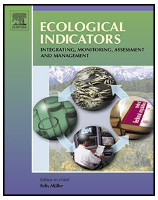
Ecological Indicators 72 (2017) 452–458

Contents lists available at ScienceDirect

Ecological Indicators

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



An environmental sustainability assessment of China's cement industry based on emergy

Xiaohong Zhang[a,*], Jianming Shen[a], Yanqing Wang[a], Yan Qi[a], Wenjie Liao[b], Wei Shui[c], Li Li[b], Hui Qi[a], Xiaoyu Yu[a]

[a] *College of Environmental Sciences, Sichuan Agricultural University-Chengdu Campus, Chengdu, Sichuan 611130, PR China*
[b] *Institute of New Energy and Low-Carbon Technology, Sichuan University, Chengdu 610065, PR China*
[c] *College of Environment and Resources, Fuzhou University, Fuzhou 350116, PR China*

ARTICLE INFO

Article history:
Received 28 December 2015
Received in revised form 23 August 2016
Accepted 25 August 2016
Available online 3 September 2016

Keywords:
China's cement industry
Emergy analysis
Resource efficiency
Environmental load
Comprehensive performance

ABSTRACT

As one of important building materials, the sustainability of cement production is widely concerned in the world. This research evaluated the sustainability of China's cement industry in 2010 using emergy analysis. Several emergy based indicators were adopted to describe the comprehensive performance of this system from different angles, including Percentage of renewability (%R), Unit emergy value (UEV), Emergy yield ratio (EYR), Emergy exchange ratio (EER), Environmental load ratio (ELR) and Emergy sustainable index (ESI). The research results show that (1) Mineral resources have absolute contribution to China's cement production; (2) Coal is the main energy source for China's cement industry; (3) China's cement industry has relatively weak competition ability due to relatively high ratio of purchased inputs; (4) China's other industries have benefited greatly from this industry by exchanges; (5) China's cement industry cannot keep sustainable in the long run due to its high environmental load; (6) the UEV of Chinese cement in 2010 is 3.64E15 sej/t (based on the emergy baseline 15.83E24 sej/yr). Finally, the related policy implications are proposed from four aspects, including (1) Accelerating the adjustment of process structure and technical innovation; (2) Promoting the substitution of raw materials or fuels; (3) Raising the price of cement products; (4) Decreasing the export of cement products.

1. Introduction

As one of basic building materials, cement has played an important role during the course of fast urbanization. China's cement output has ranked first in the world since 1985, accounting for 60% of the world's cement production in 2012 (Global Cement, 2013). China's cement output had increased by 2.03 times from 0.73 billion tons in 2002 to 2.21 billion tons in 2012 (National Bureau of Statistics of China, 2003, 2013), with an annual growth rate of 11.7% in this period. Cement production consumes large quantities of raw materials and energy (heat and electricity). Its manufacturing process is very complex (Huntzinger and Eatmon, 2009; Van Oss and Padovani, 2002, 2003), involving a number of materials, pyroprocessing techniques, and fuel sources (e.g., coal, petroleum, coke, natural gas, fuel oil, biomass, or different types of wastes). The main emissions of cement production are atmospheric pollutants from the kiln system, and they are derived from the physic-chemical reactions involving the raw material calcination (decarbonisation of limestone) and fuel combustion (Nadal et al., 2009). The cement industry has caused quantities of air emissions due to high fossil energy consumption. Pang et al. (2013) reported that the total coal and electricity consumption of Chinese cement industry in 2009 was 186.62 million tons and 1.38 billion kWh, respectively, which resulted in the atmospheric emissions of sulfur dioxide (SO_2), nitrogen oxides (NOx), and particulates at 0.89 million, 1.69 million and 3.58 million tons, respectively (Mao et al., 2012; Ministry of Environmental Protection of PRC, 2010). Carbon dioxides (CO_2) emissions from Chinese cement industry accounted for 15% of national emissions and 5%–8% of global emissions (Jiang et al., 2012; Huntzinger and Eatmon, 2009; Scrivener and Kirkpatrick, 2008). Besides, the cement industry is also a significant emission source of other hazardous compounds (Wang, 2013; Lei et al., 2011), such as carbon monoxide (CO) and heavy metals. For China's cement industry, the key factors that contribute to overall environmental burden are the direct emissions of nitrogen oxides (NOx), particulates, and carbon dioxide (CO_2) into the atmosphere, as well as the use of coal during cement production (Chen et al., 2015).

---

[*] Corresponding author.
E-mail address: zxh19701102@126.com (X. Zhang).

http://dx.doi.org/10.1016/j.ecolind.2016.08.046
1470-160X/

China's cement industry has the absolute contribution to the world cement output (Global Cement, 2013), and thus the related resource and environmental issues have also become increasingly serious (Pang et al., 2013; Wang, 2013; Jiang et al., 2012; Mao et al., 2012; Lei et al., 2011; Ministry of Environmental Protection of PRC, 2010; Huntzinger and Eatmon, 2009; Scrivener and Kirkpatrick, 2008). Therefore, the sustainability of cement production has been concerned widely. Many scholars have investigated this issue using different methods, such as life cycle assessment (LCA) (Chen et al., 2015; Valderrama et al., 2012; Josa et al., 2004), material flow analysis (MFA) (Wang et al., 2016; Gao et al., 2016; Hu et al., 2015; Vargas and Halog, 2015; Woodward and Duffy, 2011), energy analysis (EA) (Wen et al., 2015; García-Gusano et al., 2015; Sui et al., 2014; Atmaca and Yumrutas, 2014; Xu et al., 2012; Hasanbeigi et al., 2010a,b; Mandal, 2010; Utlu et al., 2006; Camdali et al., 2004), economic evaluation (EE) (Wang et al., 2015; Uwasu et al., 2014; Li et al., 2013; Hasanbeigi et al., 2010a,b), LCA and EE (Reza et al., 2013), etc. Therein, LCA has become a key methodology to evaluate the environmental performance of products, services and processes; however, this method still has some flaws, derived from the assumptions made in the definition of the system (Galvez-Martos and Schoenberger, 2014), its environmental impact allocation (Sayagh et al., 2010) and the weights' decision by expert scoring. MFA ignores the differences among diverse kinds of materials due to their various characteristics, and thus its results could deviate from the practical situation to some degree. EA overlooks the differences among energy sources due to diverse formation processes and different ability to do work. EE method ignores natural contribution to economy. Due to these flaws, decision-making, based on these methods, could adversely affect resources conservation and environmental protection to some degree. Emergy analysis (EmA), founded by Odum (1988, 1996), assesses one system based on a common measure, i.e. solar eMergy joules. It considers natural contribution to economic activity, and it also distinguishes the differences among different products and service. Therefore, this method establishes an organic connection between human economic system and the environment. The results from EmA can provide more integrated information for decision-makers. Due to the obvious advantages over other methods, EmA has been widely used to evaluate comprehensive performances of systems with different scales, including production systems (Pan et al., 2016a,b; Zeng et al., 2013; Lu et al., 2012; Li et al., 2011a,b; Lu et al., 2010; Lu and Campbell, 2009; Zhang et al., 2009; Pulselli et al., 2008a; Bastianoni and Marchettini, 1996), cities (Zucaro et al., 2014; Zhang et al., 2011; Pulselli et al., 2008b), nations (Hu et al., 2014; Lou and Ulgiati, 2013; Zhang et al., 2012; Ulgiati et al., 2011), and the world as a whole (Campbell et al., 2014; Odum et al., 2000; Brown and Ulgiati, 1999). As far as cement production is concerned, several scholars have explored its environmental sustainability using EmA (Pulselli et al., 2008a; Buranakam, 1998; Haukoos, 1995; Roudebush, 1992). However, the emergy related researches on Chinese cement industry is lacking in the public literature. As the largest cement producer and consumer in the world, the sustainability of Chinese cement industry should be concerned. In recent years, many Chinese scholars have evaluated diverse ecological economic systems using EmA; however, the unit emergy value of cement adopted in their works often came from other countries or regions, which could reduce the accuracy of their research results to some degree.

This research concentrates on China's cement industry, and it aims to (1) assessing the comprehensive performance of China's cement industry so as to provide some beneficial suggestions for the policy-makers, and (2) providing the unit emergy value (UEV) of China's cement for the emergy related researches in China in the future.

2. Materials and methods

2.1. Research object

Since common Portland cement accounts for approximately 98% of China's total cement output (Xu, 2013), this work chose 1 ton common Portland cement production (The percent of clinker is 70%.) as its function unit to reflect the national average level. All inputs and outputs were based on this functional unit. The analysis boundary of this work started from raw materials and energy sources mining, and ended at the gate of the cement factories.

2.2. Methods

2.2.1. Emergy analysis

Emergy is the available energy of one kind required directly and indirectly to make a product or service (Odum, 1996, 1988), and its unit is emjoule. At present, emergy is expressed as solar emergy, and its unit is solar emjoules (sej) (Jorgensen et al., 2004). The theory of EmA is rooted in thermodynamics and general systems ecology (Brown and Bardi, 2001). So EmA aims to describe the relationships between human-made systems and the biosphere. This method assigns a value to products and services by converting them into equivalents of one common form of energy (solar energy joule), which can act as the common denominator. In doing so, different types of resources (energy, matter or currency), can be measured and compared to each other (Liu et al., 2015).

Within the framework of EmA, the quality of energy sources and any other resource is measured by the inputs of energy, materials and information required to make it (Brown et al., 2011). More specially, the emergy of different products is assessed by multiplying mass quantities (kg) or energy quantities (J) or currency ($) by a unit emergy value (transformity or specific emergy or emergy to money ratio). A unit emergy is the solar emergy required directly or indirectly to make 1 J or kilogram of a product or service or 1 US$. When a process is evaluated, previously calculated unit emergy values can be used to determine the emergy (sej) of commonly used products or services (Pulselli et al., 2007).

Following the recommendations of Odum (2000), all transformities calculated prior to 2000 have been multiplied by a factor 1.68 to account for the increase in global emergy base of reference from 9.44E24 sej/yr to 15.83E24 sej/yr. And then the total emergy driving the system can be determined by adding up the emergy of all inflows, and is assigned to the product or service delivered (Campbell et al., 2005; Brown and Ulgiati, 2001). After all the flows in study have been quantified, a set of indicators can be established to assess the environmental performance of the system itself (Ulgiati and Brown, 2002).

2.2.2. Emergy flow of Chinese cement production

As shown in Fig. 1, the main inputs include renewable resources (fresh water), nonrenewable inputs (limestone, clay, sandstone and gypsum), and purchased inputs (coal, petroleum, natural gas and labor & service). The outputs are cement products.

2.2.3. The corresponding emergy based indicators

The emergy based indicators adopted in this study were depicted as follows.

(1) Percentage of renewability (%R): It is the ratio of renewable inputs to total inputs in terms of emergy, and describes the renewability of a system. Generally the higher the ratio, the more sustainable the system in study is.

(2) Unit emergy value (UEV, sej/t): UEV is defined as the equivalent solar emergy required by per unit of product. And this indica-