Inventory analysis for a household biogas system

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Abstract

This paper proposes an inventory analysis for the household biogas system in Gongcheng, China. The results show that (1) Biogas-linked agro-ecosystem has a longer utilization chain for agricultural wastes, which takes in nonrenewable resources and outputs renewable resources. Therefore, household biogas system is an effective measure in relieving energy shortage, reducing environmental pollution and realizing the sustainable agriculture in the rural areas. (2) The efficiency of the household biogas system is at a low level, and still needs to be promoted. In order to increase the energy conversion efficiency and energy use ratio, more attempts should be dedicated to the technological advancement of biogas fermentation and multipurpose utilization. (3) The proposed method may help us understand the household biogas system more clearly and directly in energy conversion and utilization mode based on energy metrics. It is convenient to find out the weak points of the agro-ecosystem that waste more energy and seek for optimal solutions accordingly.

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1. Introduction

The biogas-linked agro-ecosystem has been widely used in the rural areas of China due to its role in mitigating the environmental pollution, reducing the usage of pesticides and fertilizers, optimizing the structure of the rural energy consumption, promoting the indoor air quality and improving the efficiency
of cooking and heating activities as well [1]. There are various modes of biogas-linked agro-ecosystems being shaped in China, such as “four in one” mode in North China and “pig-biogas-fruit” mode in South China. These systems bring in economic and environmental benefits by using the biogas, biogas residue and biogas slurry [2].

In a biogas-linked agro-ecosystem, household biogas system is the key unit to combine clean energy production and agricultural utilization. Current studies on biogas-linked agro-ecosystem and household biogas system mainly focused on issues of economic benefit [3-6], greenhouse gas mitigation [7-10], energy alternative source [11-13], etc. Life-cycle analysis and inventory analysis have been used to assess the impacts of specific biogas project or a sort of biogas-linked agro-ecosystem mode on the region’s economy and environment. Household biogas system can influence the economic and environmental benefits of biogas-linked agro-ecosystem directly by changing the way energy flows and how it is converted through it. Thus, a life-cycle accounting for household biogas system based on energy metric may help to find out how energy flows through the system and how it is converted, thus providing proper suggestions on how to improve the performance of the agro-ecosystem and obtain more benefits.

Exergy as a useful energy metric can measure different forms of energy and different states of matter and describe the energy quality in different forms and states. It has been used in physical & chemical processes analysis, natural resources accounting, industrial & agricultural systems analysis, environmental impact assessment, etc [14]. B. Chen and G.Q. Chen investigated the agricultural products flow to the Chinese society from 1980 to 2002 based on energy as a unified quantifier of natural resources, with the annual policy analysed corresponding to the resource inflow [15,16], and presented a systematic assessment framework for ecological economy of China. Within the framework, a typical system diagram devised for a general ecological economy with four arm fluxes for free local natural resources, purchased economic investment, environmental impact and economic yield, system indices of the renewability index, exergy yield ratio, exergy investment ratio, environmental resource to yield ratio, system transformity and environmental stress index, were defined for a congregated systems ecological assessment with essential implications for sustainability. A detailed case study of the Chinese agriculture from 1980 to 2000 with respect to cropping, forestry, stockbreeding and fishery sectors, extensive exergy accounting and systems assessment were also carried out with emphases on annual and structural variations against social political transitions [17]. The cumulative exergy as efficiency and sustainability measures was decomposed into technical efficiency and cumulative exergy allocated efficiency for agricultural production and applied to OECD agricultural systems [18]. Banerjee and Tierney assessed ten candidate energy systems for rural villages in developing countries by means of five published methods to undertake the environmental impact assessment based on exergy analysis [19].Yang et al. used cumulative exergetic method to identify the renewability of the total corn-ethanol production in China when capturing all natural non-renewable resources consumed in the integrated process including agricultural crop production, corn transportation, industrial conversion and waste treatment with a modified exergy-based indicator to quantify the renewability of corn-ethanol production process [20].

In this study, an exergy-based accounting method for household biogas system is proposed. The exergy input/output of each subsystem is analyzed, and the exergy efficiency of the whole agro-ecosystem is calculated.

2. Methodology

2.1. Accounting framework

The household biogas system includes three units: construction, operation and utilization. These units are further detailed into several technical steps of the life cycle. The construction unit includes the steps of tank construction and pipe installation. Energy flows into this unit in the forms of construction materials and energy source. The common construction materials are cement, bricks, sand, gravel, rebar,
and plastic film, etc. In addition, some auxiliary parts are needed, such as pipes, biogas lamps and biogas stoves. The energy source is mainly consumed by the vehicles that carry the construction materials and the equipments, which mix concrete. Emission from the construction unit includes the vehicle emissions and construction dust.

The operation unit includes the steps of raw material transportation, fermentation, product transportation and regular management. Energy flows into this unit in the forms of fermentation materials and energy source. There are rich raw materials for fermentation from the eco-environment, such as straws, human or animal wastes, domestic sewage, industrial and life organic waste, etc. In the rural areas, human or animal wastes are the most common raw materials. Yet, owing to the transformation of livestock breeding from household management to large-scale intensive mode, there is a shortage of raw materials for household biogas system. And in order to pursue high efficiency of biogas production, straws, leaves and weeds are also added as the raw materials for fermentation in some regions. One or two reloading means replacing the stale raw materials with the fresh ones is necessary for the household biogas system to ensure the normal operation. The energy source for this unit is mainly consumed by the vehicles carrying the raw materials and the products, e.g., biogas residue and biogas slurry. Emission from the operation unit includes the vehicle emissions and gas escaping from the biogas tank.

All of the products from household biogas system could produce benefits via the biogas-linked agro-ecosystem. For example, biogas residue and biogas slurry used in farm production and stock farming will help increase income, and biogas can satisfy the needs of energy for rural living. Energy flows into this unit in the forms of energy source consumed by auxiliary facilities when utilizing the products. Emission from this unit mainly comes from the phases of energy consumption, biogas combustion and volatilization of biogas residue and biogas slurry.

2.2. Energy accounting

As conversions between different forms of energy are restricted by the second law of thermodynamics, exergy as available energy could be interpreted as the ability one form of energy possesses to convert to other forms of energy. Physical exergy of one state of matter is in existence as a result of the difference in physical condition, such as temperature, pressure, velocity and elevation, from its environment, while chemical exergy exists as a result of the difference in chemical composition. Exergy coefficient means the exergy content of unit matter or energy, and it can indicate the qualitative difference between different forms of energy. In this paper, exergy metric is used as a unified standard to measure all the materials and energy input and output of each unit during the life cycle of the household biogas system. The accounting procedures can be described as follows:

1. List the input/output of each step in the accounting framework;
2. Account the exergy input and exergy output of each unit respectively with reference to [21-24];
3. Calculate the exergy conversion efficiency and utilization rate.

Overall, the exergy conversion rate and exergy utilization rate are capable of depicting the energy production and consumption performances of the whole household biogas system and therefore can be regarded as a potential sustainability indicator.

3. Case study

Gongcheng Yao-Autonomous County of Guangxi lies in the northeast of Guangxi Zhuang Autonomous Region. It has an area of 2,049 km² and a population of 290 thousands. Gongcheng has started the “Poverty Relief Program” ever since 1984, which combines the construction of biogas tank and poverty alleviation. In 1990, the “three in one” mode of biogas-linked agro-ecosystem were developed, which linked the farm production and stock farming to the biogas tank with the multipurpose usage of biogas, biogas residue and biogas slurry. By the end of 2009, Gongcheng has had a household
biogas system construction scale of 63.6 thousands and a popularization rate of 91.6%. The typical household biogas system in Gongcheng is analyzed in this paper, of which the tank is 8 cubic meters and the service life in average is estimated to be 15 years. Considering the optimum life-span of the system, we confine the study time scenario within 10 years.

4. Results & Discussions

The exergy conversion rate is calculated to be 49.02%, and the exergy utilization rate is 21.60%, implying that the exergy efficiency of the whole household biogas system is only 10.59%.

Compared with the traditional agro-ecosystem, biogas-linked agro-ecosystem has a longer utilization chain for agricultural wastes, which takes in nonrenewable resources and outputs renewable resources. However, the exergy efficiency of the household biogas system is still at a low level, and needs to be promoted. Improving the process technology and optimizing the fermentation condition may be a good choice to increase the exergy conversion rate. Meanwhile, technological innovation in the multi-purpose use of biogas residue and biogas slurry may increase the exergy utilization rate.

The exergy-based inventory analysis of household biogas system proposed in this paper extends the exergy accounting framework and contributes to the agricultural engineering research field. The method may help us understand how the household biogas system can be improved with proper energy conversion and utilization mode. As a result, it is convenient to find out the weak points of the agricultural engineering system that waste more energy and seek for optimal solutions accordingly.

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