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Exergy-based systems account of national resource utilization: China 2012

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ABSTRACT

Resource input is the prerequisite to maintain the operation of socio-economic systems. Exergy analysis provides a wide and clear vision of the use and degradation of natural resources, with essential implications to sustainability. This paper aims to perform an exergy-based system account of the resource utilization in China, one of the most complex societies around the world. An overall systems diagram with seven independent and complimentary social departments is designed to illustrate the clear-cut processes of resource use and exergy destruction and loss. The national total input of resource exergy in 2012 reached 158.11 EJ, with the net input of 155.87 EJ. Its per capita resource consumption increased to 111.95 GJ, compared with 51.5 GJ in 2003. *Industry* accounted for 26.3% of the total resource exergy consumption, followed by *Conversion* 23.2%, *Household* 18.3%, *Agriculture* 10.2%, *Tertiary* 10.0%, *Exaction* 6.7% and *Transportation* 5.3%. The sectoral conversion coefficients of resource exergy were estimated as 91.92% for *Extraction*, 34.58% for *Conversion*, 29.75% for *Agriculture*, 32.18% for *Industry*, 18.46% for *Transportation*, 34.28% for *Tertiary* and only 1.28% for *Household*. The structure and efficiencies of resource exergy use of the Chinese society haven't witnessed a prominent improvement in the recent decade, and its resource utilization performance was still inferior to those of some industrialized societies. Exergy-based unified accounting for a benchmark year provides solid foundation for resource policy formation and can serve as the tool for identifying resource footprint and sustainable development mode.

1. Introduction

Natural resources are the material basis and basic driving force to sustain socio-economic development (Warr and Ayres, 2012). The use of resources is an irreversible course, while excessive consumption of non-renewable resources will have adverse effects on human society (Nguyen and Yamamoto, 2007). Using a unified accounting tool, such as thermodynamic concepts, to measure the availability of resources and evaluate resource use efficiency is a pre-requisite to evaluate natural resource utilization and related environmental impacts (Chen, 2006; Dewulf et al., 2008; Valero et al., 2015). As the outcome of the combination of the first and second laws of thermodynamics, exergy is defined as the maximum amount of work which can be produced by a system such as a flow of matter or energy carrier as it comes into equilibrium with a reference environment (Szargut, 2005; Sciubba and Wall, 2007). Distinguishing from the traditional economic analysis, exergy accounting with solid scientific basis provides a unified way for the measurement of all kinds of natural and human-made resources (Wall, 1977; Tsatsaronis, 2007). The potential usefulness or ability to perform work for each type of natural resource is its exergy content. Exergy analysis can provide a wide and clear vision of the use and degradation of natural resources (Sciubba, 2005; Valero and Valero, 2010). Owing to the scarcities of diverse resources (Szargut, 1978; Chen, 2005, 2006; Hermann, 2006), minimizing resource exergy utilization at different scales is essential for promoting sustainable development (Gong and Wall, 2001; Dincer and Rosen, 2007; Gasparatos and Scolobig, 2012).

Societal exergy account for the use and conversion of natural resources was firstly introduced by Wall (1977) covering both energy carriers and materials. Since then, exergy analysis has developed into a widely accepted approach for the unified account of resources extraction, conversion and consumption. The accounting of resources exergy can reflect the internal exergy change of irreversibility and provide a better understanding of the resource use and degradation in a society

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(Wall, 1990; Zhang and Chen, 2010). In recent two decades, a large number of studies have analyzed the resource exergy utilization of different countries (e.g., Ertesvåg and Mielnik, 2000; Ayres et al., 2003; Ertesvåg, 2005; Warr et al., 2008; Gasparatos et al., 2009a; Koroneos et al., 2011; Seckin et al., 2012; Al-Ghandoor, 2013; Gong and Wall, 2016), concrete regions (e.g., Liu et al., 2011; Bligh and Ugursal, 2012; Nielsen and Jørgensen, 2015), and specific industrial sectors or production systems (e.g., Dincer et al., 2004; Ji and Chen, 2006; Ignatenko et al., 2007; Koroneos and Nanaki, 2008; Chen et al., 2009; Gasparatos et al., 2009b; Yang et al., 2009; Ahamed et al., 2011; Chen et al., 2011; Zhang et al., 2011; Sanaei et al., 2012; Zhang et al., 2012b; Seckin et al., 2013; Liu et al., 2014; Yang and Chen, 2014; Shao and Chen, 2015; Wu et al., 2015; Bühler et al., 2016), which have provided strong evidence that exergy analysis is a valuable practical technology to quantify resource use. Moreover, systems account of exergy resource utilization for typical macroscopic systems can effectively reveal their functioning or metabolism structure and provide the basis for the ecological diagnosis of the large complex socio-economic systems, with essential implications to physical sustainability (Gong and Wall, 2001; Dewulf and Langenhove, 2005; Rosen et al., 2008).

As one of the most complex social systems around the world, China's social metabolisms are maintained by a large quantity of energy and material resources (Dai et al., 2012). An et al. (2014) reported that the natural resources input such as energy resources kept pace with the rapid growth of the country's gross domestic product (GDP). Given the complexity of social systems, the extraction and procurement of natural resources in the Chinese society regularly encompass raw coal, crude oil, natural gas, hydropower, wind power, nuclear power, agricultural products, forest yields, bio-fuels (straw, firewood), metal ores, nonmetal minerals, recycling materials and others, while the outputs as products or services consist of nonferrous metals, steel, chemicals, electricity, paper, food, lighting, mechanical work, space heating, cooking, water and process heating, transportation, etc. (Zhang and Chen, 2010). Some scholars have performed exergy-based resource accounting for the Chinese society in a given year (e.g., Chen and Chen, 2006; Chen et al., 2006; Chen and Qi, 2007; Zhang and Chen, 2010; Shao et al., 2013) and in the time-series periods (Chen and Chen, 2007a,b,c; Chen et al., 2014; An et al., 2014). For instance, Chen et al. (2014) and An et al. (2014) investigated the variation of natural resource production in China within an exergy foundation. By considering the network structure of societal exergy fluxes, Chen and Qi (2007) and Zhang and Chen (2010) presented the system account of resource uses in China 2003 and 2006, respectively. In addition, Chen and his colleagues (e.g., Chen and Chen, 2009; Dai et al., 2012, 2014) focused on the extended exergy analyses for China society including socio-economic factors such as labor and capital. Nevertheless, the literature list of exergy analysis of the Chinese society, specifically focusing on the resource utilization, is still very short.

It is worth noting that the current resource situation within China including the scale and structure of resources input/output become more complicated, when the country is speeding up the process of industrialization and urbanization. China recorded as the world's largest primary energy producer and consumer, and this country alone consumed about half of global coal in 2012 (BP, 2016). The degree of dependence on commodity imports such as oil, natural gas, ores and some agricultural products continue to increase, and the influences of foreign trade on the economy are continually expanding. The main industrial products have also expanded rapidly in the recent decade. For instance, the outputs of crude steel, ten major nonferrous metals, motor vehicles, ethylene, cement, plate glass, electricity, chemical fiber and primary plastic in 2012 were 3.9, 3.3, 4.6, 2.6, 2.4, 2.8, 2.5, 4.4 and 3.8 times of those in 2000, respectively (NBSC, 2013). In view of the drastic socioeconomic transition, previous studies are insufficient to explain the current state of the Chinese society and may be no longer applicable to an efficient understanding of the country's resource use (Brockway et al., 2015). Therefore, this context necessitates a systematic accounting and assessment for China's resources utilization with a unitary and objective measure, adapting to the new circumstance.

The aim of this paper is to systematically examine the resource procurement, allocation and consumption of the Chinese society in 2012 based on exergy unifying accounting method. For the Chinese society broken down into seven independent and supplementary sectors as the subsystems, a systems account of resource exergy utilization can illustrate the complex process and network relationship of resource exergy fluxes. A new system diagram is devised to display the integrity and hierarchy of resource exergy utilization across the social network. Furthermore, comparisons of resource utilization structures and efficiencies with other societies and the Chinese society in previous years will facilitate the understanding of the country's resource use patterns on the international and development horizons. An overall exergy analysis of national resource utilization will be useful for identifying resource metabolism pattern of specific social system and providing solid foundation in establishing effective regulatory strategies of economic activities to accelerate a shift towards sustainability.

2. Methodology and data sources

In the accounting of resource exergy in a society, it is important to understand the main factors that affect exergy conversion process, and to simplify the complex data processing to avoid repetitive and trivial calculation (Chen and Qi, 2007). Resource input into the Chinese society contains the imported, gathered and extracted commodities as exergy carriers. The entrance and boundary points are set at the same level to avoid repetitive and cross calculations of exergy fluxes. To keep consistency with previous studies, the Chinese society is classified into seven sectors, i.e., the extraction (Ex), conversion (Co), agriculture (Ag), industry (In), transportation (Tr), tertiary (Te) and households (Do). The extraction sector includes mining and quarrying, and oil and natural gas refining and processing. The conversion sector mainly refers to electricity and heat production from power and heat plants. The department of agriculture is the source of people's food and clothing, covering crop farming, forestry, animal husbandry, fishery, water conservancy and food processing. In this study, the industry sector mainly refers to the manufacturing industries except oil refineries. The transportation sector represents the commercial transportation services (passenger, goods) as well as services directly related to transportation (e.g., storage, dak). The tertiary sector includes wholesale, retail, hotels, entertainment, restaurant, finance, real estate, construction, and public services such as governments, hospitals, and schools, but excluding transportation services (Zhang and Chen, 2010). The domestic sector comprises urban households and rural households.

All the resource data are processed according to the special characteristics of sectoral socioeconomic status as embodied in relevant statistics. In the updated energy statistical yearbook of China (CESY, 2014), the usual energy carriers include coal, coke, oil and petroleum products, natural gas, electricity and district heat. Most primary energy data are available from China Electric Power Yearbook 2013 (CEPY, 2013), China Energy Statistical Yearbook 2014 (CESY, 2014) and China Statistical Yearbook 2013 (NBSC, 2013). The lower heating values of traditional fossil fuels including coal, oil and natural gas are adopted from China Energy Statistical Yearbook 2014.

The mineral resources can be divided into three parts in terms of ferrous metal minerals, non-ferrous metal minerals and non-metallic minerals. Corresponding statistical data can be obtained from Chinese Iron and Steel Yearbook 2013 (CISIY, 2013), China Mining Yearbook 2013 (CMY, 2013), China Nonferrous Metals Yearbook 2013 (CNMY, 2013) and China Statistical Yearbook 2013 (NBSC, 2013).

The biomass resources are supplied by agricultural production in terms of cropping, forest, stockbreeding and fishery. The agricultural statistical data are mainly available from China Agriculture Yearbook 2013 (CAY, 2013) (e.g., rice, wheat, oil crops, other agricultural