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Environmental sustainability assessment in the process industry: A case study of waste-to-energy plants in Spain

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ABSTRACT

This study proposes a technical procedure based on a life cycle approach for implementation of the environmental sustainability assessment (ESA) of several waste-to-energy (WtE) plants located in Spain. This methodology uses two main variables: the natural resources sustainability (NRS) and the environmental burdens sustainability (EBS). NRS includes the consumption of energy, materials, and water, whereas EBS considers five burdens to air, five burdens to water, and two burdens to land. To reduce the complexity of ESA, all variables were normalised and weighted using the threshold values proposed in the European Pollutant Release and Transfer Register regulation. The results showed the plants studied had a greater consumption of natural resources than Spain, ranging from 1.1 to 2.0 times higher than the Spanish reference consumption. The comparison of Spain with the BREF reference on waste incineration showed that only in the variable related to materials, did Spain have a lower consumption (1.80 times lower). In terms of EBS, air and land impacts were the highest contributors to global burden. The WtE plants presented higher burdens to air and water than Spain, whereas only one plant exceeded the average burden to land of Spain. Finally, this paper demonstrated the usefulness of the ESA methodology to reduce the complexity of LCA and assist the decision-making process in choosing the best option from an environmental point of view. This procedure can be used to obtain an overview of the environmental performance of WtE plants, as well as to assess individual burdens and thereby determine the main environmental hotspots, thereby improving the critical points of the process.

1. Introduction

The high rate of waste generation in the society today has brought waste management to be a priority in European policies. The European Regulation proposes waste prevention, recycling and reuse, and finally waste incineration and landfilling as fundamental principles to waste management (EC, 2008). Despite landfilling remaining the most common practice, waste incineration and recycling have increased in recent years. The primary objective of municipal solid waste incineration (MSWI) is to treat waste by reducing the solid waste mass and allowing energy recovery. For this reason, the original designation of "incinerator" was dropped, and today it is discussed as "energy from waste" or "waste to energy" (WtE) (Margallo et al., 2014a). The basic linear structure of a WtE plant may include incoming storage and pre-treatment of waste, thermal treatment with energy recovery and conversion, flue gases and wastewater treatment, and the management and treatment of ash and slag (EC-IPPC, 2006). Different types of thermal treatments are applied to different types of wastes; however, not all thermal treatments are suited to all wastes. The most common technologies are Grate Incinerators (GI), Rotary Kilns (RK), Fluidised Beds (FB), and pyrolysis and gasification systems. For municipal solid waste (MSW) and refuse derived fuels (RDF), GIs are widely applied; FBs and RKs are also applied, but to a lesser extent (Margallo et al., 2012). Despite the benefits of waste incineration, their high combustion temperatures require very specific materials be used in their construction, increasing installation and maintenance costs. Also, additional combustible material is required when the available waste does not reach the required heating value or when it has high water content (Rodríguez and Irabien, 2013). Moreover, this technology has unfortunately gained a bad reputation because of its environmental impact, specifically due to its emissions of acid gases, dioxins and furans (PCDD/F), and greenhouse gases (Margallo et al., 2012). In this regard, the environmental sustainability assessment (ESA) is a powerful tool to identify the environmental strengths and drawbacks of waste management

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in WtE plants. Several methodologies, such as life cycle assessment (LCA), social cost-benefit analysis (CBA), and pricing carbon emissions, are useful to analyse the environmental performance of waste management. All these techniques have advantages and disadvantages, so it is not possible to determine which methodology is more valid to evaluate the ESA. CBA has been applied in several works i.e., to examine the effectiveness of MSW management systems in Taiwan (Weng and Fujiwara, 2011), and to evaluate final waste disposal methods in The Netherlands (Dijkgraaf and Vollebergh, 2004). Other authors included the social path in their studies, such as Jamasb and Nepal (2010) that assessed the economic and environmental aspects of waste-to-energy in the UK, and Manni and Runhaar (2014) that evaluated the pay-as-you-throw scheme of MSW reduction in Switzerland. Nevertheless, LCA is one of the most accepted approaches because is a standardised method. In this context, an increasing number of publications related to the LCA of waste management have appeared in recent years (Laurent et al., 2014). Most LCA studies have been conducted in Europe; in particular, several works evaluated MSW management systems in Italy (Arena and Di Gregorio, 2014; De Feo and Malvano, 2009; Buttol et al., 2007), Denmark (Kirkeby et al., 2006), Portugal (Ferrão et al., 2014), and Spain (Aranda-Usón et al., 2013; Bovea et al., 2010; Bovea and Powell, 2006; Muñoz et al., 2004; Rodríguez-Iglesias et al., 2003). Nowadays, an important role is also played by the BRIC countries (Brazil, Russia, India, and China); these are nations that will generate a large amount of MSW in the future. In this context, an important number of works related to the waste management systems in China (Zhao et al., 2011), India (Mondal et al., 2010), Russia (Tulokhonova and Ulanova, 2013), and Brazil (Leme et al., 2014) have been also reported.

In addition, LCA studies evaluating incineration processes have become common. The aim of the published LCA works on waste incineration was to assess the advantages, drawbacks, and environmental impacts of the technology. In Italy, the environmental performance of several WtE plants was assessed by Morselli et al. (2007, 2008), and a prediction of the environmental impacts of a new incineration plant was reported by Scipioni et al. (2009). In France, 110 incinerators have been compared with regard to their environmental impact (Beylot and Villeneuve, 2013), and in China, the environmental impact of waste incineration with auxiliary coal has been evaluated (Zhao et al., 2012). Other studies compared thermal treatment technologies such as GI and FB (Chen and Christensen, 2010), flue gas cleaning systems (Moller et al., 2011; Chevalier et al., 2003), energy recovery strategies (Giugliano et al., 2008; Consonni et al., 2005a,b), management options for pollution control of residues from waste incineration (Fruergaard et al., 2010), and several Bottom Ash (BA) treatments (Margallo et al., 2014a; Huntzinger and Eatmon, 2009; Birgisdottir et al., 2006). Incineration was also compared with other technologies; in particular, the environmental impacts of incineration were compared with those of waste recycling (Merrild et al., 2008) and landfilling in studies conducted in Brazil (Mendes et al., 2004), Thailand (Liamsanguan and Gheewala, 2008), Italy (Cherubini et al., 2009, 2008), and China (Dong et al., 2014). Other authors extended these comparisons further to include gasification and pyrolysis processes (Zaman, 2010) and the mechanical biological treatment (MBT) (Koci and Trecakova, 2011) in the comparison.

Most existing LCA studies use conventional impact assessment methods such as CML 2001 (Guinèe et al., 2001), EDIP 97 (Wenzel et al., 1997), or Eco-indicator 99 (Goedkoop et al., 2000). These methods use a set of metrics, which in some cases could be difficult to understand and thus confuse the process comparisons. A reduction in the complexity of LCA would improve the comprehension of the results and thus assist the decision-making process. In this regard, the goal of the present work is to propose a technical method for conducting an ESA of an organic waste incineration process using two main variables: the natural resources sustainability (NRS) and the environmental burdens sustainability (EBS). NRS includes the consumption of energy, materials, and water; whereas EBS is based on the environmental sustainability metrics proposed by the Institution of Chemical Engineers, IChemE (IChemE, 2002). Currently, NRS and EBS are rarely normalised; thus, they are treated as functions rather than as variables. Considering the previously developed methodology (Irabien et al., 2009) for the normalisation of the environmental burdens (EB), which is based on the threshold values proposed in the regulation of the European Pollutant Release and Transfer Register, the so called E-PRTR regulation (EC, 2006), a similar procedure based on the average consumption of natural resources (NR) of Spanish MSWI plants was used for the normalisation of NRS. In this way, NRS and EBS can be normalised, and the comparison between NR and EB can be accomplished. This methodology will help the decision maker choose the best option within ESA, reducing its complexity because the two main functions can be converted into comparable variables that can be used later in a multi-objective optimisation. As a case study, several WtE plants located in Spain were selected to assess and compare the environmental performance of these plants. The analysis was conducted for the Cradle-to-Gate, Gate-to-Gate and Gate-to-Grave stages of processing. In particular, the purpose of this paper is firstly to apply a life cycle model of waste incineration (Margallo et al., 2014b) to several WtE plants in Spain. Specifically, the incineration of organic waste fraction was studied to evaluate the environmental impacts of the plants, determining the critical points of the process. The paper also shows a comparison of the environmental performance of the plants by means of the ESA methodology. IChemE metrics were applied successfully to compare the conventional and alternative passivation processes (Garcia et al., 2013), several arsenic removal treatments (Dominguez-Ramos et al., 2014), and BA treatments against ash recycling (Margallo et al., 2014a). This paper also uses EB to evaluate land pollution, uses the normalisation of the NR based on the average consumption of resources of the Spanish WtE plants, and employs a weighting procedure to reduce the LCA results to only two variables: NRS and EBS.

2. Methodology

LCA evaluates processes or products from cradle-to-grave (ISO, 2006a). This approach includes three types of analysis (Dominguez-Ramos et al., 2014), described as follows:

Cradle to Gate (Cr–Ga): This analysis describes the environmental burdens generated by the transformation of natural/primary resources into usable forms of resources, and encompasses all individual transformation processes including raw materials extraction, manufacturing, and transportation.

Gate to Gate (Ga–Ga): This analysis evaluates the environmental burdens generated by transformation of final resources into a product, process, or service.

Gate to Grave (Ga–Gr): This analysis considers the burdens from the final emissions to the environment and the burdens from the consumption of the final resources for the selected environmental management practice.

LCA should be applied using the ISO 14040 series (ISO, 2006a), which describes the LCA as a four-stage process involving: (a) the definition of the goal and scope of the analysis; (b) life cycle inventory (LCI) analysis; (c) life cycle impact assessment (LCIA); and (d) interpretation. LCIA is composed of two mandatory (i.e., classification and characterisation) and two optional steps (i.e., normalisation and weighting). This paper developed an ESA methodology that includes the four steps proposed in the LCIA. The advantage of this procedure regarding the conventional