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Published in:
Waste Management

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

Publication date:
2015

Document Version
Peer reviewed version

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

Accepted for publication in *Waste Management*

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

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A definitive version is published in Waste Management, vol 37, pp 104-115, doi:10.1016/j.wasman.2014.06.011"

Abstract

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

1. Introduction

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

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

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

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

2. Methodology

2.1. Selection of papers for review

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

2.2. Review approach

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

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

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

3. Results and discussion

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

3.1 Goal and scope definition

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

68 % of the LCA case-studies either compared several WtE technologies against each other, or compared WtE with other waste management options. In addition to the 68 % of case-studies comparing specific technologies, about 26 % of the studies included WtE as an integrated part of a waste management system in combination with other technologies, e.g. Arena et al. (2003) and Tonini and Astrup (2012). Very few studies applied LCA for process optimization: only 12 case-studies (5%) used LCA for improvement of specific sub-units of individual plants (e.g. Scipioni et al., 2009, Møller 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.

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

3.2 Key technical parameters

3.2.1 Waste composition

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

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

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.

Generally, air-pollution-control (APC) systems were very poorly described. Figure 5 illustrates that more than 50 % of the case-studies did not describe the specific technology applied. This essentially prevents verification of the inventories (if provided) for emissions and material/energy consumption, thereby preventing the applicability of the studies to be evaluated. Omitting information about gas cleaning also significantly reduces transparency with respect to geographical and temporal scope, i.e. whether the technology is typical for the region and time period assessed. Only a 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, 2007).

3.2.3 Energy recovery

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

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

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

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

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 %).

For most parameters, extremely large variations (up to >10 orders of magnitude in some cases) could be observed across the reviewed studies (see Table S10, supplementary material). These large variations were especially pronounced for emissions of trace compounds to air (e.g. PCDD/F, Hg, Cd, and As), but also for in-plant consumption of electricity and auxiliary fuels. These discrepancies in inventory data can only partly be explained by technological differences and variations in geographical and temporal scope of the studies. For example, systematic comparisons of historical developments in air-pollution-control systems (Damgaard et al., 2010) have demonstrated far less variations in air emissions, and thereby also environmental impacts, than the variations indicated by the reviewed studies.

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 the data generation or the manuscript writing. Examples are PCDD/F emissions in the order of 600 mg/Mg of waste (Hong et al., 2006), Hg emissions of 15 g/Mg of wood waste in case of steam gasification (Khoo et al., 2009), and oil consumption of more than 300 kg/Mg of waste in a fluidized bed reactor (Ning et al., 2013). These values are significantly higher than most other studies and the values should at least have been 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.

3.3 Key methodological choices

3.3.1 LCI modeling approach

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

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 not specify whether capital goods were included. About 23 % of the case-studies reported that capital goods were intentionally excluded based on an argument that the contribution was negligible overall. Based on recent literature, however, this conclusion is questionable if an LCA involves aspects such as resource depletion, eutrophication and toxicity related impacts.

3.3.3 Avoided burdens from energy production

Of the 238 case-studies in which energy recovery was considered (assuming that energy 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 (see Figure 10, left). In 6 % of the case-studies, energy substitution was not included and environmental benefits from avoided production of energy and saving of fuels were not addressed. Only in 11 % of the case-studies energy substitution was included but not specified. Considering the importance of energy substitution for the overall LCA results (Finnveden et al., 2005, Moberg et al., 2005, Laurent et al., 2014a, 2014b, Finnveden et al., 2009), the high share of studies including avoided energy production is 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).

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

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

3.3.4 Sensitivity and uncertainty analysis

Several approaches for assessing uncertainties within waste LCA exist (e.g. Wang and Shen, 2013, Clavreul et al., 2013, Clavreul et al., 2012). Accepting the validity of the mathematical models involved in the LCA calculations, studies should address both scenario and parameter uncertainties to evaluate the robustness of the LCA conclusions. 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.

3.4 Overall conclusions from the LCA results

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

The majority of studies (25 out of 29 scientific articles) comparing recycling and landfilling with WtE confirmed the waste hierarchy (recycling > WtE > landfilling) for the waste materials investigated. The remaining studies concluded that WtE was 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 regarding energy recovery efficiencies and the substituted energy (e.g. substituting natural gas or an average mix decreased the environmental benefits associated with WtE). Regardless of assumptions, all studies recommended that recycling of WEEE, metals and C&D waste was preferable over incineration (e.g. Hischier et al., 2005, Ortiz 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 energy recovery from these fractions.

Most studies (25 out of 29 scientific articles) clearly indicated WtE as preferable over landfilling. A few studies concluded landfilling to be preferable for specific material fractions and under specific assumptions for the energy systems: plastic bags (Khoo et al., 2010), specific material fractions such as paper and plastic when a limited LCA time horizon was considered (Moberg et al., 2005), packaging waste (Wollny et al., 2001), and RDF when the substituted energy was based on natural gas (Montejo et al., 2013). Most of these results are not surprising: state-of-the-art landfilling may induce significant CO_2 and other environmental savings related to carbon sequestration and energy recovery, and may perform comparable to WtE for specific waste fractions and/or under specific energy system conditions as documented in e.g. Tonini et al. (2013), Manfredi et al. (2011), and Manfredi et al. (2009).

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

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

3.5 Critical inconsistencies in existing literature

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

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

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

- 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, 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.,

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

4. Conclusions

The review included 136 peer-reviewed journal articles involving life cycle assessment (LCA) of the following waste-to-energy (WtE) technology types: incineration, co-combustion, pyrolysis, and gasification. In total, these journal articles reported results from 250 individual case-studies or scenarios. By far the most case-studies assessed incineration, while relatively few studies addressed technologies such as pyrolysis/gasification and co-combustion in detail. Very few of the reviewed studies provided a sufficient description of i) goal and scope of the assessment, ii) the 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.

Supplementary Material

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

Literature

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Table 1. Overview of the aspects addressed in the review. The classification of each aspect is listed supplemented with a brief description (*italic*) 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*)**
Goal and scope	- 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
	- 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)*
Technical parameters and inventory data	- Waste input	
	o 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	
	o 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)*
	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
	o 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
	o PCDD/F removal	Activated carbon, Catalytic bag, Not specified
	o deNOx system	SNCR *(Selective non catalytic reactor)*, SCR *(Selective catalytic reactor)*, Not specified
	o Data origin	Full-scale, Pilot-scale, Lab-scale, Literature, Database, Mix literature/database, Mix measured/literature, Not specified
	o Gas combustion system	Engine, boiler, Gas turbine, Not specified
	- Energy recovery	
	o Type of energy recovered	Electricity and heat, Only electricity, Only heat, No recovery, Transport fuel, Not specified
	o Energy recovery efficiency	Based on LHV, Based on literature, Not specified
	o Availability of district heating	Available, Not available, To be built, Not specified, Heat not recovered
	- Management of residues	
	o Bottom ash	Landfill, Road construction, Other recycling/reuse, Not specified
	o APC residues	Landfill, Stabilization + landfill, Other recycling/reuse, Not specified
	o Fly ash	Landfill, Stabilization + landfill, Other recycling/reuse, Together with APC *(i.e. considered all together)*, Backfilling old mines, Not specified
	o Sludge from WW treatment	to WWTP, Intentionally excluded, Not specified, Not relevant, Landfilled
	- Inventory data	
	o Air emissions	*Selected air emissions (NO_x, N_2O, SO_x, CO, dust, PCDD/F, Hg, Pb, As, Cr, Cu, Cd, Mn, Ni) when reported*
	o Input of energy	*Auxiliary fuels, electricity, and heat consumed in the process*
	o Input of materials	*Materials and chemicals consumed in the process*

Methodological choices in LCA modeling	- LCA modeling approach	
	○ 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 coeffici related to input of mass and chemicals, or energy)*
	- Capital goods	Included, Intentionally excluded, Not specified
	- Savings from energy production	
	○ 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	
	○ Type of uncertainty analysis	Sensitivity on parameters only, Scenario analysis only, Uncertainty propagation only, Sensitivity+scenario, Sensitivity+propagation, Scenario+propagation, All, None

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

List of figure captions

Figure 1. Temporal development of LCA case-studies on thermal WtE technologies. Bars indicate number of case-studies in individual years, left y-axis, while diamonds represent the cumulative number of case-studies (244), right y-axis.

Figure 2. Overview of functional unit, goal of the LCA and waste types included in the reviewed case-studies.

Figure 3. Overview of information provided on waste composition in the reviewed case-studies.

Figure 4. Overview of thermal technologies included in the reviewed case-studies.

Figure 5. Overview of technical aspects related to air-pollution-control (APC) systems in the reviewed case-studies.

Figure 6. Overview of energy recovery options and calculation principles in the reviewed case-studies.

Figure 7. Overview of residues management in the reviewed case-studies.

Figure 8. Overview of overall LCI modeling approaches included in the reviewed case-studies (TC: transfer coefficients).

Figure 9. Overview of capital goods modeling in the reviewed case-studies.

Figure 10. Overview of energy substitution approaches in the reviewed case-studies.

Figure 11. Overview of sensitivity/uncertainty analysis in the reviewed case-studies.

Figure 01

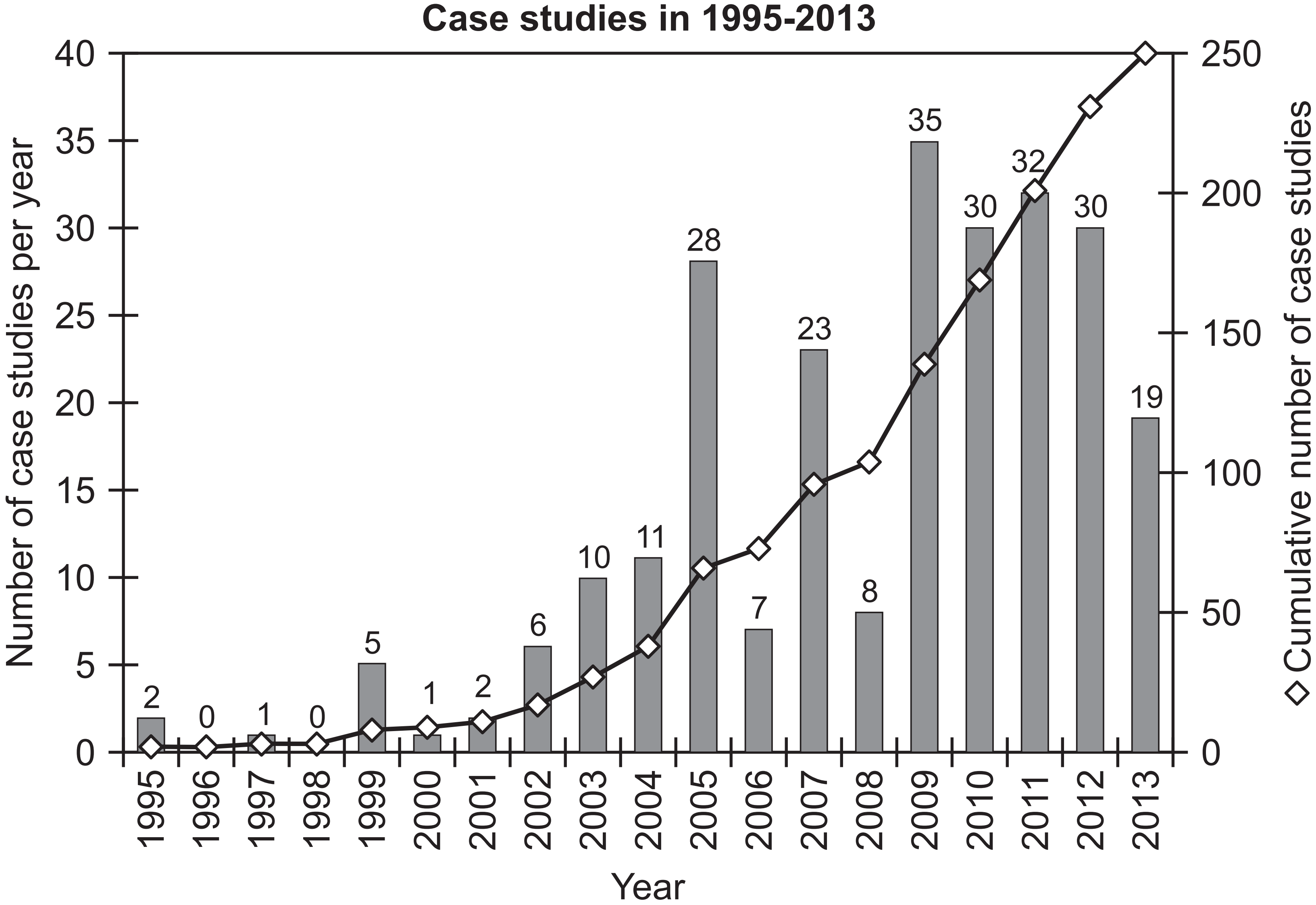
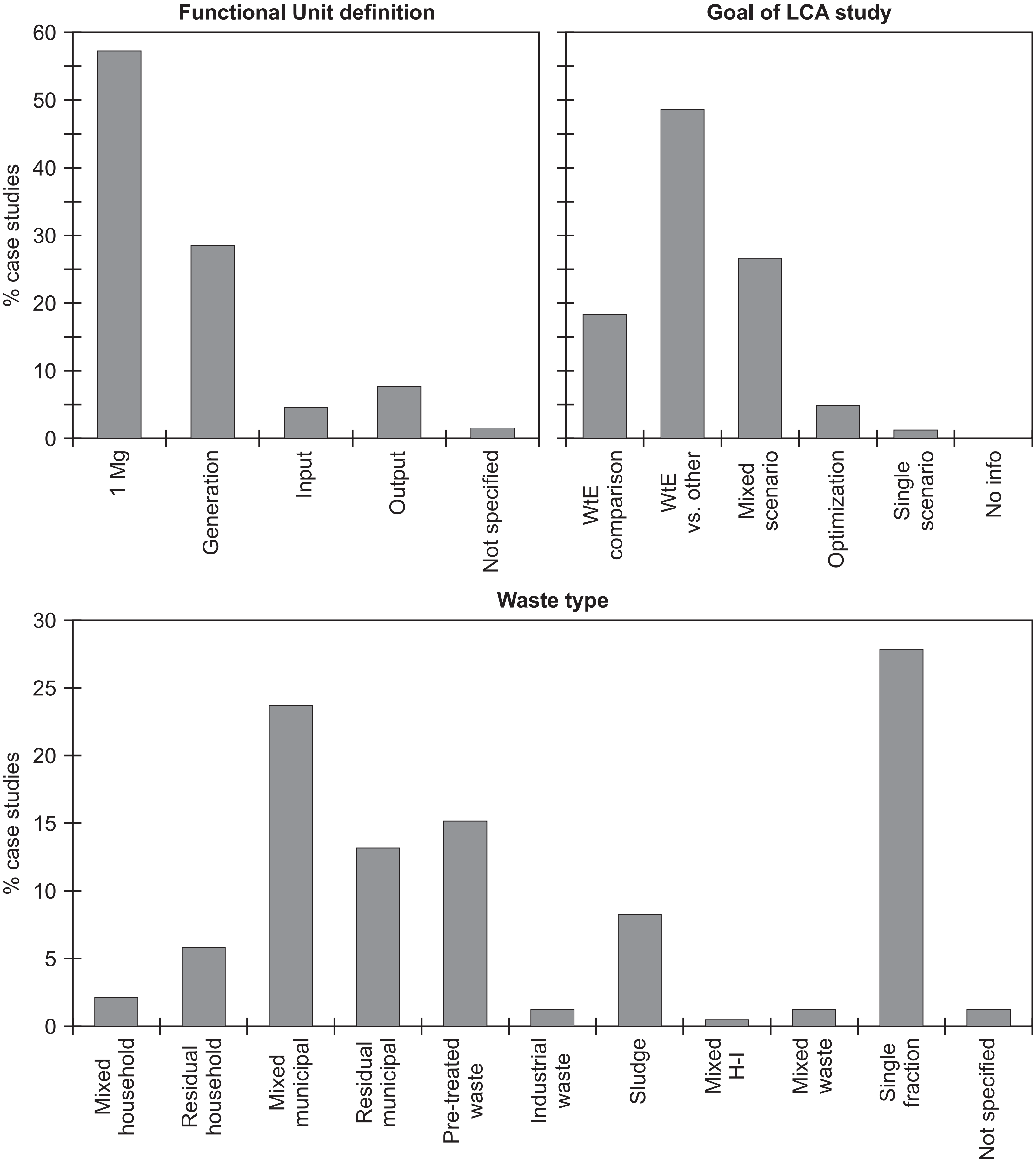
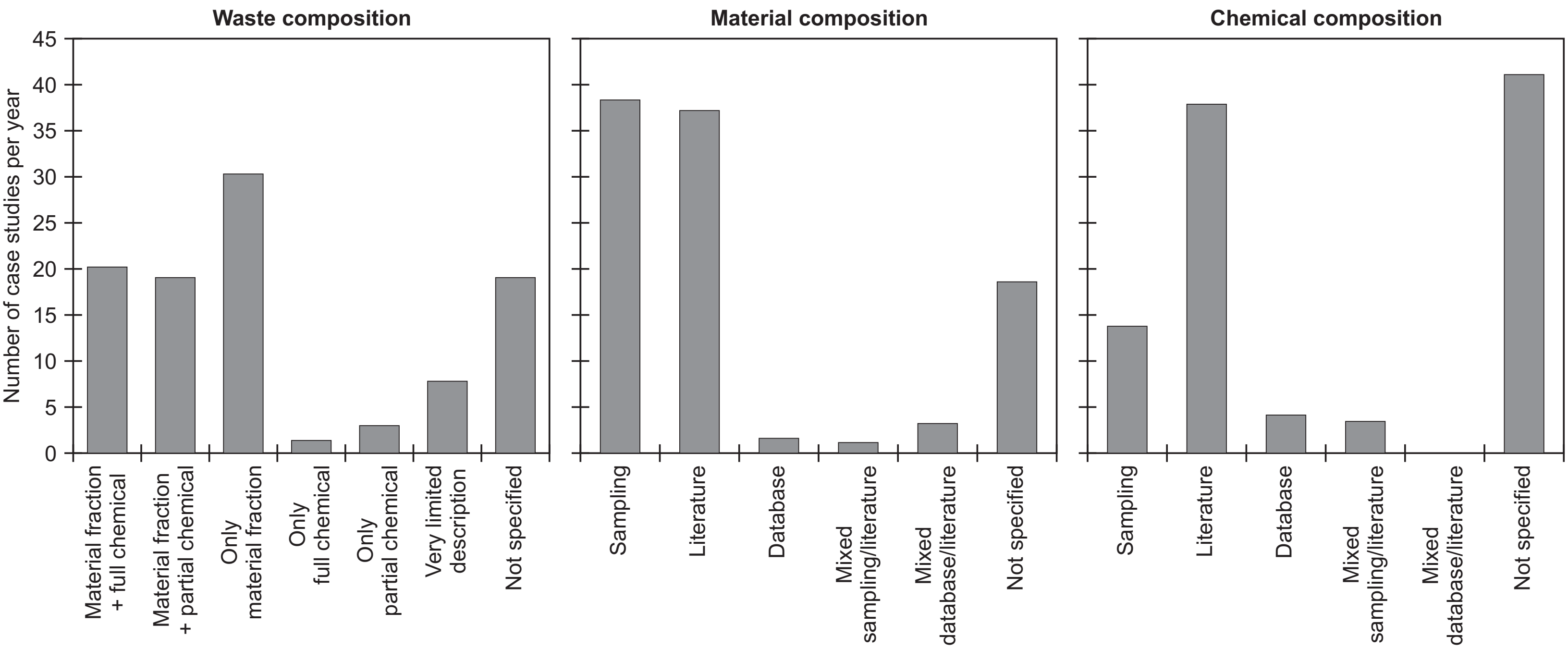

Case studies in 1995-2013
Number of case studies per year
Cumulative number of case studies
Year
0
5
10
15
20
25
30
35
40
0
50
100
150
200
250
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2
0
1
0
5
1
2
6
10
11
28
7
23
8
35
30
32
30
19

Figure 02



Functional Unit definition
% case studies
60
50
40
30
20
10
0
1 Mg
Generation
Input
Output
Not specified
Goal of LCA study
WtE comparison
WtE vs. other
Mixed scenario
Optimization
Single scenario
No info
Waste type
% case studies
30
25
20
15
10
5
0
Mixed household
Residual household
Mixed municipal
Residual municipal
Pre-treated waste
Industrial waste
Sludge
Mixed H-I
Mixed waste
Single fraction
Not specified

Figure 03



Waste composition
Material composition
Chemical composition
Number of case studies per year
0
5
10
15
20
25
30
35
40
45
Material fraction + full chemical
Material fraction + partial chemical
Only material fraction
Only full chemical
Only partial chemical
Very limited description
Not specified
Sampling
Literature
Database
Mixed sampling/literature
Mixed database/literature
Not specified
Sampling
Literature
Database
Mixed sampling/literature
Mixed database/literature
Not specified

Figure 04

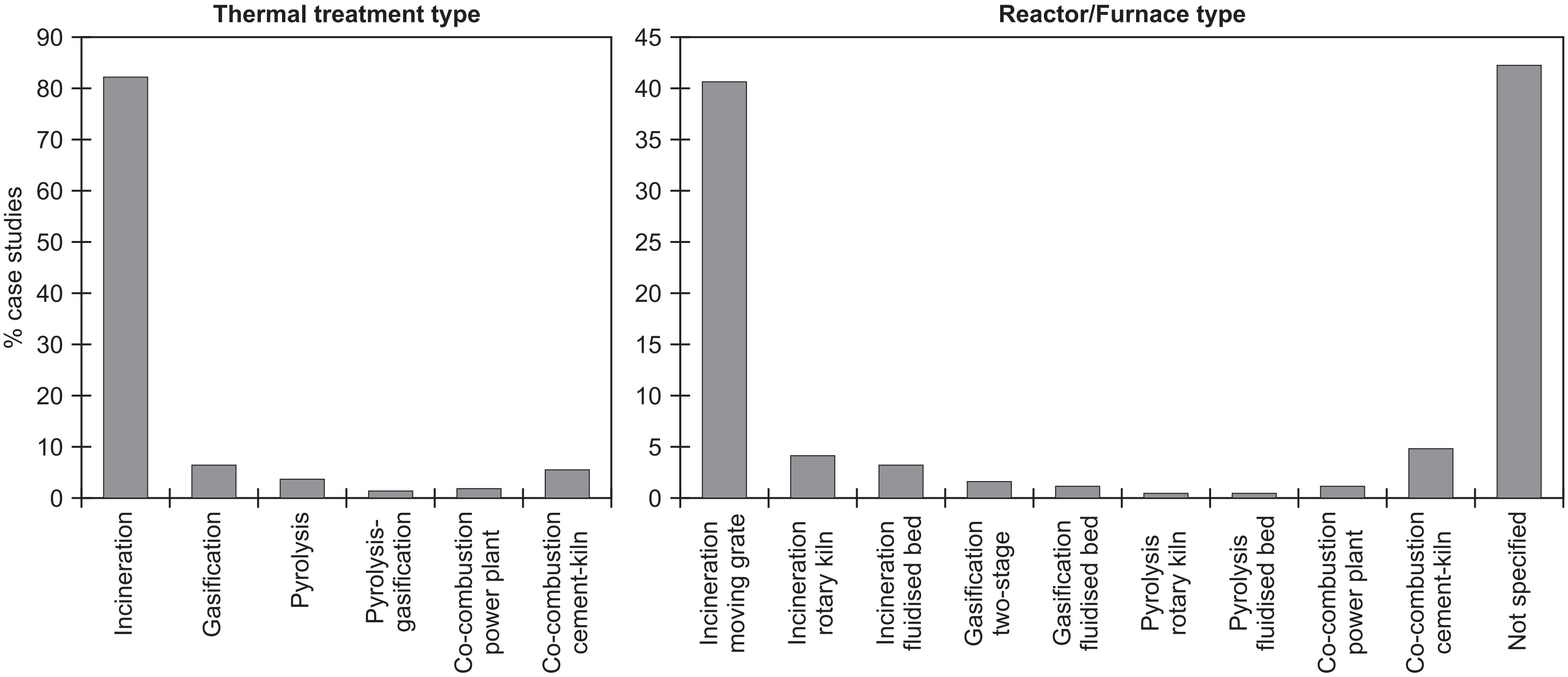
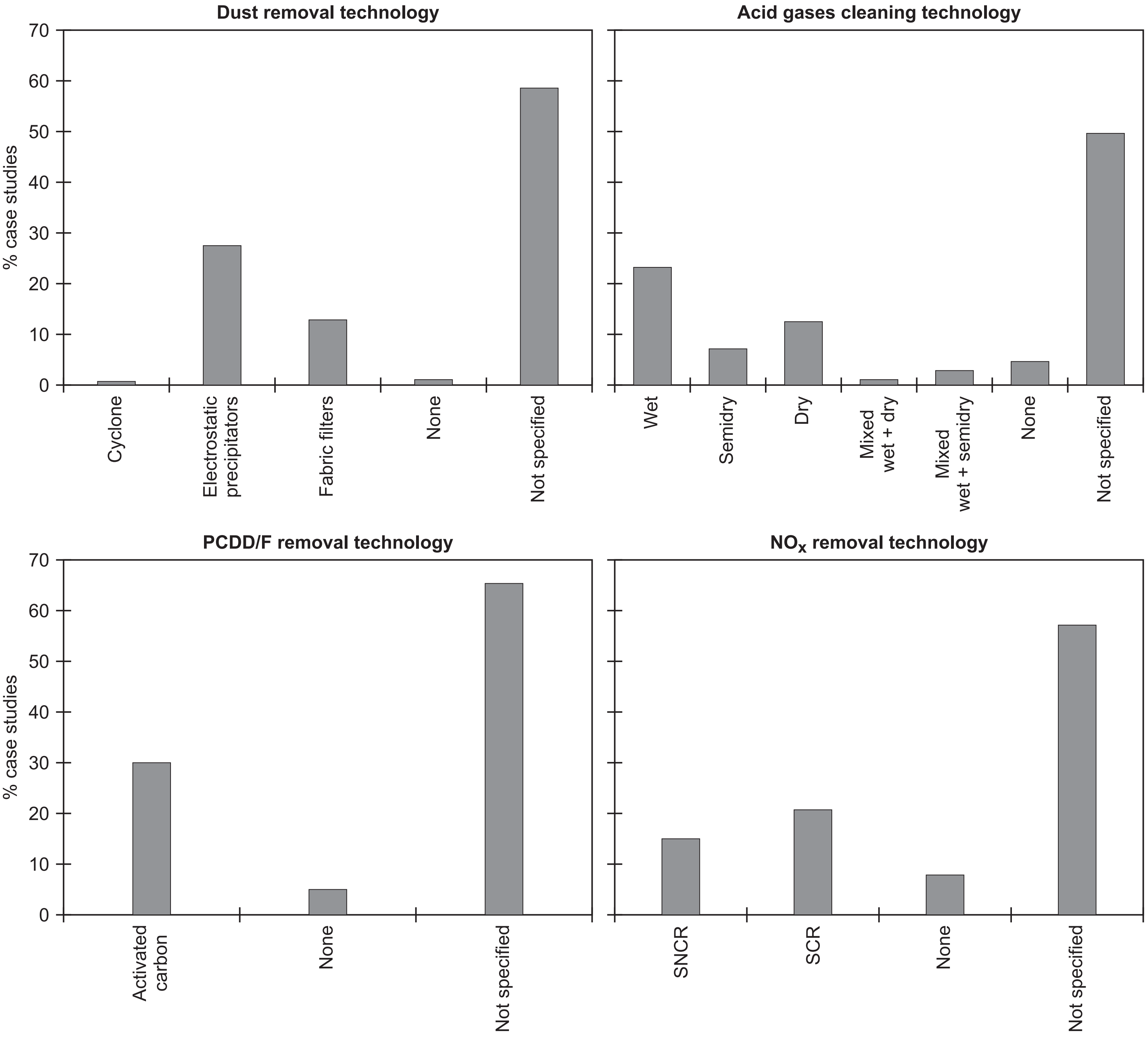

Thermal treatment type
% case studies
0
10
20
30
40
50
60
70
80
90
Incineration
Gasification
Pyrolysis
Pyrolysis-gasification
Co-combustion power plant
Co-combustion cement-kiln
Reactor/Furnace type
0
5
10
15
20
25
30
35
40
45
Incineration moving grate
Incineration rotary kiln
Incineration fluidised bed
Gasification two-stage
Gasification fluidised bed
Pyrolysis rotary kiln
Pyrolysis fluidised bed
Co-combustion power plant
Co-combustion cement-kiln
Not specified

Figure 05



Dust removal technology

Acid gases cleaning technology

PCDD/F removal technology

NO_x removal technology

Figure 06

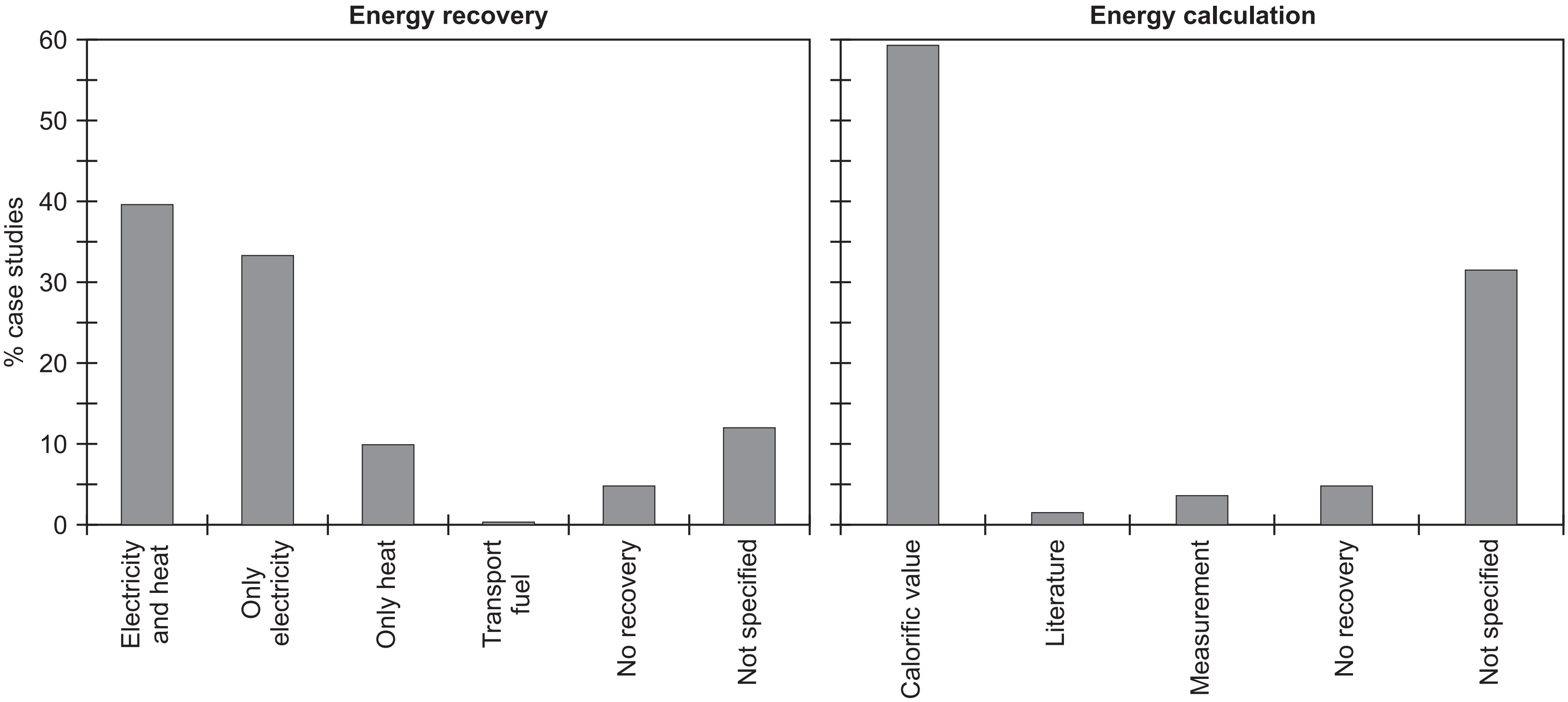

Energy recovery
Energy calculation
% case studies
60
50
40
30
20
10
0
Electricity and heat
Only electricity
Only heat
Transport fuel
No recovery
Not specified
Calorific value
Literature
Measurement
No recovery
Not specified

Figure 07

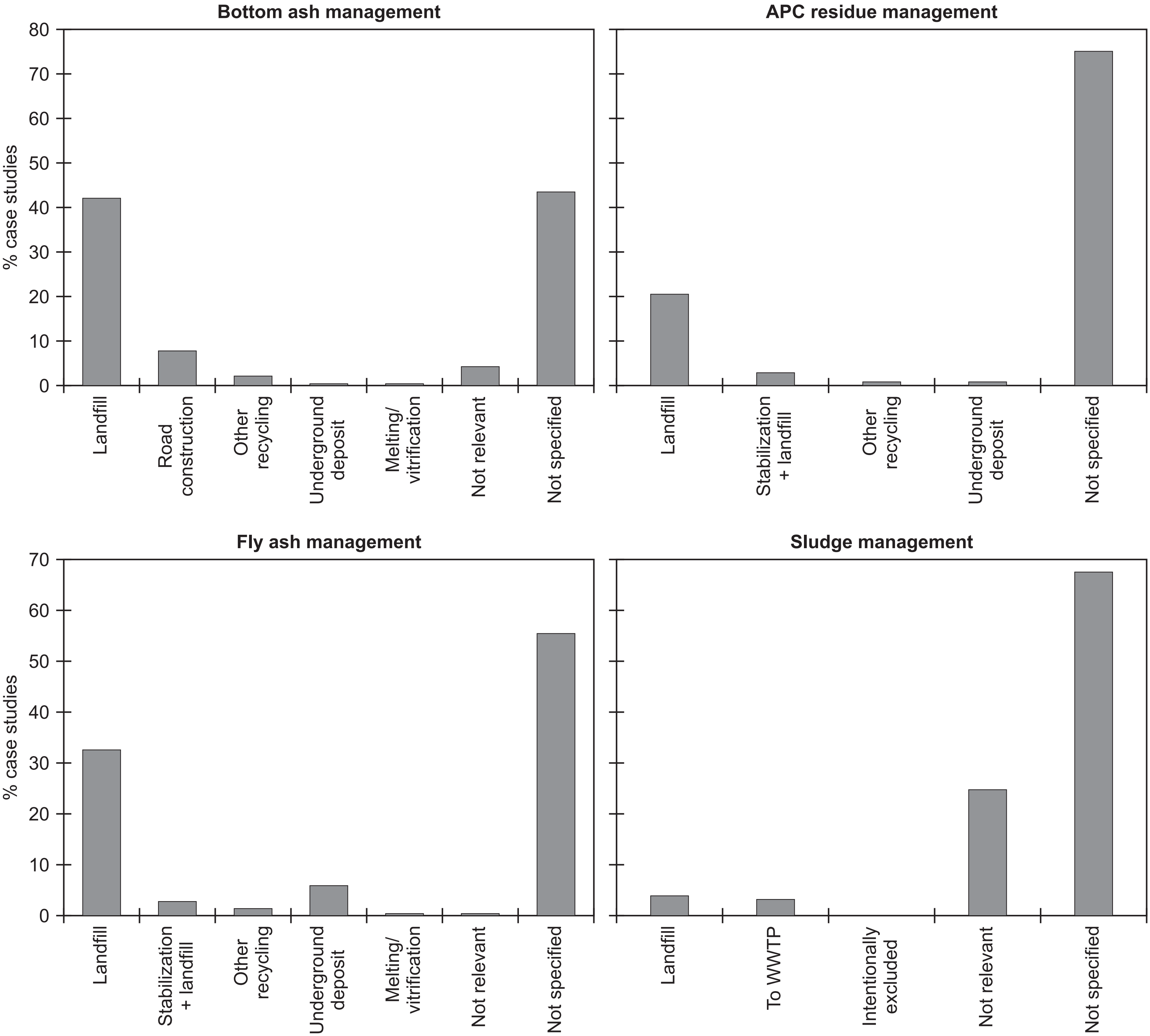

Bottom ash management
APC residue management
Fly ash management
Sludge management
% case studies
80
70
60
50
40
30
20
10
0
Landfill
Road construction
Other recycling
Underground deposit
Melting/ vitrification
Not relevant
Not specified
Stabilization + landfill
To WWTP
Intentionally excluded

Figure 08

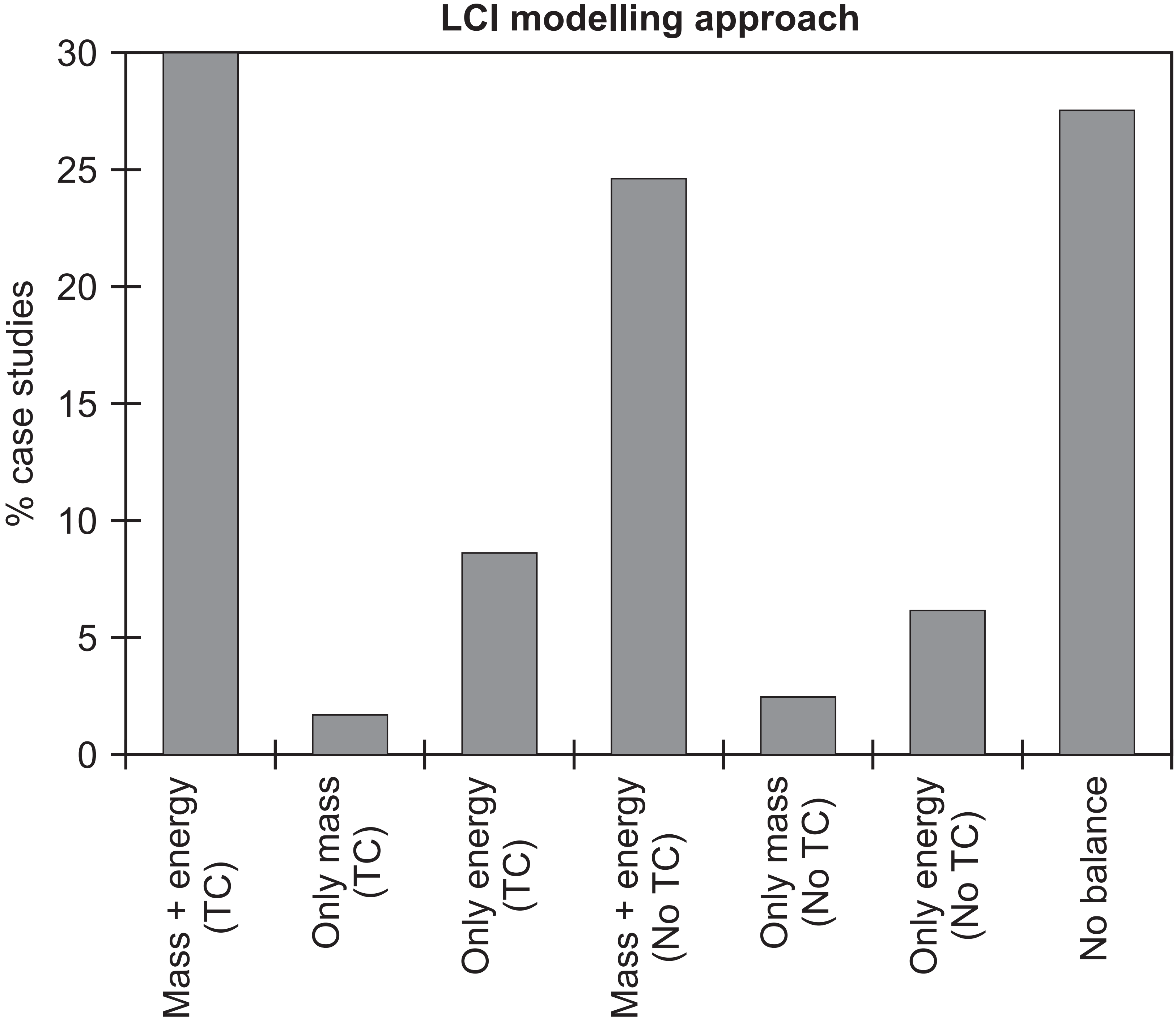
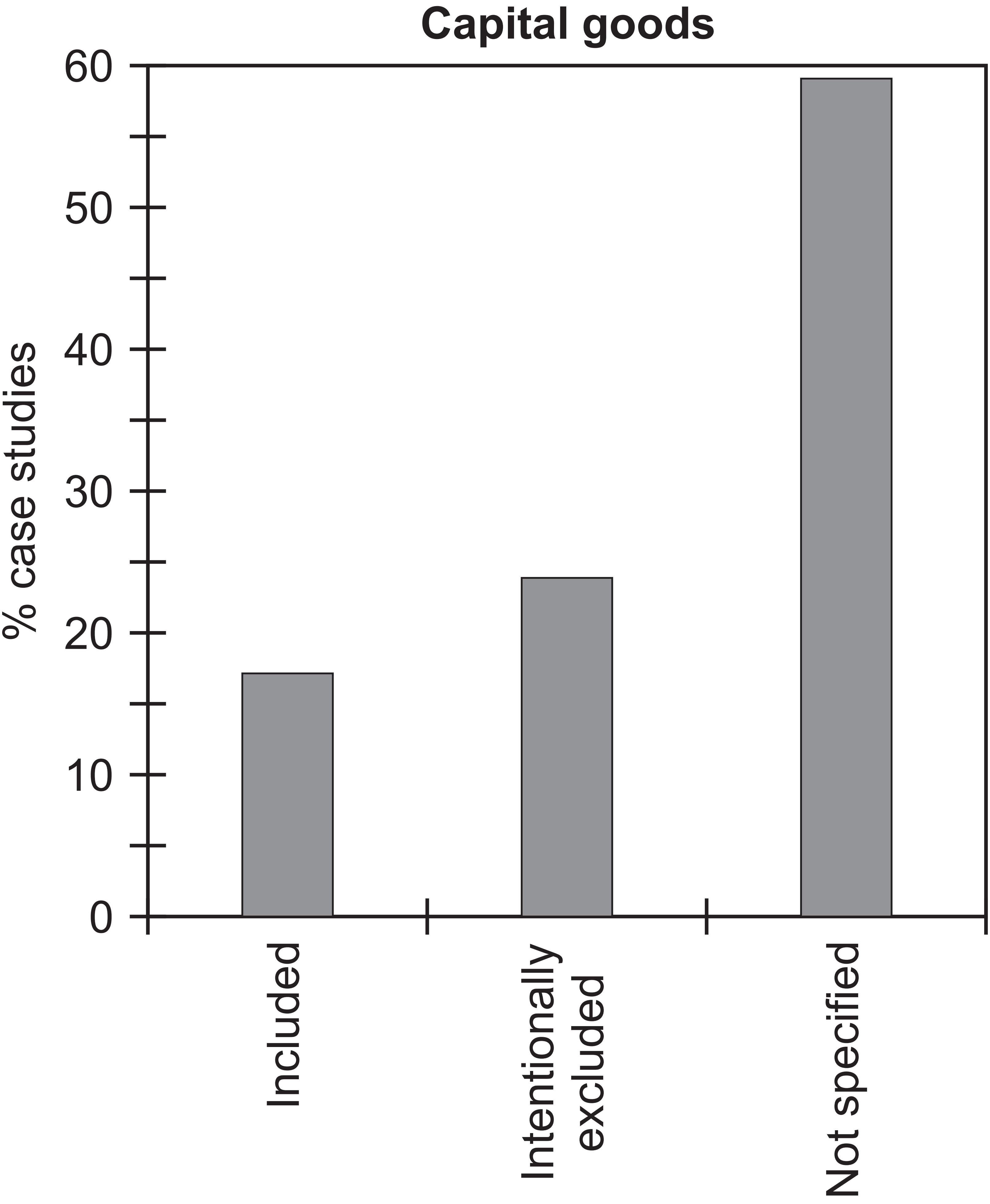
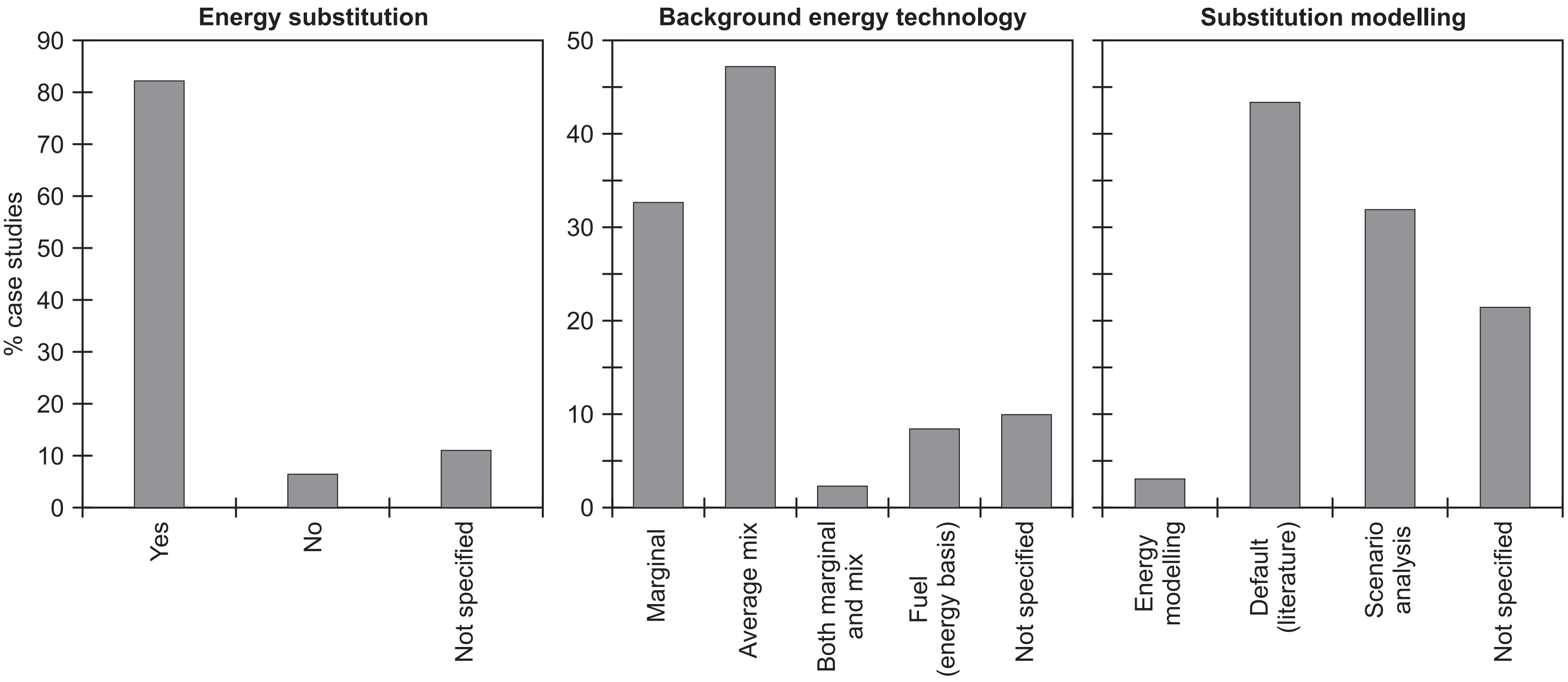

LCI modelling approach
% case studies
30
25
20
15
10
5
0
Mass + energy (TC)
Only mass (TC)
Only energy (TC)
Mass + energy (No TC)
Only mass (No TC)
Only energy (No TC)
No balance

Figure 09



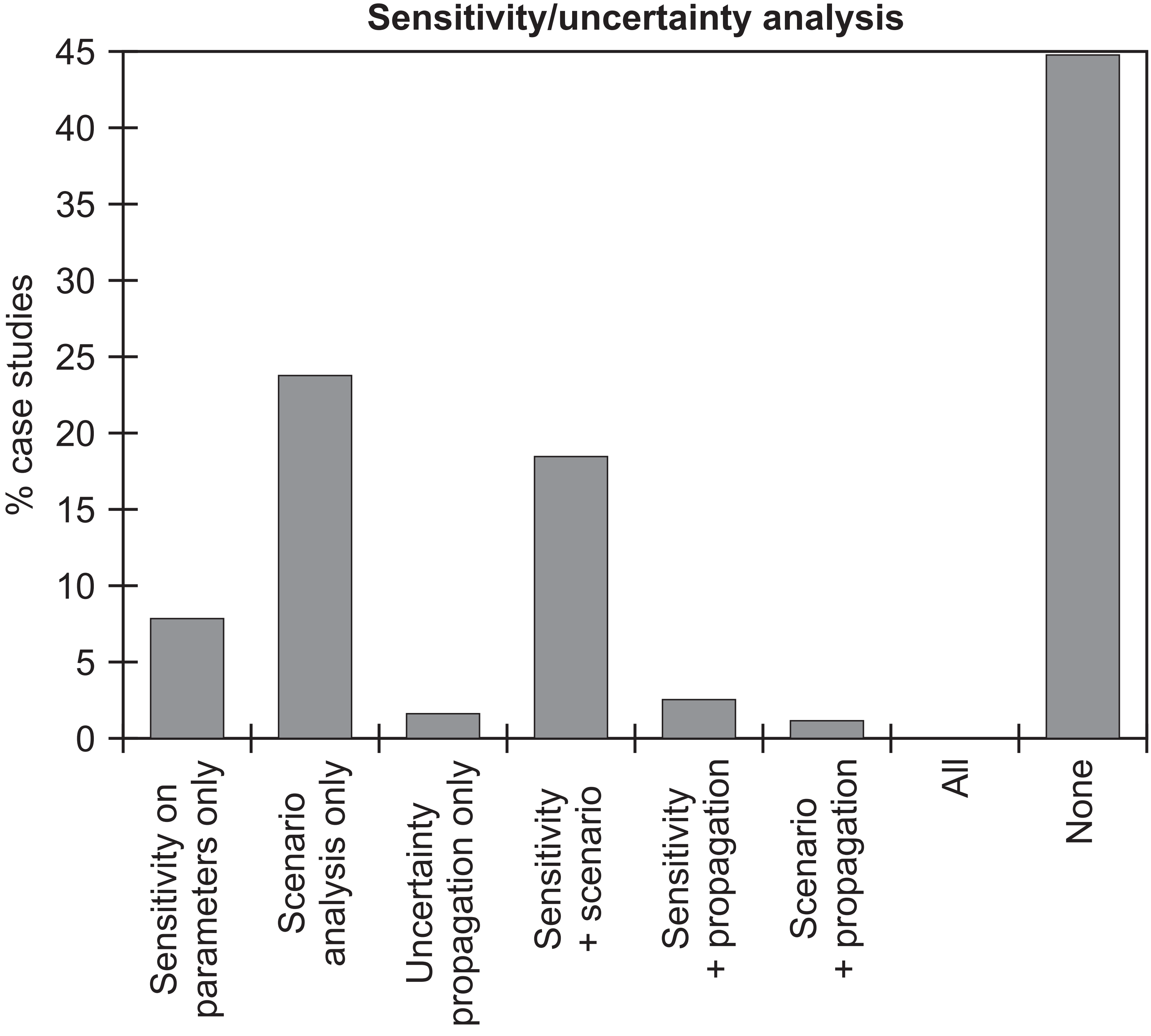
Capital goods
60
50
40
30
20
10
0
% case studies
Included
Intentionally excluded
Not specified

Figure 10



Energy substitution
Background energy technology
Substitution modelling
% case studies
90
80
70
60
50
40
30
20
10
0
Yes
No
Not specified
50
40
30
20
10
0
Marginal
Average mix
Both marginal and mix
Fuel (energy basis)
Not specified
Energy modelling
Default (literature)
Scenario analysis
Not specified

Figure 11


Sensitivity/uncertainty analysis
% case studies
45
40
35
30
25
20
15
10
5
0
Sensitivity on parameters only
Scenario analysis only
Uncertainty propagation only
Sensitivity + scenario
Sensitivity + propagation
Scenario + propagation
All
None