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Investigating impact of waste reuse on the sustainability of municipal solid waste (MSW) incineration industry using emergy approach: A case study from Sichuan province, China

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ABSTRACT

China has become the largest generator of municipal solid waste (MSW) in the world with its rapid urbanization, population growth and raising living standard. Among diverse solid waste disposal technologies, MSW incineration has been becoming an attractive choice. In terms of systematic point, an integrated MSW incineration system should include an incineration subsystem and a bottom ash (BA) disposal subsystem. This paper employed an extend emergy assessment method with several improved indicators, which considers the emissions' impact, to evaluate the comprehensive performances of an integrated MSW incineration system. One existing incineration plant in Yibin City, Sichuan Province, China, as a case study, is evaluated using the proposed method. Three alternative scenarios (scenario A: the incineration subsystem + the BA landfill subsystem; scenario B: the incineration subsystem + the concrete paving brick production subsystem using BA as raw material; scenario C: the incineration subsystem + the non-burnt wall brick production subsystem using BA as raw material) were compared. The study results reveal that the ratio of positive output is 1.225, 2.861 and 1.230, the improved environmental loading ratio is 2.715, 2.742 and 1.533, and the improved environmental sustainability index is 0.451, 1.043 and 0.803 for scenario A, B and C respectively. Therefore, reuse of BA can enhance the sustainability level of this integrated system greatly. Comparatively, scenario B has the best comprehensive performance among the three scenarios. Finally, some targeted recommendations are put forward for decision-making.

1. Introduction

MSW (municipal solid waste), which mainly comes from residential life, commercial activities and institutional activities, is comprised of food waste, paper, plastics, glass, textiles, scrap metals, wood, etc., and it can't be naturally degraded over relatively short times (Cherubini et al., 2008). Due to rapid urbanization process, high growth rate of population and the improvement of living standard, the generation quantity of Chinese MSW reached about 178 million tons in 2014 (National Bureau of Statistics of the People's Republic of China, 2015), and it will attain approximately 282 million tons by 2020, with an annual increase rate of 8–10% (Zhao et al., 2016b). MSW has exceeded the biosphere' assimilative capacity and induced numerous detrimental impacts, such as stink generation, spontaneous combustion, land occupation, soil and water contamination, diseases proliferation, etc. Meanwhile, many natural resources (such as mineral resources, fossil energy resources, etc.) have become depleting due to overexploitation and great waste from human activities, which challenges the limit resource supply capacity of biosphere (Agostinbo et al., 2013). Thus, the proper disposal of MSW has become one of the major challenges China's government faces.

Presently, the predominant practices of MSW disposal in China include landfills (65.5%) and incineration (32.5%) (Hong et al., 2017). Therein, landfilling is the main MSW disposal way, but the disposal option is no longer considered as a sustainable way, due to occupying land, having a high risk of leachate leakage, green-

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house effect from the methane gas emission, etc. By contrast, MSW incineration can convert most waste into heat and electricity, dramatically reduce MSW mass (about 80%) and volume (90% or so), and substantially mitigate land resource constrains in densely populated regions. Experiences from some developed countries show that MSW incineration is an effective way for centralized MSW disposal (Lombardi et al., 2015; Marchi et al., 2017; Rajaeifar et al., 2017), and it is also a critical need for improving the living environment, achieving scientific urban development and establishing a resource-saving and environmentally-friendly society (Liu et al., 2017a,b; Srivastava et al., 2015; Zhang et al., 2010a,b). In recent years, the waste incineration industry has a good market prospect in China (Fu et al., 2015), the number of waste incineration plants has significantly increased from 47 in 2003 to 220 in 2015 and the quantity of incinerated MSW has also risen from 3.7 million tons in 2003 to 61.7 million tons in 2015 (National Bureau of Statistics of the People's Republic of China, 2015). However, MSW incineration systems could also lead to some secondary environmental problems, such as ash residue, air pollution emissions, etc., which must be properly addressed through extra natural and artificial inputs to run the related treatment or disposal systems. Consequently, some third pollution emissions could be produced directly and indirectly from those treatment or disposal systems. As a result, the comprehensive performance of MSW incineration systems has been widely concerned in recent years. To this end, several methodologies or their combinations have been applied to evaluate performances of incineration systems, including energy analysis (Edwards et al., 2016; Tan et al., 2015), life cycle assessment (LCA) (Ayodele et al., 2017; Beylot and Villeneuve, 2013; Birgisdo′ttir et al., 2007; Havukainen et al., 2017; Jeswani and Azapagic, 2016; Liu et al., 2017a,b; Parkes et al., 2015; Zhao et al., 2012), material flow analysis (MFA) (Sadhukhan and Martinez-Hernandez, 2017), economic analysis (Gradus et al., 2017; Massarutto, 2015; Mikic and Naunovic, 2013; Tan et al., 2014; Zhao et al., 2016a,b); environmental and economic evaluation based on a multi-step approach (Panepinto and Zanetti, 2018), combination of economic analysis and energy analysis (Udomsri et al., 2010), among others. Therein, energy analysis ignores the quality differences of energy from diverse energy sources, and it also ignores environmental contributions to economic development. LCA focuses on resource depletion and emissions' impact; however, it also doesn't consider environmental contribution to economic activities, and the weights based on expert scoring could incur certain subjectivity (Feng and Mai, 2016; Goldstein et al., 2016). MFA is a basic method which can identify the main material flows and estimate the environmental loading of a given system. Nevertheless, it can't capture the quality differences among diverse materials flows due to their different characteristics, so the study results could deviate from the reality to some degree (Ohnishi et al., 2017). Economic analysis just considers economic streams measured by market-based value, but it doesn't consider environmental contributions and the related emissions' impacts. Generally these methods can help us to understand the performance of incineration systems from a special perspective in the scope of technoshpere, but they ignore environmental contribution to economic activities (Zhang et al., 2014b), and their conclusions could be incomplete for decision-making. Thus, the performances of waste incineration processes should be evaluated from a systemic perspective so as to consider all the contributions derived from both economic and environmental systems, and the related adverse impacts on human and environment.

To overcome these abovementioned shortcomings, many researchers have applied emergy analysis (EmA) to evaluation the performance of waste incineration industry (Hao et al., 2006; Lei and Wang, 2008; Lou, 2004; Marchettini et al., 2007; Zhang et al., 2011). EmA, formally found by Odum in 1980s (Odum, 1988, 1996), is a systemic method based on systematic ecology and energy ecology. This method can unify different kinds of energy, material, goods and services into the common unit, i.e. solar energy joule; meanwhile, it can also integrate the contribution of environment and socio-economy into the performance of a given system. At present, EmA has been widely applied to evaluation of different kinds of systems' performance. Therein, Lou (2004) assessed a MSW disposal case by using EmA, and their research indicated MSW incineration had the advantages of reduced resource intensity; however, this work has not considered the contribution of the chemical materials and pollution emissions' impacts on this system' performance. Marchettini et al. (2007) applied EmA to evaluation of three different MSW disposal technologies (including landfills, incineration and composting), but they ignored emissions' impacts. Liu et al. (2013) carried out an emergy evaluation for a MSW disposal practice in Liaoning province, China, through considering the emissions' impacts on ecosystem, economy and human health integrity; however, this study didn't integrate emissions' impacts into specific performance indicators for comparison of given systems' sustainability level; meanwhile, this work still ignored renewable resources' contribution from the environment (such as waste, air, etc.). Luo and Ding (2009) adopted classic emergy indicators to assess the MSW incineration system, and they considered renewable resources from the environment (waste, air, water, etc.); however, they ignored the impacts of pollution emissions. Winfrey and Tilley (2016) developed an emergy-based treatment sustainability index to evaluate waste treatment systems, the waste itself is used as one of inputs, but this index only considered the emissions' impact on the environment. Liu et al. (2017a,b) constructed an integrated emergy-LCA analysis to compare four different garbage treatment systems, but this study didn't consider the emissions' impacts in their emergy evaluation.

Up to now, there are few studies to evaluate the comprehensive performances of a holistic MSW incineration system, including an incineration subsystem and the related bottom ash (BA) disposal subsystem; meanwhile, the emissions' impacts are often ignored or underestimated in the related works. Due to the pros and cons of MSW incineration practices, it is necessary to construct an integrated MSW incineration system, composed of an incineration subsystem and a solid residue disposal subsystem, so as to investigating its comprehensive performance more completely. The main objective of this work was to assess the comprehensive performance of this holistic system using an extended emergy assessment method through considering emissions' impact. In doing so, the following issues could be addressed more completely under the background of the combined environmental- social- economic system than other methods abovementioned under the background of the social- economic system, including environmental contribution to an integrated MSW treatment system, effect of pollution emissions and waste reuse on the resources efficiency, the environmental loading and the comprehensive performance of this system. As a case study, the proposed methods and indicators were applied to investigation of the three scenarios for a MSW incineration plant in Sichuan Province, China, so as to provide some targeted suggestions for the decision-makers.

2. The case study

The incineration plant we analyzed is located in Yibin City (E103°36′–105°20′, N27°50′–29°16′), in the south of Sichuan Province, China. It has a population of about 4.47 million in 2014 (The Urban Statistical Yearbook of Yibin, 2015). It belongs to a humid subtropical monsoon climate zone, and it has an average