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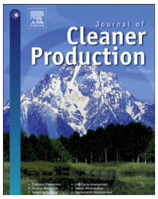

Emergy based resource intensities of industry sectors in China

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ABSTRACT

Emergy analysis can facilitate unified system resources accounting. By combining emergy method with input–output modeling technology, this paper developed an eco-thermodynamic input–output model of the 2007 China economy to account for the sector-specific resource intensities. The results show that the resource intensities for Chinese industry sectors present a distribution with a certain pattern which may vary over three orders of magnitude, measured in terms of resource consumption against economic capital generation. At the scale of the entire economy, the emergy intensities for the resource extraction sectors of non-metallic minerals and metallic ores are the highest. Sectors with the smallest emergy to money ratios are service sectors which rely less on primary natural resources. The sector of coal mining is found to have the largest resource intensity of 6.19E+16 seJ/1E+4 CNY among all sectors, while the sectoral intensity of scrap and waste is only 6.44E+14 seJ/1E+4 CNY, the least one. The insight obtained by juxtaposing resource intensities as well as their structures of industry sectors is useful to identify opportunities for reducing resource intensities that could enable improvements in their ecological sustainability.

1. Introduction

The reason behind resource analysis is to quantify the connection between human activities and the resource demand with respect to its increasing scarcity. The most common use of resource analysis has been for the identification and reduction of sources of inefficiency in manufacturing processes and equipment (Ottinger, 2006; Song and Zheng, 2016; Szargut et al., 1988; Ukidwe and Bakshi, 2007), and also in evaluating the trade-off between resources consumption and economic benefits. Since knowledge about the flow and transformation of resources is proving to be useful for evaluating and understanding the behavior of industrial and ecological systems, various efforts have been made to estimate the natural resources consumption and environmental emissions for typical industrial sectors and the socio-economy as a whole in China (Chen and Qi, 2007; Du et al., 2016). However, relevant decision making at national scale necessitates more systematic accounting of the economy in the context of sectoral resource intensity and structure. Resource intensity is a measure of resources (e.g., materials, energy, and water) required for the provision of a unit of goods or service. It is usually expressed as a ratio between resources input and product or service provided (expressed in value, mass, volume, or other unit deemed as appropriate). Generally, the sectoral resources intensity can provide essential information associated with a country's technology level as well as its economic structure. As to resource structure, it is usually considered from a renewable or non-renewable perspective. Processes with a larger percentage of renewable resource inputs need to be identified, since they are likely to be more sustainable than those using a larger percentage of nonrenewable resource (Lefroy and Rydberg, 2003; Martin et al., 2006).

Certainly, sustainability could not be truly evaluated at any single scale without the consideration of the broader life cycle (Song et al., 2016). However, an important challenge and source of much debate and controversy in life cycle assessment (LCA) is the need to interpret multiple attributes representing different types of resources consumed and emissions, i.e., the issues of unified accounting. Conventional LCA has achieved great progress in classification, characterization and assessment of the impact of emissions (Ukidwe and Bakshi, 2008), but relatively less achievement was made for dealing with the diversity of resources and their use. Although indicators such as Abiotic Depletion Potential and Surplus Energy are available for denoting resource use, they are best suited for non-renewable resources only, and implicitly

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assume the substitutability between resources (Baral and Bakshi, 2010). Other methods such as Material Flow Analysis (MAF) and Net Energy Analysis (NEA) have been developed to quantify the reliance of life cycle on natural resources. Similarly, these methods could not capture the quality differences between different resources and combine them (Cornelissen and Hirs, 2002), and also ignore the contribution of ecosystem goods and service such as wind, sunlight, soil loss to economic activity.

For any case, the efforts to reduce environmental footprint or resource intensity need to be supported by models that can provide unified resource accounting and permit easier interpretation on a consistent basis. The emergy method has been developed for quantifying the role of ecological resource in a life cycle (Odum, 1996). Based on the principles of energetics, system theory and system ecology, it was first presented by H.T. Odum in 1983, in order to fully integrate the values of energy, materials, and information in a common unit measured in solar equivalent joule, which provides a way to understanding the behavior of self-organized systems, evaluating ecological goods and services as well as analyzing ecological and economic systems (Brown and Herendeen, 1996; Hau and Bakshi, 2004; Odum and Odum, 1983). As one of the life cycle oriented method, emergy (with unit emjoule) analysis therefore is totally different from the conventional energy (with unit joule) analysis that merely accounts for the remaining available energy at present, and which is proved to be a feasible approach to evaluate the status and position of different energy carriers in the universal energy hierarchy. The ratio of the emergy required to make a product to the available energy of the product is defined as the transformity of the product. The units of the transformity are emjoules J^{-1}, abbreviated as seJ J^{-1}; other unit emergy values (UEVs) are the specific emergy, emjoules kg^{-1} (seJ kg^{-1}) and the emergy to money ratio, emjoules $\$^{-1}$ (seJ $\$^{-1}$). For a specific industry sector, the resource intensity can be expressed by its UEVs, i.e., emergy demand per unit output. To derive the emergy embodied in a resource or commodity, it is of fundamental importance to trace back through all resource and energy that are used to produce it and express each in the amount of solar energy that went into their production chain. In fact, emergy analysis considers all systems to be networks of energy flows and determines the emergy value of the systems involved through a synthetic approach, providing a general accounting mechanism that allows us to view the economy and the environment on the same income statement and balance sheet.

In such case, emergy analysis has the potential to serve as an important method for unified resource accounting in LCA by considering the role of natural resources and their qualities (Raugei et al., 2014). It assumes the earth to be driven by three primary energy sources: the solar energy, deep earth heat and tidal energy. And it purports that all living systems sustain one another by participating in a network of energy flow via converting low quality energy into both higher quality energy and degraded heat energy. An important feature and improvement of emergy analysis is its ability to consider the role of ecosystem services in economic activities. It is worthwhile to note that accounting for ecological services is very essential for any method that is meant to evaluate or encourage sustainability (Baral and Bakshi, 2010). What's more, emergy analysis is also claimed to be able to account for quality differences among resources via its transformity. In general, nonrenewables tend to have higher transformities than renewables. During the last three decades, emergy with its corresponding indices and ratios has been proved to be an effective and robust tool to understand the resource flows supporting both the natural ecosystem and macro-economic system, and it has shown that it can be used to measure their overall performances and sometimes sustainability (Odum, 1996; Zhang et al., 2009). Therefore, it has been widely used to analyze systems as diverse as ecosystems, industries, and economies (Cai et al., 2009; Pang et al., 2015; Zhang et al., 2007, 2009, 2011, 2012, 2013, 2014). On the national scale, more than 20 countries, such as Switzerland, France, Japan, Norway, Canada, Brazil, Turkey, Italy and the US, were analyzed and discussed based on the emergy approach (Odum and Odum, 1983; Ulgiati et al., 1994). Further more, the emergy-based National Environmental Accounting Database (NEAD) involving detailed information for over 150 countries for the full array of resources that underlie economies has been established (Sweeney et al., 2007). The mainland China as an economic system has also been studied from the perspective of emergy accounting and included in the NEAD (Jiang et al., 2008; Yang et al., 2010). However, most of the available researches on Chinese economy using emergy method regard the whole system as a black box, calculating only inputs and outputs while ignoring the resource flows between sectors within the system.

Unlike the previous study, this paper develops an eco-thermodynamic input–output model of the 2007 China economy that accounts for the resource flow in the 135-sector benchmark economic input–output model by combining emergy method with input–output modeling technology. The main objectives of this paper are as follows: (1) to determine and interpret the emergy based resource intensities for China's 135 industry sectors in 2007, (2) to compare their resource structures of industry sectors in terms of renewable and nonrenewable consideration, and (3) to identify the opportunities for reducing intensities and for encouraging industrial restructuring that can enable improvement of their ecological sustainability.

2. Methodology

2.1. *Eco-thermodynamic input–output model*

Input-output analysis is a well-established tool in economic analysis, where the interdependencies across different sectors of the economy are represented by a set of linear equations (Leontief, 1936). Extending economic input–output analysis to resources consumption and emissions yield environmental burdens at the scale of individual economic sectors for LCA (Bullard and Herendeen, 1975; Lave et al., 2000). In such case, the standard Leontief input–output (I–O) model has been extended to the so-called environmentally extended input–output model (EIO) to capture resource consumption flows in the economy. This model integrates economic input–output models with information about physical flows to and from various economic sectors and can easily account for direct and indirect flows within the same supply chain (Duchin, 1998). Thus, every sector extracts direct resources from the earth, and then indirectly through the embodied resource intensity in inputs from other sectors. This “top-down” approach for assessing environmental impacts of the whole economy has been widely applied for national energy analyses after the energy crisis in the early 1970s (Lin and Polenske, 1995; Peters and Hertwich, 2008). Recently this I–O based technology has been widely adopted to track both direct and indirect effects as embodiments in an economic system, e.g., to calculate embodied consumption of energy resources, water resources and greenhouse gas (GHG) emissions in national economy accounts (Chen et al., 2010; Chen and Chen, 2010; Costanza, 1980; Lenzen, 1998; Ukidwe and Bakshi, 2007) and international trade (Shui and Harriss, 2006). Bakshi and coworkers have developed a model for thermodynamic input-output analysis by combing the economic model with data about the use of resources in specific economic sectors and their transformities (Ukidwe and Bakshi, 2004, 2007). For a more detailed description of input–output analysis, underlying assumptions

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