Energy Policy 68 (2014) 264–272

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Extended exergy-based sustainability accounting of a household biogas project in rural China

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HIGHLIGHTS

- Extended exergy is used to describe the sustainability level of biogas projects.
- A set of extended exergy based sustainability indicator is established.
- Biogas project has high renewability and greenhouse gas emission abatement potential.
- Multiple utilization of biogas digestate is a promising way to improve sustainability.

ARTICLE INFO

Article history:
Received 14 September 2013
Received in revised form
4 December 2013
Accepted 16 January 2014
Available online 10 February 2014

Keywords:
Sustainability
Household biogas
Extended exergy

ABSTRACT

Biogas has been earmarked as one of the leading renewable energy sources capable of mitigating environmental emissions in rural areas. Thus, developing an accounting technique is of particular importance in coping with increasing problems related to renewable agriculture and rural energy supply. In this study, extended exergy was generalised for the sustainability evaluation of biogas projects. Furthermore, a series of extended exergy-based indicators was presented as benchmarking from the perspectives of resources, economics and greenhouse gas (GHG) emissions. The sustainability of a "Three-in-One" biogas production system in southern China was thereby evaluated based on the proposed framework. The results show that economic costs concentrate in the construction phase. GHG emissions are mainly derived from bricks and cement, with proportions of 36.23% and 34.91%, respectively. The largest resource depletion occurs during the consumption of feedstock (87.06%) in the operation phase. Compared with other renewable energy conversion systems, the biogas project has a higher renewability (0.925) and economic return on investment ratio (6.82) and a lower GHG emission intensity (0.012). With the merit of bridging thermodynamics and externality, the extended exergy-based approach presented in this study may effectively appraise the energy and environmental performance of biogas projects.

1. Introduction

Over the past decade, China has been confronted with an energy crisis characterised by a severe resource shortage and an irrational energy consumption structure. By the end of 2009, household energy consumption in rural China was 0.52 billion tce, 33.03% of which was constituted by commercial energy (coal and electricity) and 47.87% by non-commercial energy (biomass such as straw and firewood) (Chen et al., 2010a). Biomass has been and will remain a significant source of energy in rural China. Therefore, emphasis should be placed on energy structure adjustment and the innovation and application of new biomass utilisation alternatives (such as biodiesel, biomass gasification and biogas production) to coordinate energy consumption, environmental conditions (especially GHG emission abatement) and economic development (Chen and Chen, 2011).

1.1. Biogas system in China

Biogas digesters have come to symbolise access to modern energy services in rural areas and are expected to considerably improve health and sanitation and yield significant socio-economic and environmental benefits (Srinivasan, 2008). In China, the first test of biogas fermentation was undertaken in the 1880s in Guangdong. In 1920, rectangular hydraulic digesters were invented by Luo GuoRui in Taiwan, China (Chen et al., 2010b). Large-scale construction of household biogas digesters began in the 1950s and has experienced three development stages. In the first stage (1950–1980), development was hindered and fluctuated

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0301-4215/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enpol.2014.01.017

dramatically due to technical limitations. During the 1980s to 2000, there was a steady increase in the installation of household biogas digesters, with an average growth rate of 4.6%. Since 2000, the development of household biogas has entered a new stage with the launching of the "Rural Household Biogas State Debt Project," which focuses on providing subsidies to biogas projects to mobilise the initiatives of peasants. As shown in Fig. 1, the total investment in household biogas projects amounted to 15.63 billion yuan from 2000 to 2009. In total, 14.53 million households were subsidised, constituting 41.4% of all household biogas holders.

A succession of laws and policies to guarantee the completion of the household biogas project were also issued in the third stage, e.g., the "Medium and Long-Term Development Plan for Renewable Energy in China", which highlighted the significance of biogas as a substitute for traditional energy sources National Development and Reform Commission (NDRC) (2007). Propelled by economic and policy incentives, the number of household biogas digesters increased from 8.48 million to 35.07 million from 2000 to 2009 at a growth rate of 17.1% (Fig. 1). By 2009, the proportion of total rural biogas energy consumption had risen to 1.9%, indicating that biogas has been playing an increasingly important role in rural household energy consumption.

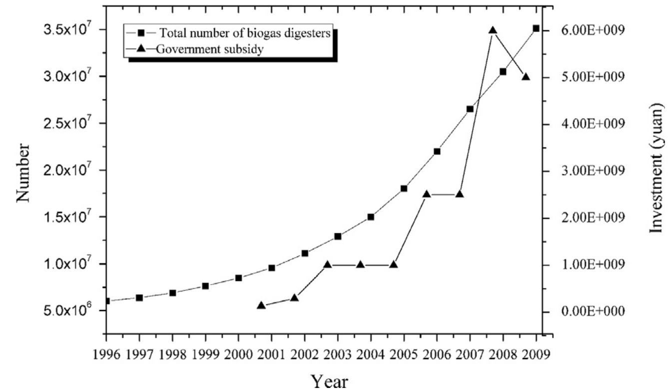

Fig. 1. Government investment and total number of household biogas digesters in China.
Data source: Ministry of Agriculture (1973–2005).

1.2. Sustainability evaluation of biogas projects

The increasing number of household biogas digesters involves a high consumption of construction materials, large transportation distances and huge feedstock inputs, which require substantial economic input and contribute to GHG emissions. Thus, it is imperative that the relative advantages and disadvantages of resource, environmental and economic perspectives of the biogas system be widely and readily available and presented in a structured, transparent and uniform manner (Nzila et al., 2012).

A wide range of research has been conducted to assess the environmental performance of biogas projects. Chevalier and Meunier (2005) asserted that the environmental impact of biogas co- or tri-generation units depended on the fraction of heat (or cold) used, the distance of crop collection, the efficiencies of the unit and NO*x* emissions. Börjesson and Berglund (2007) analysed the overall environmental impact generated when biogas systems were introduced and replaced various reference systems for energy generation, waste management and agricultural production. A life-cycle energy and environmental assessment for a biogas–digestate utilisation system in China was also performed by Chen et al. (2012). Regarding the resource aspect, Ishikawa et al. (2006) compared an on-farm biogas plant with a centralised one from an energetic point of view. Berglund and Börjesson (2006) assessed the energy balance in biogas production and described how the net energy output from biogas systems was affected by the raw materials digested, system design and the allocation method chosen. The energy efficiencies of different biogas systems, including single and co-digestion of multiple feedstock, different biogas utilisation pathways and waste-stream management strategies, were evaluated by Pöschl et al. (2010). The cumulative energy demand (CED) and environmental (GHG emissions) profiles associated with the production of electricity derived from biogas have been identified by Bacenetti et al. (2013) from a cradle-to-grave perspective. Meanwhile, economic analysis has also been addressed in previous research. For example, Rubab and Kandpal (1996) developed a methodology for the financial evaluation of biogas technology for domestic use in India. Rajendran et al. (2013) conducted a techno-economic evaluation and sensitivity analysis for a textile-based biogas digester and concluded that a biogas project was a positive investment, unless the price of kerosene were to fall to less than 0.18 USD/L.

Although there are different approaches for embodied energy, GHG emission or economic performance evaluation of biogas projects, most work focused on the quantification of one or two parameters. For example, Wang et al. (2013) introduced life cycle assessment (LCA) into emergy evaluation to analyse each production step of a large-scale biogas project in China and compared the economic and ecological performance of the biogas production system and biogas plus electricity production system. Yabe (2013) estimated the environmental and economic benefits of centralised biogas plants running on cow manure in Hokkaido. Rehl and Müller (2013) identified the most ecological and economical feasible anaerobic digestion method by applying different energy conversion technologies based on life cycle cost (LCC) and LCA methodologies. Chen and Chen (2013) conducted a LCA of coupling biogas production to agro-industry in terms of energy, environmental and economic performance, indicating that each production stage following the biogas/digestate utilisation chain was beneficial across all three aspects.

Still, there were few integrated evaluations that reflected the overall sustainability performance of biogas projects. Jury et al. (2010) discussed the resource depletion and environmental damage of methane production by mono-fermentation of cultivated crops. Nzila et al. (2012) proposed a multi-criteria sustainability assessment (MCSA) to evaluate the sustainability of biogas technologies from environmental, economic and technical perspectives. Gosens et al. (2013) assessed the comparative contribution of household-scale biogas installations to the broad set of sustainability objectives in the Chinese biogas policy framework, which targeted household budget, fuel collection workload, forest degradation, indoor air quality and health, renewable energy supply and climate change.

The inclusion of many different forms of inputs in sustainability evaluations requires that they be expressed in the same or equivalent energy form so that they may be combined and compared on an equivalent basis. Thus, a uniform accounting framework that integrates environmental and resource indicators should be developed to make the sustainability evaluation of bioenergy more intuitive and transferable. Extended exergy, one type of ecological thermodynamic theory, is suggested as an effective method for assessing sustainability via the normalisation of raw material inputs, labour and capital inputs and non-energetic externalities in the resource conversion process (Milia and Sciubba, 2006; Sciubba et al., 2008).

1.3. Extended exergy analysis

The concept of exergy was first proposed by Rant in 1956 and defined as the maximum amount of work that can be produced by a system or a flow of matter or energy as it comes into equilibrium