental for the fulfillment of its economic returns as well as energy saving and emission mitigation benefits [45].

For a long time, the phenomenon of emphasizing the construction but neglecting management has caused a profound impact on the development of rural household biogas projects in China. The Government often encourages the uptake of family-size bio-digesters by providing financial aid, leading to the successful development of pilot projects. Financial aids including subsidies and microfinance schemes are designed to facilitate the construction of new digesters, but more importantly, it can be concluded from this study that some incentives have to be provided for their sustained operation. In practice, the operation process of a biogas digester will encounter many bottlenecks, such as unavailability of fermentation material, poor follow-up management as well as the imperfect subsidy policy [45].

Livestock and poultry manure, especially those from pigs, are the main fermentation sources for biogas in rural China. With the changes of rural lifestyle, less materials for fermentation (animal manure, human excreta and other organic waste) is available because more and more pigs and other livestock are being kept and fed at intensive farms instead of individual households. Although alternative fermentation materials are regarded as replacements to supplement the inadequate manure source, including agricultural waste, solid municipal waste, as well as industrial organic waste and energy crops [46], the technical know-how is not advanced enough and economically viable to farmers. One of the possible approaches is to formulate policies for a manure exchange market between peasants and aquaculture enterprises. Nevertheless, the strategy of the wide promotion of household biogas projects should be re-examined with regard to the changes of resource and transition of rural society. Medium and large-scale biogas plants may comply with the changes in manure production associated with large scale animal husbandry.

The follow-up management of biogas digesters is another key issue in the operation of these units. Usually, the operation and maintenance work is poorly accomplished by farmers themselves, due to their low level education and lack of technical advice. Important aspects such as regular cleaning of the digested slurry to ensure normal operation are neglected by farmers. The biogas tank and pipes often leak biogas after short operation times due to the poor construction quality and equipment. In fact, there are no standards to guide the production of the necessary components and equipment for household scale biogas systems, which are usually gathered from different market sources and have to be modified in order to fit together. Therefore, more financial and technical support, as well as policy on standardization of digester construction and technical support is badly needed to ensure the sustained operation of digesters, at least beyond the payback period of the various benefits (finance, energy saving, and GHG emission mitigation).

Although the results from this study intuitively provide a basis for energy savings and carbon reduction benefits based on long term system viability, the local farmers' choices are largely determined by the short term economic benefits and other related factors, since environmental support is generally not perceived as an important aspect in biogas development and management. To rural families who receive services from the biogas digesters, the benefits include cleaner energy, time saved on firewood collection, as well as digest slurry used as organic fertilizer; Increased off-farming

employment income in urban areas, unstable biogas supply as well as relatively complicated operation and maintenance (for not well educated local farmers) make rural house biogas projects less and less attractive. Farmers would like to go to work in cities and then purchase commercial energy supplies such as coal and electricity using money earned in city. The indirect benefits acquired from a household biogas system, such as mitigation of methane, a powerful GHG released from the open decomposition of animal wastes, and preventing carbon dioxide emissions from burning firewood and fossil energy, have no direct impact on farmers' attitudes toward biogas systems. These positive externalities of the household biogas utilization can be internalized by subsidies or compensation [47,48]. Some research has pointed out that society is likely to benefit more than just the individual recipient does [49]. The current subsidy schemes largely focus on the construction stage, but do not necessarily ensure sustained operation, which is essential for the environmental benefits. Therefore, there is an urgent need to readjust the related subsidy system to encourage household digester owners to maximize the utilization of carbon emission reduction potential by ensuring long-term running, e.g., the subsidies could be provided on the basis of the actual consumption of biogas from digesters by rural families. It is important to note that an overall evaluation of the ecological service function of rural household biogas program should be implemented, which will provide the criteria for subsidies or ecological compensation.

5. Conclusions

A systematic energy and GHG emission analysis of the household biogas project in rural China is conducted to find the energetic and GHG emission cost of biogas utilization and its energy saving and GHG emission reduction benefits with regard to different running time scenarios. In a typical household biogas system with a 8 m³ digester which is very popular in South China and known as the Three In One Model, the energy cost (E_{cost}) requirement and the GHG emission per unit output of biogas are 2.19 J and 4.54×10^{-5} g CO₂-eq, respectively. The non-renewable energy cost (NE_{cost}) is 0.56 J, indicating a relatively acceptable renewability of the biogas system with respect to full life cycle normal operation. The analysis also indicates that a large proportion of energy invested and GHGs are derived from the digester construction phase and the three required renovations for their large concrete and steel usage. Further, considering the disposal of manure and energy substitution, the results show that the total energy saved (E_{ben}) and GHG emission mitigated (GHG_{ben}) by a rural household biogas digester are 9.89×10^{10} J and 50.45 t CO₂-eq during its 20 year entire life cycle. By scenario analysis of running life, the household biogas system must be run for at least 10 and 3 years, respectively, to enjoy these positive net energy saving and GHGs emission reduction benefits. However, in practice, rural household biogas projects suffer from a high rate of obsolescence, due to fermentation material shortages, poor follow-up services and inappropriate financial subsidies.

With regard to the sustainable operation of the household biogas project, several points should be clarified in consideration of the analysis result in this paper. Firstly, the strategy of the wide promotion of household biogas projects should be re-examined with regard to the changes of resource availability and the transition of rural society. Medium and large-scale biogas plants may comply better with the changes in manure production associated with large scale animal husbandry. Secondly, the equipment standardization and professional technical services for maintenance are a primary urgent task. Lastly,

institutional innovation on economic subsidy methods is essential, with respect to the energy saving and GHG emission reduction benefits of rural household biogas systems in China.

It is important to note that the results obtained in this study could have been affected by the rough estimation of parameters like manure disposal and problems inherent in the input-output method for estimation of embodied resource coefficients. Nevertheless, it is a starting point for systematic evaluation of rural household biogas projects as well as other renewable energy alternatives.

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Conflicts of Interest

The authors declare no conflict of interest.

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