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Factors influencing the life cycle burdens of the recovery of energy from residual municipal waste

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ABSTRACT

A life cycle assessment was carried out to assess a selection of the factors influencing the environmental impacts and benefits of incinerating the fraction of municipal waste remaining after source-separation for reuse, recycling, composting or anaerobic digestion. The factors investigated were the extent of any metal and aggregate recovery from the bottom ash, the thermal efficiency of the process, and the conventional fuel for electricity generation displaced by the power generated. The results demonstrate that incineration has significant advantages over landfill with lower impacts from climate change, resource depletion, acidification, eutrophication human toxicity and aquatic ecotoxicity. To maximise the benefits of energy recovery, metals, particularly aluminium, should be reclaimed from the residual bottom ash and the energy recovery stage of the process should be as efficient as possible. The overall environmental benefits/burdens of energy from waste also strongly depend on the source of the power displaced by the energy from waste, with coal giving the greatest benefits and combined cycle turbines fuelled by natural gas the lowest of those considered. Regardless of the conventional power displaced incineration presents a lower environmental burden than landfill.

1. Introduction

In European and other developed nations, waste management is being transformed from a disposal to a resource recovery activity. This reflects rising concerns on sustainability, restrictions on landfill availability for certain wastes and international and national policies. For example, under the terms of the Waste Framework Directive (2008/98/EC), EU member states are required to achieve a municipal waste recycling rate (including composting) of 50% by 2020 (European Commission, 2008). Recycling rates vary widely across Europe; in 2012 they ranged from 62% in Austria to less than 1% in Romania with four member states (Austria, Belgium, Germany and the Netherlands) having already achieved the 50% target (Eurostat, 2014). However, reaching these recycling rates still leaves a substantial amount of residual waste. For example, if England were to achieve the recycling target of 50% this would leave 11.5 million tonnes of municipal waste remaining for management by other means.

The Waste Framework Directive also calls on member states to adopt the waste hierarchy while noting that, for some specific waste streams, a departure from the hierarchy should be made if the application of life-cycle thinking demonstrates that this departure represents the best overall environmental outcome. Applying the waste hierarchy means that the recovery of energy from waste should normally only be considered for wastes remaining such as residual municipal waste and other mixed low-grade materials. Conventional mass-burn energy from waste (EfW) is the most commonly applied energy recovery technique and seven EU member states currently burn more than a third of their municipal waste (Eurostat, 2014) and have demonstrated that recycling rates of above 50% can be combined with significant use of EfW to minimise the amount going to landfill.

Life cycle assessment (LCA) is an environmental management tool for the evaluation of the overall environmental burdens (impacts and benefits) of providing and using goods and services. The international standards ISO 14040 and 14044 (BSI, 2006a,b) specify the procedure for carrying out and reporting LCA studies. LCAs are now widely used in assessing the environmental impacts and benefits of different waste management options and several software packages have been developed specifically for waste-related LCAs. These tools have been reviewed in detail by Gentil et al. (2010).

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This paper reports on an LCA to evaluate the environmental impacts of processing residual municipal waste by EfW. It considers the environmental impacts and benefits of each stage of the EfW operation (energy recovery, metals and aggregate recovery and residue landfill) in terms of impact category (climate change, acidification etc.) and the chemical species responsible for each impact.

We also assess the effect on the results of changes in the efficiency of the power generation stage and changes in the type of fuel used to generate the power displaced by the electricity produced by the EfW.

2. Review of previous studies

Several LCA studies have been undertaken to compare different ways of managing specific waste components. Many of these have focussed on comparing recycling with other options. Generally, recycling is the most environmentally-advantageous way of recovering value from uncontaminated source-segregated materials (Chilton et al., 2010; Michaud et al., 2010; Hanan, 2012; Merrild et al., 2012, for example). However, in a study based in Denmark Merrild et al. (2012) noted that burning plastics and cardboard in a high thermal efficiency combined heat and power (CHP) displacing coal fired heat and power, EfW was better than recycling in terms of climate change impacts for both materials and photochemical ozone formation for plastics.

Other authors have considered the entire municipal waste stream and these tended to focus on comparisons between landfill and thermal processing (Gunamantha and Sarto, 2012; Assamoi and Lawryshyn, 2012, for example) or on comparing different thermal processing technologies (for example, Bates, 2009; Watson et al., 2009; Burnley et al., 2012; Rigamonti et al., 2012). The results of these studies were all highly dependent on the thermal efficiency of the energy recovery process and the conventional fuel displaced by the recovery process. Mathiesen et al. (2009) discussed some of the issues in identifying the "marginal technology" (the energy production technology or technologies displaced by the EfW) and noted that making the selection was a complex process which should be subject to sensitivity analysis when performing LCA studies.

Kaplan et al.'s (2009) LCA of EfW and landfill in the USA selected 1 MW h of electrical power production rather than mass of waste managed as the functional unit. They concluded that EfW emitted less $CO_{2(eq)}$, SO_2 and NOx than coal-fired power or from landfill with power generation, but more of each pollutant than conventional gas-fired power. EfW performed better than landfill without energy recovery (where the landfill gas is vented or flared) in terms of $CO_{2(eq)}$ and SO_2, but worse in terms of NOx. A sensitivity analysis found a 12.5% reduction in CO_2 emissions when the ferrous metal was recycled from the bottom ash and the results were highly sensitive to the thermal efficiency of the EfW process. However, the choice of 1 MW h of electrical power as the functional unit did not allow a direct comparison of EfW and landfill as waste management methods. Other impact categories such as toxicity and resource depletion were not considered.

Some authors have considered different EfW technologies such as processing the waste to produce a refuse derived fuel (RDF) followed by conventional combustion, gasification or pyrolysis. RDF production and combustion tended to be less beneficial than burning unprocessed waste unless the RDF could be burned in a much higher efficiency process (Bates, 2009; Rigamonti et al., 2012). Gasification and pyrolysis studies were limited by the lack of reliable data on full-scale facilities, but theoretical studies by Watson et al. (2009) and Burnley et al. (2011) failed to demonstrate any benefits of gasification over conventional EfW in terms of greenhouse gas emissions. However, gasification may result in reduced emissions in other impact categories. Arena and Di Gregorio (2013) compared operational data from a Korean gasifier (which processed untreated residual municipal waste) with typical European 'mass burn' EfWs. Energy efficiency and climate change impacts were not assessed, but it was noted that the gasifier produced a less leachable residue with a greater potential for reuse as an aggregate and so achieved a greater reduction in landfill needs.

The recovery of metals from EfW bottom ash is becoming common practice, not least because metal recovery is financially beneficial and improves the quality of any aggregate recovered from the ash. Grosso et al. (2011) modelled the quantities of steel and aluminium that could be reclaimed from EfW in Italy, but did not consider the environmental implications of this. In a later LCA study Rigamonti et al. (2012) calculated that metals recycling was responsible for around half of the reduction in human toxicity life cycle impacts of EfW and also contributed in a minor way towards climate change emissions reduction.

Clearly, there have been many studies looking at the overall environmental burdens of waste recycling and recovery processes. However few, if any, consider the precise chemical species and material resources that are responsible for the burdens. Knowledge of the overall burdens gives an indication of the areas where improvements should be made to a particular technology, but a detailed breakdown of the burdens is essential in order to prioritise improvements (for example should SO_2 or NO_x be targeted as a priority if acidification impacts are to be reduced?).

A key factor influencing the results of waste LCA studies is the assumption made about the "marginal energy" – the fuel for the conventional power and heat displaced by the waste management system – as pointed out by Mathiesen et al. (2009). This marginal energy is best defined as the electricity and heat that are taken offline when the waste-derived energy is available. Lund et al. (2010) noted that the debate in the literature goes back to 1998. The selection of marginal energy source can often be simply a matter of policy. For example, the UK government position is that power produced by combined cycle gas turbines (CCGT) is the marginal fuel because that represents the current trend in new plant commissioning (DECC, 2008). In contrast, Denmark uses coal as the marginal fuel because one aspect of national policy on climate change is to phase out coal-fired power generation. In reality, the marginal source will vary. For example Lund et al. (2010) commented that where coal is the lowest cost fuel it will be used as base load and therefore only be the marginal fuel during periods of low demand. However, if gas is used to meet peak demand periods, this will be the marginal fuel when power demand is at its peak. The complexity of the situation has been demonstrated in the UK where the use of coal increased by 24% in 2012 (DECC, 2013) due to the low price of coal. Weber et al. (2010) took the USA as an example and noted that it can be almost impossible to determine the electricity mix for a given location at any one time with factors including total power demand, the complexity of the distribution grid and contractual issues confusing the picture. They noted that, in extreme cases, the CO_2 emissions associated with a product or service could differ by a factor of 100 depending on the assumptions made. They concluded that the international community should strive to ensure a consistent approach was taken perhaps through the production of national and regional emission factors for conventionally-produced power.

Cleary (2009) reviewed 20 published waste management LCA studies and noted that eight of them did not mention or were unclear on the source of the displaced energy, six took the marginal fuel to be coal because it was the least efficient source and the remaining six used the national average mix for the country in question. Cleary observed that none of the studies carried out