

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

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

Published in: Waste Management

Link to article, DOI: 10.1016/j.wasman.2014.06.011

Publication date: 2015

Document Version Peer reviewed version

Link back to DTU Orbit

Citation (APA): Astrup, T. F., Tonini, D., Turconi, R., & Boldrin, A. (2015). Life cycle assessment of thermal Waste-to-Energy technologies: Review and recommendations. *Waste Management, 37*, 104-115. https://doi.org/10.1016/j.wasman.2014.06.011

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.

- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Life Cycle Assessment of Thermal Waste-to-Energy Technologies: Review and Recommendations

Astrup, T.F.; Tonini, D.; Turconi, R. and Boldrin, A.

Department of Environmental Engineering Technical University of Denmark Kgs. Lyngby, Denmark

"NOTE: this is the author's version of a work that was accepted for publication in Waste Management journal. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Minor changes may have been made to this manuscript since it was accepted for publication. A definitive version is published in Waste Management, vol 37, pp 104-115, doi:10.1016/j.wasman.2014.06.011"

23 Abstract

24 Life cycle assessment (LCA) has been used extensively within the recent decade to 25 evaluate the environmental performance of thermal Waste-to-Energy (WtE) 26 technologies: incineration, co-combustion, pyrolysis and gasification. A critical review 27 was carried out involving 250 individual case-studies published in 136 peer-reviewed 28 journal articles within 1995 and 2013. The studies were evaluated with respect to 29 critical aspects such as: i) goal and scope definitions (e.g. functional units, system 30 boundaries, temporal and geographic scopes), ii) detailed technology parameters (e.g. 31 related to waste composition, technology, gas cleaning, energy recovery, residue management, and inventory data), and iii) modeling principles (e.g. energy/mass 32 33 calculation principles, energy substitution, inclusion of capital goods and uncertainty 34 evaluation). Very few of the published studies provided full and transparent descriptions 35 of all these aspects, in many cases preventing an evaluation of the validity of results, 36 and limiting applicability of data and results in other contexts. The review clearly 37 suggests that the quality of LCA studies of WtE technologies and systems including 38 energy recovery can be significantly improved. Based on the review, a detailed 39 overview of assumptions and modeling choices in existing literature is provided in 40 conjunction with practical recommendations for state-of-the-art LCA of waste-to-41 energy.

42

43 **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.

53 Within the recent decade, life cycle assessment (LCA) has been used extensively 54 to evaluate the environmental benefits and drawbacks of waste management, including 55 energy recovery technologies. Both individual waste-to-energy (WtE) technologies 56 (among the others Scipioni et al., 2009, Boesch et al., 2014, Turconi et al., 2011, Tonini 57 et al., 2013, Møller et al., 2011) as well as the role of these technologies within the 58 entire waste management systems (among the others Eriksson et al., 2007, Finnveden et 59 al., 2007, Finnveden et al., 2005, Fruergaard et al., 2010, Moberg et al., 2005, Manfredi 60 et al., 2011, Christensen et al., 2009, Merrild et al., 2012, Song et al., 2013, Tunesi, 61 2011, Bernstad and la Cour Jansen, 2011, Rigamonti et al. 2014) have been assessed. 62 While anaerobic degradation of organic waste is a well-established technology, today 63 energy recovery based on thermal conversion of waste is the most widespread WtE 64 technology (ISWA, 2012). The main thermal technologies are: i) waste incineration at 65 dedicated plants, ii) co-combustion with other fuels, iii) thermal gasification, and iv) 66 thermal pyrolysis. While mass-burn waste incineration generally is the most robust 67 technology accepting a wide range of waste materials (size, sources), also other 68 technologies such as fluidized-bed incineration exist (a more homogeneous waste input is needed here). Co-combustion, gasification, and pyrolysis are generally less 69 70 widespread and mainly applied on pre-treated waste or sub-streams of urban waste (e.g. 71 Solid Recovered Fuels, SRF, or Refuse Derived Fuels, RDF).

72 Although LCA as an assessment tool is fairly mature and overall assessment 73 guidelines exist outlining the main assessment principles, relatively little 74 methodological consistency exist between individual LCA studies in literature as highlighted by Laurent et al. (2014a, 2014b). Technology modeling principles, LCA 75 76 principles (e.g. attributional vs. consequential assessment), choices of impact 77 assessment methodologies, key WtE technology parameters (e.g. energy recovery 78 efficiencies), emission levels, and choices related to the environmental value of energy 79 substitution varies significantly between LCA studies (Laurent et al., 2014a). Existing 80 LCA guidelines (e.g. ISO 2006a and ISO 2006b) attempt to overcome these 81 inconsistencies by providing a more standardized framework for performing and 82 reporting LCA studies. However although these guidelines are extremely valuable, the 83 concrete implementation of the provided assessment principles still allow ample room 84 for interpretation. Consequently, in some cases LCA results can be found in literature 85 indicating that anaerobic digestion is preferable (e.g. Khoo et al., 2010) while waste 86 incineration may appear optimal in other cases (e.g. Manfredi et al., 2011, Fruergaard 87 and Astrup, 2011), seemingly based on similar waste types or similar technologies. 88 Methodological challenges and inconsistencies in relation to LCA is not specific for 89 WtE technologies (Laurent et al., 2014a, 2014b); however as WtE technologies may 90 play an increasingly important role in many countries, a detailed and systematic review 91 of assessment choices and inventory data specifically related to thermal WtE 92 technologies are needed. Reaching robust and widely accepted conclusions based on the 93 variety of results in existing LCA studies of WtE technologies requires detailed insight 94 and understanding of the specific systems modeled in the studies as well as the LCA 95 modeling principles applied in the individual studies. This substantially limits the 96 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.

100 The demand for consistency and transparency within waste LCA is increasing 101 dramatically and to perform state-of-the-art LCA studies, a systematic overview of 102 modeling and assessment choices is needed. The aim of this paper is to provide such an 103 overview based on a critical review of existing LCA studies of WtE in literature, 104 focusing on thermal WtE technologies. The specific objectives are: i) to critically 105 analyze existing LCA studies involving WtE technologies with respect to key 106 assessment choices, ii) to identify the most important methodological aspects and 107 technology parameters, and iii) to provide recommendations for state-of-the-art LCA of 108 WtE technologies.

109

110 2. Methodology

111 **2.1. Selection of papers for review**

112 LCA of waste management technologies and systems has gained momentum within the 113 last 10-15 years and the approaches used have developed significantly in the same 114 period (Laurent et al., 2014a, 2014b, Ekvall et al., 2007, Finnveden et al., 2009). 115 Existing literature therefore covers considerable variations with respect to focus and 116 approach. To ensure consistency, literature included in the review was selected based on 117 the following overall criteria: i) the study was published in a peer-reviewed scientific 118 journal; ii) the LCA study focused on waste management and included at least one 119 thermal WtE technology as a key part of the study; iii) an impact assessment was 120 performed and more than one impact category was included; and iv) the study was 121 reported in English. Studies published until December 2013 were included.

123 **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 128 129 comprehensive description of the study context was provided. The aim was thereby to 130 qualitatively evaluate how appropriate the LCA modeling described the system in 131 question. The description of technical parameters concerning thermal WtE processes 132 and the influence of these parameters on the results were evaluated. The waste input to 133 the WtE technology was evaluated with respect to the description of the waste type (all 134 waste types typically addressed in "waste management studies" were included: e.g. 135 households waste, mixed municipal solid waste, RDF/SRF, combustible industry waste, 136 or single fractions), waste composition (i.e. presence of individual material fractions 137 and their chemical composition) and the origin of these data. Key technology aspects of 138 the WtE processes were evaluated relative to thermal technology, energy recovery, and 139 residue management: i) plant type, ii) energy recovery and type of energy output, iii) 140 flue gas cleaning techniques (e.g. air-pollution-control: dust removal, acid gas 141 neutralization, deNO_x, etc.), and iv) residue types, generation and management. Finally, 142 available quantitative data for emissions and consumption of energy/materials were 143 extracted from the reviewed studies.

144 Key methodological aspects of the reviewed studies were addressed focusing on:
145 i) the overall modeling approach and whether the study accounted for and balanced
146 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.

149

150 **3. Results and discussion**

A total of 136 journal articles were identified, including 250 individual case-studies of technologies for thermal treatment of waste (Figure 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.

158

159 **3.1 Goal and scope definition**

160 Goal and scope definition includes specification of the aim of the study, its functional 161 unit (FU, quantitatively and qualitatively describing the service provided by the 162 assessed system), and the corresponding system boundaries. Goal and scope definitions 163 are fundamental for the interpretation of results and thereby for the outcome of LCA 164 studies (Laurent et al., 2014b, Finnveden et al., 2009, ISO 2006a, ISO 2006b). Most of 165 the reviewed case-studies applied an FU defined with respect to the waste input, e.g. as 166 a unit mass of waste received at the WtE facility (58 % of the case-studies). This FU 167 indicates an assessment perspective related to "waste management" or "treatment of X 168 Mg of waste", which subsequently allows comparison between individual "treatment 169 technologies". About 28 % of the case-studies had a FU represented by the waste 170 generation in a given area or region. Relatively few case-studies had FUs related to 171 specific inputs or outputs from the WtE facilities, or did not define the FU at all. About 172 68 % of the LCA case-studies either compared several WtE technologies against each 173 other, or compared WtE with other waste management options. In addition to the 68 % 174 of case-studies comparing specific technologies, about 26 % of the studies included 175 WtE as an integrated part of a waste management system in combination with other 176 technologies, e.g. Arena et al. (2003) and Tonini and Astrup (2012). Very few studies 177 applied LCA for process optimization: only 12 case-studies (5%) used LCA for 178 improvement of specific sub-units of individual plants (e.g. Scipioni et al., 2009, Møller 179 et al., 2011). Figure 2 provides an overview of goal and scope related aspects.

The waste input to the WtE facility is the starting point of the energy recovery process and is therefore essential for the LCA study (Laurent et al., 2014a, 2014b). Within the reviewed case-studies, a wide variety of waste materials have been addressed: from mixed household waste to single material fractions. About 38 % of the studies defined the waste input as "mixed municipal waste" and "residual municipal waste", while another 16 % addressed pre-treated waste (e.g. Solid Recovered Fuels, SRF) and yet another 27 % focused on single material fractions in the waste.

187 Time horizon, geographical and temporal scopes are important within LCA for 188 the applicability of the results and comparability with similar studies (Laurent et al., 189 2014a, 2014b, Finnveden et al., 2009, ISO 2006a, ISO 2006b, Finnveden, 1999, 190 Turconi et al., 2013). Most of the studies did not define the time horizon (75 %), 191 thereby not transparently reporting the included emissions and/or addressing the 192 dynamics e.g. related to long-term emissions from solid residues. A little less than half 193 (43 %) of the studies did not specify the temporal scope, i.e. the time period that the 194 technology and assessment addressed. Conversely, most studies (96 %) mentioned the 195 country or regional settings of the study.

Overall, relatively few (i.e. 41 case-studies or 16 %) of the reviewed LCA studies managed to provide full descriptions of the goal and scope (i.e. including detailed and transparent descriptions of the functional unit, the goal of the study, the time horizon, the geographical and temporal scopes), thereby essentially preventing direct comparison of results between studies and at the same time limiting the possibilities for full apprehension of the provided conclusions.

202

203 **3.2 Key technical parameters**

204 **3.2.1 Waste composition**

205 While the waste type addressed in the studies is important for the overall framework of 206 the study, the detailed composition of the waste may be critical with respect to the 207 emissions from the WtE facilities (e.g. Astrup et al., 2011). While 70 % of the case-208 studies provided a detailed description of the material fractions present in the waste (i.e. 209 quantities of plastic, paper, organic materials, etc.), only 44 % provided information 210 about the chemical composition of the waste and/or material fractions (see Figure 3). 211 About 18 % of the studies provided no description at all regarding chemical 212 composition, while 8 % provided only very limited description. This clearly represents a 213 limitation with respect to the LCA modeling as many emissions from thermal processes 214 (e.g. metals) are affected by the waste input chemistry (i.e. the emission represents a 215 certain fraction of the input quantity, e.g. Astrup et al., 2011). Although the lower 216 heating value (LHV) of the waste can be considered a critical parameter in relation to 217 WtE, LHV was reported in only 57 % of the case-studies, ranging between values such 218 as 1.4 MJ/kg ww (food waste, Nakakubo et al., 2012) and 46.9 MJ/kg ww (PET plastic, 219 Xie et al., 2013).

220 For those studies actually including waste composition data, the traceability of 221 the included data was limited. Of the studies including composition data, 18 % did not 222 report the origin of the data for material fractions, and 40 % did not specify the origin of 223 data for chemical composition (i.e. providing a clear reference to publications providing 224 the information). Omitting waste composition data in relation to LCA of WtE 225 technologies significantly reduces the transparency of the study, but also render the 226 results questionable as i) it may be unclear to which extent the study addresses 227 contaminants in the waste, and ii) essentially prevent reproducibility of the study.

228

229 **3.2.2 Thermal technologies**

Mass-burn incineration based on moving grate systems was the most frequently assessed technology. About 82 % of the case-studies focused on incineration; about half of these specified that the technology involved a moving grate (Figure 4). Significantly less attention has been placed on other WtE technologies such as pyrolysis, gasification, co-combustion in power plants and in cement-kilns. For a more balanced understanding of the environmental performance of WtE technologies, this clearly suggests that more studies are needed focusing on other technologies than incineration.

237 Generally, air-pollution-control (APC) systems were very poorly described. 238 Figure 5 illustrates that more than 50 % of the case-studies did not describe the specific 239 technology applied. This essentially prevents verification of the inventories (if 240 provided) for emissions and material/energy consumption, thereby preventing the 241 applicability of the studies to be evaluated. Omitting information about gas cleaning 242 also significantly reduces transparency with respect to geographical and temporal scope, 243 i.e. whether the technology is typical for the region and time period assessed. Only a 244 few case-studies clearly specified that individual gas cleaning units were not present,

e.g. in the case of poor or old plants (Morselli et al., 2007, Liamsanguan and Gheewala,246 2007).

247

248 **3.2.3 Energy recovery**

249 Energy recovery is one of the most important technical aspects of WtE technologies and 250 critical for the outcome of LCA studies (e.g. Boesch et al., 2014, Turconi et al., 2011, 251 Tunesi, 2011, Turconi et al., 2013). Figure 6 presents an overview of how energy 252 recovery was included in the reviewed case-studies. Energy recovery was included in 253 about 83 % of the studies, with electricity recovery being most important (73 % of the 254 case-studies), while heat was the only energy type recovered in 10 % of the studies. 255 About 5 % of the studies clearly stated that no energy recovery was performed at the 256 plant. About 12 % of the studies did not mention energy recovery at all. Of the 183 257 case-studies including electricity as an energy recovery option, 37 % stated the gross 258 electric efficiency, while 52 % mentioned the net electricity efficiency. Of the case-259 studies including heat recovery, 59 % reported the net heat recovery used in the 260 modeling (if no details were provided, net heat recovery was assumed).

261 An overview of the reported recovery efficiencies is provided in Table 2, 262 including average values calculated for individual technologies. The numerical variations are considerable, most likely as a result of geographical and temporal 263 264 differences between studies. For those studies reporting the temporal scope of the LCA 265 (i.e. 43 %), the recovery efficiencies were plotted against the temporal scope of the 266 study (see Figure S2 in the supplementary material). No clear trends for temporal 267 developments could be identified; however, large variations could be observed within 268 similar temporal scopes, suggesting that other factors had a larger influence on the 269 energy recovery efficiencies than temporal scope of the study.

270 For incineration, energy recovery efficiencies varied from 0 to 34 % (electricity) 271 and 0 to almost 88 % (heat), illustrating the wide variety of specific technologies and/or 272 facilities assessed in the reviewed studies. Although only very few studies of other 273 technologies than incineration existed, electricity efficiencies for co-combustion 274 appeared to be in the upper end of the range for incineration, while heat efficiencies 275 appeared to be significantly lower than for incineration. Gasification and pyrolysis 276 efficiencies could not be compared directly as the reported efficiencies were based on 277 gas-to-energy output conversion, excluding the syngas generation itself. Difference in 278 heat recovery between incinerators may not necessarily be related to technological 279 features, but may also be a consequence of local heat markets (e.g. Fruergaard et al., 280 2010). About 59 % of the case-studies related the energy recovery to the energy content 281 of the waste itself, while 31 % of the studies did not specify how the energy calculations 282 were performed. A few cases used default values from literature (2 %) or measured data 283 (4 %).

284

285 **3.2.4 Residue management**

Residue management was included only in about half of the case-studies (see Figure S3, supporting material). About 34 % did not specify whether or how residues were included in the modeling. Only in 11 % of the cases, the studies specified that residue management was intentionally excluded. In these cases, the justification was generally that residue management was not a "significant issue" overall; however, without providing evidence or support for the statement.

Of the studies providing information about residue management, the fate of the residues was generally poorly described (see Figure 7). Regarding APC residues (considered a combination of neutralization products and fly ashes unless otherwise

295 specified) and sludge from treatment of wastewater, more than 60 % of the case-studies 296 did not specify the management. Bottom and fly ashes were somewhat better addressed 297 with, respectively, around 42 % and 55 % of the studies specifying the management of 298 these ashes, respectively. In both cases, landfilling was the most commonly used option, 299 rather than recovery and material utilization. While the reviewed studies focusing on 300 WtE technologies may cover residue management only to a limited extent, a few studies 301 in literature provide dedicated LCA modeling of the management of APC residues (e.g. 302 Fruergaard et al., 2010) as well as utilization vs. landfilling of bottom ashes (e.g. 303 Birgisdottir et al., 2007).

304

305 3.2.5 Material/energy and emissions inventories

Input-output inventory tables are typically used to provide overview of all relevant
inputs (e.g. material and energy consumption) to WtE technologies as well as outputs
(e.g. air emissions). Only 14 % of the case-studies provided detailed inventory data.
About 57 % of the cases provided part of the inventories, in several cases limited to
very few data.

Besides completeness, the origin and quality of the inventory data may be of significant importance. For about 32 % of the case-studies, no information concerning the origin of inventory data was provided. About 20 % and 6 % of the studies applied data from literature and databases, respectively (see Figure S4, supplementary material). In only about 34 % of the case-studies, actual emission data originating from specific measurements related to the assessed system was included; the data mainly originated from full-scale facilities (i.e. 30 %).

318 For most parameters, extremely large variations (up to >10 orders of magnitude 319 in some cases) could be observed across the reviewed studies (see Table S10,

320 supplementary material). These large variations were especially pronounced for 321 emissions of trace compounds to air (e.g. PCDD/F, Hg, Cd, and As), but also for in-322 plant consumption of electricity and auxiliary fuels. These discrepancies in inventory 323 data can only partly be explained by technological differences and variations in 324 geographical and temporal scope of the studies. For example, systematic comparisons of 325 historical developments in air-pollution-control systems (Damgaard et al., 2010) have 326 demonstrated far less variations in air emissions, and thereby also environmental 327 impacts, than the variations indicated by the reviewed studies.

328 While not possible to examine based on the reviewed studies themselves, some of the observed differences in inventory data may be potential mistakes, either related to 329 330 the data generation or the manuscript writing. Examples are PCDD/F emissions in the 331 order of 600 mg/Mg of waste (Hong et al., 2006), Hg emissions of 15 g/Mg of wood 332 waste in case of steam gasification (Khoo et al., 2009), and oil consumption of more 333 than 300 kg/Mg of waste in a fluidized bed reactor (Ning et al., 2013). These values are 334 significantly higher than most other studies and the values should at least have been 335 argued relative to typical values found in literature.

Inventory data can be considered critical for the transparency of an individual study. But as specific inventory data from one study are often re-used by other studies in new LCA modeling contexts, the need for critical evaluation of values and comparison with well-documented studies in literature, before LCA modeling, should be evident.

341

342 3.3 Key methodological choices

343 **3.3.1 LCI modeling approach**

344 The approach used for modeling of emissions and energy recovery in LCA of WtE 345 technologies is potentially more important than in other types of LCA (Damgaard et al., 346 2010, Hellweg et al., 2001, Turconi et al., 2011), as these two aspects represent the 347 main environmental loads and potential benefits. In 55 % of the case-studies, the LCI 348 data appeared or was claimed to be based on mass and energy balances (see Figure 8). 349 In about 30 % of the cases, transfer coefficients (TC) were used to correlate the waste 350 input composition (chemistry and energy content) with the outputs from the WtE 351 process. Very few of these studies applied TCs to balance only mass or only energy (2 352 % and 8 %, respectively, of all cases). Another third of the case-studies (27 %) did not 353 mention applying any form of mass and energy balancing, suggesting that emissions 354 and/or flows in these cases could be inaccurate. The remaining third of the studies (33 355 %) applied some level of mass and/or energy balancing, but without specifying 356 correlations between inputs and outputs. In such cases, the LCA modeling results may 357 not be directly applicable to situations where the same WtE technology is used in the 358 context of different waste input compositions. Without sufficient information about the 359 modeling approach, the results may potentially include a significant (but unquantifiable) 360 error.

361

362 3.3.2 Capital goods

The environmental impacts related to capital goods, i.e. facilities and equipment, have only very recently been addressed systematically (e.g. Brogaard et al., 2013). In relation to WtE technologies, capital goods may have a significant influence on the LCA results, in particular for impact categories such as resource depletion, eutrophication and toxicity related impact categories (Brogaard et al., 2013). Only 19 % of the reviewed case-studies included capital goods (see Figure 9), while about 58 % of the studies did 369 not specify whether capital goods were included. About 23 % of the case-studies 370 reported that capital goods were intentionally excluded based on an argument that the 371 contribution was negligible overall. Based on recent literature, however, this conclusion 372 is questionable if an LCA involves aspects such as resource depletion, eutrophication 373 and toxicity related impacts.

374

375 **3.3.3 Avoided burdens from energy production**

376 Of the 238 case-studies in which energy recovery was considered (assuming that energy 377 was recovered unless explicitly stated as "not recovered"), substitution of energy within the energy system was modelled in 83 % of the cases by means of system expansion 378 379 (see Figure 10, left). In 6 % of the case-studies, energy substitution was not included 380 and environmental benefits from avoided production of energy and saving of fuels were 381 not addressed. Only in 11 % of the case-studies energy substitution was included but 382 not specified. Considering the importance of energy substitution for the overall LCA 383 results (Finnveden et al., 2005, Moberg et al., 2005, Laurent et al., 2014a, 2014b, 384 Finnveden et al., 2009), the high share of studies including avoided energy production is 385 encouraging.

Various approaches for quantification of the substituted energy exist in literature (e.g. Münster et al., 2013, Mathiesen et al., 2009, Fruergaard et al., 2009); this may at least partly be related to the overall LCA assessment approach, i.e. whether attributional or consequential modeling is applied. While attributional studies may include a mix or average of energy sources in a region, consequential LCA studies should involve the marginal technologies responding to an induced change in the energy system (Weidema, 2003, Weidema et al., 1999).

393 In 197 case-studies energy substitution was included. Of these about 46 % 394 applied the local energy mix for the substitution, while 34 % used a marginal energy 395 technology (Figure 10, middle). In 9 % of the studies, energy substitution was modeled 396 as direct substitution of a fuel, e.g. in the case of avoided consumption of coal in case of 397 co-combustion in cement-kilns or power plants. However, as the overall modeling 398 approach (attributional vs. consequential) was specified only in relatively few cases, it 399 was not possible to assess whether energy substitution was performed consistently with 400 the modeling approach.

401 Very few case-studies, 3 % (Figure 10, right), based decisions regarding energy 402 substitution on energy modeling (e.g. Bergsdal et al., 2005). Involving energy 403 modeling, i.e. modeling the consequences of an induced change in the energy supply 404 system from WtE, indicates a consequential approach to quantification of the 405 environmental impacts from WtE and an interest in regional conditions covered by the 406 energy model. A more generic approach would be to quantify energy substitution based 407 on scenario analysis, e.g. testing different possibilities for substituted fuels (e.g. Tonini 408 et al., 2013). About 33 % of the case-studies applied scenario analysis as basis for 409 energy substitution, while 43 % of the cases involved an energy mix based on literature 410 data. In 21 % of the cases, no explanation was provided regarding energy substitution.

411

412 **3.3.4 Sensitivity and uncertainty analysis**

413 Several approaches for assessing uncertainties within waste LCA exist (e.g. Wang and 414 Shen, 2013, Clavreul et al., 2013, Clavreul et al., 2012). Accepting the validity of the 415 mathematical models involved in the LCA calculations, studies should address both 416 scenario and parameter uncertainties to evaluate the robustness of the LCA conclusions. 417 Although recommended in international guidelines (e.g. Hauschild et al., 2012), 46 % of the case-studies did not include any assessment of uncertainties (see Figure 11). About
29 % of the cases included sensitivity analysis on selected parameters, while scenario
uncertainties were only evaluated in 41 % of the case-studies. Detailed quantification of
uncertainties, i.e. uncertainty propagation, was included in only 5 % of the case-studies.
This clearly indicates that the robustness of the majority of LCA results provided in
literature for WtE technologies is very poorly evaluated and the applicability of results
may be questionable.

425

426 **3.4 Overall conclusions from the LCA results**

427 Most of the reviewed studies focused on comparing WtE technologies with other 428 alternatives or included WtE as part of mixed scenarios with a variety of waste 429 technologies. For this reason, and because of possible variations in the technological 430 system (e.g. waste composition, technical performance, and framework conditions), it 431 was therefore not possible to single out one WtE technology over another. However, 432 some overall trends could be observed (see Table S12, supplementary materials).

433 The majority of studies (25 out of 29 scientific articles) comparing recycling and 434 landfilling with WtE confirmed the waste hierarchy (recycling > WtE > landfilling) for 435 the waste materials investigated. The remaining studies concluded that WtE was 436 preferable or comparable to recycling of paper and plastic (e.g. Manfredi et al., 2011). Generally, these differences were a consequence of differences in assumptions 437 438 regarding energy recovery efficiencies and the substituted energy (e.g. substituting 439 natural gas or an average mix decreased the environmental benefits associated with 440 WtE). Regardless of assumptions, all studies recommended that recycling of WEEE, 441 metals and C&D waste was preferable over incineration (e.g. Hischier et al., 2005, Ortiz 442 et al., 2010, Scharnhorst et al., 2006, Wäger et al., 2011). This was mainly due to the

significant environmental savings from avoided virgin production and low energyrecovery from these fractions.

445 Most studies (25 out of 29 scientific articles) clearly indicated WtE as preferable 446 over landfilling. A few studies concluded landfilling to be preferable for specific 447 material fractions and under specific assumptions for the energy systems: plastic bags 448 (Khoo et al., 2010), specific material fractions such as paper and plastic when a limited 449 LCA time horizon was considered (Moberg et al., 2005), packaging waste (Wollny et 450 al., 2001), and RDF when the substituted energy was based on natural gas (Montejo et 451 al., 2013). Most of these results are not surprising: state-of-the-art landfilling may 452 induce significant CO₂ and other environmental savings related to carbon sequestration 453 and energy recovery, and may perform comparable to WtE for specific waste fractions 454 and/or under specific energy system conditions as documented in e.g. Tonini et al. 455 (2013), Manfredi et al. (2011), and Manfredi et al. (2009).

456 Only few studies compared pyrolysis and gasification with direct combustion, 457 incineration, and co-combustion in power plants or cement kilns (Saft, 2007, Bientinesi 458 and Petarca, 2009, Nakakubo et al., 2012, Assefa et al., 2005, Gunamantha and Sarto, 459 2012, Hellweg et al., 2005). Overall these studies found pyrolysis and gasification 460 preferable over incineration and co-combustion in cement kilns. Only one case 461 (Nakakubo et al., 2012) pyrolysis and co-combustion in cement kilns were found 462 comparable (sludge treatment). In another case (Hellweg et al., 2005), incineration and 463 gasification were found comparable for the non-toxic impact categories, but gasification 464 appeared better for the toxic categories due to an advanced metal recovery system for 465 slags. In all cases, the assumptions regarding energy and metal recovery efficiencies 466 were crucial for the results. Often, the inventory data applied for incineration did not 467 represent state-of-the-art technologies and the technological scope of the compared WtE468 technologies were not always consistent.

469 No clear recommendation regarding RDF co-combustion in power plants or 470 cement kilns compared with direct incineration of untreated MSW could be found. 471 Three studies (Arena et al., 2003, Belboom et al., 2011, Houillon and Jolliet, 2005) 472 indicated incineration as preferable, while four (Cherubini et al., 2009, Blengini et al., 473 2012, Rigamonti et al., 2012, Ning et al., 2013) highlighted co-combustion as the best 474 option. Following this trend, also Tsiliyannis (1999) and Fruergaard and Astrup (2011) 475 showed a comparable performance for the non-toxic impact categories, mainly related 476 to the energy recovery. However, Fruergaard and Astrup (2011) also highlighted that 477 the improved flue-gas cleaning at waste incinerators (stricter emissions limits for Hg, 478 As, heavy metals, dioxins, etc.) may outperform that of coal-fired power plants, thus 479 inducing important savings in the toxic categories.

480

481 **3.5** Critical inconsistencies in existing literature

482 Overall, very few of the reviewed LCA studies provided sufficient description of goal 483 and scope of the LCA modeling and of the technologies included in the assessment. 484 Omitting this information prevents the necessary linking between the functional unit, 485 the waste composition and the WtE technology assessed, and further renders it 486 impossible to evaluate whether selected technical parameters match the temporal and 487 geographical scope of the assessment. Most studies in literature omitted key parts of the 488 technology system in the LCA modeling, e.g. air-pollution-control, residue 489 management, and capital goods, which may significantly affect the overall LCA results. 490 In cases where specific technology elements (e.g. air-pollution-control systems) were in

491 fact included, or appeared to be included, the underlying data were often very poorly492 described.

In addition to the scope and technology aspects, also the description of the LCA modeling approaches was often weak. This means that the validity of calculation principles could not be assessed and ultimately reproduced. With energy recovery modeling as an example, only 39 % of the studies provided both the LHV of the waste input and heat and electricity efficiencies, thereby allowing the reader to reproduce calculations. In all other cases, the validity of the energy calculations could not be fully examined.

While the LCA field has developed tremendously over the recent two decades and an acceptance of the complexities related to waste LCA modeling is increasing, this review clearly suggests that the quality of the peer-review process involved in scientific publishing of WtE LCA studies may be questionable.

504

505 **3.6 Recommendations for state-of-the-art LCA of WtE technologies**

506 Based on the reviewed literature, a range of practical recommendations for performing507 state-of-the-art LCA of WtE technologies and systems were identified:

508

- The LCA assessment approach, i.e. consequential or attributional, should be
 clearly stated. Most of the reviewed studies omitted this.
- The functional unit should not only describe the service provided by the system
 (e.g. utilization of 1 Mg of waste) but should be supplemented with a transparent
 description of temporal, geographical, and technological scope.
- Choice of technologies and recovery efficiencies should reflect the geographical, 515 temporal, and technological scope. New emerging technologies not yet

demonstrated in full-scale, should be compared with alternative technologies appropriate for the time period when a full-scale installation of the technology can be expected (e.g. Tonini et al., 2013). This means that performance, plant capacity, efficiencies, emission control, etc. of alternative technologies should be forecasted and matched, and the comparison not be based on old landfills or poorly performing incinerators represented by obsolete technologies and datasets.

LHV, material and preferably chemical composition of the waste should be reported, or alternatively a clear reference to the data source should be provided.
 Similar for the inventory data (particularly air emissions and consumption data).
 For green accounts and other non-peer-reviewed sources, (current) web links should be provided with the reference.

Energy substitution principles (marginal vs. average mix) should reflect the
 LCA assessment approach (consequential vs. attributional) and the temporal
 scope. Future marginal energy sources could be identified for example based on
 national energy plans or projections from energy agencies (e.g. IEA). Political
 targets could also be used to justify energy substitution as such targets may
 likely promote technology implementation/phase-out.

Detailed descriptions of mass, substance and energy flows in the WtE
 technology system should be provided (e.g. in supporting materials). Examples
 of consistent and transparent LCI reporting could be found in Blengini et al.
 (2012) or Rigamonti et al. (2012).

Uncertainty aspects should be systematically addressed, either by sensitivity
 analysis or by propagation of uncertainties. The type of uncertainty assessment
 should be clearly described (e.g. following the principles by Clavreul et al.,

541 2012). Examples of this can be found in Clavreul et al. (2013), Clavreul et al.
542 (2012), and Tonini et al. (2012).

- Environmental impacts from capital goods should be addressed if possible,
 either as part of a sensitivity analysis or by specifically including capital goods
 in the assessment (Brogaard et al., 2013, Brogaard and Christensen, 2012). Data
 on capital goods, however, are relatively scarce and inventory data are needed
 for several waste technologies (e.g. gasification, pyrolysis, mechanical biological treatment, recycling facilities including unit separation equipment).
- Environmental impacts associated with toxic emissions and resource depletion
 should be addressed. While climate change related impacts are typically affected
 by energy recovery efficiencies and energy substitution, specific differences
 between efficient state-of-the-art waste technologies are more likely to be
 observed in relation to resource depletion and toxicity related impacts (see
 Tonini et al., 2013). Including only non-toxic impact categories may therefore
 be insufficient.

556

557 **4. Conclusions**

558 The review included 136 peer-reviewed journal articles involving life cycle assessment 559 (LCA) of the following waste-to-energy (WtE) technology types: incineration, co-560 combustion, pyrolysis, and gasification. In total, these journal articles reported results 561 from 250 individual case-studies or scenarios. By far the most case-studies assessed 562 incineration, while relatively few studies addressed technologies such as 563 pyrolysis/gasification and co-combustion in detail. Very few of the reviewed studies 564 provided a sufficient description of i) goal and scope of the assessment, ii) the 565 technologies included, and the iii) the calculation principles applied for quantification of emissions and energy recovery. Consequently, the LCA results reported in the studies could be verified only in very few cases. This clearly questions the peer-review process involved prior to publication of the studies, but also significantly limits the applicability of inventory data and LCA results provided by the existing studies. The overview of assumptions and data applied in existing LCA literature offered by this review provides a consistent platform for future studies to ensure transparency and clear argumentation for assessment choices when addressing WtE technologies.

573

574 Supplementary Material

575 The supplementary material includes: i) a full list of references of the 136 reviewed 576 journal articles, ii) detailed review-metrics for all 250 case-studies, iii) list of extracted 577 inventory data, and iv) overview of main conclusions in the LCA studies.

578

579 Literature

Arena, U., Mastellone, M.L., Perugini, F., 2003. The environmental performance of
alternative solid waste management options: a life cycle assessment study. Chem.
Eng. J. 96, 207-222.

- Assefa, G., Eriksson, O., Frostell, B., 2005. Technology assessment of thermal
 treatment technologies using ORWARE. Energ. Conv. Manage. 46, 797-819.
- Astrup, T., Riber, C., Pedersen, A.J., 2011. Incinerator performance: effects of changes
 in waste input and furnace operation on air emissions and residues. Waste Manage.
 Res. 29, 57-68.
- Belboom, S., Renzoni, R., Verjans, B., Leonard, A., Germain, A., 2011. A life cycle
 assessment of injectable drug primary packaging: comparing the traditional process
 in glass vials with the closed vial technology (polymer vials). Int. J. Life Cycle
 Assess. 16, 159-167.

- Bergsdal, H., Stromman, A., Hertwich, E., 2005. Environmental assessment of two
 waste incineration strategies for central Norway. Int. J. Life Cycle Assess. 10, 263272.
- Bernstad, A., la Cour Jansen, J., 2011. A life cycle approach to the management of
 household food waste A Swedish full-scale case study. Waste Manage. 31, 18791896.
- 598 Bientinesi, M., Petarca, L., 2009. Comparative environmental analysis of waste
 599 brominated plastic thermal treatments. Waste Manage. 29, 1095-1102.
- Birgisdóttir H., Bhander G., Hauschild M.Z., Christensen T.H., 2007. Life cycle
 assessment of disposal of residues from municipal solid waste incineration: recycling
 of bottom ash in road construction or landfilling in Denmark evaluated in the
 ROAD-RES model. Waste Manage. 27, S75–84.
- Blengini, G.A., Fantoni, M., Busto, M., Genon, G., Zanetti, M.C., 2012. Participatory
 approach, acceptability and transparency of waste management LCAs: Case studies
 of Torino and Cuneo. Waste Manage. 32, 1712-1721.
- Boesch, M.E., Vadenbo, C., Saner, D., Huter, C., Hellweg, S., 2014. An LCA model for
 waste incineration enhanced with new technologies for metal recovery and
 application to the case of Switzerland. Waste Manage. 34, 378-389.
- Brogaard, L.K., Riber, C., Christensen, T.H., 2013. Quantifying capital goods for waste
 incineration. Waste Manage. 33, 1390-1396.
- Brogaard, L.K., Christensen, T.H., 2012. Quantifying capital goods for collection and
 transport of waste. Waste Manage. Res. 30, 1243-1250.
- 614 Cherubini, F., Bargigli, S., Ulgiati, S., 2009. Life cycle assessment (LCA) of waste
 615 management strategies: Landfilling, sorting plant and incineration. Energy 34, 2116616 2123.
- 617 Christensen, T.H., Simion, F., Tonini, D., Møller, J., 2009. Global warming factors
- modelled for 40 generic municipal waste management scenarios. Waste Manage.
 Res. 27, 871-884.
- 620 Clavreul, J., Guyonnet, D., Christensen, T.H., 2012. Quantifying uncertainty in LCA621 modelling of waste management systems. Waste Manage. 32, 2482-2495.
- 622 Clavreul, J., Guyonnet, D., Tonini, D., Christensen, T.H., 2013. Stochastic and
- 623 epistemic uncertainty propagation in LCA. Int. J. Life Cycle Assess. 18, 1393-1403.

- Damgaard, A., Riber, C., Fruergaard, T., Hulgaard, T., Christensen, T.H., 2010. Lifecycle-assessment of the historical development of air pollution control and energy
 recovery in waste incineration. Waste Manage. 30, 1244-1250.
- Ekvall, T., Assefa, G., Björklund, A., Eriksson, O., Finnveden, G., 2007. What lifecycle assessment does and does not do in assessments of waste management. Waste
 Manage. 27, 989-996.
- 630 Eriksson, O., Finnveden, G., Ekvall, T., Björklund, A., 2007. Life cycle assessment of
- fuels for district heating: A comparison of waste incineration, biomass- and naturalgas combustion. Energy Policy 35, 1346-1362.
- Finnveden, G., 1999. Methodological aspects of life cycle assessment of integrated solid
 waste management systems. Resour. Conserv. Recycl. 26, 173-187.
- Finnveden, G., Björklund, A., Reich, M.C., Eriksson, O., Sörbom, A., 2007. Flexible
 and robust strategies for waste management in Sweden. Waste Manage. 27, S1-S8.
- Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S.,
 Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in Life Cycle
 Assessment. J. Environ. Manage. 91, 1-21.
- Finnveden, G., Johansson, J., Lind, P., Moberg, Å., 2005. Life cycle assessment of
 energy from solid waste—part 1: general methodology and results. J. Clean. Prod.
 13, 213-229.
- Fruergaard, T., Astrup, T., 2011. Optimal utilization of waste-to-energy in an LCA
 perspective. Waste Manage. 31, 572-582.
- Fruergaard, T., Christensen, T.H., Astrup, T., 2010. Energy recovery from waste
 incineration: Assessing the importance of district heating networks. Waste Manage.
 30, 1264-1272.
- Fruergaard, T., Hyks, J., Astrup, T., 2010. Life-cycle assessment of selected
 management options for air pollution control residues from waste incineration. Sci.
 Total Environ. 408, 4672–4680.
- Fruergaard, T., Astrup, T., Ekvall, T., 2009. Energy use and recovery in waste
 management and implications for accounting of greenhouse gases and global
 warming contributions. Waste Manage. Res. 27, 724-737.

- Gunamantha, M., Sarto, 2012. Life cycle assessment of municipal solid waste treatment
 to energy options: Case study of KARTAMANTUL region, Yogyakarta. Renew.
 Energ. 41, 277-284.
- Hauschild, M., Goedkoop, M., Guinée, J., Heijungs, R., Huijbregts, M., Jolliet, O.,
 Margni, M., Schryver, A., Humbert, S., Laurent, A., Sala, S., Pant, R., 2012.
 Identifying best existing practice for characterization modeling in life cycle impact
 assessment. Int. J. Life Cycle Assess. 18, 1-15.
- Hellweg, S., Doka, G., Finnveden, G., Hungerbuhler, K., 2005. Assessing the ecoefficiency of end-of-pipe technologies with the environmental cost efficiency
 indicator A case study of solid waste management. J. Ind. Ecol. 9, 189-203.
- Hellweg, S., Hofstetter, T., Hungerbuhler, K., 2001. Modeling waste incineration for
 life-cycle inventory analysis in Switzerland. Environ. Model. Assess. 6, 219-235.
- Hischier, R., Wäger, P., Gauglhofer, J., 2005. Does WEEE recycling make sense from
 an environmental perspective? The environmental impacts of the Swiss take-back
 and recycling systems for waste electrical and electronic equipment (WEEE).
 Environ. Impact Assess. Rev. 25, 525-539.
- Hong, R.J., Wang, G.F., Guo, R.Z., Cheng, X., Liu, Q., Zhang, P.J., Qian, G.R. 2006.
 Life cycle assessment of BMT-based integrated municipal solid waste management:
 Case study in Pudong, China. Resour. Conserv. Recy. 49, 129–146
- Houillon, G., Jolliet, O., 2005. Life cycle assessment of processes for the treatment of
 wastewater urban sludge: energy and global warming analysis. J. Clean. Prod. 13,
 287-299.
- ISO, 2006a. Environmental Management-Life Cycle Assessment-Principles and
 Framework, 2nd ed.; ISO 14040; 2006-07-01; ISO: Geneva, 2006.
- ISO, 2006b. Environmental Management-Life Cycle Assessment-Requirements and
 Guidelines, 1st ed.; ISO 14040; 2006-07-01; ISO: Geneva, 2006.
- 680 ISWA, 2012. Waste-to-Energy State-of-the-Art-Report. Statistics, 6th edition. Ramboell:
- 681 Copenhagen (Denmark). Available at http://www.waste-management-
- 682 world.com/content/dam/wmw/online-
- articles/documents/2013/ISWA_WtE_State_of_the_Art_Report_2012_08_FV.pdf
- 684 (accessed March 2014).

- Khoo, H.H., 2009. Life cycle impact assessment of various waste conversion
 technologies. Waste Manage. 29, 1892-1900.
- Khoo, H.H., Lim, T.Z., Tan, R.B.H., 2010. Food waste conversion options in
 Singapore: Environmental impacts based on an LCA perspective. Sci. Total Environ.
 408, 1367-1373.
- 690 Laurent, A., Bakas, I., Clavreul, J., Bernstad, A., Niero, M., Gentil, E., Hauschild, M.Z.,
- 691 Christensen, T.H., 2014a. Review of LCA studies of solid waste management
- 692 systems Part I: Lessons learned and perspectives. Waste Manage. 34, 573–588.
- Laurent, A., Clavreul, J., Bernstad, A., Bakas, I., Niero, M., Gentil, E., Christensen,
 T.H., Hauschild, M.Z., 2014b. Review of LCA studies of solid waste management
 systems Part II: Methodological guidance for a better practice. Waste Manage. 34,
- 696
 589–606.
- Liamsanguan, C., Gheewala, S.H., 2007. Environmental assessment of energy
 production from municipal solid waste incineration. Int. J. Life Cycle Assess. 12,
 529-536.
- Manfredi, S., Tonini, D., Christensen, T.H., Scharff, H., 2009. Landfilling of waste:
 accounting of greenhouse gases and global warming contributions. Waste Manage.
 Res. 27, 825-836.
- Manfredi, S., Tonini, D., Christensen, T.H., 2011. Environmental assessment of
 different management options for individual waste fractions by means of life-cycle
 assessment modelling. Resour. Conserv. Recycl. 55, 995-1004.
- Mathiesen, B.V., Münster, M., Fruergaard, T., 2009. Uncertainties related to the
 identification of the marginal energy technology in consequential life cycle
 assessments. J. Clean. Prod. 17, 1331-1338.
- Merrild, H., Larsen, A.W., Christensen, T.H., 2012. Assessing recycling versus
 incineration of key materials in municipal waste: The importance of efficient energy
 recovery and transport distances. Waste Manage. 32, 1009-1018.
- 712 Moberg, Å., Finnveden, G., Johansson, J., Lind, P., 2005. Life cycle assessment of
- energy from solid waste—part 2: landfilling compared to other treatment methods. J.
 Clean. Prod. 13, 231-240.

- Møller, J., Munk, B., Crillesen, K., Christensen, T.H., 2011. Life cycle assessment of
 selective non-catalytic reduction (SNCR) of nitrous oxides in a full-scale municipal
 solid waste incinerator. Waste Manage. 31, 1184-1193.
- Montejo, C., Tonini, D., Márquez, M.C., Astrup, T.F., 2013. Mechanical-biological
 treatment: Performance and potentials. An LCA of 8 MBT plants including waste
 characterization. J. Environ. Manage. 128, 661-673.
- Morselli, L., Luzi, J., Robertis, C.D., Vassura, I., Carrillo, V., Passarini, F., 2007.
 Assessment and comparison of the environmental performances of a regional incinerator network. Waste Manage. 27, S85-S91.
- Münster, M., Finnveden, G., Wenzel, H., 2013. Future waste treatment and energy
 systems examples of joint scenarios. Waste Manage. 33, 2457-2464.
- Nakakubo, T., Tokai, A., Ohno, K., 2012. Comparative assessment of technological
 systems for recycling sludge and food waste aimed at greenhouse gas emissions
 reduction and phosphorus recovery. J. Clean. Prod. 32, 157-172.
- Ning, S., Chang, N., Hung, M., 2013. Comparative streamlined life cycle assessment for
 two types of municipal solid waste incinerator. J. Clean. Prod. 53, 56-66.
- 731 Ortiz, O., Pasqualino, J.C., Castells, F., 2010. Environmental performance of
 732 construction waste: Comparing three scenarios from a case study in Catalonia, Spain.
 733 Waste Manage. 30, 646-654.
- Rigamonti, L., Grosso, M., Møller, J., Martinez Sanchez, V., Magnani, S., Christensen,
 T.H., 2014. Environmental evaluation of plastic waste management scenarios.
 Resour. Conserv. Recycl. 85, 42-53.
- Rigamonti, L., Grosso, M., Biganzoli, L., 2012. Environmental Assessment of RefuseDerived Fuel Co-Combustion in a Coal-Fired Power Plant. J. Ind. Ecol. 16(5), 748739 760.
- 740 Scipioni, A., Mazzi, A., Niero, M., Boatto, T., 2009. LCA to choose among alternative
- design solutions: The case study of a new Italian incineration line. Waste Manage.29, 2462-2474.
- Saft, R.J., 2007. Life cycle assessment of a pyrolysis/gasification plant for hazardous
 paint waste. Int. J. Life Cycle Assess. 12, 230-238.

- Scharnhorst, W., Hilty, L.M., Jolliet, O., 2006. Life cycle assessment of second
 generation (2G) and third generation (3G) mobile phone networks. Environ. Int. 32,
 656-675.
- Song, Q., Wang, Z., Li, J., 2013. Environmental performance of municipal solid waste
 strategies based on LCA method: a case study of Macau. J. Clean. Prod. 57, 92-100.
- Tonini, D., Astrup, T., 2012. Life-cycle assessment of a waste refinery process for
 enzymatic treatment of municipal solid waste. Waste Manage. 32, 165-176.
- Tonini, D., Hamelin, L., Wenzel, H., Astrup, T., 2012. Bioenergy Production from
 Perennial Energy Crops: A Consequential LCA of 12 Bioenergy Scenarios including
- Land Use Changes. Environ. Sci. Technol. 46, 13521-13530.
- Tonini, D., Martinez-Sanchez, V., Astrup, T.F., 2013. Material Resources, Energy, and
 Nutrient Recovery from Waste: Are Waste Refineries the Solution for the Future?
 Environ. Sci. Technol. 47, 208962-8969.
- Tsiliyannis, C.A., 1999. Report: Comparison of environmental impacts from solid waste
 treatment and disposal facilities. Waste Management and Research 17, 231-241.
- Tunesi, S., 2011. LCA of local strategies for energy recovery from waste in England,
 applied to a large municipal flow. Waste Manage. 31, 561-571.
- Turconi, R., Boldrin, A., Astrup, T., 2013. Life cycle assessment (LCA) of electricity
 generation technologies: Overview, comparability and limitations. Renew. Sust.
 Energ. Rev. 28, 555-565.
- Turconi, R., Butera, S., Boldrin, A., Grosso, M., Rigamonti, L., Astrup, T., 2011. Life
 cycle assessment of waste incineration in Denmark and Italy using two LCA models.
 Waste Manage. Res. 29, 78-90.
- Wäger, P.A., Hischier, R., Eugster, M., 2011. Environmental impacts of the Swiss
 collection and recovery systems for Waste Electrical and Electronic Equipment
 (WEEE): A follow-up. Sci. Total Environ. 409, 1746-1756.
- Wang, E., Shen, Z., 2013. A hybrid Data Quality Indicator and statistical method for
 improving uncertainty analysis in LCA of complex system application to the
 whole-building embodied energy analysis. J. Clean. Prod. 43, 166-173.
- Weidema, B., 2003. Market information in life cycle assessment. Environmental project
- 775 863. Available at: http://www.norlca.org/resources/780.pdf (accessed January 2014).

- Weidema, B., Frees, N., Nielsen, A.M., 1999. Marginal production technologies for
 Life Cycle Inventories. Int. J. Life Cycle Assess. 4, 48-56.
- Wollny, V., Dehoust, G., Fritsche, U.R., Weinem, P., 2001. Comparison of Plastic
 Packaging Waste Management Options: Feedstock Recycling versus Energy
 Recovery in Germany. J. Ind. Ecol. 5, 49-63.
- 781 Zaman, A.U., 2010. Comparative study of municipal solid waste treatment technologies
- using life cycle assessment method. Int. J. Environ. Sci. Technol. 7, 225-234.
- 783
- 784
- 785

786 Table 1. Overview of the aspects addressed in the review. The classification of each aspect is listed supplemented with a brief description (*italic*)

787 when relevant. MSW indicates Municipal Solid Waste representing waste typically collected from households and small business/industry.

	Element	Classifications used in this study (description in Italic)
	- Functional unit	1 Mg, Generation (waste generated in a Region), Input (amount of waste entering a treatment facility), Output (amount of energy produced), Not specified
Goal and scope	- Type of LCA study	WtE comparison, WtE vs. other (WtE vs. other technologies), Mixed scenarios (different technologies in the same scenarios), Optimization (-oriented), Not specified
	- Time horizon	Time horizon of the LCA study (e.g. 100 years)
	- Geographical scope	Globe, Continent, International, Nation, Region, Municipality, Plant, Sub-plant (a section of a plant, e.g. air-pollution-control system), Not specified
	- Temporal scope	Temporal scope of the study (e.g. the study focuses on conditions and technologies for 2014, or for 2020, or for 2050, etc.)
	- Waste input	
	0 Waste type	Mix household (no source-segregation), Residual household (H) (household left-over after source-segregation), Mix Municipal (mixed MSW), Residual Municipal (MSW after so segregation), Industrial (I), Sludge (S), Mix H-I, Mix H-S, Mix I-S, Mix H-I-S, Single fraction, Pre-treated (SRF, etc.), Not specified
	o Waste composition	Material fraction + full chemical (>20 elements), Material fraction + partial chemical (< 10 elements), Only material fraction, Only full chemical, Only partial chemical, Very li description, No description
	o Data origin	Sampling (own data), Literature, Database, Not specified, Mix literature/database, Mix measured/literature
	- Technology	
	• Type of thermal treatment	Incineration, pyrolysis, gasification, co-combustion (power plant or cement kiln)
	o Plant capacity	Amount of waste potentially treated or of power output (e.g. Mg/year)
	◦ Type of reactor	Inc - Moving grate, Inc - Rotary kiln, Inc - Fluidised bed, Gas - updraft, Gas - Downdraft, Gas - Rotary kiln, Gas - Fluidised bed, Not specified
	 Dust removal 	Cyclone, Electrostatic precipitators (ESPs), Fabric or bag house filters, High efficiency Ventury scrubbers, Not specified
	o Treatment of acid gases	Wet, Semidry, Dry, Not specified
	0 PCDD/F removal	Activated carbon, Catalytic bag, Not specified
Technical	o deNOx system	SNCR (Selective non catalytic reactor), SCR (Selective catalytic reactor), Not specified
parameters and	o Data origin	Full-scale, Pilot-scale, Lab-scale, Literature, Database, Mix literature/database, Mix measured/literature, Not specified
inventory data	 Gas combustion system 	Engine, boiler, Gas turbine, Not specified
	- Energy recovery	
	 Type of energy recovered 	Electricity and heat, Only electricity, Only heat, No recovery, Transport fuel, Not specified
	 Energy recovery efficiency 	Based on LHV, Based on literature, Not specified
	 Availability of district heating 	Available, Not available, To be built, Not specified, Heat not recovered
	- Management of residues	
	◦ Bottom ash	Landfill, Road construction, Other recycling/reuse, Not specified
	 APC residues 	Landfill, Stabilization + landfill, Other recycling/reuse, Not specified
	\circ Fly ash	Landfill, Stabilization + landfill, Other recycling/reuse, Together with APC (i.e. considered all together), Backfilling old mines, Not specified
	 Sludge from WW treatment 	to WWTP, Intentionally excluded, Not specified, Not relevant, Landfilled
	- Inventory data	
	 Air emissions 	Selected air emissions (NOx, N2O, SOx, CO, dust, PCDD/F, Hg, Pb, As, Cr, Cu, Cd, Mn, Ni) when reported
	◦ Input of energy	Auxiliary fuels, electricity, and heat consumed in the process
	 Input of materials 	Materials and chemicals consumed in the process

	 LCA modeling approach 					
	o Mass/Energy balance	Mass+energy (TC), Only mass (TC), Only energy (TC), Mass+energy, Only mass, Only energy, No balance. TC: transfer coefficients (the balance explicitly uses transfer coefficients (the balance explicitly uses transfer coefficients (the balance explicitly uses transfer coefficients) and chemicals, or energy)				
Methodological	- Capital goods	Included, Intentionally excluded, Not specified				
choices in LCA	- Savings from energy production					
modeling	 Type of energy substituted 	Fuel source (or mix of fuels) substituted by the electricity recovered in the scenario under assessment				
	 Energy substitution model 	Marginal, Average mix, Not specified				
	- Uncertainty/sensitivity analysis					
	o Type of uncertainty analysis	Sensitivity on parameters only, Scenario analysis only, Uncertainty propagation only, Sensitivity+scenario, Sensitivity+propagation, Scenario+propagation, All, None				

- 790 Table 2. Overview of energy recovery efficiencies in case-studies reporting such data.
- 791 Average and standard deviation (st.dev.) is provided when more than two case-studies
- 792 was available. Gasification and pyrolysis efficiencies are based on gas-electricity and
- 793 gas-heat conversions only.

	Gross electricity efficiency		Net electricity efficiency			Net heat efficiency			
	N. case- studies	Range (%)	Average ±st.dev. (%)	N. case- studies	Range (%)	Average ±st.dev. (%)	N. case- studies	Range (%)	Average ±st.dev. (%)
Incineration	61	0-34	21±7.0	87	-2-30	19±7.5	68	0-87.7	44±28.4
Co-combustion in cement-kilns	1	4.38	-	0	-	-	0	-	-
Co-combustion in power plants	2	34-40	-	2	34.0	-	3	26-40	31±8.1
Gasification	2	33-34	-	5	14.5-27.2	20±5.3	2	33-45.5	-
Pyrolysis	1	18.0	-	1	15.25	-	1	70.3	-
Pyrolysis-gasification	1	35.0	-	0	-	-	1	40.0	-

796	List o	of figure	captions

798	Figure 1. Temporal development of LCA case-studies on thermal WtE technologies.
799	Bars indicate number of case-studies in individual years, left y-axis, while diamonds
800	represent the cumulative number of case-studies (244), right y-axis.
801	
802	Figure 2. Overview of functional unit, goal of the LCA and waste types included in
803	the reviewed case-studies.
804	
805	Figure 3. Overview of information provided on waste composition in the reviewed
806	case-studies.
807	
808	Figure 4. Overview of thermal technologies included in the reviewed case-studies.
809	
810	Figure 5. Overview of technical aspects related to air-pollution-control (APC) systems
811	in the reviewed case-studies.
812	
813	Figure 6. Overview of energy recovery options and calculation principles in the
814	reviewed case-studies.
815	
816	Figure 7. Overview of residues management in the reviewed case-studies.
817	
818	Figure 8. Overview of overall LCI modeling approaches included in the reviewed
819	case-studies (TC: transfer coefficients).
820	

- 821 Figure 9. Overview of capital goods modeling in the reviewed case-studies.
- 822
- 823 Figure 10. Overview of energy substitution approaches in the reviewed case-studies.
- 824
- 825 Figure 11. Overview of sensitivity/uncertainty analysis in the reviewed case-studies.























