Waste Management 37 (2015) 104–115

Contents lists available at ScienceDirect

Waste Management

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

Life cycle assessment of thermal Waste-to-Energy technologies: Review and recommendations

Thomas Fruergaard Astrup *, Davide Tonini, Roberto Turconi, Alessio Boldrin

Technical University of Denmark, Department of Environmental Engineering, Miljoevej, Building 113, 2800 Kgs. Lyngby, Denmark

ARTICLE INFO

Article history:
Available online 19 July 2014

Keywords:
Waste-to-Energy
Municipal solid waste
Incineration
Thermal treatment
Energy
Life cycle assessment

ABSTRACT

Life cycle assessment (LCA) has been used extensively within the recent decade to evaluate the environmental performance of thermal Waste-to-Energy (WtE) technologies: incineration, co-combustion, pyrolysis and gasification. A critical review was carried out involving 250 individual case-studies published in 136 peer-reviewed journal articles within 1995 and 2013. The studies were evaluated with respect to critical aspects such as: (i) goal and scope definitions (e.g. functional units, system boundaries, temporal and geographic scopes), (ii) detailed technology parameters (e.g. related to waste composition, technology, gas cleaning, energy recovery, residue management, and inventory data), and (iii) modeling principles (e.g. energy/mass calculation principles, energy substitution, inclusion of capital goods and uncertainty evaluation). Very few of the published studies provided full and transparent descriptions of all these aspects, in many cases preventing an evaluation of the validity of results, and limiting applicability of data and results in other contexts. The review clearly suggests that the quality of LCA studies of WtE technologies and systems including energy recovery can be significantly improved. Based on the review, a detailed overview of assumptions and modeling choices in existing literature is provided in conjunction with practical recommendations for state-of-the-art LCA of Waste-to-Energy.

1. Introduction

Energy recovery from waste is an essential part of modern waste management. Within the last decades, waste management has changed from being a sector primarily focusing on treatment and final disposal of residual streams from society to now being a sector that contributes significantly to energy provision and secondary resource recovery. In the transition towards more sustainable energy supply, energy recovery from waste is gaining increasing interest as an option for reducing dependence on imported fossil fuels. In a future with higher shares of intermittent energy sources such as wind and photo voltaic, and phase-out of coal, energy recovery from waste may provide an alternative to increased used of constrained non-fossil resources such as biomass.

Within the recent decade, life cycle assessment (LCA) has been used extensively to evaluate the environmental benefits and drawbacks of waste management, including energy recovery technologies. Both individual Waste-to-Energy (WtE) technologies (among the others Scipioni et al., 2009; Boesch et al., 2014; Turconi et al., 2011; Tonini et al., 2013; Møller et al., 2011) as well as the role of these technologies within the entire waste management systems (among the others Eriksson et al., 2007; Finnveden et al., 2007; Finnveden et al., 2005; Fruergaard et al., 2010; Moberg et al., 2005; Manfredi et al., 2011; Christensen et al., 2009; Merrild et al., 2012; Song et al., 2013; Tunesi, 2011; Bernstad and la Cour Jansen, 2011; Rigamonti et al., 2014) have been assessed. While anaerobic degradation of organic waste is a well-established technology, today energy recovery based on thermal conversion of waste is the most widespread WtE technology (ISWA, 2012). The main thermal technologies are: (i) waste incineration at dedicated plants, (ii) co-combustion with other fuels, (iii) thermal gasification, and (iv) thermal pyrolysis. While mass-burn waste incineration generally is the most robust technology accepting a wide range of waste materials (size, sources), also other technologies such as fluidized-bed incineration exist (a more homogeneous waste input is needed here). Co-combustion, gasification, and pyrolysis are generally less widespread and mainly applied on pre-treated waste or sub-streams of urban waste (e.g. Solid Recovered Fuels, SRF, or Refuse Derived Fuels, RDF).

Although LCA as an assessment tool is fairly mature and overall assessment guidelines exist outlining the main assessment principles, relatively little methodological consistency exist between individual LCA studies in literature as highlighted by Laurent et al. (2014a, 2014b). Technology modeling principles, LCA principles

* Corresponding author. Tel.: +45 45251558.
E-mail address: thas@env.dtu.dk (T.F. Astrup).

http://dx.doi.org/10.1016/j.wasman.2014.06.011
0956-053X/

(e.g. attributional vs. consequential assessment), choices of impact assessment methodologies, key WtE technology parameters (e.g. energy recovery efficiencies), emission levels, and choices related to the environmental value of energy substitution varies significantly between LCA studies (Laurent et al., 2014a). Existing LCA guidelines (e.g. ISO 2006a and ISO 2006b) attempt to overcome these inconsistencies by providing a more standardized framework for performing and reporting LCA studies. However although these guidelines are extremely valuable, the concrete implementation of the provided assessment principles still allow ample room for interpretation. Consequently, in some cases LCA results can be found in literature indicating that anaerobic digestion is preferable (e.g. Khoo et al., 2010) while waste incineration may appear optimal in other cases (e.g. Manfredi et al., 2011; Fruergaard and Astrup, 2011), seemingly based on similar waste types or similar technologies. Methodological challenges and inconsistencies in relation to LCA is not specific for WtE technologies (Laurent et al., 2014a, 2014b); however as WtE technologies may play an increasingly important role in many countries, a detailed and systematic review of assessment choices and inventory data specifically related to thermal WtE technologies are needed. Reaching robust and widely accepted conclusions based on the variety of results in existing LCA studies of WtE technologies requires detailed insight and understanding of the specific systems modeled in the studies as well as the LCA modeling principles applied in the individual studies. This substantially limits the usability of LCA results for decision-makers and opens for yet other LCA case-studies which may not provide novel insights from a research perspective. Consequently, this situation may significantly limit the overall value of LCA studies for future implementation of WtE technologies in society.

The demand for consistency and transparency within waste LCA is increasing dramatically and to perform state-of-the-art LCA studies, a systematic overview of modeling and assessment choices is needed. The aim of this paper is to provide such an overview based on a critical review of existing LCA studies of WtE in literature, focusing on thermal WtE technologies. The specific objectives are: (i) to critically analyze existing LCA studies involving WtE technologies with respect to key assessment choices, (ii) to identify the most important methodological aspects and technology parameters, and (iii) to provide recommendations for state-of-the-art LCA of WtE technologies.

2. Methodology

2.1. Selection of papers for review

LCA of waste management technologies and systems has gained momentum within the last 10–15 years and the approaches used have developed significantly in the same period (Laurent et al., 2014a, 2014b; Ekvall et al., 2007; Finnveden et al., 2009). Existing literature therefore covers considerable variations with respect to focus and approach. To ensure consistency, literature included in the review was selected based on the following overall criteria: (i) the study was published in a peer-reviewed scientific journal; (ii) the LCA study focused on waste management and included at least one thermal WtE technology as a key part of the study; (iii) an impact assessment was performed and more than one impact category was included; and (iv) the study was reported in English. Studies published until December 2013 were included.

2.2. Review approach

The review addressed the following main aspects: (i) definition of goal and scope of the study, (ii) description of technical parameters and life cycle inventory (LCI) data, iii) methodological choices of LCA modeling. An overview of these aspects is provided in Table 1.

In relation to "goal and scope definition", it was assessed whether a clear and comprehensive description of the study context was provided. The aim was thereby to qualitatively evaluate how appropriate the LCA modeling described the system in question. The description of technical parameters concerning thermal WtE processes and the influence of these parameters on the results were evaluated. The waste input to the WtE technology was evaluated with respect to the description of the waste type (all waste types typically addressed in "waste management studies" were included: e.g. households waste, mixed municipal solid waste, RDF/SRF, combustible industry waste, or single fractions), waste composition (i.e. presence of individual material fractions and their chemical composition) and the origin of these data. Key technology aspects of the WtE processes were evaluated relative to thermal technology, energy recovery, and residue management: (i) plant type, (ii) energy recovery and type of energy output, (iii) flue gas cleaning techniques (e.g. air-pollution-control: dust removal, acid gas neutralization, $deNO_x$, etc.), and (iv) residue types, generation and management. Finally, available quantitative data for emissions and consumption of energy/materials were extracted from the reviewed studies.

Key methodological aspects of the reviewed studies were addressed focusing on: (i) the overall modeling approach and whether the study accounted for and balanced mass and energy flows, (ii) inclusion of capital goods, (iii) energy substitution principles, and (iv) inclusion of uncertainty and/or sensitivity analysis. Finally, overall trends in results between the reviewed studies were identified and discussed.

3. Results and discussion

A total of 136 journal articles were identified, including 250 individual case-studies of technologies for thermal treatment of waste (Fig. 1). The complete list of studies is provided in the supplementary material (Table S13). Only few studies were performed prior to 2002, no studies before 1995 was found. Throughout the following sections, comparability between studies is discussed and understood as the possibility for the reader to appreciate the LCA results based on transparent reporting of assumptions, assessment methodology, technical parameters, etc.

3.1. Goal and scope definition

Goal and scope definition includes specification of the aim of the study, its functional unit (FU, quantitatively and qualitatively describing the service provided by the assessed system), and the corresponding system boundaries. Goal and scope definitions are fundamental for the interpretation of results and thereby for the outcome of LCA studies (Laurent et al., 2014b; Finnveden et al., 2009; ISO 2006a; ISO 2006b). Most of the reviewed case-studies applied an FU defined with respect to the waste input, e.g. as a unit mass of waste received at the WtE facility (58% of the case-studies). This FU indicates an assessment perspective related to "waste management" or "treatment of X Mg of waste", which subsequently allows comparison between individual "treatment technologies". About 28% of the case-studies had a FU represented by the waste generation in a given area or region. Relatively few case-studies had FUs related to specific inputs or outputs from the WtE facilities, or did not define the FU at all. About 68% of the LCA case-studies either compared several WtE technologies against each other, or compared WtE with other waste management options. In addition to the 68% of case-studies comparing specific technologies, about 26% of the studies included WtE as an integrated part of a waste management system in combination with other technologies, e.g. Arena et al. (2003) and Tonini and