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Exergy based renewability assessment: Case study to ecological wastewater treatment

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ABSTRACT

The renewability assessment has seldom been a core issue in previous studies. This work presents a framework to assess the renewability of a production system based on the unified ecological evaluation method of embodied cosmic exergy analysis. For the first time, both historical renewable and nonrenewable resources uses of each social product input of a system are individually and completely traced and measured by the embodied cosmic exergy as available energy. A set of indicators have also been devised to assess the resources utilization efficiency and renewability of a production system. To demonstrate the framework, a case study is carried out for a pilot constructed wetland wastewater treatment system in Beijing. The resources utilization style and renewability of the case system are analyzed and assessed. The presented framework can be easily transplanted to assess the renewability of other products, which could contribute a lot to meet the goal of sustainable development.

1. Introduction

1.1. Renewability assessment of a production system

Renewability assessment is of great importance for sustainable development, which often has two implications. One is directly related to renewable resource, which tries to calculate the input/output ratio of a specific renewable resource based on benefit analysis. It is only applicable to these renewable systems, e.g., wind farm as renewable energy technology and wastewater treatment as renewable water technology (Chen et al., 2011b,c; Malça and Freire, 2006; Shao and Chen, 2013; Yang and Chen, 2012; Yang et al., 2013).

The other is to investigate the sustainability of a concerned system by identifying the renewable resources component from its total historical resources use, whose scope is much larger than that of the former one. It can be carried out for all kinds of production systems and can provide us with the specific renewability index for each final product. As it can be very useful for sustainable development by means of renewability labeling strategy for all products, the present work aims at contributing a universal framework to assess the renewability of various production systems.

Thermodynamic accounting methods, especially emergy analysis developed by Odum, have been widely applied to analyze the historical resources uses of various systems (Björklund et al., 2001; Chen et al., 2009, 2011d; Grönlund et al., 2004; Vassallo et al., 2009). A set of indicators have been proposed, among which the indicator of RI (renewability index) concerning the original renewable natural resources was devised to carry out renewability assessment. However, only a part of the natural renewable resources directly utilized by the concerned system, such as sunlight and rain, have been identified as renewable resources in previous studies, with the historical renewable resources uses of various purchased products being ignored or misdeemed as nonrenewable resources.

As a matter of fact, only a few energy sources can be regarded as complete renewable or nonrenewable resources according to their replenishing time. For example, sunlight and wind energy are renewable resources and fossil fuels are nonrenewable resources. As for almost all the economic products and social services (termed as social products hereafter), both renewable and nonrenewable resources have been consumed during their productions. In order

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to assess the overall renewability of a production system supported by various kinds of social products, the renewable resources use of each product or service input should be concerned.

1.2. The method of embodied cosmic exergy analysis

Emergy was initially proposed by Odum to evaluate the energy of one kind previously required to generate a product or service (Odum, 1988, 1996). Since solar energy is conventionally believed to be the primary driving force of the ecosphere, solar emergy in terms of embodied solar energy has been prevailing in previous emergy studies. Most of the existing renewability related studies have applied the solar emergy analysis method. But solar emergy based on embodied energy has suffered from the intractable problem of double counting and is incapable to measure the depletion of energy since energy can never be consumed. Odum and others came to realize this and exergy embodiment emphasizing available energy has been proposed to re-explain and re-define emergy (Bastianoni et al., 2007; Odum, 1996; Sciubba and Ulgiati, 2005). It has soon become popular on a par with emergy analysis in resources accounting field (Chen et al., 2014; Dai et al., 2014, 2015; Shao et al., 2013a; Yang and Chen, 2014; Yang et al., 2009).

Cumulative exergy was proposed by Szargut et al. to analyze the sum of direct and indirect exergy inputs embodied in supply chain of a product and service (Szargut et al., 2002). Based on both the concepts of emergy theory and cumulative exergy method, Chen developed embodied cosmic exergy (or cosmic emergy) to measure the energy transformation hierarchy of each production process. According to the theory, earth is a cosmic heat engine operating between the solar radiation as a heat source and the cosmic background microwave (CBM) field as a cold sink, and the cosmic exergy originated in the thermal difference between solar and CBM radiations is proved to be the ultimate driving force of the ecosphere instead of solar energy (Chen, 2005, 2006).

The embodied cosmic exergy synthesis successfully overcomes the double counting problem of solar emergy by renovating emergy power base and is more systematic than cumulative exergy method by including the contribution of natural environment instead of sole non-renewable resources (Jiang et al., 2010). Chen has analyzed the global cosmic exergy budget in his original framework, on the basis of which a lot of studies have been carried out to assess the resources uses of various ecosystems (Chen et al., 2010, 2011d; Jiang et al., 2010).

Considering that macro-economic statistic based input–output analysis can cover all transaction activities of social products within an economy by means of a network modeling, Chen and his collaborators have integrated the embodied cosmic exergy into input–output framework and achieved fruitful results (Chen and Chen, 2010, 2011). These studies have not only evaluated the resources use style of the concerned economy through a top-down analysis, but also provided us with an average embodied cosmic exergy database for all products and services within the economy. Furthermore, they have distinguished clearly between renewable resources and nonrenewable resources inputs in the basic modeling process, whose results can be utilized to systematically identify both historical renewable and nonrenewable resources uses of each product or service within a specific economy.

With the application of embodied cosmic exergy analysis and input–output analysis based database, this work is to present a framework to assess the renewability of a production system through tracing the historical renewable resources use along its supply chains. The rest of the paper is organized as following: Section 2 describes the method of embodied cosmic exergy, procedures and indicators of renewability assessment framework and materials used in this study; a case study is performed by carrying out embodied cosmic exergy analysis for a pilot constructed wetland as ecological wastewater treatment engineering in Beijing, the results of which are presented and discussed in Sections 3 and 4, respectively; finally the conclusions are drawn in Section 5. The renewability assessment framework and related indicators presented in this paper can be utilized to trace lifecycle renewable resources uses of various production systems, which would contribute a lot to the sustainable development of the economy.

2. Methods and materials

2.1. Embodied cosmic exergy analysis

As developed by Chen, the method of embodied cosmic exergy analysis has a solid theory basis, in which the global cosmic exergy budget with respect to main terrestrial processes has been systematically studied (Chen, 2005, 2006). Subsequently, Chen and his collaborators have developed a whole set of embodied cosmic exergy scheme (Chen et al., 2010; Ji, 2008; Jiang, 2007; Jiang et al., 2010). Revised from the energy circuit symbols developed by Odum, the exergy circuit symbols (see Fig. 1) have been devised to illustrate the elements and flows within the ecosystem. In contrast to the unit of solar Joule (sej) in solar emergy, the unit of cosmic Joule (Jc) has been applied to measure the available energy as cosmic exergy.

The embodied cosmic exergy transformity (termed as transformity hereafter in this paper) is defined as the magnitude of cosmic exergy input required for making one unit product or service with reference to emergy synthesis. Lots of works have been done previously to calculate the tranformity database for various natural resources and social products. Nowadays researchers are able to choose appropriate transformity data according to their needs rather than calculate the transformity of each concerning input by their own.

The embodied cosmic exergy transformities of the environmental inputs can be derived from classical references due to the relative stable balance of earth after the long-term evolution (Chen, 2005, 2006; Ji, 2008; Jiang, 2007; Jiang et al., 2010). As for the social products and services, in the light of different technical efficiencies and economic structures, the same products from different economy communities or different years have different transformities. Special attention should be paid to choose an appropriate transformity database for various inputs in order to perform a well embodied cosmic exergy analysis.

The input–output analysis (IOA) is a network modeling approach utilizing the statistics and organizing matrices of all the intermediate inputs into goods and services of the whole economic interactions (Leontief, 1970). It has been extended to analyze the environmental impacts of an economic system soon after its proposal, which has also been introduced to thermodynamic accounting field (Baral and Bakshi, 2010; Chen and Chen, 2010, 2011; Ukidwe and Bakshi, 2004). Recently the method of systems IOA has been developed by Chen et al. to calculate the embodied ecological element intensities for all products and services within the economy (Chen and Chen, 2010, 2011). The embodied cosmic exergy as an integrated measurement of resources use has also been concluded as one of the concerned ecological elements. Since the systems IOA based embodied cosmic exergy transformity database can provide us with consistent and unified intensity data, it has been applied to estimate the renewable and nonrenewable resources uses of a production system in this work.

2.2. Procedure of renewability assessment and related indicators

The diagram for the embodied cosmic exergy based renewability assessment of a production system is shown in Fig. 2, which is drawn by using the exergy circuit symbols illustrated in Fig. 1.