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Integrated gasification and plasma cleaning for waste treatment: A life cycle perspective

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ABSTRACT

In the past, almost all residual municipal waste in the UK was landfilled without treatment. Recent European waste management directives have promoted the uptake of more sustainable treatment technologies, especially for biodegradable waste. Local authorities have started considering other options for dealing with residual waste. In this study, a life cycle assessment of a future 20 MWe plant using an advanced two-stage gasification and plasma technology is undertaken. This plant can thermally treat waste feedstocks with different composition and heating value to produce electricity, steam and a vitrified product. The objective of the study is to analyse the environmental impacts of the process when fed with seven different feedstocks (including municipal solid waste, solid refuse fuel, reuse-derived fuel, wood biomass and commercial & industrial waste) and identify the process steps which contribute more to the environmental burden. A scenario analysis on key processes, such as oxygen production technology, metal recovery and the appropriate choice for the secondary market aggregate material, is performed. The influence of accounting for the biogenic carbon content in the waste from the calculations of the global warming potential is also shown. Results show that the treatment of the refuse-derived fuel has the lowest impact in terms of both global warming potential and acidification potential because of its high heating value. For all the other impact categories analysed, the two-stage gasification and plasma process shows a negative impact for all the waste streams considered, mainly due to the avoided burdens associated with the production of electricity from the plant. The plasma convertor, key characteristic of the thermal process investigated, although utilising electricity shows a relatively small contribution to the overall environmental impact of the plant. The results do not significantly vary in the scenario analysis. Accounting for biogenic carbon enhanced the performance of biomass and refuse-derived fuel in terms of global warming potential. The main analysis of this study has been performed from a waste management perspective, using 1 ton of waste as functional unit. A comparison of the results when 1 kWhe of electricity produced is used as functional unit shows similar trends for the environmental impact categories considered.

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1. Introduction

In 2008, 53% of the household waste produced in the UK was sent to a landfill, while only 1% was treated by incineration. By 2012, the proportion of household waste treated by incineration plants had risen to 17%, while 37% was still sent to landfill (EUROSTAT, 2014). The drivers of this change have been the need to produce a cleaner and affordable energy and to divert the waste from landfill as required by the European Landfill and Waste Framework Directives (European Commission, 2008, 1999). Until recently, the main alternative to landfill which has been considered for the treatment of municipal solid waste (MSW) is incineration (Arafat et al., 2013; Song et al., 2013; Ning et al., 2013). However, local authorities have started looking at other thermochemical treatment options to deal with municipal solid waste, including pyrolysis, gasification and plasma arc technologies, pushed by public environmental concerns and fierce opposition to new incineration plants. Waste gasification or pyrolysis is not a new concept. Although pyrolysis and gasification have been used extensively in the past to produce charcoal, coke or other fuels, it is only recently that these technologies have received increasing attention due to their higher recycling rates, lower emissions, higher energy efficiencies, lower costs, smaller footprints and

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reduced visual impact (Materazzi et al., 2013). In particular, fluidized beds are considered as one of the most effective technologies for gasification or pyrolysis due to their high process flexibility (Arena and Di Gregorio, 2014). Even so, the majority of the existing energy-from-waste plants are grate-fired boilers (i.e. incinerators) (Leckner, 2015).

In the UK, public investments are supporting the design, installation and operation of advanced waste-to-energy technologies to achieve high recovery efficiency and flexibility and to demonstrate the improved efficiencies offered by gasification over other technologies (DEFRA, 2013). A number of multi-stage advanced thermochemical treatments have been developed including fast pyrolysis with combustion, and gasification, usually in a fluidised bed, with the resulting syngas cleaned by secondary high temperature oxidation or a two stage gasification–plasma process (Evangelisti et al., 2015). An example of the latter has been developed by Advanced Plasma Power (APP). This process combines two commercially proven modules: a fluidised bed gasifier and a plasma converter to clean and condition the gas to produce a high quality syngas which can be used in a range of applications from direct power generation to the production of substitute natural gas, hydrogen and/or liquid biofuels. One of the potentialities of a two-stage gasification–plasma process over a more traditional thermochemical treatment of the waste, such as a single stage gasification plant, is the significant reduction of the tars in the syngas. Tars are in fact undesirable because of various problems associated with condensation, formation of tar aerosols and polymerisation to form more complex structures, which may damage process equipment as well as end-use devices (e.g. gas engines and fuel cells). In a two-stage gasification and plasma process the tars are almost completely converted into H_2 and CO, resulting in high syngas yield, little by-products and nearly 100% carbon conversion efficiency (Materazzi et al., 2014). A pilot refuse-derived fuel (RDF) plant for trials and experimental purposes has been developed recently and several design studies are ongoing for a 20 MWe plant.

Life cycle assessment (LCA) is a tool that can be used to compare such technologies and to evaluate their environmental performances allowing decision makers to be correctly informed (Moberg et al., 2005). LCA has previously been used to assess waste to energy treatments of MSW, accounting from the collection processes to electricity generation (Astrup et al., 2014; Consonni et al., 2005; Evangelisti et al., 2014). However, relatively few studies have been published on the life cycle assessment of advanced thermal treatments for MSW (Al-Salem et al., 2014; Khoo, 2009; Pressley et al., 2014; Zaman, 2013). Moreover, the majority of these studies are comparative LCA where the advanced thermal treatment is evaluated against more traditional technologies, rather than pure attributional LCA studies which give full understanding of a specific technology (Al-Salem et al., 2014; Khoo, 2009; Zaman, 2013). As noted by Astrup et al. (2014), very few of the existing LCA studies on waste-to-energy technologies provide sufficient description of the technologies investigated and the key assumptions of the LCA; as a consequence, the applicability of inventory data and LCA results provided by the majority of the existing studies are limited (Astrup et al., 2014).

The goal of this paper is to evaluate the life cycle environmental impact of a two-stage thermochemical process, i.e. a gasification–plasma process (G–Pl), for the treatment of solid waste, assessing different waste composition and heating values. Several environmental impact categories are analysed and a hot spot analysis is performed to identify the more polluting sections of the process. A scenario analysis on some key processes is presented. Overall the study is intended to be performed ensuring transparency in the methodological choices and robustness of the results and recommendations provided.

2. LCA methodology

Life cycle assessment is one of the most developed and widely used environmental assessment tools for comparing alternative technologies when the location of the activity is already defined (Clift et al., 2000; Clift, 2013). LCA quantifies the amount of materials and energy used and the emissions and waste over the complete supply chain (i.e. life cycles) of goods and services (Baumann and Tillman, 2004). Moreover, it helps determining the “hot spots” in the system, i.e. those activities that have the most significant environmental impact and should be improved in the first instance, thus enabling identification of more environmentally sustainable options (Clift, 2006).

In LCA, a multifunctional process is defined as an activity that fulfils more than one function, such as a waste management process dealing with waste and generating energy (Ekvall and Finnveden, 2001). It is then necessary to find a rational basis for allocating the environmental burdens between the functions. The problem of allocation in LCA has been the topic of much debate (e.g. Clift et al., 2000; Heijungs and Guinée, 2007). The ISO standards recommend that the allocation should be avoided “expanding the product system to include the additional functions related to the co-products” (ISO, 2006a,b). This can be performed by broadening the system boundaries to include the avoided burdens of conventional productions (i.e. substitution by system expansion) (ILCD, 2010; Eriksson et al., 2007). The same approach is recommended by the UK product labelling standard provided that it can be proved that the recovered material or energy is actually put to the use claimed (BSI, 2011). This approach is applied in this study. Following the methodological approach of Clift et al. (2000) for Integrated Waste Management (IWM), a pragmatic distinction is made between Foreground and Background, considering the former as ‘the set of processes whose selection or mode of operation is affected directly by decisions based on the study’ and the latter as ‘all other processes which interact with the Foreground, usually by supplying or receiving material or energy’. The burdens evaluated here are considered under three categories (Clift et al., 2000): direct burdens, associated with the use phase of the process/service; indirect burdens, due to upstream and downstream processes (e.g. energy provision for electricity or diesel for transportation); and avoided burdens associated with products or services supplied by the process (e.g. energy or secondary material produced by the system). Following conventional practices (BSI, 2011) secondary data for the indirect and avoided burdens are taken as the averages for the background system, while primary data are used for the Foreground operations.

Carbon dioxide from biogenic carbon is sometimes excluded from the comparison (Christensen et al., 2009) because it forms part of the renewable carbon cycle, theoretically removed from the atmosphere in succeeding products. However, in this study carbon dioxide emissions from biogenic carbon are included in the estimates for the Global Warming Potential (GWP) because the assessment is based on existing waste streams with defined carbon content so that the production of the materials in the waste does not enter the analysis. Therefore the total carbon content of the waste is considered, with no distinction between biogenic and non-biogenic carbon in the baseline. A further analysis is presented in Section 4.3 where the results of the global warming potential excluding biogenic carbon are showed.

Currently more than thirty software packages exist to perform LCA analysis, with differing scope and capacity: some are specific for certain applications, while others have been directly developed by industrial organisations (Manfredi and Pant, 2012). In this study GaBi 6 has been used (PE International, 2013). GaBi 6 contains databases developed by PE International, it incorporates industry organisations’ databases (e.g. Plastics Europe, Aluminium

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