Ecological Informatics 26 (2015) 78–84

Contents lists available at ScienceDirect

Ecological Informatics

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

Sustainability of a typical biogas system in China: Emergy-based ecological footprint assessment

X.F. Wu [a], Q. Yang [b,c,*], X.H. Xia [d], T.H. Wu [c], X.D. Wu [a], L. Shao [a], T. Hayat [e,f], A. Alsaedi [e], G.Q. Chen [a,e,**]

[a] College of Engineering, Peking University, Beijing 100871, PR China
[b] State Key Laboratory of Coal Combustion, Huazhong University of Science and Technology, Wuhan 430074, PR China
[c] Department of New Energy Science and Engineering, School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, PR China
[d] Institute of China's Economic Reform and Development, Renmin University of China, Beijing 100872, PR China
[e] NAAM Group, Faculty of Science, King Abdulaziz University, Jeddah 21589, Saudi Arabia
[f] Department of Mathematics, Quaid-i-Azam University, Islamabad 45320, Pakistan

ARTICLE INFO

Article history:
Received 27 October 2013
Received in revised form 15 June 2014
Accepted 20 June 2014
Available online 1 July 2014

Keywords:
"Pig–biogas–fish" system
Ecological footprint
Emergy
Sustainability

ABSTRACT

Integrated biogas utilization has experienced a rapid development in recent years in rural China, for both renewable energy production and waste treatment. On the basis of a modified Ecological Footprint (EF) indicator, this paper provides a comprehensive assessment of a "pig–biogas–fish" system, a typical household integrated biogas-utilization system in southern China, by focusing on the resources consumed and produced within the system. The method of Emergy Environmental Footprint as a combination of EF and emergy accounting is introduced to quantify the sustainability of the overall biogas system and its three subsystems. Results reveal that the resource use intensity of the "pig–biogas–fish" system, defined as the ratio of footprint investment to footprint delivered, is 0.48. Compared with the conventional animal husbandry system, the "pig–biogas–fish" system proves to be of higher sustainability. And the findings have essential policy making implications supportive to a further spread of integrated biogas-utilization modes in rural areas.

1. Introduction

Sustainable development, namely development that meets the needs of the present without compromising the ability of future generations to meet their own needs, was defined by the World Commission on Environment and Development (WCED) in 1987 for the first time (Oyedepo, 2012). As a guiding principle for the long-term global development, sustainable development consists of three pillars: economic development, social development and environmental protection (Li et al., 2014; UN, 2011; Zhang and Chen, 2010a). China is a staunch supporter of sustainable development. In 1994, Chinese government issued "China's Agenda 21", which outlined a comprehensive and long-term strategy of sustainable development in China. And then in 1996, sustainable development was incorporated into the national strategies, and was put into enforcement (Han et al., 2013; NDRC, 2012; Shao and Chen, 2013). As a developing country with peasants taking up 60% of the population, China takes the development of economy and ecology of rural areas as one of the most important policies (Zhang et al., 2009). To propel the sustainable development of rural areas, the Chinese government has been on a constant endeavor to promote the biogas construction with policy preferences, financial support, and technology inputs (Chen et al., 2006). Since the Eleventh Five-Year Plan, up to 21.2 billion Yuan have been invested in the construction of biogas systems in rural areas by the government, of which about two thirds is used for the household biogas systems that directly generate a rapid growth of the amount of household biogas digesters (ChinaIRN, 2013). By the end of 2011, about 40 million household biogas digesters gained their application, accounting for 23% of the total households in the countryside (Cao, 2012).

In recent years, integrated biogas-utilization modes, linking biogas production and the agricultural industry, have become a major trend of household biogas utilization in China (Chen and Chen, 2012). These modes have common characters of time multi-sequence, space multi-level and ability to meet local household requirements (Li et al., 2012; Zeng et al., 2007). There are three main modes in China, namely the northern "four in one", the northwestern "five-matching" and the southern "pig–biogas–fruit" or "pig–biogas–fish". However, it cannot be disregarded that these biogas systems not only provide energy and goods, but also require materials and work force for construction, operation and maintenance process. So the sustainability of the present rural household biogas system in China is worth researching. As the representative of the southern biogas systems in China, a "pig–biogas–fish"

---

[*] Correspondence to: Q. Yang, Department of New Energy Science and Engineering, School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, PR China.

[**] Correspondence to: G.Q. Chen, College of Engineering, Peking University, Beijing 100871, PR China.

E-mail addresses: qyang@mail.hust.edu.cn (Q. Yang), gqchen@pku.edu.cn (G.Q. Chen).

http://dx.doi.org/10.1016/j.ecoinf.2014.06.006
1574-9541/© 2014 Elsevier B.V. All rights reserved.

system in Jingzhou, Hubei province, is chosen as a case study in this paper.

Wackernagel and Rees (1996, 1997) proposed Ecological Footprint (EF) as an indicator of the carrying capacity of regions, nations and the globe, and afterwards extended it as an indicator of sustainability. As a resource accounting tool that makes demand for biological capital visible, measurable, and manageable, EF urges decision makers to identify strategies for sustainable development and gains its popularity among academics (Chen et al., 2005; Zhang and Zhang, 2004). Previous studies concerning EF fall into two groups. One includes the general EF model used at the national or provincial level to describe the overall demand for ecosystem services (Chen et al., 2007; Wackernagel et al., 2004a; Wang and Chen, 2009). The other deals with the component EF model used to identify the footprint associated with specific business or consumer behaviors (Cerutti et al., 2013; Herva and Roca, 2013; Wiedmann, 2009). However, comprehensive evaluation of renewable energy like biogas with ecological footprint as an important indicator is still lacking.

Several researchers have analyzed typical biogas systems with other methods. Martin et al. (2011) utilized the life cycle approach to present the environmental impacts of the integration of biogas and ethanol; Wang and Wang (2006) explored the statistical method to analyze the impacts of household biogas systems on farmers' cropping behaviors with descriptive statistics and econometric models; Chen and Chen (2012) applied an emergy synthesis analysis to assess the efficiency and emission mitigation effect of a biogas-linked agrosystem in China. Most of the previous studies took biogas systems as energy systems, and focused mainly on their benefit for replacing the traditional energy, ignoring their effect on waste treatment (Berglund and Börjesson, 2006; Nzila et al., 2012; Patterson et al., 2011; Wang et al., 2010; Zhang et al., 2013). A biogas project, apart from being a source of renewable energy used for heating and electricity, can also be a way for organic waste management, to reduce pollution and improve the living environment for local residents. This specially applies to wastes from animal husbandry, an activity that has recently become a pillar industry of the agricultural economy (Zhang and Chen, 2010b; Zhou et al., 2007). Following the impressive development of the animal husbandry in rural areas, the production of manure has been on a continual increase, thus causing a series of environmental problems and even some social problems for poor living conditions in China, like "the hollow phenomenon", which reflects that more and more farmers in the countryside choose to work and live in the city (Gao et al., 2006). To fill these above-mentioned blanks, the present paper aims at quantifying the environmental sustainability of the chosen "pig–biogas–fish" system by employing an integration of the EF method with the emergy method. Moreover, the biogas system is studied as an ecological system in this paper with the benefit of refuse treatment taken into consideration.

The structure of the paper is organized as follows: methodology and data sources are described in Section 2; results are presented and discussed in Section 3; finally, summary statements are drawn in Section 4.

2. Methodology and materials

2.1. Ecological footprint (EF)

EF is defined as the aggregate area of Earth ecosystems that is needed to produce all resources consumed within an economic process or system, and to absorb all wastes generated (Wackernagel et al., 2004b). By comparing the area required to support a certain lifestyle with the area actually available, the EF method offers a way to assess if the consumption is sustainable from the perspective of available productive capacity (Van Den Bergh and Verbruggen, 1999). The key principle of EF is the relationship between our consumption of resources and the productive area on Earth, based on the awareness that such area provides support to the daily production and life of human beings (and other species): all commodities and ecosystem services can be treated as a product of the land. The practical implementation of the EF method can be summarized in relation to human consumption and waste production according to six major components of productive space: arable land, pasture, forest, sea space, built-up land and fossil energy land; EF aggregates different categories of space to a total footprint value by means of equivalence factors, which reflect the category's relative biomass yield in contrast to world average level. As for an ecological evaluation indicator, it should reflect both the quantity and quality of the resource. However, the focus of the EF method is only on the quantity of biomass produced from different types of productive areas, and it fails to consider the resource's quality, which is the intrinsic value of the ecological products (Chen and Chen, 2007; Shao et al., 2013).

Since the introduction of the EF concept to China in 1999, it has induced vast attention in the academic field and some potential improvements have been proposed in the current EF method. Zhao et al. (2005) tried to combine EF with emergy accounting, given the fact that both methods aim to solve the same problem through accounting of resources and throughputs, through estimating the gap between the demand by humanity and available natural services, and finally through evaluating resource utilization by humans. What's more, the emergy method emphasizes a donor or supply-value of goods or services, which is not fully addressed by the EF method (Shao et al., 2013; Zhao et al., 2013). Chen and Chen (2006) modified the EF concept based on ecological thermodynamics. They compared emergy-based ecological footprint with EF in a time series (1981–2001) study of the Chinese society, and suggested the emergy-based ecological footprint to serve as an extended indicator of EF, capable of avoiding some questionable assumptions of EF calculation procedures.

2.2. Emergy

Defined as the availability of energy (exergy) of one kind (usually solar) that is used-up in transformations directly or indirectly to make a product or service, with the unit solar emjoule (seJ) (Odum, 1988, 1994, 1996), emergy brings into the assessment of different input flows on an equivalency basis (reference to solar radiation) as well as the biosphere support over time for resource generation (Ulgiati et al., 1995, 2011). It tracks both quality and quantity of the resources used, and embodies the degraded available energy in an organized hierarchy. Through accounting of the supply-side resource flows, the emergy method measures the amount of resources obtained from the context of environment, and quantifies the relationship between man and nature (Brown and Ulgiati, 2004; Chen et al., 2009, 2010; Sciubba and Ulgiati, 2005). In this research, the resources consumed and the waste and products generated by the biogas system are firstly translated to a common emergy unit, and then aggregated to a total emergy-based footprint to analyze its overall sustainability. The detailed steps are presented below.

To assess a resource quality, Odum (1996) introduced the concept of transformity, *t*, as the solar emergy required to generate a joule of product or service, expressed as joules of available energy ($\text{seJ} \cdot \text{J}^{-1}$) (Jiang et al., 2007, 2008; Zhou, 2008). When the product or service of a process is expressed in mass units, the quality factor is named "specific emergy" (with units of $\text{seJ} \cdot \text{kg}^{-1}$). Since product and service flows can also be expressed by other units (e.g. monetary and time units), a more general terminology can be used as Unit Emergy Value (*UEV*, $\text{seJ} \cdot \text{hr}^{-1}$; $\text{seJ} \cdot \$^{-1}$; $\text{seJ} \cdot \text{ha}^{-1}$, etc.) (Brown and Ulgiati, 2004). Through a path-dependent integration, *UEV* calculations are determined by the process yielding the product or service; the larger the transformity, the greater the environmental support required or provided. It is worthwhile to note that *UEV*s for a wide variety of goods and services can be obtained from previous studies to facilitate the emergy analysis. However, *UEV* of a given object of the same category may have different values due to the specific geographic location and the production process (Yang et al., 2013). Nowadays, a latest systematic database of embodied ecological