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The inclusion of economic and environmental factors in the ecological cumulative exergy consumption analysis of industrial processes

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ABSTRACT

Resource, economic, and environmental impacts are three major factors in the evaluation of industrial processes. All of them might imply certain contributions of ecosystems services. A comprehensive accounting of these factors is critical to sustainability assessment of industrial activities at the ecological scale. Ecological Cumulative Exergy Consumption (ECEC) analysis is a promising approach to address these issues. However, the current knowledge on ECEC is incomplete, especially in economic investment and environmental impact. In this paper, ECEC analysis is extended to quantify purchased resources and pollutant emissions of industrial production. Accordingly, an extended ECEC framework is proposed, integrating the resource, economic, and environmental factors. Furthermore, for better understanding of sustainability, a concept of Ecological Life Cycle Cost (ELCC) is put forward, revealing the relationship between the ECEC and traditional economic evaluation. Finally, a case study of China's raw coal production is used to illustrate the features of these proposed frameworks. The ECEC and ELCC analyses indicate the great ecological influence of raw coal which has been underestimated by the traditional assessment approaches.

1. Introduction

Ecosystems provide the basis for sustainable development of human society and modern industries. However, they would be rapidly degraded due to over exploitation. So a comprehensive accounting of the contributions of ecosystems is necessary for the sustainability assessment of industrial activities. Emergy theory (Odum, 1996; Ulgiati and Brown, 2009) is one of the significant contributions to energy analysis that aims to quantify the ecological value of resources and services. It assumes that the Earth's ecosphere is a closed system with solar insolation, deep earth heat, and tidal energy as major original inputs. These inputs drive the productions of all natural resources and services. Solar emergy (Odum, 1996; Ulgiati and Brown, 2009), measured in solar-equivalent Joule (seJ), is the available energy (exergy) needed to produce these natural resources or services if solar radiation were the only input.

Emergy theory is conceptually appealing because it recognizes what ecosystems have done to make natural resources (or services) available for humans. Ecosystems concentrate and upgrade resources at their corresponding cost of seJ. For the sustainability analysis of any industrial process, this insight is of extreme importance. Emergy theory evaluates the stress or impact of industrial production on the sustainability of ecosystems.

However, the application of solar emergy in industrial analysis has confused many researchers (Hau and Bakshi, 2004a; Sciubba and Ulgiati, 2005). Firstly, the relationships between emergy accounting and other traditional engineering approaches, such as exergy analysis (Szargut et al., 1988, 2002) and Life Cycle Assessment (LCA) (Goedkoop and Spriensma, 1999; ISO 14040, 2006), have not been clear until recently, causing rejection of emergy theory (Sciubba and Ulgiati, 2005; Bastianoni et al., 2007). Secondly, the Maximum Empower Principle (Odum, 1996) claimed by emergy analysis, i.e. all self-organizing systems tend to maximize their rate of emergy use or empower, turns out to be controversial in industrial cases (Ayres, 2004).

It is also important to point out that most of the controversial aspects of emergy analysis are not relevant to the insight of using transformities (unit emergy value) of ecosystem goods and services to indicate the contribution of ecosystems. As discussed by Hau and

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Bakshi (2004b), solar emergy could be equivalent to Cumulative Exergy Consumption (CEC) (Szargut et al., 1988, 2002) when ecosystems are also included in the life cycle calculation, and may be referred to as Ecological CEC (ECEC). ECEC and solar emergy would be the same when analysis boundary, allocation approach, and method for combining global energy inputs are identical. Yet, the concept of ECEC avoids from the confusions discussed above (Hau and Bakshi, 2004b; Zhang et al., 2010). Its relationships with other traditional engineering approaches are clear. Legitimacy of the Maximum Empower Principle is irrelevant to the applicability of ECEC analysis. Thus, ECEC provides a way to apply solar emergy into the sustainability analysis of industrial processes. Many works in this area could be found (Baral et al., 2012; Yang et al., 2013).

However, researches on ECEC (or solar emergy) are still far from complete (Liu et al., 2011; Yang et al., 2013; Arbault et al., 2014). Firstly, most studies on ECEC (or solar emergy) of industrial productions focus on the resource side of life cycle, paying less attention to economic investment and environmental impacts (Hau and Bakshi, 2004b; Baral et al., 2012). Secondly, the knowledge about ECEC is also too sophisticated for general public to understand, limiting its applicability to most industries.

This paper reviews existing insights on economic investment and environmental impacts of ECEC (or solar emergy), and attempts to establish a way to quantify the economic and environmental factors of industrial production by ECEC. This trial could not be regarded as perfect, but it represents an awareness of the importance of economic and environmental factors on the sustainability of industrial production. The quantitative accounting of purchased resources and pollutant emissions in addition to natural resources would definitely contribute to a more comprehensive ECEC.

Another attempt of this paper is to uncover the relationships between ECEC and economic evaluations such as Life Cycle Cost (LCC) (Craighill and Powell, 1996; Pa et al., 2013) by an Ecological Life Cycle Cost (ELCC). ELCC is put forward to make ECEC analysis more understandable for general public and more applicable for industrial engineering.

The major aim of this paper is to extend the theoretical framework of ECEC (or solar emergy) for simultaneously accounting for the resource, the economic, and the environmental factors of industrial processes. Another shortcoming of ECEC (or solar emergy) analysis is the uncertainty in transformity values due to consideration of system level energy and material flows. Discussions on this issue are also an area of active research (Brown et al., 2011; Yang et al., 2010; Brown and Ulgiati, 2010). But this challenge is no different from those faced by any holistic approach including LCA and exergy analysis, and it is out of the scope of this paper.

2. Extension of ecological cumulative exergy consumption

2.1. The previous ecological cumulative exergy consumption

The Ecological Cumulative Exergy Consumption (ECEC) has been defined as the allocated values of exergy consumed in a series of cluster-interlinked processes leading from the original resources to the final product or service (Hau and Bakshi, 2004b; Yang et al., 2013). The original resources are those extracted from solar insolation, deep earth heat, and tidal energy (measured in solar-equivalent Joule). ECEC analysis is based on the hypothesis that ecosystems provide all the goods and services at cost of solar-equivalent Joule. ECEC aims to account for these ecosystem goods and services so that be an indicator of ecosystems contributions to industrial production.

The resource factor of an industrial process could be quantified as the ECEC of "natural capital (NC)" via Eq (1) (Hau and Bakshi, 2004b). Here, natural resources are classified as either renewable or nonrenewable. Their solar-equivalent Joule are aggregated accordingly (Odum, 1996; Rugani et al., 2013). A detailed description of the aggregation scheme can be found in the work of Hau and Bakshi (2004b) as well as in the Supporting information, section 1.

$$\mathrm{ECEC_{NC}} = \mathrm{Max}\{Q_{\mathrm{R},\,i} \times \mathrm{Tr}_{\mathrm{R},\,i}\} + \sum\{Q_{\mathrm{NR},j} \times \mathrm{Tr}_{\mathrm{NR},j}\} \quad (1)$$

here Q_R and Q_{NR} are the quantity of renewable and non-renewable resources, respectively. Tr_R and Tr_{NR} are the solar transformities of renewable and non-renewable resources, and they represent the solar-equivalent Joule required to provide unit resource. Researches on transformities data could be found in literatures (Odum, 1996; Rugani et al., 2013).

While many researches focus on the resource factor of ECEC (Odum, 1996; Hau and Bakshi, 2004b; Baral et al., 2012), few of them pay attentions to the economic investment and environmental impacts. Economic investment and environmental impacts are undeniable features of industrial processes, distinguished from natural processes, as shown in Fig. 1. Some studies (Ukidwe and Bakshi, 2004; Zhang et al., 2009; Arbault et al., 2014) reported on these issues but they are isolated or incomplete, making it difficult for reaching a comprehensive accounting of ECEC. This section attempts to establish an ECEC framework to quantify the economic and environmental factors in addition to the resource factor of industrial production.

2.2. Expanding to account for purchased resources

Economic investment is an indispensable factor on industrial processes that does not exist in natural processes. No industries could survive without economic investment, because industries need to purchase economic goods and services such as raw materials, equipment, utilities, and labors. The production of these "purchased resources" would definitely lead to a considerable quantity of ECEC.

In previous researches, the ECEC of purchased resources was calculated by multiplying the monetary value of purchased resources and the overall ECEC/Money ratio (EMR) of the socioeconomic system (Odum, 1996; Liu et al., 2011). But many studies (Clift and Wright, 2000; Ukidwe and Bakshi, 2004) pointed out that one unique EMR for all the purchased resources could result in fallacies. It is evident that currency circulation of 1 RMB devoted to energy production has a higher requirement for ecosystem goods and services with respect to 1 RMB of other products like food or

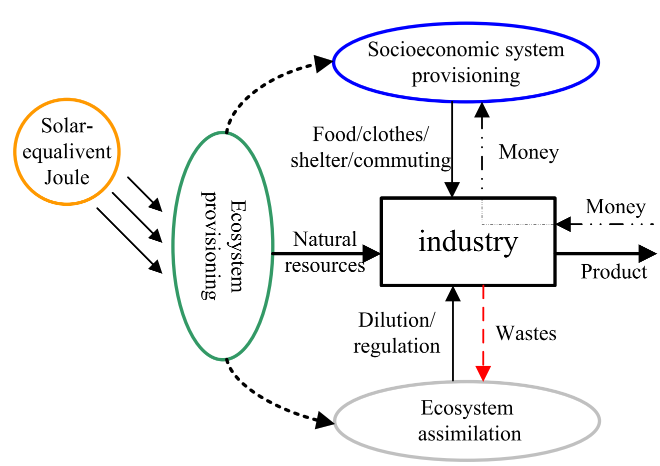

Fig. 1. The resource, economic and environmental factors of industrial processes.