Waste Management 37 (2015) 26–44

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

A review of technologies and performances of thermal treatment systems for energy recovery from waste

Lidia Lombardi [a,*], Ennio Carnevale [b], Andrea Corti [c]

[a] *Niccolò Cusano University, via Don Carlo Gnocchi, 3, 00166 Rome, Italy*
[b] *Industrial Engineering Department, University of Florence, via Santa Marta, 3, 50129 Florence, Italy*
[c] *Department of Information Engineering and Mathematics, University of Siena, via Roma, 56, 53100, Italy*

ARTICLE INFO

Article history:
Available online 18 December 2014

Keywords:
Waste-to-Energy
Energy efficiency
Combustion
Incineration
Gasification
Pyrolysis

ABSTRACT

The aim of this work is to identify the current level of energy recovery through waste thermal treatment. The state of the art in energy recovery from waste was investigated, highlighting the differences for different types of thermal treatment, considering combustion/incineration, gasification and pyrolysis. Also different types of wastes – Municipal Solid Waste (MSW), Refuse Derived Fuel (RDF) or Solid Refuse Fuels (SRF) and some typologies of Industrial Waste (IW) (sludge, plastic scraps, etc.) – were included in the analysis. The investigation was carried out mainly reviewing papers, published in scientific journals and conferences, but also considering technical reports, to gather more information.

In particular the goal of this review work was to synthesize studies in order to compare the values of energy conversion efficiencies measured or calculated for different types of thermal processes and different types of waste.

It emerged that the dominant type of thermal treatment is incineration associated to energy recovery in a steam cycle. When waste gasification is applied, the produced syngas is generally combusted in a boiler to generate steam for energy recovery in a steam cycle. For both the possibilities – incineration or gasification – cogeneration is the mean to improve energy recovery, especially for small scale plants. In the case of only electricity production, the achievable 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%. In small-medium plants, net electric efficiency is constrained by scale effect and remains at values around 20–24%. Other types of technical solutions – gasification with syngas use in internally fired devices, pyrolysis and plasma gasification – are less common or studied at pilot or demonstrative scale and, in any case, offer at present similar or lower levels of energy efficiency.

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1. Introduction

Thermal treatment of waste is an inalienable part of every integrated waste management system (Porteous, 2005). European strategy for waste management imposes that “the following waste hierarchy shall apply as a priority order in waste prevention and management legislation and policy: prevention; preparing for re-use; recycling; other recovery, e.g. energy recovery; and disposal” (Directive 2008/98/EC). Thus, it is very clear that the use of landfills must be residual and devoted to pre-treated wastes (not biologically active or not containing motile hazardous substances). Re-use and recycling are aimed at pursuing effective material recovery. For those streams of waste, for which the material recovery is not effectively applicable, the energy recovery is the path to be followed, considering also that when applying the waste

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Abbreviations: ASR, automotive shredded residues; C&IW, commercial & industrial waste; CHP, Combined Heat and Power; DMS, direct melting system; EfW, Energy from Waste; FBC, fluidized bed combustor; FGR, Flue Gas Recirculation; FGT, flue gas treatment; GT, gas turbine; GTCC, gas turbine combined cycle; HHV, Higher Heating Value; HT, high temperature; HW, hazardous waste; ICE, internal combustion engine; IHW, Industrial Hazardous Waste; IW, Industrial Waste; LCA, Life Cycle Assessment; LHV, Lower Heating Value; LT, low temperature; MBT, Mechanical Biological Treatment; MSW, Municipal Solid Waste; P, pressure; P_{cond}, condenser pressure; P_{el}, electrical power output; P_{th}, thermal power input; RDF, Refuse Derived Fuel; SC, separate collection; SCR, selective catalytic reduction; SEP, specific electricity production; SHP, specific heat production; SNCR, selective non-catalytic reduction; SRF, Solid Refuse Fuel; T, temperature; T_{out}, gas temperature at boiler outlet; WtE, Waste to Energy; η_{el}, electric efficiency; η_{th}, thermal efficiency.

[*] Corresponding author. Tel.: +39 366 6381000.
E-mail address: lidia.lombardi@unicusano.it (L. Lombardi).

http://dx.doi.org/10.1016/j.wasman.2014.11.010
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hierarchy, "measures to encourage the options that deliver the best overall environmental outcome, should be taken. This may require specific waste streams departing from the hierarchy where this is justified by life-cycle thinking on the overall impacts of the generation and management of such waste" (Directive 2008/98/EC).

Thus an integrated waste management system should be designed on the integration of different types of treatment processes: recycling processes for material recovery and, in case, biological treatments for appropriate streams, as well as thermal treatments for energy recovery, and should be provided with service landfills for disposal of residues generated by the other treatments.

In this text by thermal treatment is meant any thermochemical conversion process that takes place at relatively high temperatures causing modifications in the chemical structure of the processed material. Thus the three main processes available for thermochemical conversion will be included within the analysis: combustion, gasification and pyrolysis of waste.

Nowadays, combustion processes, generally called incineration, are the most commonly widespread thermal treatments applied for different types of waste, including Municipal Solid Waste (MSW), intended as unsorted residual waste (i.e. the waste left downstream of separate collection), Solid Refuse Fuels (SRF), Industrial Waste (IW), and Industrial Hazardous Waste (IHW). Incineration of waste is generally associated to energy recovery, in the form of electricity and/or heat production. Only IHW is often disposed by incineration (without energy recovery), since energy recovery for this waste can result quite complex due to the presence of several pollutants in the generated flue gas. Obviously, energy recovery is beneficial also for IHW, reducing operating costs and external energy consumption (Stehlík, 2012), and it is applied when possible.

In recent decades, the main interests toward thermal treatments were due to their ability to significantly reduce the solid waste in mass (about 70–80%) and in volume (about 80–90%), allowing preserving landfill space, as well as to eliminate the tendency of waste to putrefy giving place to sanitary problems (this last aspect being especially important in the past) (Gohlke and Martin, 2007).

Nowadays, an important additional attractiveness toward waste thermal treatments is given by the possibility of making significant energy recovery, thanks to the technological developments achieved in this field (Stehlík, 2012) and, in the case of MSW, to the increased energy content with respect to the past, because of the change in the consumers' habits and the increase in the upstream separate collection (Calabrò, 2010). The Lower Heating Value (LHV) for the major part of MSW incinerated in EU passed from 10.0 to 10.3 GJ/Mg from 2001 to 2010 (Reimann, 2012). Several waste streams have a relatively high LHV. In the case of SRF in EU (cfr. CEN/TS 15359, 2006), the LHV must be more than 3 GJ/Mg and can be higher than 25 GJ/Mg: Arena and Di Gregorio (2014) measured a LHV in the range 18.6–21.3 GJ/Mg for SRF obtained from MSW; while the previous term "Refuse Derived Fuel" (RDF) was not given by any legal definition and it was interpreted differently across countries. For Automotive Shredder Residue (ASR), classified as IHW, the LHV lays in the range 19–29 GJ/Mg (Vermeulen et al., 2011). Biostabilised sewage sludge LHV, on dry basis, may range from 7 GJ/Mg (Werle and Wilk, 2010) to 23 GJ/Mg (Tyagi and Lo, 2013). Other industrial waste flows, interesting for their energy content, are scrap wood (LHV of 16 GJ/Mg); sugarcane bagasse (LHV of 18.6 GJ/Mg); plastics scraps (LHV of 32.8 GJ/Mg) (Tsai, 2010); deinking sludge (HHV[1] of 6.4–7 GJ/Mg on dry basis) (Ouadi et al., 2013) and pulper residues (LHV of about 21 GJ/Mg, when the water content is reduced to 10%) (Lombardi et al., 2012) from the recycled paper process; and in general Commercial and Industrial Waste (C&IW), for which Lupa et al. (2011) measured an average LHV of 9.47 GJ/Mg. Mixed plastic wastes, obtained as by-products of the sorting process of end-of-use plastic packaging from separate collection, are also rather high energy content waste streams, being their LHV about 31.7–40.2 GJ/Mg (Arena et al., 2011).

Pavlas et al. (2009) state that the thermal treatment of waste with energy recovery belongs to the preferred sources of renewable energy and that the waste stops to be a problem becoming an available fuel. Producing energy from waste contributes to primary energy savings in conventional utility systems (Pavlas et al., 2010). According to this approach, two main advantages are highlighted: the waste is processed and, at the same time, energy is produced. For this reason, today, the thermal treatment plants associated to energy production are commonly addressed to as Waste to Energy (WtE) or even Energy from Waste (EfW) plants.

Concerning the degree of renewability of carbon contained in the MSW (carbon is about 25% in mass for waste with LHV of 10 GJ/Mg), one should consider that this carbon is bound in a variety of materials such as food waste, garden waste, waste wood, paper, cardboard, textile waste and plastics. Gohlke (2009) affirms that more than half of the carbon is biogenic in origin, while the remaining part is fossil in origin, as also confirmed by C14 technique analysis of WtE stack gas, that for several plants analyzed in the USA in 2007–2008 showed that two-thirds of the carbon in US MSW is biogenic (US Department of Energy, 2007). Palstra and Meijer (2010) measured biogenic flue gas CO_2 fractions within 48–50% at waste incineration plant in The Netherlands and similarly Fellner et al. (2007) show that the ratio of biogenic energy source in MSW supplied to a plant in Austria range from 36% to 53%.

Gohlke (2009) calculated that for a new WtE plant with moderate steam parameters (48.5 MW_{LHV} combustion power, 40 bar/380 °C, no heat recovery, net electric efficiency $20.6\%_{LHV}$), assuming that 56% of MSW is biogenic in origin, the specific CO_2 emission is about 0.4 Mg per MWh of produced electricity, and compared this values with the specific emissions of fossil fuel power plants (for example a coal power plant can emit about 0.84 Mg of CO_2 per MWh of produced electricity).

In this regard, some authors invite to consider that when the source separation of organic waste, paper and cardboard is carried out successfully, the share of the renewable energy content of MSW may be lower than previously cited values (Horttanainen et al., 2013).

1.1. Source of data

The data used in this work come mainly from scientific literature (international journals and conferences) and public reports. Table 1 summarizes the data sources reported in the reference list on the basis of the considered thermal process (incineration, gasification, plasma, pyrolysis) and the type of document ("others" includes different types of reports). Also, in reference to the incineration process, statistics are given about how many sources consider MSW rather than RDF/SRF, as well as each of the three incineration technologies later discussed (see Section 2.1). The total sum of the numbers in the table differs from the number of the sources reported in the reference list. This is because the same source may refer to both MSW and RDF/SRF, as well as to more than one technology (e.g. sources that compare incineration to gasification). Moreover, some of the sources in the reference list deal with waste characterization and other topics here discussed.

Among the various source documents, several data were extracted from the Waste-to-Energy State-of-the-Art Report (2012) published by the International Solid Waste Association

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[1] Higher Heating Value (HHV).

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