EDITORIAL

Life Cycle Assessment of Waste Management

Are We Addressing the Key Challenges Ahead of Us?

Thomas Fruergaard Astrup, Kostyantyn Pivnenko, Marie Kampmann Eriksen, and Alessio Boldrin

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

Within the past decade, life cycle assessment (LCA) of waste management solutions has come a very long way—from a situation in which the establishment and evaluation of individual technology scenarios was in itself a major achievement (e.g., Abeliotis et al. 2012; Cadena et al. 2009; Bergsdal et al. 2005) to the current, much more mature level in which extensive and integrated scenarios are evaluated in view of uncertainties, methodological implications, and detailed framework conditions (e.g., Tonini et al. 2018; Ripa et al. 2017). While this development may reflect attempts to more accurately model waste management solutions, the current level also illustrates the complexities associated with environmental LCA of waste management systems. Looking ahead, however, the key questions are: Which are the most eminent challenges that should be tackled, and how do current studies address these challenges?

The environmental benefits quantified in waste LCA studies are often directly proportional to the amounts of waste materials routed to a particular recycling technology, whereas the specific composition, properties, and presence of targeted resources in the waste materials may not be fully addressed. This suggests that the actual efforts associated with recovering and recycling of resources in waste may not be fully reflected by current LCA modeling approaches.

The current political focus on material recycling and the circular economy represents an important backdrop setting for waste LCA studies. Within industrial ecology, however, these concepts far from represent novel thinking. Resource efficiency, recovery, and recycling, as well as closing of material loops, have been on the agenda at least since the seminal article by Frosch and Gallopoulos (1989) that is said to have launched the field. Regardless of the specific terminology applied, material recycling is receiving considerable attention by media, decision makers, and researchers alike (European Council 2018; Ellen MacArthur Foundation 2013; EEA 2011). The European Union has recently decided to increase recycling targets for a range of waste material fractions and at the same time attempts to reduce the ambiguity in recycling rate calculations (European Council 2018; EC 2015a). Both initiatives increase the demands for documentation of benefits from recycling and add pressure on stakeholders within the recycling chain. While the overall intention is to minimize dependence on raw material import and increase resource efficiency as well as innovation and job creation, these policies also intend to improve the overall environmental performance of society over a wide range of impact categories (EC 2015b). Although numerous studies in the literature have demonstrated that material recycling is environmentally beneficial (e.g., WRAP 2010; Villanueva and Wenzel 2007), challenges exist in relation to the specific implementation of the European policies and, in particular, the selection of individual processing and recycling chains over others (Vadenbo et al. 2014). The ability of LCA to provide consistent assessments, however, also represents an opportunity for waste LCA studies to provide tangible inputs into policy making.

Providing meaningful inputs to decision makers calls for responsibility. It is well established that many existing waste LCA studies fail at providing even the most basic documentation about goal and scope, framework conditions, technology inventory data, and assessment assumptions in general (Astrup et al. 2015; Laurent et al. 2014). The results from such studies are, at best, opaque but may easily be biased. In a regulatory transition

DOI: 10.1111/jiec.12811

Volume 22, Number 5

period with society moving toward more material recycling, it is imperative that waste LCA studies reflect state-of-the-art approaches, offer well-documented results, show awareness of the methodological challenges associated with LCA of waste systems, and are accompanied by transparent discussions on weaknesses and uncertainties. Although this is demanding, the alternative is hardly useful.

This special feature contains a collection of articles that pinpoint a range of methodological challenges and provide examples of how to address them within waste LCA studies. This editorial outlines the most critical methodological aspects and highlights key perspectives from the individual studies.

What Are the Challenges?

A specific challenge in relation to material recycling and policy implementation is the traditional regulatory focus on waste amounts, rather than environmental performance of a waste solution (EC 2015b). In a circular economy perspective, this could mean that simple use of waste materials for new purposes (assuming regulatory acceptance) may be prioritized over the solution providing the largest environmental benefits; for example, if the recycled material displaces materials of low quality or does not displace virgin material at all, the overall environmental benefits from recycling are minor if at all present (Zink and Geyer 2017; Sevigné-Itoiz et al. 2015). While LCA offers a methodology that may address precisely this conflict, waste LCA studies also struggle with finding the right approach to reflect resource quality and displacement, rather than merely relying on material quantities (Vadenbo et al. 2017; Zink et al. 2016). In other words, the environmental benefits quantified in waste LCA studies are often directly proportional to the amounts of waste materials routed to a particular recycling technology, whereas the specific composition, properties, and presence of targeted resources in the waste materials may not be fully addressed (e.g., Zink et al. 2016; Shen et al. 2010; Rigamonti et al. 2009a, 2009b). This suggests that the actual efforts associated with recovering and recycling of resources in waste may not be fully reflected by current LCA modeling approaches.

Another critical aspect is availability and quality of the inventory data describing the involved waste technologies and processes. Waste management is characterized by activities representing impacts to the environment, while the environmental benefits from resource recovery activities generally occur downstream of the waste system itself through displacement of other products and services (Vadenbo et al. 2017). As such, in-depth knowledge of the involved waste conversion and treatment processes, the emissions and properties of the outputs from these processes, and the relevant technology configurations and associated performances are all required to appropriately model the waste management system. To provide a balanced assessment, however, similar knowledge is needed also for the alternative management of the waste in question. This means that robust inventory data for a wide range of waste technologies are needed for state-of-the-art LCA studies involving municipal solid waste, regardless of whether the goal of a study focuses on a specific circular economy solution. This aspect, however, has often been overlooked in waste LCA studies.

Assuming that a relevant range of technology inventory data is available, ensuring appropriate selection and representation of the study goal and scope is not necessarily trivial (Brogaard et al. 2014). Traditional waste management involves a range of archetype processes, for example, waste collection, mechanical sorting, biological and thermal treatment and conversion, recycling, and landfilling. However, within each process type, a wide range of technology configurations are possible, partly depending on the geographic and temporal scope, but also depending on the technology level itself. While existing inventory datasets do not fully reflect the variety of technology options, an LCA study nevertheless involves—implicitly or not—selection among technology configurations. Obviously, this selection should appropriately reflect the scope of the study. Particularly for waste systems, these choices may be critical, as the foreground waste system represents the main environmental impacts, as previously indicated. Again, this aspect is often overlooked by waste LCA studies (e.g., Astrup et al. 2015).

Waste prevention—that is, reuse, source reduction, and cleaner waste materials—is possibly the most important challenge of them all, both in the context of LCA and in society itself. Prevention effects are inherently difficult to quantify and regulate; in many countries, this has resulted in somewhat limited attention from regulatory agencies (Recreate 2017). While this may gradually change in Europe with the current legislative focus (EC 2015b), the regulatory implications go beyond the waste management system itself: Products need to be designed to avoid waste generation. As waste LCA studies typically apply a zero-burden assumption, in which the upstream environmental impacts associated with production, distribution, and use phases of materials in the waste are excluded from the system boundaries, evaluating environmental benefits from waste prevention is not straightforward. Typically, the environmental impacts found upstream from the waste system by far outweigh the impacts represented by waste management and the savings from downstream recycling (e.g., Dormer et al. 2013). So far, only a few attempts have been made in the literature to address this topic (e.g., Dolci et al. 2016; Nessi et al. 2012; Gentil et al. 2011).

Summarizing the above, this special feature focuses on the following five aspects related to LCA of waste management systems:

1. Representation of the environmental benefits associated with recycling and selection of impact indicator types (Ortego et al. 2018).
2. Providing systematic technology inventory data for representation of variabilities in technology implementation (Beylot et al. 2017).
3. Application of experimental data as the basis for environmental assessment of waste management (Capobianco et al. 2017).

4. Selection of technology data for appropriate representation of goal and scope of LCA studies (Henriksen et al. 2017).
5. Quantification and communication of environmental benefits from waste prevention (Hutner et al. 2018).

The above studies were all presented at the 1st International Conference on Life Cycle Assessment of Waste held in Cetraro, Italy, in 2016. The second iteration of the conference in 2018 was held in Copenhagen, Denmark (for details, please refer to www.wasteLCA.org).

Sustainability Assessment Using Thermodynamic Rarity

Based on a case representing resource recovery from end-of-life vehicles (ELVs), Ortego and colleagues (2018) applied thermodynamic rarity as a metric to illustrate the potential benefits of resource recovery and recycling. This is done by estimating the embedded exergy costs (rarity) of selected critical metals present in four different ELV types (conventional and electrified vehicles). By comparing recycled mass with thermodynamic rarity, a potential "hidden value" of critical metals is identified. Ortego and colleagues (2018) highlight that current recycling targets may fail in increasing recycling of critical metals in vehicles when solely based on mass. Thermodynamic rarity is found to be a useful metric that may be used both by regulators and automobile manufacturers in the design phase. The study identifies a range of specific metals with insignificant weight contributions to ELV recycling (i.e., molybdenum, cobalt, niobium, and nickel), but with more prominent importance as measured by thermodynamic rarity.

Waste Incineration Inventory Data

Beylot and colleagues (2017) provide an elaborate dataset for 90 French municipal solid waste incinerators covering the period of 2012 to 2015. The study addresses variations in technology configurations, energy efficiencies, consumption of reagents for flue gas cleaning, and process-specific air emissions. The data are provided as a basis for future LCA studies of waste management in France and illustrate the rather extensive efforts that are ideally required as a basis for a national-level LCA of waste management. The study further identifies a range of reagent consumptions and air emissions that are significantly affected by the investigated technology configurations.

Application of Experimentally Based Emission Data

With an example of soil utilization for regeneration of brownfield sites (e.g., urban and abandoned areas characterized by debris and various levels of contamination from previous activities), Capobianco and colleagues (2017) illustrate how analytical data from lab experiments are applied to estimate environmental emissions within an LCA. Based on leaching data for selected brownfield soils and stabilization/solidification processes, the performance of soil regeneration is evaluated relative to traditional landfilling of the soils. The study demonstrates that while the soil treatment may be environmentally preferable to landfilling for some impact categories, the cement binder added in the treatment process is found to be critical for the overall environmental performance of the regeneration solution. In contrast, the leaching data obtained from the lab experiments are found not to be decisive for the LCA results.

Links between Technology Data and Assessment Scope

The importance of data selection and compliance with the study scope is further highlighted by Henriksen and colleagues (2017). With landfilling as an illustrative technology case, the study investigates the importance of technology configuration and inventory data modeling relative to the context and scope of an LCA study. By evaluating 52 discrete landfill technology configurations and datasets (e.g., landfill type, regional conditions, leachate, and landfill gas management), the study demonstrates that inventory modeling has profound effects on the LCA results. Common examples of selecting site-specific inventory data for representation of an average, non-specific location or use of aggregated data for representation of a site-specific case study are in both cases demonstrated as providing biased results that may not be aligned with the study scope.

Assessment of Waste Prevention and Communication of Results

Hutner and colleagues (2018) assesses waste prevention measures through a community-based approach involving several steps intended to quantify and communicate potential effects from local prevention activities. Based on a literature review, existing approaches are evaluated and subsequently discussed among stakeholders for determination of criteria for indicator and case-study selection and, finally, communication of results. By means of LCA, the approach is applied on a range of cases, for example, provision of drinking water in offices and electronic workstations in administration, and identifies potential impact reductions based on selected waste prevention measures. The study thereby demonstrates the importance of transparent involvement of stakeholders from scoping an LCA study to communicating the results.

Concluding Thoughts

While the LCA studies mentioned above may not offer conclusive solutions to all the challenges discussed in this editorial, these studies nevertheless represent important steps on the way to improved insight into methodological choices, more transparent LCA results, and more robust and unbiased conclusions. In combination and individually, the studies also illustrate the considerable methodological challenges that still lie ahead of us within the field of waste LCA. We see the ongoing development of waste LCA as an important component of the work of industrial ecologists studying when and how to close resource loops. And we sincerely hope that the special feature provides both insight and inspiration for future research, paving the way for high-quality and relevant decision support for the benefit of society.

References

Abeliotis, K., A. Kalogeropoulos, and K. Lasaridi. 2012. Life cycle assessment of the MBT plant in Ano Liossia, Athens, Greece. *Waste Management* 32 (1): 213–219.

Astrup, T. F., D. Tonini, R. Turconi, and A. Boldrin. 2015. Life cycle assessment of thermal waste-to-energy technologies: Review and recommendations. *Waste Management* 37: 104–115.

Bergsdal, H., A. H. Strømman, and E. G. Hertwich. 2005. Environmental assessment of two waste incineration strategies for central Norway. *International Journal of Life Cycle Assessment* 10 (4): 263–272.

Beylot, A., A. Hochar, P. Michel, M. Descat, Y. Ménard, and J. Villeneuve. 2017. Municipal solid waste incineration in France: An overview of air pollution control techniques, emissions, and energy efficiency. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12701.

Brogaard, L.K., A. Damgaard, M.B. Jensen, M. Barlaz, and T.H. Christensen. 2014. Evaluation of life cycle inventory data for recycling systems. *Resources, Conservation and Recycling* 87: 30–45.

Cadena, E., J. Colón, A. Artola, A. Sánchez, and X. Font. 2009. Environmental impact of two aerobic composting technologies using life cycle assessment. *International Journal of Life Cycle Assessment* 14 (5): 401–410.

Capobianco, O., G. Costa, and R. Baciocchi. 2017. Assessment of the Environmental Sustainability of a Treatment Aimed at Soil Reuse in a Brownfield Regeneration Context. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12648.

Dolci, G., S. Nessi, L. Rigamonti, and M. Grosso. 2016. Life cycle assessment of waste prevention in the delivery of pasta, breakfast cereals, and rice. *Integrated Environmental Assessment and Management* 12(3): 445–458.

Dormer, A., D.P. Finn, P. Ward, and J. Cullen. 2013. Carbon footprint analysis in plastics manufacturing. *Journal of Cleaner Production* 51: 133–141.

EC. 2015a. *Commission Staff Working Document. Additional analysis to complement the impact assessment SWD (2014) 208 supporting the review of EU waste management targets*. Brussels, Belgium: European Commission (EC).

EC. 2015b. *Proposal for a directive of the European Parliament and of the Council amending Directive 2008/98/EC on waste, COM (2015) 595*. Brussels, Belgium: European Commission (EC).

EEA. 2011. Earnings, jobs and innovation: The role of recycling in a green economy. Copenhagen, Denmark: European Environmental Agency (EEA) (8): 28. http://www.eea.europa.eu/publications/earnings-jobs-and-innovation-the. Accessed June 2018.

Ellen MacArthur Foundation. 2013. Towards the circular economy. *Ellen MacArthur Foundation* 1: 1–96.

European Council. 2018. *Waste management and recycling: Council adopts new rules*. Press Release, 259/18, 22/05/2018. Brussels, Belgium. http://www.consilium.europa.eu/en/press/press-releases/2018/05/22/waste-management-and-recycling-council-adopts-new-rules/. Accessed June 2018.

Frosch, R.A. and N.E. Gallopoulos. 1989. Strategies for manufacturing. *Scientific American* 261(3): 144–152.

Gentil, E.C., D. Gallo, and T.H. Christensen. 2011. Environmental evaluation of municipal waste prevention. *Waste Management* 31 (12): 2371–2379.

Henriksen, T., T.F. Astrup, and A. Damgaard. 2017. Linking data choices and context specificity in life cycle assessment of waste treatment technologies: A landfill case study. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12709.

Hutner, P., D. Stindt, A. Thorenz, and A. Tuma. 2018. Transdisciplinary development of a life-cycle based approach to measure and communicate waste prevention effects in local authorities. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec12781.

Laurent, A., J. Clavreul, A. Bernstad, I. Bakas, M. Niero, E. Gentil, T.H. Christensen, and M.Z. Hauschild. 2014. Review of LCA studies of solid waste management systems—Part II: Methodological guidance for a better practice. *Waste Management* 34 (3): 589–606.

Nessi, S., L. Rigamonti, and M. Grosso. 2012. LCA of waste prevention activities: A case study for drinking water in Italy. *Journal of Environmental Management* 108: 73–83.

Ortego, A., A. Valero, A. Valero, and E. Restrepo. 2018. Vehicles and critical raw materials: A sustainability assessment using thermodynamic rarity. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12737.

Recreate. 2017. Stepping up waste prevention–challenges and opportunities for. Policy brief no. 7, September 2017. Berlin/Brussels. http://www.recreate-net.eu/dweb/system/files/files/PolicyBriefs/RECREATE_PolicyBrief_no7.pdf. Accessed June 2018.

Rigamonti, L., M. Grosso, and M. Giugliano. 2009a. Life cycle assessment for optimising the level of separated collection in integrated MSW management systems. *Waste Management* 29(2): 934–944.

Rigamonti, L., M. Grosso, and M.C. Sunseri. 2009b. Influence of assumptions about selection and recycling efficiencies on the LCA of integrated waste management systems. *International Journal of Life Cycle Assessment* 14 (5): 411–419.

Ripa, M., G. Fiorentino, V. Vacca, and S. Ulgiati. 2017. The relevance of site-specific data in life cycle assessment (LCA). The case of the municipal solid waste management in the metropolitan city of Naples (Italy). *Journal of Cleaner Production* 142: 445–460.

Sevigné-Itoiz, E., C.M. Gasol, J. Rieradevall, and X. Gabarrell. 2015. Contribution of plastic waste recovery to greenhouse gas (GHG) savings in Spain. *Waste Management* 46: 557–567.

Shen, L., E. Worrell, and M.K. Patel. 2010. Open-loop recycling: A LCA case study of PET bottle-to-fibre recycling. *Resources, Conservation and Recycling* 55 (1): 34–52.

Tonini, D., P.F. Albizzati, and T.F. Astrup. 2018. Environmental impacts of food waste: Learnings and challenges from a case study on UK. *Waste Management* 76: 744–766.

Vadenbo, C., S. Hellweg, and T.F. Astrup. 2017. Let's be clear(er) about substitution: A reporting framework to account for product displacement in life cycle assessment. *Journal of Industrial Ecology* 21(5): 1078–1089.

Vadenbo, C., S. Hellweg, and G. Guillén-Gosálbez. 2014. Multi-objective optimization of waste and resource management in industrial networks—Part I: Model description. *Resources, Conservation and Recycling* 89: 52–63.

Villanueva, A. and H. Wenzel. 2007. Paper waste—recycling, incineration or landfilling? A review of existing life cycle assessments. *Waste Management (New York, NY)* 27(8): S29–S46.

WRAP (Waste & Resource Action Program). 2010. *Environmental benefits of recycling—2010 update*. Final report. Branbury, UK: WRAP.

Zink, T. and R. Geyer. 2017. Circular economy rebound. *Journal of Industrial Ecology* 21(3): 593–602.

Zink, T., R. Geyer, and R. Startz. 2016. A market-based framework for quantifying displaced production from recycling or reuse. *Journal of Industrial Ecology* 20 (4): 719–729.

Conflict of interest statement: The authors declare no conflict of interest.

Address correspondence to: Thomas Fruergaard Astrup, Technical University of Denmark, Department of Environmental Engineering, Building 115, Kgs. Lyngby 2800, Denmark. Email: thas@env.dtu.dk