

Technical University of Denmark



## 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](https://doi.org/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. DOI: 10.1016/j.wasman.2014.06.011

**DTU Library**  
Technical Information Center of Denmark

---

### 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  
32 management, and inventory data), and iii) modeling principles (e.g. energy/mass  
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**

44 Energy recovery from waste is an essential part of modern waste management. Within  
45 the last decades, waste management has changed from being a sector primarily focusing  
46 on treatment and final disposal of residual streams from society to now being a sector  
47 that contributes significantly to energy provision and secondary resource recovery. In

48 the transition towards more sustainable energy supply, energy recovery from waste is  
49 gaining increasing interest as an option for reducing dependence on imported fossil  
50 fuels. In a future with higher shares of intermittent energy sources such as wind and  
51 photo voltaic, and phase-out of coal, energy recovery from waste may provide an  
52 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  
69 is needed here). Co-combustion, gasification, and pyrolysis are generally less  
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  
75 highlighted by Laurent et al. (2014a, 2014b). Technology modeling principles, LCA  
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

97 which may not provide novel insights from a research perspective. Consequently, this  
98 situation may significantly limit the overall value of LCA studies for future  
99 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.

122

## 123 **2.2. Review approach**

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

128 In relation to “goal and scope definition”, it was assessed whether a clear and  
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<sub>x</sub>, 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,

147 and iv) inclusion of uncertainty and/or sensitivity analysis. Finally, overall trends in  
148 results between the reviewed studies were identified and discussed.

149

### 150 **3. Results and discussion**

151 A total of 136 journal articles were identified, including 250 individual case-studies of  
152 technologies for thermal treatment of waste (Figure 1). The complete list of studies is  
153 provided in the supplementary material (Table S13). Only few studies were performed  
154 prior to 2002, no studies before 1995 was found. Throughout the following sections,  
155 comparability between studies is discussed and understood as the possibility for the  
156 reader to appreciate the LCA results based on transparent reporting of assumptions,  
157 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.

180         The waste input to the WtE facility is the starting point of the energy recovery  
181 process and is therefore essential for the LCA study (Laurent et al., 2014a, 2014b).  
182 Within the reviewed case-studies, a wide variety of waste materials have been  
183 addressed: from mixed household waste to single material fractions. About 38 % of the  
184 studies defined the waste input as "mixed municipal waste" and "residual municipal  
185 waste", while another 16 % addressed pre-treated waste (e.g. Solid Recovered Fuels,  
186 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.

196 Overall, relatively few (i.e. 41 case-studies or 16 %) of the reviewed LCA  
197 studies managed to provide full descriptions of the goal and scope (i.e. including  
198 detailed and transparent descriptions of the functional unit, the goal of the study, the  
199 time horizon, the geographical and temporal scopes), thereby essentially preventing  
200 direct comparison of results between studies and at the same time limiting the  
201 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**

230 Mass-burn incineration based on moving grate systems was the most frequently  
231 assessed technology. About 82 % of the case-studies focused on incineration; about half  
232 of these specified that the technology involved a moving grate (Figure 4). Significantly  
233 less attention has been placed on other WtE technologies such as pyrolysis, gasification,  
234 co-combustion in power plants and in cement-kilns. For a more balanced understanding  
235 of the environmental performance of WtE technologies, this clearly suggests that more  
236 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,

245 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  
263 variations are considerable, most likely as a result of geographical and temporal  
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**

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

292 Of the studies providing information about residue management, the fate of the  
293 residues was generally poorly described (see Figure 7). Regarding APC residues  
294 (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**

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

311 Besides completeness, the origin and quality of the inventory data may be of  
312 significant importance. For about 32 % of the case-studies, no information concerning  
313 the origin of inventory data was provided. About 20 % and 6 % of the studies applied  
314 data from literature and databases, respectively (see Figure S4, supplementary material).  
315 In only about 34 % of the case-studies, actual emission data originating from specific  
316 measurements related to the assessed system was included; the data mainly originated  
317 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  
329 of the observed differences in inventory data may be potential mistakes, either related to  
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.

336         Inventory data can be considered critical for the transparency of an individual  
337 study. But as specific inventory data from one study are often re-used by other studies  
338 in new LCA modeling contexts, the need for critical evaluation of values and  
339 comparison with well-documented studies in literature, before LCA modeling, should  
340 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**

363 The environmental impacts related to capital goods, i.e. facilities and equipment, have  
364 only very recently been addressed systematically (e.g. Brogaard et al., 2013). In relation  
365 to WtE technologies, capital goods may have a significant influence on the LCA results,  
366 in particular for impact categories such as resource depletion, eutrophication and  
367 toxicity related impact categories (Brogaard et al., 2013). Only 19 % of the reviewed  
368 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  
378 the energy system was modelled in 83 % of the cases by means of system expansion  
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.

386 Various approaches for quantification of the substituted energy exist in literature  
387 (e.g. Münster et al., 2013, Mathiesen et al., 2009, Fruergaard et al., 2009); this may at  
388 least partly be related to the overall LCA assessment approach, i.e. whether attributional  
389 or consequential modeling is applied. While attributional studies may include a mix or  
390 average of energy sources in a region, consequential LCA studies should involve the  
391 marginal technologies responding to an induced change in the energy system  
392 (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

418 the case-studies did not include any assessment of uncertainties (see Figure 11). About  
419 29 % of the cases included sensitivity analysis on selected parameters, while scenario  
420 uncertainties were only evaluated in 41 % of the case-studies. Detailed quantification of  
421 uncertainties, i.e. uncertainty propagation, was included in only 5 % of the case-studies.  
422 This clearly indicates that the robustness of the majority of LCA results provided in  
423 literature for WtE technologies is very poorly evaluated and the applicability of results  
424 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).  
437 Generally, these differences were a consequence of differences in assumptions  
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. Hirschier et al., 2005, Ortiz  
442 et al., 2010, Scharnhorst et al., 2006, Wäger et al., 2011). This was mainly due to the

443 significant environmental savings from avoided virgin production and low energy  
444 recovery 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 CO<sub>2</sub> 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 WtE  
468 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 poorly  
492 described.

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

500 While the LCA field has developed tremendously over the recent two decades  
501 and an acceptance of the complexities related to waste LCA modeling is increasing, this  
502 review clearly suggests that the quality of the peer-review process involved in scientific  
503 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 performing  
507 state-of-the-art LCA of WtE technologies and systems were identified:

508

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

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

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

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

534 • Detailed descriptions of mass, substance and energy flows in the WtE  
535 technology system should be provided (e.g. in supporting materials). Examples  
536 of consistent and transparent LCI reporting could be found in Blengini et al.  
537 (2012) or Rigamonti et al. (2012).

538 • Uncertainty aspects should be systematically addressed, either by sensitivity  
539 analysis or by propagation of uncertainties. The type of uncertainty assessment  
540 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).

543 • Environmental impacts from capital goods should be addressed if possible,  
544 either as part of a sensitivity analysis or by specifically including capital goods  
545 in the assessment (Brogaard et al., 2013, Brogaard and Christensen, 2012). Data  
546 on capital goods, however, are relatively scarce and inventory data are needed  
547 for several waste technologies (e.g. gasification, pyrolysis, mechanical-  
548 biological treatment, recycling facilities including unit separation equipment).

549 • Environmental impacts associated with toxic emissions and resource depletion  
550 should be addressed. While climate change related impacts are typically affected  
551 by energy recovery efficiencies and energy substitution, specific differences  
552 between efficient state-of-the-art waste technologies are more likely to be  
553 observed in relation to resource depletion and toxicity related impacts (see  
554 Tonini et al., 2013). Including only non-toxic impact categories may therefore  
555 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



566 emissions and energy recovery. Consequently, the LCA results reported in the studies  
567 could be verified only in very few cases. This clearly questions the peer-review process  
568 involved prior to publication of the studies, but also significantly limits the applicability  
569 of inventory data and LCA results provided by the existing studies. The overview of  
570 assumptions and data applied in existing LCA literature offered by this review provides  
571 a consistent platform for future studies to ensure transparency and clear argumentation  
572 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**

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

583 Assefa, G., Eriksson, O., Frostell, B., 2005. Technology assessment of thermal  
584 treatment technologies using ORWARE. *Energ. Conv. Manage.* 46, 797-819.

585 Astrup, T., Riber, C., Pedersen, A.J., 2011. Incinerator performance: effects of changes  
586 in waste input and furnace operation on air emissions and residues. *Waste Manage.*  
587 *Res.* 29, 57-68.

588 Belboom, S., Renzoni, R., Verjans, B., Leonard, A., Germain, A., 2011. A life cycle  
589 assessment of injectable drug primary packaging: comparing the traditional process  
590 in glass vials with the closed vial technology (polymer vials). *Int. J. Life Cycle*  
591 *Assess.* 16, 159-167.

- 592 Bergsdal, H., Stromman, A., Hertwich, E., 2005. Environmental assessment of two  
593 waste incineration strategies for central Norway. *Int. J. Life Cycle Assess.* 10, 263-  
594 272.
- 595 Bernstad, A., la Cour Jansen, J., 2011. A life cycle approach to the management of  
596 household food waste – A Swedish full-scale case study. *Waste Manage.* 31, 1879-  
597 1896.
- 598 Bientinesi, M., Petarca, L., 2009. Comparative environmental analysis of waste  
599 brominated plastic thermal treatments. *Waste Manage.* 29, 1095-1102.
- 600 Birgisdóttir H., Bhandar G., Hauschild M.Z., Christensen T.H., 2007. Life cycle  
601 assessment of disposal of residues from municipal solid waste incineration: recycling  
602 of bottom ash in road construction or landfilling in Denmark evaluated in the  
603 ROAD-RES model. *Waste Manage.* 27, S75–84.
- 604 Blengini, G.A., Fantoni, M., Busto, M., Genon, G., Zanetti, M.C., 2012. Participatory  
605 approach, acceptability and transparency of waste management LCAs: Case studies  
606 of Torino and Cuneo. *Waste Manage.* 32, 1712-1721.
- 607 Boesch, M.E., Vadenbo, C., Saner, D., Huter, C., Hellweg, S., 2014. An LCA model for  
608 waste incineration enhanced with new technologies for metal recovery and  
609 application to the case of Switzerland. *Waste Manage.* 34, 378-389.
- 610 Brogaard, L.K., Riber, C., Christensen, T.H., 2013. Quantifying capital goods for waste  
611 incineration. *Waste Manage.* 33, 1390-1396.
- 612 Brogaard, L.K., Christensen, T.H., 2012. Quantifying capital goods for collection and  
613 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, 2116-  
616 2123.
- 617 Christensen, T.H., Simion, F., Tonini, D., Møller, J., 2009. Global warming factors  
618 modelled for 40 generic municipal waste management scenarios. *Waste Manage.*  
619 *Res.* 27, 871-884.
- 620 Clavreul, J., Guyonnet, D., Christensen, T.H., 2012. Quantifying uncertainty in LCA-  
621 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.

- 624 Damgaard, A., Riber, C., Fruergaard, T., Hulgaard, T., Christensen, T.H., 2010. Life-  
625 cycle-assessment of the historical development of air pollution control and energy  
626 recovery in waste incineration. *Waste Manage.* 30, 1244-1250.
- 627 Ekvall, T., Assefa, G., Björklund, A., Eriksson, O., Finnveden, G., 2007. What life-  
628 cycle assessment does and does not do in assessments of waste management. *Waste*  
629 *Manage.* 27, 989-996.
- 630 Eriksson, O., Finnveden, G., Ekvall, T., Björklund, A., 2007. Life cycle assessment of  
631 fuels for district heating: A comparison of waste incineration, biomass- and natural  
632 gas combustion. *Energy Policy* 35, 1346-1362.
- 633 Finnveden, G., 1999. Methodological aspects of life cycle assessment of integrated solid  
634 waste management systems. *Resour. Conserv. Recycl.* 26, 173-187.
- 635 Finnveden, G., Björklund, A., Reich, M.C., Eriksson, O., Sörbom, A., 2007. Flexible  
636 and robust strategies for waste management in Sweden. *Waste Manage.* 27, S1-S8.
- 637 Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S.,  
638 Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in Life Cycle  
639 Assessment. *J. Environ. Manage.* 91, 1-21.
- 640 Finnveden, G., Johansson, J., Lind, P., Moberg, Å., 2005. Life cycle assessment of  
641 energy from solid waste—part 1: general methodology and results. *J. Clean. Prod.*  
642 13, 213-229.
- 643 Fruergaard, T., Astrup, T., 2011. Optimal utilization of waste-to-energy in an LCA  
644 perspective. *Waste Manage.* 31, 572-582.
- 645 Fruergaard, T., Christensen, T.H., Astrup, T., 2010. Energy recovery from waste  
646 incineration: Assessing the importance of district heating networks. *Waste Manage.*  
647 30, 1264-1272.
- 648 Fruergaard, T., Hyks, J., Astrup, T., 2010. Life-cycle assessment of selected  
649 management options for air pollution control residues from waste incineration. *Sci.*  
650 *Total Environ.* 408, 4672–4680.
- 651 Fruergaard, T., Astrup, T., Ekvall, T., 2009. Energy use and recovery in waste  
652 management and implications for accounting of greenhouse gases and global  
653 warming contributions. *Waste Manage. Res.* 27, 724-737.

654 Gunamantha, M., Sarto, 2012. Life cycle assessment of municipal solid waste treatment  
655 to energy options: Case study of KARTAMANTUL region, Yogyakarta. *Renew.*  
656 *Energ.* 41, 277-284.

657 Hauschild, M., Goedkoop, M., Guinée, J., Heijungs, R., Huijbregts, M., Jolliet, O.,  
658 Margni, M., Schryver, A., Humbert, S., Laurent, A., Sala, S., Pant, R., 2012.  
659 Identifying best existing practice for characterization modeling in life cycle impact  
660 assessment. *Int. J. Life Cycle Assess.* 18, 1-15.

661 Hellweg, S., Doka, G., Finnveden, G., Hungerbuhler, K., 2005. Assessing the eco-  
662 efficiency of end-of-pipe technologies with the environmental cost efficiency  
663 indicator - A case study of solid waste management. *J. Ind. Ecol.* 9, 189-203.

664 Hellweg, S., Hofstetter, T., Hungerbuhler, K., 2001. Modeling waste incineration for  
665 life-cycle inventory analysis in Switzerland. *Environ. Model. Assess.* 6, 219-235.

666 Hirschler, R., Wäger, P., Gauglhofer, J., 2005. Does WEEE recycling make sense from  
667 an environmental perspective? The environmental impacts of the Swiss take-back  
668 and recycling systems for waste electrical and electronic equipment (WEEE).  
669 *Environ. Impact Assess. Rev.* 25, 525-539.

670 Hong, R.J., Wang, G.F., Guo, R.Z., Cheng, X., Liu, Q., Zhang, P.J., Qian, G.R. 2006.  
671 Life cycle assessment of BMT-based integrated municipal solid waste management:  
672 Case study in Pudong, China. *Resour. Conserv. Recy.* 49, 129–146

673 Houillon, G., Jolliet, O., 2005. Life cycle assessment of processes for the treatment of  
674 wastewater urban sludge: energy and global warming analysis. *J. Clean. Prod.* 13,  
675 287-299.

676 ISO, 2006a. Environmental Management-Life Cycle Assessment-Principles and  
677 Framework, 2nd ed.; ISO 14040; 2006-07-01; ISO: Geneva, 2006.

678 ISO, 2006b. Environmental Management-Life Cycle Assessment-Requirements and  
679 Guidelines, 1st ed.; ISO 14040; 2006-07-01; ISO: Geneva, 2006.

680 ISWA, 2012. Waste-to-Energy State-of-the-Art-Report. Statistics, 6<sup>th</sup> edition. Ramboell:  
681 Copenhagen (Denmark). Available at [http://www.waste-management-](http://www.waste-management-world.com/content/dam/wmw/online-articles/documents/2013/ISWA_WtE_State_of_the_Art_Report_2012_08_FV.pdf)  
682 [world.com/content/dam/wmw/online-](http://www.waste-management-world.com/content/dam/wmw/online-articles/documents/2013/ISWA_WtE_State_of_the_Art_Report_2012_08_FV.pdf)  
683 [articles/documents/2013/ISWA\\_WtE\\_State\\_of\\_the\\_Art\\_Report\\_2012\\_08\\_FV.pdf](http://www.waste-management-world.com/content/dam/wmw/online-articles/documents/2013/ISWA_WtE_State_of_the_Art_Report_2012_08_FV.pdf)  
684 (accessed March 2014).

- 685 Khoo, H.H., 2009. Life cycle impact assessment of various waste conversion  
686 technologies. *Waste Manage.* 29, 1892-1900.
- 687 Khoo, H.H., Lim, T.Z., Tan, R.B.H., 2010. Food waste conversion options in  
688 Singapore: Environmental impacts based on an LCA perspective. *Sci. Total Environ.*  
689 408, 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.
- 693 Laurent, A., Clavreul, J., Bernstad, A., Bakas, I., Niero, M., Gentil, E., Christensen,  
694 T.H., Hauschild, M.Z., 2014b. Review of LCA studies of solid waste management  
695 systems – Part II: Methodological guidance for a better practice. *Waste Manage.* 34,  
696 589–606.
- 697 Liamsanguan, C., Gheewala, S.H., 2007. Environmental assessment of energy  
698 production from municipal solid waste incineration. *Int. J. Life Cycle Assess.* 12,  
699 529-536.
- 700 Manfredi, S., Tonini, D., Christensen, T.H., Scharff, H., 2009. Landfilling of waste:  
701 accounting of greenhouse gases and global warming contributions. *Waste Manage.*  
702 *Res.* 27, 825-836.
- 703 Manfredi, S., Tonini, D., Christensen, T.H., 2011. Environmental assessment of  
704 different management options for individual waste fractions by means of life-cycle  
705 assessment modelling. *Resour. Conserv. Recycl.* 55, 995-1004.
- 706 Mathiesen, B.V., Münster, M., Fruergaard, T., 2009. Uncertainties related to the  
707 identification of the marginal energy technology in consequential life cycle  
708 assessments. *J. Clean. Prod.* 17, 1331-1338.
- 709 Merrild, H., Larsen, A.W., Christensen, T.H., 2012. Assessing recycling versus  
710 incineration of key materials in municipal waste: The importance of efficient energy  
711 recovery and transport distances. *Waste Manage.* 32, 1009-1018.
- 712 Moberg, Å., Finnveden, G., Johansson, J., Lind, P., 2005. Life cycle assessment of  
713 energy from solid waste—part 2: landfilling compared to other treatment methods. *J.*  
714 *Clean. Prod.* 13, 231-240.

- 715 Møller, J., Munk, B., Crillesen, K., Christensen, T.H., 2011. Life cycle assessment of  
716 selective non-catalytic reduction (SNCR) of nitrous oxides in a full-scale municipal  
717 solid waste incinerator. *Waste Manage.* 31, 1184-1193.
- 718 Montejo, C., Tonini, D., Márquez, M.C., Astrup, T.F., 2013. Mechanical–biological  
719 treatment: Performance and potentials. An LCA of 8 MBT plants including waste  
720 characterization. *J. Environ. Manage.* 128, 661-673.
- 721 Morselli, L., Luzi, J., Robertis, C.D., Vassura, I., Carrillo, V., Passarini, F., 2007.  
722 Assessment and comparison of the environmental performances of a regional  
723 incinerator network. *Waste Manage.* 27, S85-S91.
- 724 Münster, M., Finnveden, G., Wenzel, H., 2013. Future waste treatment and energy  
725 systems – examples of joint scenarios. *Waste Manage.* 33, 2457-2464.
- 726 Nakakubo, T., Tokai, A., Ohno, K., 2012. Comparative assessment of technological  
727 systems for recycling sludge and food waste aimed at greenhouse gas emissions  
728 reduction and phosphorus recovery. *J. Clean. Prod.* 32, 157-172.
- 729 Ning, S., Chang, N., Hung, M., 2013. Comparative streamlined life cycle assessment for  
730 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.
- 734 Rigamonti, L., Grosso, M., Møller, J., Martinez Sanchez, V., Magnani, S., Christensen,  
735 T.H., 2014. Environmental evaluation of plastic waste management scenarios.  
736 *Resour. Conserv. Recycl.* 85, 42-53.
- 737 Rigamonti, L., Grosso, M., Biganzoli, L., 2012. Environmental Assessment of Refuse-  
738 Derived Fuel Co-Combustion in a Coal-Fired Power Plant. *J. Ind. Ecol.* 16(5), 748-  
739 760.
- 740 Scipioni, A., Mazzi, A., Niero, M., Boatto, T., 2009. LCA to choose among alternative  
741 design solutions: The case study of a new Italian incineration line. *Waste Manage.*  
742 29, 2462-2474.
- 743 Saft, R.J., 2007. Life cycle assessment of a pyrolysis/gasification plant for hazardous  
744 paint waste. *Int. J. Life Cycle Assess.* 12, 230-238.

745 Scharnhorst, W., Hilty, L.M., Jolliet, O., 2006. Life cycle assessment of second  
746 generation (2G) and third generation (3G) mobile phone networks. *Environ. Int.* 32,  
747 656-675.

748 Song, Q., Wang, Z., Li, J., 2013. Environmental performance of municipal solid waste  
749 strategies based on LCA method: a case study of Macau. *J. Clean. Prod.* 57, 92-100.

750 Tonini, D., Astrup, T., 2012. Life-cycle assessment of a waste refinery process for  
751 enzymatic treatment of municipal solid waste. *Waste Manage.* 32, 165-176.

752 Tonini, D., Hamelin, L., Wenzel, H., Astrup, T., 2012. Bioenergy Production from  
753 Perennial Energy Crops: A Consequential LCA of 12 Bioenergy Scenarios including  
754 Land Use Changes. *Environ. Sci. Technol.* 46, 13521-13530.

755 Tonini, D., Martinez-Sanchez, V., Astrup, T.F., 2013. Material Resources, Energy, and  
756 Nutrient Recovery from Waste: Are Waste Refineries the Solution for the Future?  
757 *Environ. Sci. Technol.* 47, 208962-8969.

758 Tsiliyannis, C.A., 1999. Report: Comparison of environmental impacts from solid waste  
759 treatment and disposal facilities. *Waste Management and Research* 17, 231-241.

760 Tunesi, S., 2011. LCA of local strategies for energy recovery from waste in England,  
761 applied to a large municipal flow. *Waste Manage.* 31, 561-571.

762 Turconi, R., Boldrin, A., Astrup, T., 2013. Life cycle assessment (LCA) of electricity  
763 generation technologies: Overview, comparability and limitations. *Renew. Sust.*  
764 *Energ. Rev.* 28, 555-565.

765 Turconi, R., Butera, S., Boldrin, A., Grosso, M., Rigamonti, L., Astrup, T., 2011. Life  
766 cycle assessment of waste incineration in Denmark and Italy using two LCA models.  
767 *Waste Manage. Res.* 29, 78-90.

768 Wäger, P.A., Hischer, R., Eugster, M., 2011. Environmental impacts of the Swiss  
769 collection and recovery systems for Waste Electrical and Electronic Equipment  
770 (WEEE): A follow-up. *Sci. Total Environ.* 409, 1746-1756.

771 Wang, E., Shen, Z., 2013. A hybrid Data Quality Indicator and statistical method for  
772 improving uncertainty analysis in LCA of complex system – application to the  
773 whole-building embodied energy analysis. *J. Clean. Prod.* 43, 166-173.

774 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).

776 Weidema, B., Frees, N., Nielsen, A.M., 1999. Marginal production technologies for  
777 Life Cycle Inventories. *Int. J. Life Cycle Assess.* 4, 48-56.

778 Wollny, V., Dehoust, G., Fritsche, U.R., Weinem, P., 2001. Comparison of Plastic  
779 Packaging Waste Management Options: Feedstock Recycling versus Energy  
780 Recovery in Germany. *J. Ind. Ecol.* 5, 49-63.

781 Zaman, A.U., 2010. Comparative study of municipal solid waste treatment technologies  
782 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 <i>Italic</i> )
Goal and scope	<ul style="list-style-type: none"> <li>- Functional unit 1 Mg, Generation (<i>waste generated in a Region</i>), Input (<i>amount of waste entering a treatment facility</i>), Output (<i>amount of energy produced</i>), Not specified</li> <li>- Type of LCA study WtE comparison, WtE vs. other (<i>WtE vs. other technologies</i>), Mixed scenarios (<i>different technologies in the same scenarios</i>), Optimization (<i>-oriented</i>), Not specified</li> <li>- Time horizon <i>Time horizon of the LCA study (e.g. 100 years)</i></li> <li>- Geographical scope Globe, Continent, International, Nation, Region, Municipality, Plant, Sub-plant (<i>a section of a plant, e.g. air-pollution-control system</i>), Not specified</li> <li>- Temporal scope <i>Temporal scope of the study (e.g. the study focuses on conditions and technologies for 2014, or for 2020, or for 2050, etc )</i></li> </ul>
Technical parameters and inventory data	<ul style="list-style-type: none"> <li>- Waste input               <ul style="list-style-type: none"> <li>o Waste type Mix household (<i>no source-segregation</i>), Residual household (H) (<i>household left-over after source-segregation</i>), Mix Municipal (<i>mixed MSW</i>), Residual Municipal (<i>MSW after source-segregation</i>), Industrial (I), Sludge (S), Mix H-I, Mix H-S, Mix I-S, Mix H-I-S, Single fraction, Pre-treated (<i>SRF, etc.</i>), Not specified</li> <li>o Waste composition Material fraction + full chemical (<i>&gt;20 elements</i>), Material fraction + partial chemical (<i>&lt; 10 elements</i>), Only material fraction, Only full chemical, Only partial chemical, Very limited description, No description</li> <li>o Data origin Sampling (<i>own data</i>), Literature, Database, Not specified, Mix literature/database, Mix measured/literature</li> </ul> </li> <li>- Technology               <ul style="list-style-type: none"> <li>o Type of thermal treatment Incineration, pyrolysis, gasification, co-combustion (power plant or cement kiln)</li> <li>o Plant capacity <i>Amount of waste potentially treated or of power output (e.g. Mg/year)</i></li> <li>o Type of reactor Inc - Moving grate, Inc - Rotary kiln, Inc - Fluidised bed, Gas - updraft, Gas - Downdraft, Gas - Rotary kiln, Gas - Fluidised bed, Not specified</li> <li>o Dust removal Cyclone, Electrostatic precipitators (ESPs), Fabric or bag house filters, High efficiency Ventury scrubbers, Not specified</li> <li>o Treatment of acid gases Wet, Semidry, Dry, Not specified</li> <li>o PCDD/F removal Activated carbon, Catalytic bag, Not specified</li> <li>o deNOx system SNCR (<i>Selective non catalytic reactor</i>), SCR (<i>Selective catalytic reactor</i>), Not specified</li> <li>o Data origin Full-scale, Pilot-scale, Lab-scale, Literature, Database, Mix literature/database, Mix measured/literature, Not specified</li> <li>o Gas combustion system Engine, boiler, Gas turbine, Not specified</li> </ul> </li> <li>- Energy recovery               <ul style="list-style-type: none"> <li>o Type of energy recovered Electricity and heat, Only electricity, Only heat, No recovery, Transport fuel, Not specified</li> <li>o Energy recovery efficiency Based on LHV, Based on literature, Not specified</li> <li>o Availability of district heating Available, Not available, To be built, Not specified, Heat not recovered</li> </ul> </li> <li>- Management of residues               <ul style="list-style-type: none"> <li>o Bottom ash Landfill, Road construction, Other recycling/reuse, Not specified</li> <li>o APC residues Landfill, Stabilization + landfill, Other recycling/reuse, Not specified</li> <li>o Fly ash Landfill, Stabilization + landfill, Other recycling/reuse, Together with APC (<i>i.e. considered all together</i>), Backfilling old mines, Not specified</li> <li>o Sludge from WW treatment to WWTP, Intentionally excluded, Not specified, Not relevant, Landfilled</li> </ul> </li> <li>- Inventory data               <ul style="list-style-type: none"> <li>o Air emissions <i>Selected air emissions (NO<sub>x</sub>, N<sub>2</sub>O, SO<sub>x</sub>, CO, dust, PCDD/F, Hg, Pb, As, Cr, Cu, Cd, Mn, Ni) when reported</i></li> <li>o Input of energy <i>Auxiliary fuels, electricity, and heat consumed in the process</i></li> <li>o Input of materials <i>Materials and chemicals consumed in the process</i></li> </ul> </li> </ul>

---

	- LCA modeling approach	
	o Mass/Energy balance	Mass+energy (TC), Only mass (TC), Only energy (TC), Mass+energy, Only mass, Only energy, No balance. <i>TC: transfer coefficients (the balance explicitly uses transfer coefficients related to input of mass and chemicals, or energy)</i>
Methodological choices in LCA modeling	- Capital goods	Included, Intentionally excluded, Not specified
	- Savings from energy production	
	o Type of energy substituted	<i>Fuel source (or mix of fuels) substituted by the electricity recovered in the scenario under assessment</i>
	o 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

---

788

789

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	-

794

795

796 **List of figure captions**

797

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.

826

Figure 01

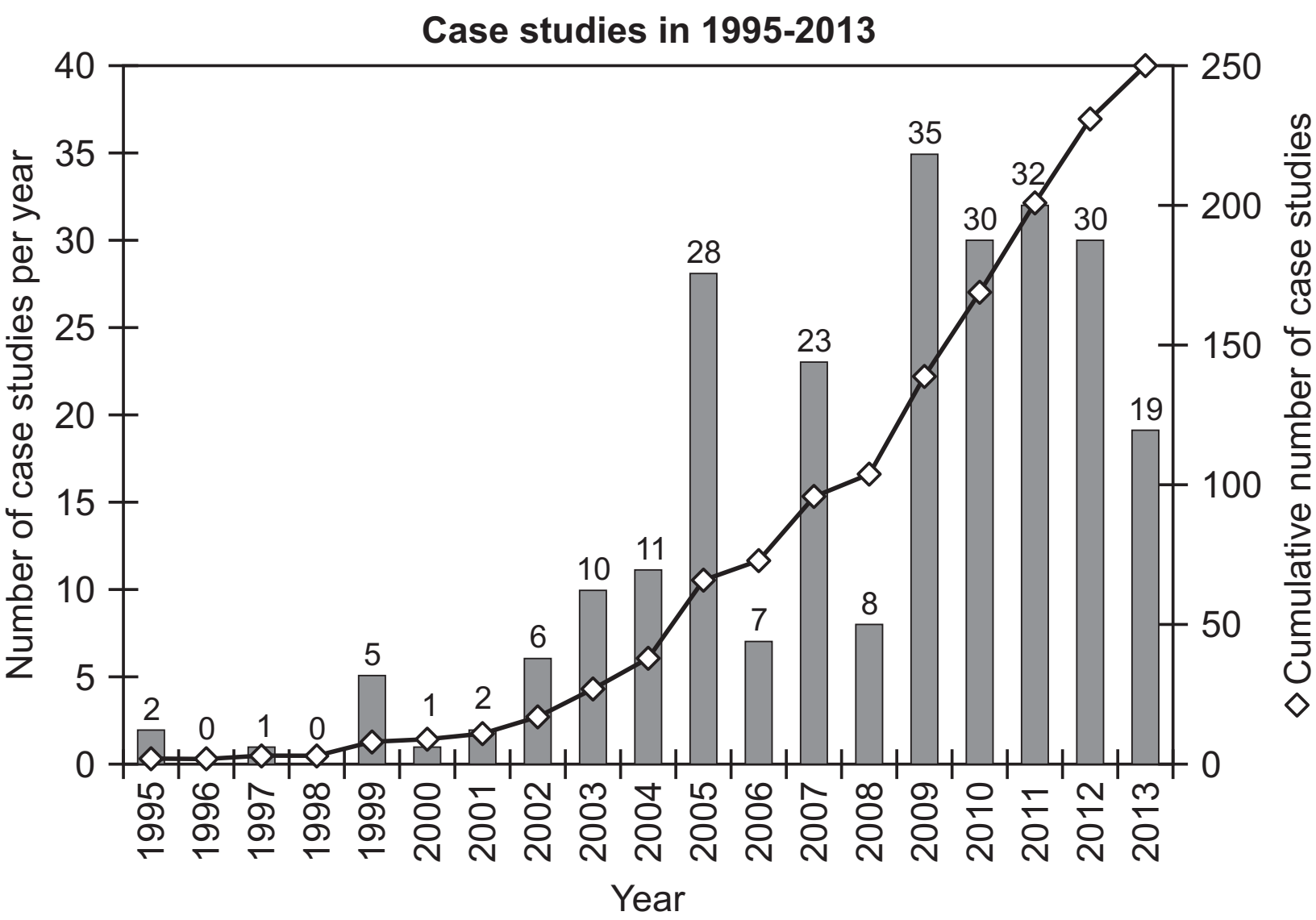


Figure 02

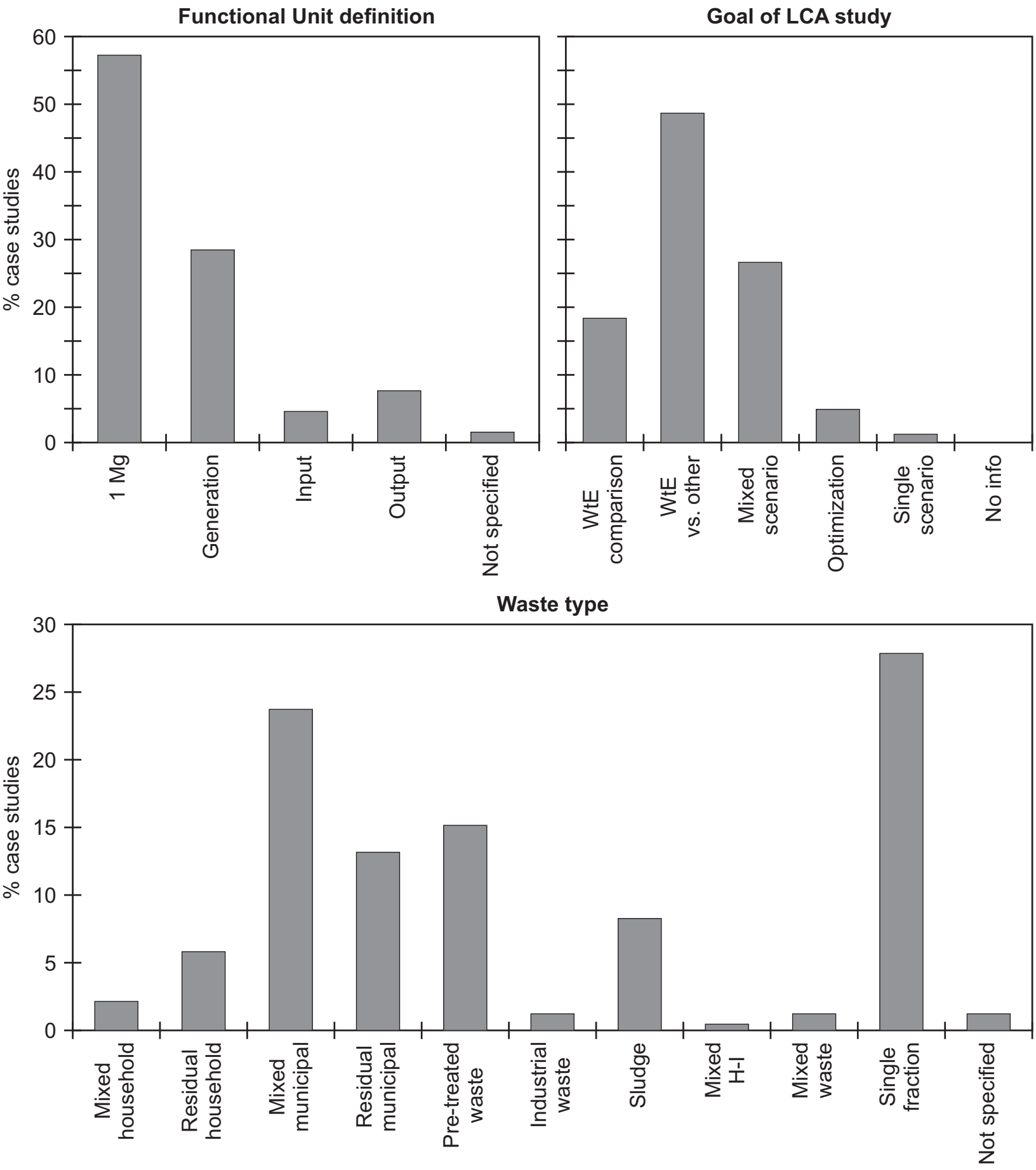


Figure 03

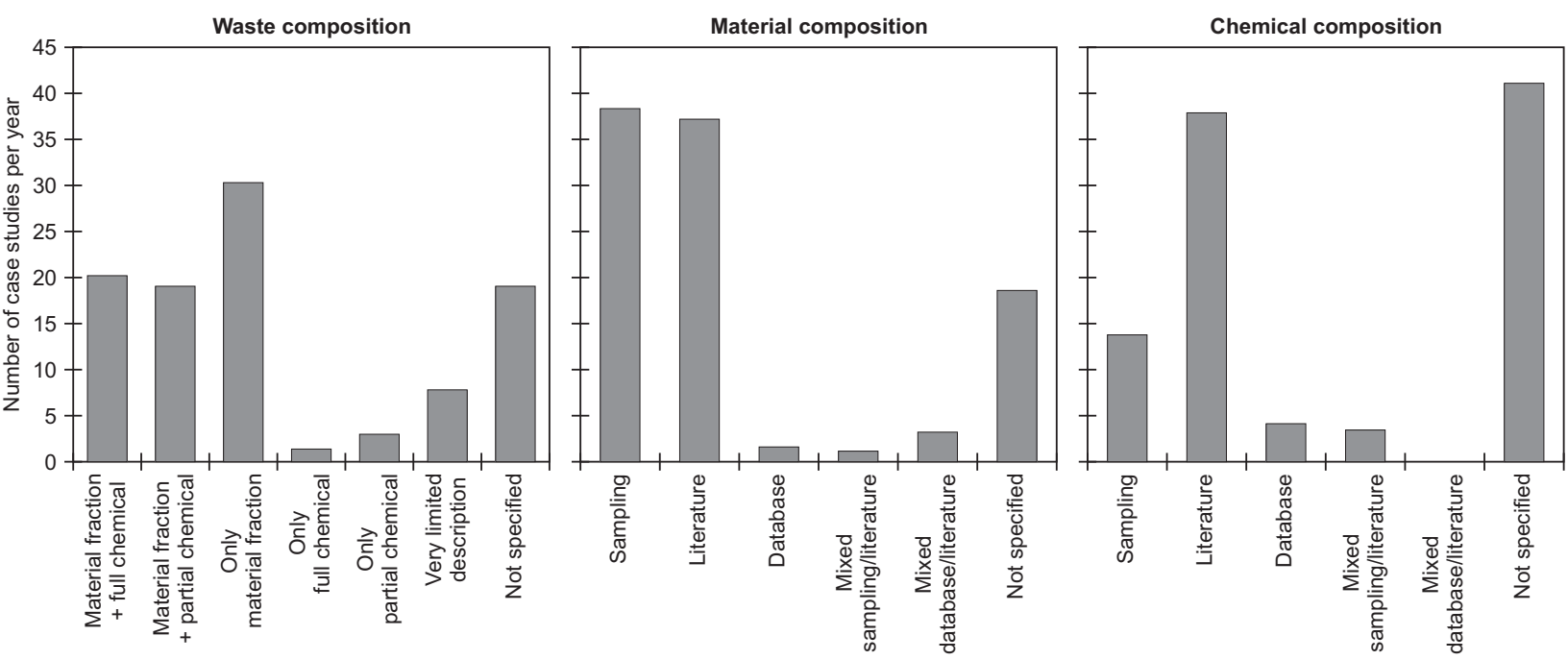




Figure 04

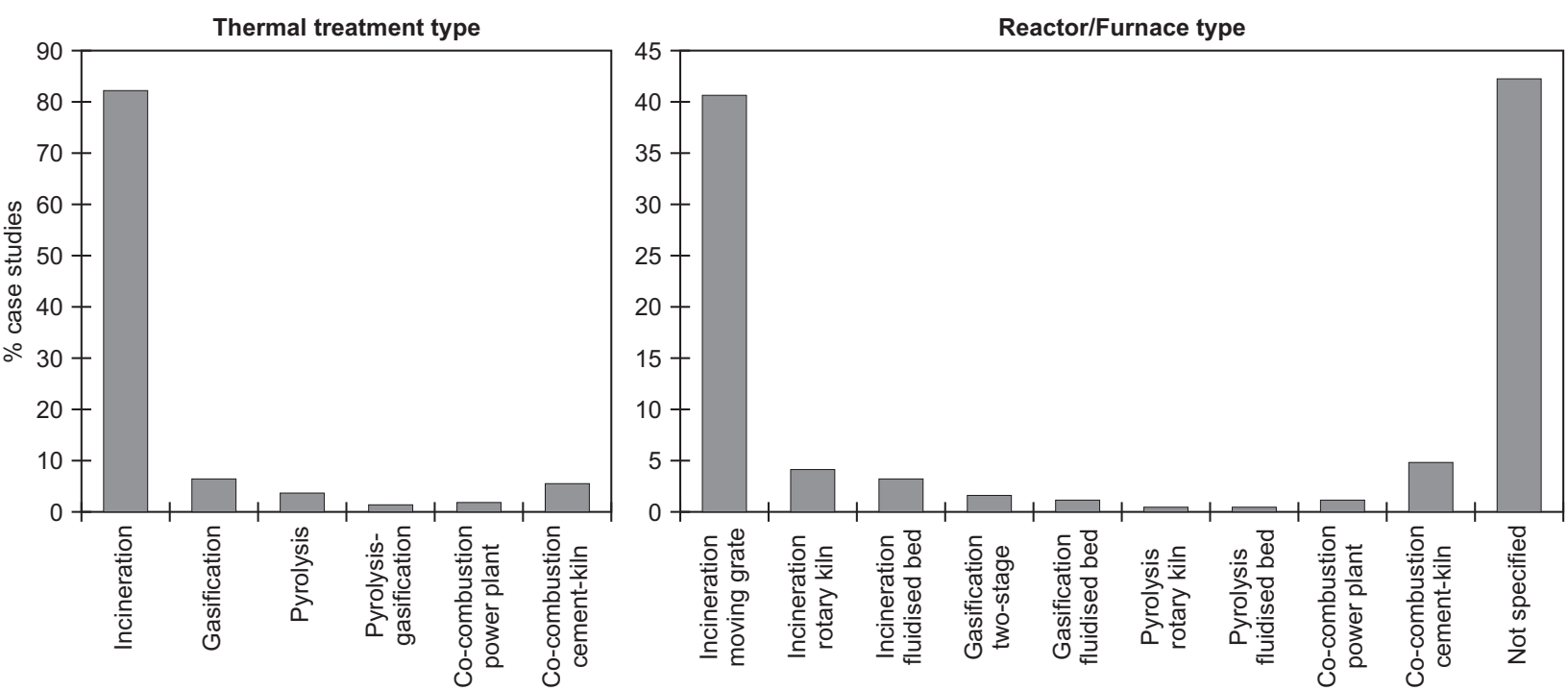


Figure 05

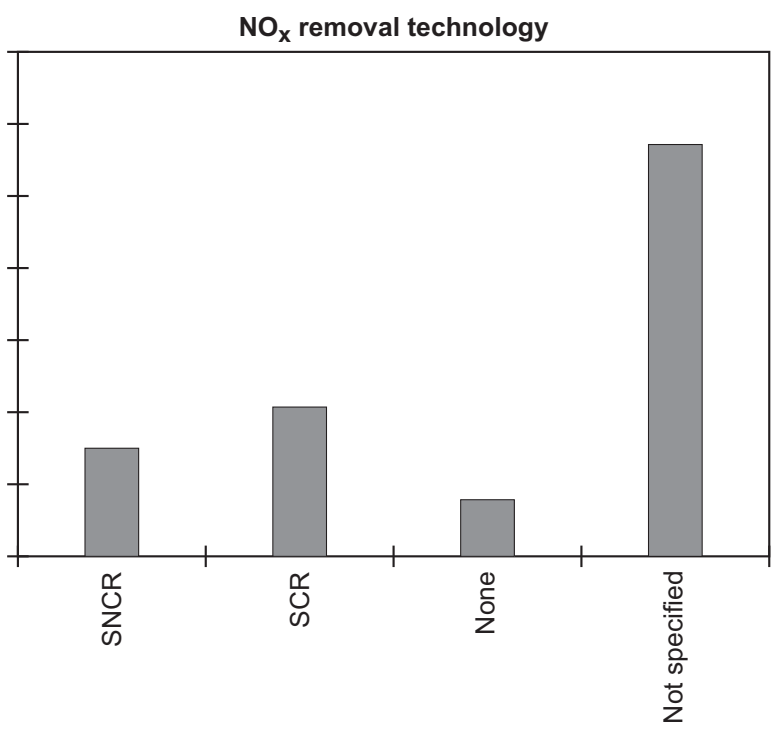
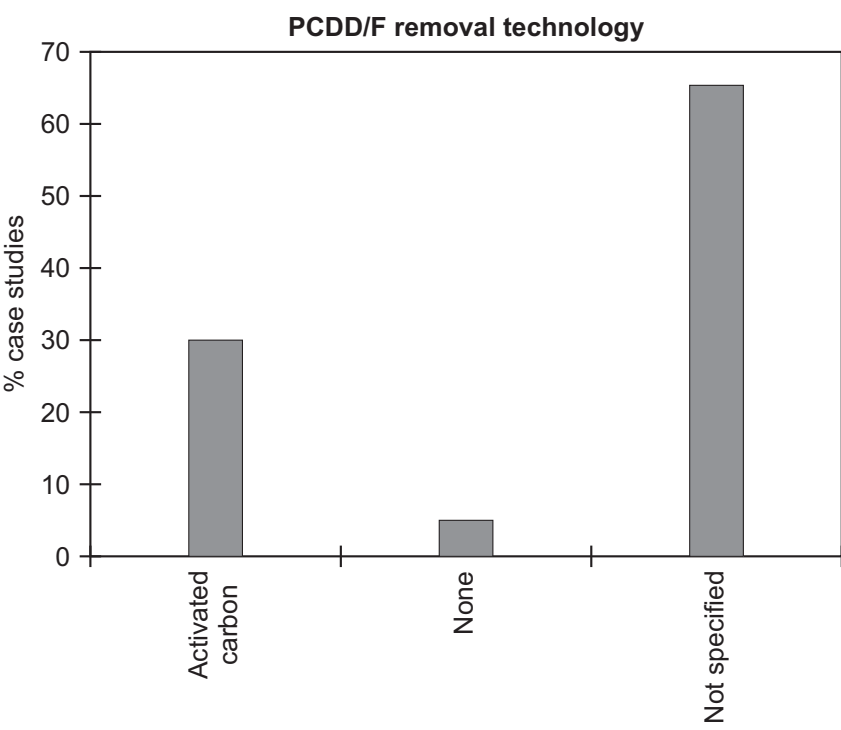
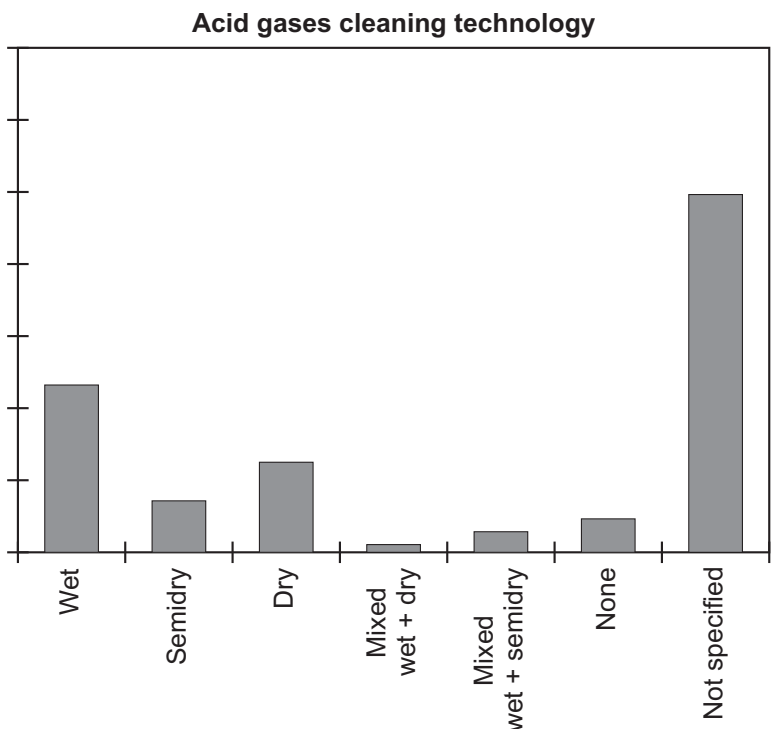
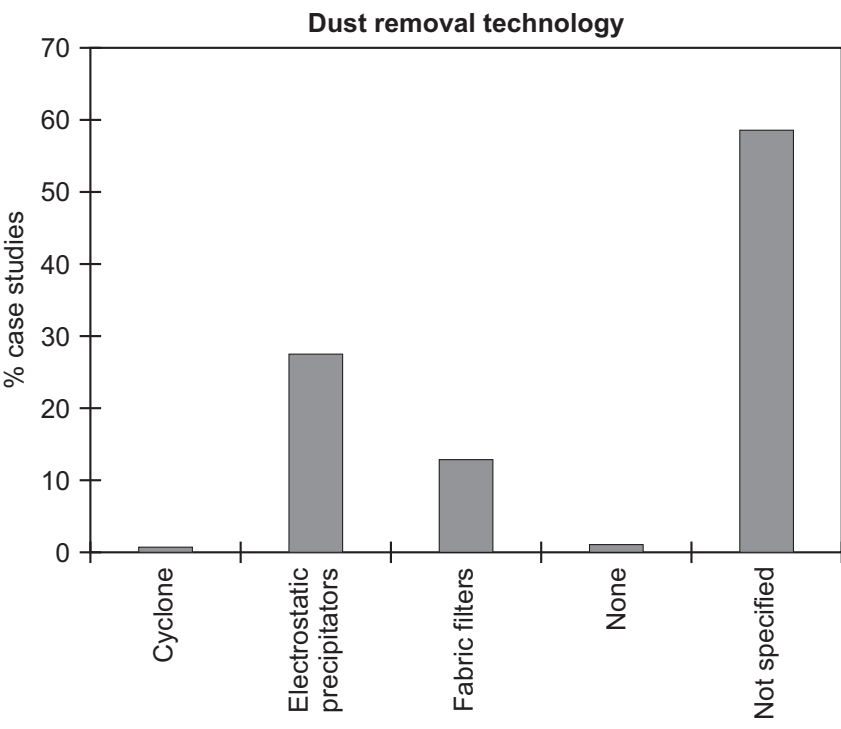


Figure 06

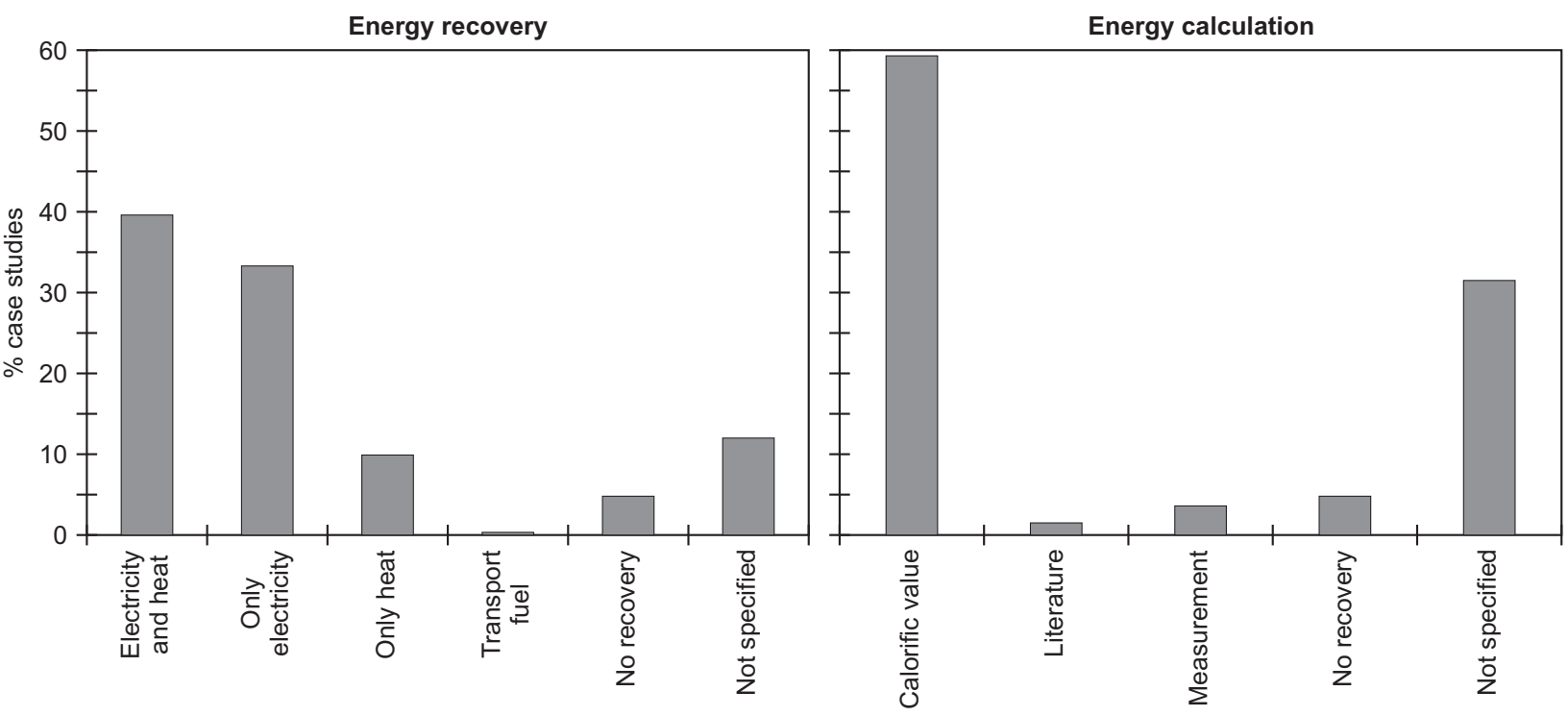


Figure 07

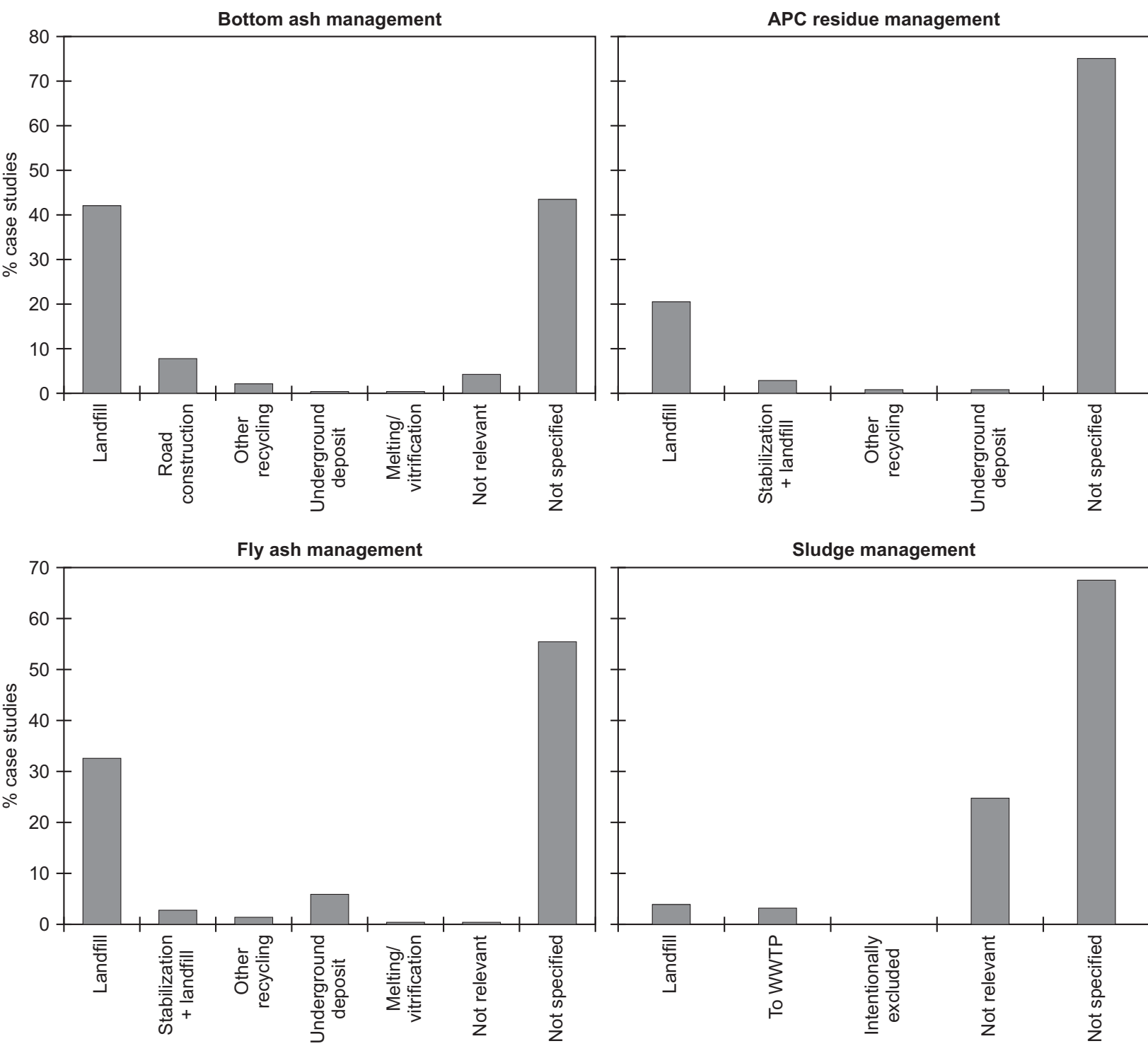
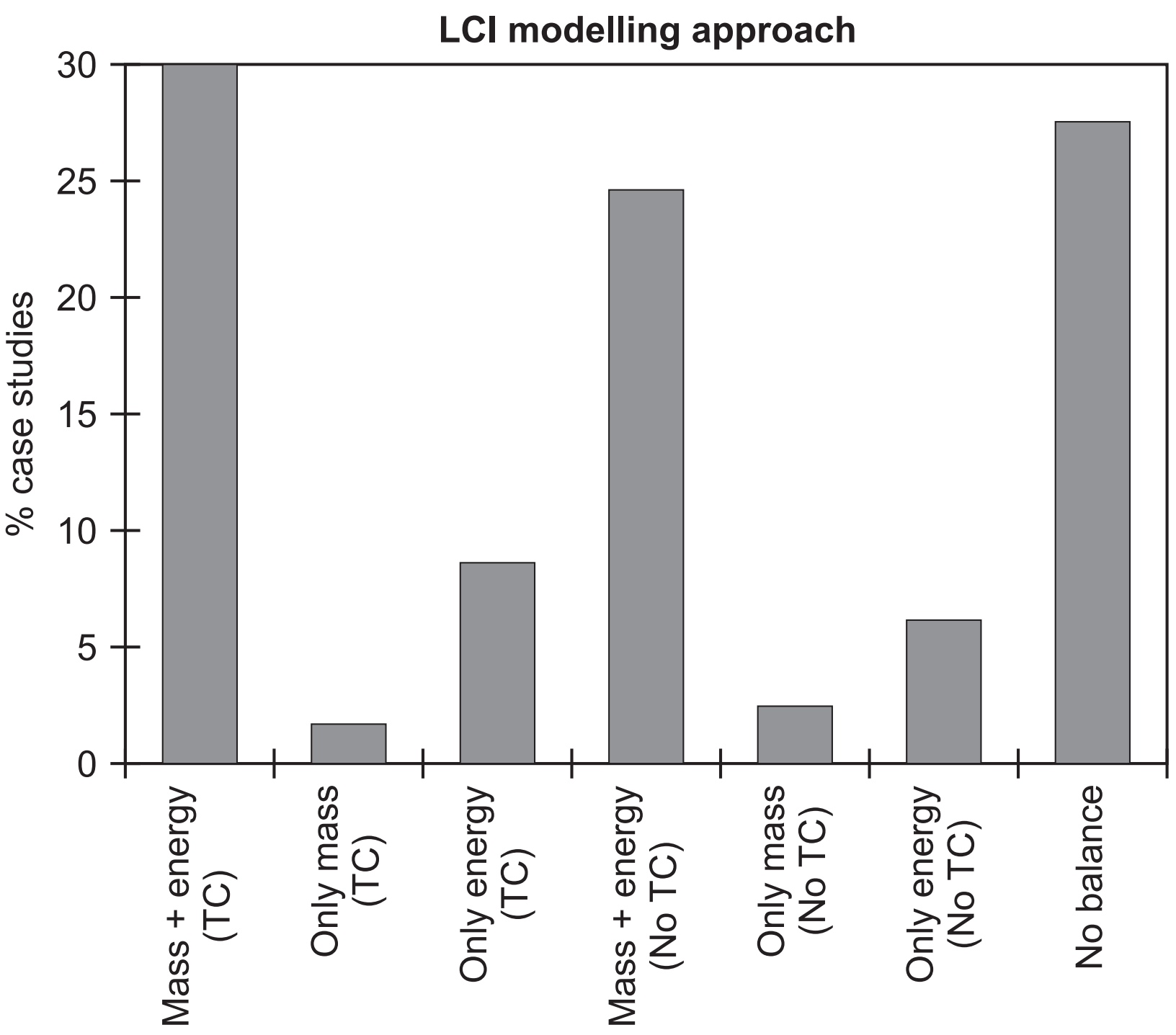


Figure 08



# Capital goods

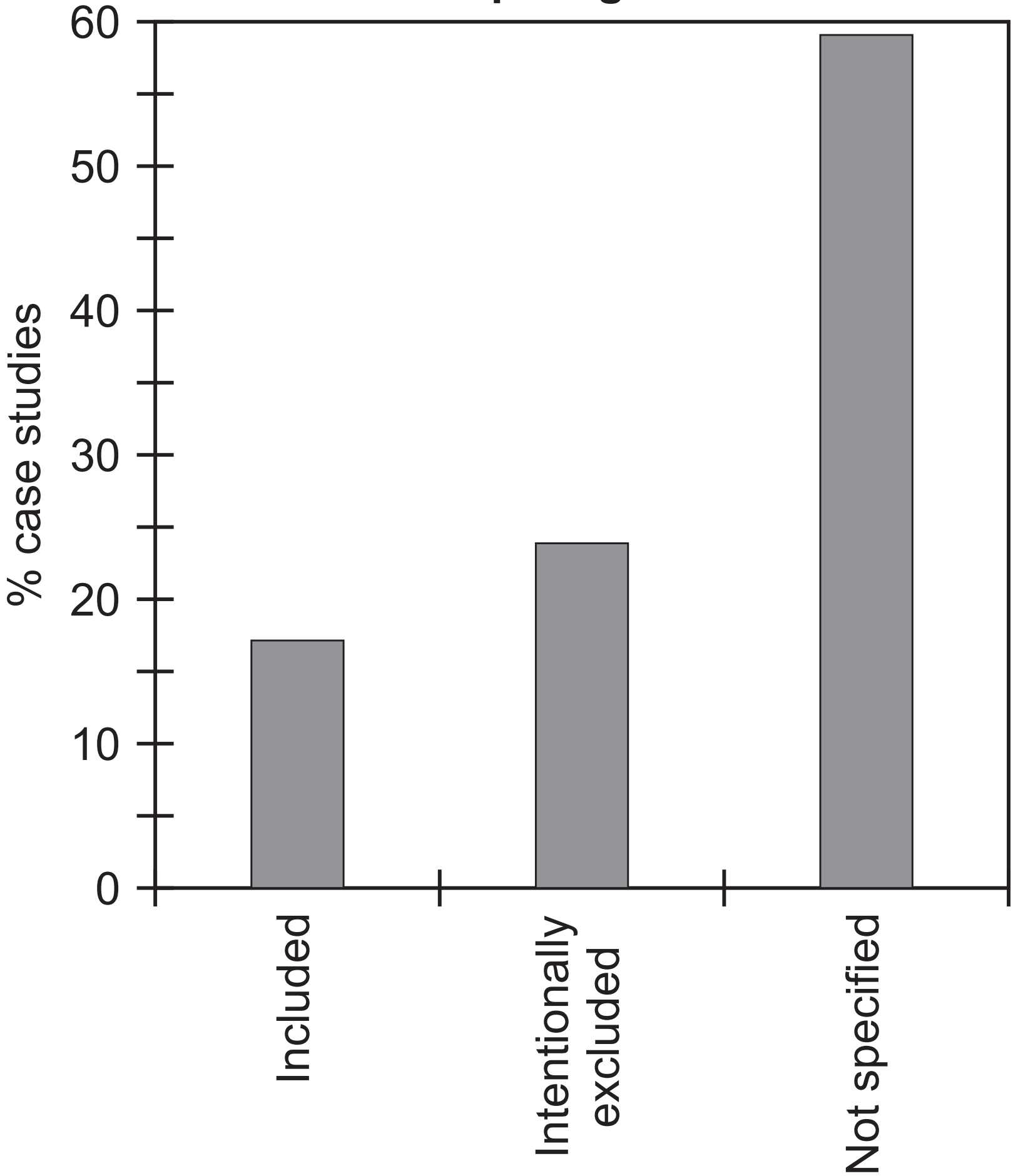


Figure 10

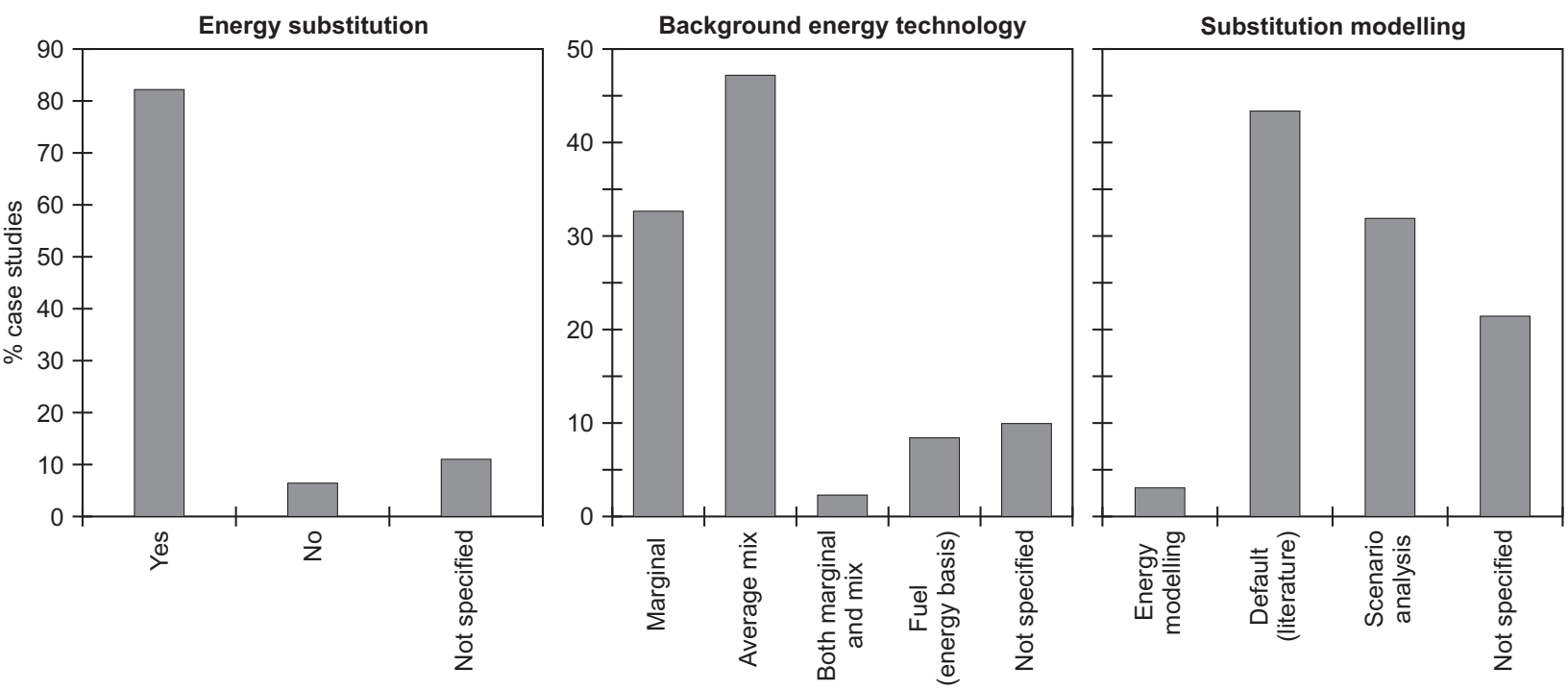


Figure 11

