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Evaluation of the environmental sustainability of different waste-to-energy plant configurations

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ABSTRACT

Residual municipal solid waste (MSW) has an average lower heating value higher than 10 GJ/Mg in the EU, and can be recovered in modern Waste-to-Energy (WtE) plants, producing combined heat and power (CHP) and reaching high levels of energy recovery. CHP is pinpointed as the best technique for energy recovery from waste. However, in some cases, heat recovery is not technically feasible – due to the absence of a thermal user (industrial plant or district heating) in the vicinity of the WtE plant – and power production remains the sole possibility. In these cases, there are some challenges involved in increasing the energy performance as much as possible. High energy recovery efficiency values are very important for the environmental sustainability of WtE plants. The more electricity and heat is produced, the better the saving of natural resources that can be achieved. Within this frame, the aim of this work is to carry out an environmental assessment, through Life Cycle Assessment, of an MSW WtE plant, considering different sizes and operated in different ways, from power production only to full cogeneration. The main assumption is that the electric conversion efficiency increases as the plant size increases, introducing technical improvements thanks to the economies of scale. Impact assessment results were calculated using ReCiPe 2008 methods.

The climate change indicator is positive when the WtE plant is operated in power production only mode, with values decreasing for the increasing size. Values for the climate change are negative when cogeneration is applied, requiring increasing cogeneration ratios for decreasing size. Similarly, the fossil fuel depletion indicator benefits from increase of both the plant size and the cogeneration rate, but it is always negative, meaning that the residual MSW burning with energy recovery always provides a saving of fossil primary energy.

Other indicator values are in general negative and are also beneficially affected by increasing the plant size, but they worsen when increasing the cogeneration rate. The remaining indicators – i.e. human toxicity and terrestrial ecotoxicity – always have positive values, which decrease for increasing plant size and increase as the cogeneration rate increases.

However, the local context should be evaluated carefully with reference to the type of electricity which is substituted and in view of a future massive production of renewable electricity, because conclusions change accordingly.

Finally, it was evaluated that the inclusion of bottom ash recovery – instead of landfilling – can significantly improve the values of several impact assessment indicators.

Abbreviations: ALO, agricultural land occupation; APCR, air pollution control residues; BA, bottom ash; CC, climate change; CHP, combined heat and power; FA, fly ash; FD, fossil fuel depletion; FE, freshwater eutrophication; FET, freshwater ecotoxicity; FGT, flue gas treatment; HT, human toxicity; IR, ionising radiation; LCA, life cycle assessment; LHV, low heating value; ME, marine eutrophication; MET, marine ecotoxicity; MRD, mineral resource depletion; MSW, municipal solid waste; NLT, natural land transformation; NR, no recovery; OD, ozone depletion; PMF, particulate matter formation; POF, photochemical oxidant formation; R, recovery; SCR, selective catalytic reduction; TA, terrestrial acidification; TET, terrestrial ecotoxicity; ULO, urban land occupation; WD, water depletion; WtE, waste-to-energy.

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1. Introduction

The European strategy for waste management attributes primary importance to the prevention of waste production and imposes a priority order in waste management based on: "preparing for re-use; recycling; other recovery, e.g. energy recovery; and disposal" (Directive 2008/98/EC). The recovery of effective goods and material has priority over other forms of recovery and is applied through re-use and recycling. On the other hand, waste disposal to landfills must be considered as the last possibility and limited to pre-treated wastes (not biologically active or not containing easily leachable hazardous substances). Hence, those waste streams for which material recovery is not effectively applicable must follow the path of energy recovery.

According to this framework, energy recovery, mainly through waste thermal treatment, is a fundamental part of the integrated waste management system, especially when related to municipal solid waste (MSW) management, for which material recovery must be accomplished upstream through a separate collection system. Nowadays, combustion processes are the most widespread thermal treatments. Unsorted residual waste (i.e. the waste left downstream of separate collection) may be significantly reduced in mass (about 70–80%) and in volume (about 80–90%) by combustion processes, thus preserving landfill space, and its energy content, which has increased over the past years (MSW Lower Heating Value (LHV) increased from 10.0 to 10.3 GJ/Mg from 2001 to 2010, in the EU, according to Reimann, 2012), can be recovered in modern Waste-to-Energy (WtE) plants.

WtE plants produce energy by recovering the heat contained in the combustion gases, through heat exchangers producing steam. Generally, when only thermal energy is generated, steam may be produced at saturated conditions, while, when electric energy or combined heat and power (CHP) are required, steam is superheated. Superheated steam may be supplied to a steam turbine for the production of power only, using a condensing turbine, or for CHP, using a back pressure or intermediate steam extraction turbine. The CHP production allows high levels of energy recovery to be achieved and it is pinpointed as one of the best techniques for energy recovery from waste (European Commission, 2006). It is also the technical solution that allows high values according to the R1 criteria – directly linked to the energy efficiency – to be reached (Directive 2008/98/EC). The introduction of the R1 criteria has proved to be an incentive for WtE plants in Europe to improve their energy efficiency, as reported by CEWEP (Reimann, 2009, 2012). However, in some cases, heat recovery is not technically feasible – due to the absence of a heat user (industrial plant or district heating) in the vicinity of the WtE plant – and thus power production remains as the only option. In these cases, there are some challenges involved in increasing the energy performance as much as possible: high values are obtainable only for large WtE plants (Pavlas et al., 2011; Consonni and Viganò, 2012).

High energy recovery efficiency values are very important also for the environmental sustainability of WtE plants. The more electricity and heat is produced, the better the saving of natural resources may be achieved. Pavlas et al. (2011) evaluated the benefits of energy recovery in WtE by CHP applying a method based on primary energy saving (PES). Damgaard et al. (2010) showed that CHP is able to provide a greater saving, in life cycle assessment (LCA) evaluations, than recovering only electricity. Grosso et al. (2010) calculated the R1 formula (see Section 2.1) and the exergy efficiency for waste-to-energy plants operating in Europe, revealing some significant differences in their performance, mainly related to the average size and to the availability of a heat market (district heating). Lombardi et al. (2015) highlighted that "in the case of only electricity production, the achievable efficiency values are strongly dependent on the plant size: for large plant size, where advanced technical solutions can be applied and sustained from an economic point of view, net electric efficiency may reach values up to 30–31%". Of course, it may happen that a large plant uses poor technical solutions, or vice versa a small plant uses improved technical solutions. However the general trend shows that the advanced technical solutions are applied in large scale plants, leading to higher electric efficiencies (Consonni et al., 2017).

Within this frame, the aim of this work is to carry out an environmental assessment, through LCA, of different configurations of MSW WtE plants, i.e. power production only vs. increasing degrees of cogeneration. Additionally, sizes ranging from small to large plants were considered, gradually including the technical improvements that may increase the overall plant performance.

2. Materials and methods

The methodology applied for evaluating the environmental burdens of the WtE process is LCA (ISO, 2006a, 2006b), so the following paragraphs report the different steps included in the methodology: goal and scope definition, inventory analysis, impact assessment.

2.1. Goal and scope definition

Definition of the goal is the first phase of the LCA, in which the purpose of the study is described. It identifies and defines the object of the assessment.

The aim of this study is to evaluate the environmental burdens – throughout the entire life cycle – of the residual MSW thermal treatment by combustion with energy recovery (i.e. WtE), comparing different possibilities for energy production, from power production only to full cogeneration, comparing different plant sizes.

The analysis was carried out in reference to the assumed material composition for the residual MSW reported in Table 1, along with the resulting chemical composition (Consonni and Viganò, 2012), which supplies an LHV of about 10,544 GJ/Mg (calculated on the chemical composition basis).

The WtE plant size was assumed to range from 12.5 to 300 MW in terms of thermal power input, hence from small to large size, according to Consonni and Viganò (2012). Along with increase of the plant size, gradual technical improvements to the plant were introduced, which enhance the overall plant energy performance (Consonni and Viganò, 2012). The main design parameters for each considered size are reported in Table 2. Assumed parameters are coherent with design parameters commonly found in EU plants (Lombardi et al., 2015; Consonni et al., 2017).

For each plant size, the performance was first calculated in the case of power production only. The produced electric energy is assumed to substitute the electric energy produced by the Italian

Table 1
Material and chemical composition assumed for the residual MSW.

Material composition [% in mass]		Chemical composition [% in mass]	
Paper and cardboard	12.00	C	27.59
Organic matter	33.00	H	4.23
Garden waste	9.00	O	17.39
Plastics	15.00	S	0.04
Metals	6.00	N	0.67
Wood	6.50	Cl	0.26
Glass	9.50	F	0.004
Textiles	9.00	Ashes	16.46
		Moisture	33.37

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