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Life cycle based emergy analysis on China's cement production

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ABSTRACT

To evaluate the sustainability of cement production in China, a life cycle inventory (LCI) based emergy analysis (EMA) method was employed in this study. According to Taylor series expansions, uncertainty analysis was also performed in order to improve the accuracy of the results. Direct renewable resources, nonrenewable resources, imported materials and energy, transport of materials, as well as ecological service for emissions dilution and CO_2 uptake were included in this study. The unit emergy value (UEV) of cement was 1.93×10^{15} sej/t with service and 1.92×10^{15} sej/t without service, respectively. Uncertainty analysis shows that the GSD^2 of the total emergy needed for cement production was 1.83. Results also indicate that key factors making dominant contributions to the total emergy needed for cement production were the consumptions of limestone, coal, and electricity. Emergy-based indicators indicate that cement industry in China brought higher environmental burden and is not sustainable. Furthermore, the results suggest that adjusting industrial structure, improving energy efficiency, and applying alternatives to replace raw materials are effective approaches to improve the sustainability of cement industry.

1. Introduction

Cement is the most widely used building material. The global cement product had increased dramatically from 2.1 billion tons in 2004 (Pulselli et al., 2008) to 4.3 billion tons in 2014 (ECA, 2015), with an annual growth of 7%. Specially, China has been the largest cement producer since 1985 (Chen et al., 2015), which accounted for 56.5% of the global cement production in 2014 (ECA, 2015). Cement industry is energy intensive (Xu et al., 2012), and has resulted in serious environmental impacts due to its large pollutants emissions (Chen et al., 2015). Although sustainability of cement production have been widely investigated from the "user side" (Hong and Li, 2011; Hashimoto et al., 2010; Huntzinger and Eatmon, 2009), only a few studies were performed from a "donor-side". However, cement industry has suffered from serious environmental problems and energy crisis during recent years, consequently, it is necessary to consider the efforts of ecosystem to cement production. Under such a circumstance, this paper aims to evaluate China's cement production from a "donor-side" by employing the emergy analysis (EMA) method.

Emergy represents the overall energy consumed in the environmental work processes to produce a product or service in units of one form of energy (Brown and Buranakarn, 2003). As a promising tool for measuring environmental management performance and making appropriate public policies (Rugani and Benetto, 2012), emergy has been widely applied in measuring agriculture systems (Zhang et al., 2012; Nakajima and Ortega, 2015), urban systems (Lei et al., 2016; Sun et al., 2016), industrial systems (Geng et al., 2014; Liu et al., 2016), and waste treatment (Winfrey and Tilley, 2016). Furthermore, studies on measuring cement production by EMA have been conducted (Haukoos, 1995; Buranakarn, 1998; Brown and Buranakarn, 2003; Pulselli et al., 2008; Cao et al., 2013). However, no studies on China's cement production by using EMA have been published in the international peer-reviewed journals. In addition, only Pulselli et al. (2008) conducted sensitivity analysis, but none of them conducted uncertainty analysis. Two published studies (Rugani and Benetto, 2012; Raugei et al., 2014) showed that the combination of life cycle inventory (LCI) and EMA could

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improve the accuracy of results. Under such a circumstance, this study aims to uncover the holistic picture of China's cement production by combining EMA with LCI. Especially, both sensitivity analysis and uncertainty analysis are performed in order to improve the reliability of research results. In addition, the updated emergy baseline (12.0×10^{24} sej/y) (Brown et al., 2016) is adopted in this study so that the research results can be more accurate for policy making. The whole paper is organized as below. After this introduction section, Section 2 details data sources and the research methods. Section 3 presents research results and Section 4 discusses policy implications. Finally, Section 5 draws research conclusions.

2. Data and methods

2.1. Data sources

Over 90% of China's cement clinker was produced by applying dry rotary kiln technology in 2013 (China Cement Association, 2014). Therefore, only cement produced by applying dry rotary kiln technology was analyzed in this study. The data used in this study were obtained from one of China's top 50 cement production enterprises, which can represent the current cement production level in China. In this enterprise, the flying ash generated from cement production process is recycled as one alternative material for cement production. Wastewater is also recycled for watering local gardens after primary treatment. Annual monitoring data (i.e., raw materials and energy consumption, and air emission) were obtained from the annual operation data of this enterprise. Detailed LCI procedures follow the previous study conducted by the authors (Chen et al., 2015).

One key feature of this study is that the updated global emergy baseline (12.0×10^{24} sej/yr) based on the latest research results of Brown et al. (2016) was employed in this study. UEVs based on other baselines were multiplied by 1.27 (from baseline of 9.44×10^{24} to 12.0×10^{24} sej/yr), or 0.76 (from baseline of 15.83×10^{24} to 12.0×10^{24} sej/yr), or 0.79 (from baseline of 15.20×10^{24} to 12.0×10^{24} sej/yr) so that they can be transformed to the same baseline. Detailed data of UEVs used in this study can be found in Table 1.

2.2. Emergy flows of cement production

The system boundary of cement production in this study was set up by using a cradle-to-gate approach, namely, cement consumption and final disposal are excluded. Fig. 1 presents a diagram of emergy flows for cement production. Direct renewable resources, indirect renewable resources needed for emission dilution and CO_2 uptake, nonrenewable resources (i.e., limestone), imported raw materials (i.e., gypsum, sandstone, pyrite cinder, and fresh water), labor & services, and transport of raw materials were included. The direct renewable resources provided by the nature enter from the left, whereas the cement product exits from the right. All the inputs were sorted out clockwise according to their UEVs.

2.3. EMA for cement production

Functional unit provides a quantified reference for related inputs and outputs of a product, process, or an activity (ISO 14040, 2006). The LCI is an investigation method in which all related raw materials and energy consumption, direct emissions, as well as waste disposal, are calculated based on the studied system (ISO 14040, 2006). In this study, 1 ton of cement product was selected as the functional unit. All materials, emissions, and energy consumption were based on this functional unit.

The total solar emergy (U) for cement production can be calculated according to Eq. (1):

$$U = \sum f_i \times UEV_i + F_1 \quad (1)$$

where f_i, UEV_i, and F_1 represent the input flow i, the unit emergy amount of input i, emergy cost for emission (i.e., SO_2, NO_x, and particulate) dilution and CO_2 uptake (Lou et al., 2015), respectively.

The environmental service needed for emission dilution and CO_2 uptake can be calculated according to the method depicted in two published studies (Ulgiati and Brown, 2002; Lou et al., 2015). The emergy cost for emission (i.e., SO_2, NO_x, and particulate) dilution can be determined by using Eq. (2):

$$F_{1,i} = 1/2 \times M_{air,i} \times v^2 \times tr_{wind} \quad (2)$$

where i, $M_{air,i}$, v, tr_{wind} represent individual pollutant i (i.e., SO_2, NO_x, and particulate), mass of air used for individual pollutant dilution, average wind speed, and the UEV of wind, respectively. The mass of air used for individual pollutant dilution can be calculated by using Eq. (3):

$$M_{air,i} = d \times (w_i/c_i) \quad (3)$$

where d, w_i, and c_i represent air density, the amount of individual pollutant i, and the acceptable concentration of individual pollutant i (MEP, 2013), respectively.

The ecological service (expressed by area) for emission dilution and CO_2 uptake can be calculated by using Eqs. (4) and (5), respectively:

$$A_i = F_{1,i}/ED \quad (4)$$

$$A_{CO^2} = W_{CO^2}/S_{CO^2} \quad (5)$$

where ED, W_{CO2}, and S_{CO2} represent the amount of renewable emergy that is available per unit of area and time (sej·m^{-2} yr^{-1}), the amount of CO_2 emission, and the amount of CO_2 sequestered per unit area (150 g m^{-2} yr^{-1}) (Lou et al., 2015), respectively.

The area (A_{CO2}) which is used to generate biomass can be translated into additional renewable emergy input (F_{CO2}). According to the emergy algebra, the largest one between $F_{1,i}$ and F_{CO2} is considered the ecological service needed for emission dilution and CO_2 uptake (F_1).

2.4. Emergy-based indicators

Fig. 2 provides a diagram of aggregated emergy flows in order to better describe the performance of cement production system. Particularly, the imported inputs (F, shown in Fig. 2) have two possibilities. F (without labor and service (L & S)) represents the emergy of net physical material inputs (I). F (with L& S) includes the emergy of imported materials, indirect labor with imported inputs, and direct labor to a system. The below indicators are used to evaluate the performance of cement production.

(1) Environmental loading ratio (ELR)

ELR (evaluating the stress of a production system to the local ecosystem) can be calculated according to Eq. (6). ELR is the ratio of the sum of local nonrenewable resources, indirect renewable resources needed for emission dilution and CO_2 uptake, and imported inputs to the direct renewable resources.