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CONFERENCE REPORT: 46TH DISCUSSION FORUM ON LCA

End-of-life and waste management in life cycle assessment—Zurich, 6 December 2011

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Abstract
Introduction Waste management is a key component in society's strategy to mitigate the adverse effects of its economic activities. Through its comprehensive system approach, life cycle assessment (LCA) is frequently put forward as a powerful tool for the assessment of waste management activities. However, many methodological challenges regarding the environmental assessment of waste treatment systems still remain, and consensus is still far from being reached in areas like the definition of (temporal) system boundaries, life cycle inventory generation, selection and use of environmental indicators, and interpretation and communication of the LCA results.
Summary of the topics presented in DF-46 The 46th Swiss Discussion Forum on Life Cycle Assessment (DF-46) consisted of three sessions. The first session tried to address policy making and implications for sustainable waste management of consumer products, e.g., information and communication technology, and food packaging. The second session focused on recent methodological developments in LCA for end-of-life treatment (EoL) activities and waste management assessment. The third session was dedicated to E-waste treatment and scarce metal recovery processes. DF-46 closed with short presentations on decision support in the areas of coprocessing, food waste, and after-treatment technologies for municipal waste incineration residues.
Conclusions The main conclusions drawn from DF-46 are: (a) the option of waste prevention, despite its prominent position in the so-called waste hierarchy, is rarely considered in LCAs on waste and EoL management, (b) although a general problem in many other applications of LCA, the differences in scope definitions and time perspectives, the use of proxies or data of poor quality, allocation, or system expansion procedures, and weighting in the impact assessment are prominent issues in LCAs of waste and EoL management and thus have to be minimized and inventory data must be as transparent as possible, (c) life cycle inventory formats have to be adapted to be able to account for new materials, such as nanoparticles and scarce metals in LCA, (d) the selection of environmental indicators requires clear guidance on their appropriate use and open communication. The selection of a set of complementary indicators is of particular importance in order to avoid that the adverse effects on the environment are merely shifted between impact categories, and (e) useful LCA tools for the environmental assessment of waste management options are currently developed to meet the evolving demands and expectations for support in decision making related to waste and EoL management today and in the future. The presentations from DF-46 are available for download (www.lcaforum.ch).

Keywords Emerging contaminants · E-waste · Optimization · Waste management · Waste policies

1 Introduction

With novel emerging products and materials, established waste management systems are continuously presented with new challenges to protect humans and the environment. Several studies (Ekvall et al. 2007; Riber et al. 2008) have suggested that life cycle assessment (LCA) is a suitable decision support method for the assessment of waste

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management activities. However, many unsolved methodological and data quality issues impede extensive application of LCA to end-of-life (EoL) and waste management. Providing a suitable platform for the discussion of such challenges, the 46th Swiss Discussion Forum on LCA (DF-46) was held at ETH Zurich (Switzerland) on 6 December 2011. The goal of the discussion forum was, on one hand, to elucidate some of the latest methodological developments in LCA and novel practical applications related to EoL, and on the other hand, to discuss strategies for strengthening the position of LCA as a decision support tool in waste management and waste-related policy making.

2 Policies and implications for end-of-life in LCA

The first session of the day was focused on general issues in LCA related to the assessment of waste treatment options and the implications for waste-related policy making. *Wolfram Scharnhorst* (Sustainable | Water | Management, Switzerland) presented an analysis of the drivers for sustainable EoL treatment in the telecommunication industry and in the building and construction sector. As GSM (2G) and UMTS (3G) networks in Europe are to be replaced during the period 2012–2016, the telecommunication industry will face large amount of EoL equipment requiring treatment. The limited availability of some of the materials used in telecommunication equipment and the concern regarding the treatment procedures in emerging economies were mentioned as two prominent environmental aspects which influence the EoL treatment. Additional incentives for recycling and material recovery are created by the rising raw material prices on the world market and the geopolitical instability in some of the regions outside Europe where the primary resources are found. Hence, the European telecommunication industry has a unique opportunity to strengthen its position and to adapt sustainable EoL treatments. The situation in the European building and construction industry, on the other hand, is different: Although a wide range of building standards and norms exist to facilitate sustainable construction, these aspects were often considered as an add-on rather than an integral part of everyday practice in the past. The fragmented interests and sharp division of stakeholders, e.g., between awarding authority, investor, constructor, owner, and tenant, were suggested as key obstacles for progress towards sustainability in the industry. Even though the gap between research and practice has resulted in numerous "lighthouse" projects, large-scale implementation is still lacking. Hence, the major challenge is to facilitate the implementation of interdisciplinary thinking into the strong and well-established engineering thinking in the industry. The necessity to sensitize the stakeholders for sustainability issues and the creation of incentives were identified as key challenges for the future to achieve more sustainable EoL treatment in the building and construction industry.

Laurence Hamon (Quantis, France) presented an overview of LCAs of alternative waste treatments, i.e., studies with "gate-to-grave" system boundaries. It was noted that the option of waste prevention is rarely considered in these studies because the functional unit is commonly defined as a certain amount of waste to be treated. Hence, the assessments of waste treatment options are frequently influenced by the perspective chosen and the assumptions made regarding energy and material recovery. In particular, the assumption of avoided production systems and the choice between a marginal and an average perspective in the assessment proved crucial for the recommendations in various waste management studies. Two issues related to carbon and carbon emission in waste treatments were highlighted in the presentation: First, the release of biogenic carbon in the form of carbon dioxide is commonly not assigned to any global warming potential, whereas methane with biogenic carbon is treated as methane emission with fossil origin. Recent guidelines for life cycle impact assessment, however, recommend that these emissions are considered separately (JRC 2010). The second issue dealt with the temporary or permanent storage of carbon in soils and landfill. It was stated that a consensus exists for integrating this aspect in the assessment but that stored carbon should be reported separately. A potential solution might be offered by dynamic LCA where the time of release of environmental exchanges is included. This discussion was followed by an illustrative case study in which three treatment options for 1 million tons of alcohol-containing grape pomace in France were assessed. The treatment options were distillation, composting, and land spreading. With respect to impacts on climate change, the option of distillation offers the largest net benefit due to the avoided burdens of the substituted product systems, followed by composting which showed a small net benefit, and direct land spreading which resulted in a small net burden. With respect to other impact categories, the general trend was similar. However, several implications of the results were highlighted:

- The result for the distillation process could be further improved by replacing fossil energy carriers consumed in the process with bio-based alternatives.
- For this study, four distilleries were included. Among the 50 distilleries operating in France, the recovery of the various coproducts of the distillation process varies which makes general conclusions on the net benefits of distillation as waste treatment option for grape pomace uncertain.
- The data quality and assumptions with regard to substituted products and the related avoided impact from

alternative production systems are essential for assessments of waste treatment options with energy or material recovery.

In the presented study, characterization of the potential benefits of compost or land spreading on soil properties was lacking. Hence, the full effects of these treatment options were not captured in the assessment. However, it is important to take the regional conditions into account, as agricultural soils in some regions might already be overloaded with nutrients.

Nina Cleeve-Edwards (Nestlé Research Centre, Switzerland) gave an overview of how LCA is used at Nestlé to assess alternative EoL options for packaging. Packaging provides the consumer with the first impression of foodstuff and beverages and often remains after the consumption. From a consumer perspective, packaging waste is a big concern and recyclable materials are perceived as very positive although studies have shown that recyclable packaging solutions do not always result in the lowest environmental burden in comparison to disposable options (Humbert et al. 2009). In addition, high recycling rates might come at the expense of high energy requirements for collection and sorting. In order to increase recycling rates, innovative approaches and collaborations and technological solutions for recycling are needed in conjunction with consumer education and policy incentives. An example from Singapore illustrated how mobile phone applications can be used to provide packaging sorting advice by scanning the barcode on the product and reading in GPS coordinates of the user in order to find a nearby collection point.

Two major challenges in LCA of EoL packaging were highlighted: First, a set of allocation rules for recycling which is accepted by all stakeholders is missing (The Consumer Goods Forum 2011). The solution of Nestlé is therefore the use of a 50:50 allocation rule if there is no generally accepted guidance available. The second challenge concerns the availability and application of EoL packaging statistics, for which three issues were highlighted: Firstly, there is no uniform database for collecting statistics on EoL packaging. Secondly, waste statistics are reported and presented with different geographic boundaries, e.g., on either state- or country-level. Furthermore, waste statistics typically do not encompass the large informal waste sectors in developing countries. It was concluded that in order to reduce environmental impacts of packaging in the EoL phase, the following approaches, which have proven to be successful, should be adopted:

- Identify available recovery options with the lowest environmental impact
- Design recoverable packaging
- Communicate and support programs to encourage consumers

To assist an environmentally sound decision making, we need to ensure that the LCA data and methodology for the EoL phase are reliable, transparent, and widely accepted.

The first session ended with a study of EoL options for two biodegradable packaging materials, presented by *Vincent Rossi* (Quantis, Switzerland). The Waste Framework Directive of the European Union (EU) prescribes that waste legislation and policy of the EU Member States shall apply a priority order where prevention of waste represents the most desirable measure followed by preparation for reuse, recycling, other recovery, and finally disposal of waste (EC 2008). However, when applying the waste hierarchy, “Member States shall take measures to encourage the options that deliver the best overall environmental outcome. This may require specific waste streams departing from the hierarchy where this is justified by life-cycle thinking on the overall impacts of the generation and management of such waste” (EC 2008). Public perception of the different waste treatments coincides well with the relative position of the treatments in the waste hierarchy. The relevance of the waste hierarchy's priority order to two biodegradable plastics, polylactic acid (PLA), and thermoplastic starch (TPS) was investigated in a case study which covered the following EoL treatment options:

- Municipal solid waste incineration (MSWI) with energy recovery
- Landfill
- Direct fuel substitution
- Mechanical recycling
- Industrial composting
- Anaerobic digestion

The results indicated that industrial composting of both PLA and TPS results in high impacts in comparison to the other treatment options, both with respect to contribution to global warming and resource depletion. This is mainly due to the relatively small credits awarded to this treatment option based on avoided burden from material and energy recovery. For the disposal in landfill, the impact with respect to global warming for PLA was relatively low due to its low degradability, whereas high degradability of TPS and consequently large amounts of methane emitted resulted in high impacts. Based on the case study results, it was concluded that contrary to public perception, composting is not necessarily the best alternative for EoL of biodegradable plastics. The results hence support a flexible application of the waste hierarchy.

3 Recent developments in scientific research

The second session of the DF-46 was focused on methodological developments in LCA related to EoL and waste management decision support. *Gabor Doka* (Doka LCA, Switzerland) presented how waste treatment activities are handled in ecoinvent v3, the upcoming version of the ecoinvent database. In the current version 2.2 of ecoinvent, the creator of a life cycle inventory (LCI) of a waste-producing activity predetermines the type of disposal process by choosing a certain disposal dataset for a specific waste material (e.g., disposal, paper, 11.2% water, to municipal incineration). This concept is omitted in ecoinvent v3 and the waste material is separated from the waste treatment activity, i.e., a waste material automatically enters a treatment market appropriate for the geographic location and the temporal setting of the waste-producing activity. The treatment activities available in a specific market are determined by the so-called database service layer of ecoinvent. If the author wishes, there is still the possibility to define a hard link between waste material and waste treatment activity. But in general, the author of an LCI dataset is relieved of the decision of how a certain waste material is treated, i.e., energy recovery, recycling, or final disposal. Hence, the dataset author does not even have to judge if an output material is a waste or a valuable by-product. It is just an intermediate exchange, leaving the activity to a market. The second new concept in ecoinvent v3 is that any activity can take up an output material and thereby become a treatment activity competing in a treatment market. There is no clear distinction anymore between disposal process and recycling process. As a third new feature, EoL treatment activity datasets can be parameterized. It is possible to enter parameters, e.g., gross efficiency of heat recovery, and mathematical relations directly into the waste treatment datasets. Intermediate exchanges (i.e., waste material and by-product) can be enhanced with properties (e.g., chemical composition, heating value, degradability, binning type, and collection type). The new concepts allow for more flexibility and higher complexity in modeling the EoL phase in life cycle inventories.

Grégoire Meylan (NSSI, ETH Zurich, Switzerland) showed in his presentation how the current Swiss cullet (waste glass) recycling system works and what challenges it faces in the future. In the study which has been carried out, future management options for discarded glass packages were environmentally and economically assessed. A hybrid LCA was combined with scenario and sensitivity analysis. The options were recycling within Switzerland or abroad and were evaluated by three recycling paradigms:

- Closed-loop recycling through color-separated cullet collection
- Closed-loop recycling through color-mixed cullet collection and optical color sorting
- Closed-loop recycling through color-separated cullet collection and high-grade downcycling

The results presented suggest that the eco-efficiency of the Swiss cullet disposal system is not dependent on color quality (i.e., color separation) nor on the type of processing (i.e., recycling or downcycling), but that the substitution of domestically produced packaging glass by imports would lead to an economical loss and higher environmental impacts. With the goal of identifying opportunities for improving the environmental performance of complex waste management systems, *Carl Vadenbo* (ESD, ETH Zurich, Switzerland) presented a method concept in which process models, LCA, and mathematical optimization techniques are combined. Optimization techniques like linear programming (LP) offer a systematic approach to identify (Pareto) optimal solutions, in this case in terms of waste and resource allocation among available waste treatment options. The feasible solutions, i.e., the decision space of the LP, are limited by model constraints which are formulated to reflect the regional context, e.g., the installed treatment capacities, waste-related policies and regulations, cost constraints, etc. The LCA methodology is applied to avoid suboptimal solutions, for which the environmental burdens are simply shifted between life cycle stages or between impact categories. Process models enable the assessment of the burdens as well as the benefits from resource substitution or from energy and material recovery in the treatment of a given waste stream, based on waste characteristics and on treatment technology levels (Boesch et al. 2009). A simple hypothetical case was used to illustrate how the resulting model can support decision making regarding the allocation of waste and resources in a waste management system. By comparing the performance of different single criteria solutions with respect to multiple environmental indicators and to system operating costs, not only improvement potentials but also tradeoffs could be identified. Future work related to the proposed method concept involves, among others, the inclusion of further process models to broaden the scope, strategies to address data and model uncertainty, and the application in a real-world case study.

The second session was closed by the presentation an emerging challenge for waste incineration plants, presented by *Tobias Walser* (ESD, ETH Zurich, Switzerland). Engineered nanoparticles (ENPs) are increasingly applied to consumer products and hence appear more and more in waste treatment processes. Even though the EoL of nano-enabled products is seen as a potential final sink for ENPs with minimal emissions to the environment, the ENP removal ability of flue gas cleaning systems has not been thoroughly investigated so far. Moreover, the trend of closing material cycles by recovery of materials from slag and fly ash might be hampered by ENP impurities. This knowledge gap is currently being addressed by a research consortium from ETH Zurich. Introducing stable nano-CeO_2 particles in the kilogram range into a full-scale incineration plant allowed the quantification and characterization of the nano-oxides in the flue and clean gas, as well as in different incineration residues, such as slag, fly ash, and quench water. The results and implications of the study will serve as basis for a thorough risk assessment and environmentally sound engineering solutions.

4 E-waste and scarce metal recovery

In the third session, the topic was EoL of E-waste and scarce metal recovery. *Carsten Dietsche* (Germany) presented the EU control of chemicals applied to E-mobility. The talk gave insights into the environmental management of the car industry and their use of different LCA approaches. Most European car manufacturers apply standards such as EMAS III, ISO 14001, and/or ISO 22628 to strive for environmental improvement and to comply with the requirements of the European Union. The car producers formed a task force within the European Automobile Manufacturers Association, where the methods and schedule for the complete materials declaration of the cars are being developed. The goal of knowing each part of a car down to the gram is challenging. However, only with such detailed data can a comprehensive inventory be collected for fair and comparable environmental assessments. Whilst the database will be open for industrial use only, the audience of the DF-46 inquired whether average information for the implementation into public LCI databases will become available. This has not been decided yet. The discussion after the talk led to the recommendation that independent bodies should collect the data from the manufacturers and provide average datasets to the automotive consortium for review. Once this panel gives the final review, such data could be integrated in publicly available, transparent LCI databases.

The second presentation was given by *Roland Hischier* (EMPA, Switzerland). In his talk about an LCA of the Swiss E-waste recycling system, he tackled the question: "Are the (secondary) resources, resulting from a highly mechanical and automated recycling system counterbalance the caused environmental impacts?" The applied material flow analysis in combination with LCA focused on Switzerland and its highly successful E-waste recycling system. Seventeen kilogram E-scrap per capita was brought to the recycling stations by the consumers in 2010. This value is exceptionally high in comparison to other Western Europe countries, with an average of approximately 3 kg per capita. The different existing recycling systems for E-waste were compared, applying various environmental impact assessment indicators. Moreover, the environmental performance of the past and the current E-waste recycling scheme was compared (Hischier et al. 2005; Wager et al. 2011). Global warming potential (GWP) and freshwater toxicity were the most affected impact categories. Concerning the disposal of the E-waste, recovery of metals proved to be the most environmentally sound option, in comparison to incineration and landfill. Within the recovery steps, the extraction of metals caused the highest impacts in all impact categories, with more than 50% of the total impacts. Collection and preprocessing of the E-scrap resulted in minimal environmental consequences because of the well-organized, highly efficient collection system.

Following Roland Hischier's talk, another facet of recovery processes of E-waste was elucidated by *Jan Tytgat* (Umicore, Belgium). He shared his experience with LCA of rechargeable batteries. Umicore is extracting valuable metals from disposed NiMH and Li-ion portable rechargeable batteries as well as from (hybrid) electric vehicle batteries. The E-scrap is melted in a self-sustaining process and various metallic fractions are obtained and further refined. Only a minimal amount of solid waste residues has to be landfilled. The commissioned LCAs were performed with scientific review by EMPA (Switzerland) and Oeko Institute (Germany). Experience from practice shows that the scope definition and the allocation of burdens and credits are crucial and difficult. Even though the LCA methodology recommends defining the scope in such a way that allocation is not necessary, in practice, the fixation of system boundaries always leads to discussion. Jan Tytgat exemplified this issue with two cases: In the first case, the use of the slag was not in the scope, and hence, neither process burdens were attached to the slag nor credits granted for the recovery of Al, Li, and Mn from the slag. In the second case, the scope was broadened to the slag which resulted in a larger LCI dataset. As a consequence, the goal of comparing two cases was difficult to achieve due to the changed scope definition in conjunction with a "dilution effect": The process improvement from the "pilot" to the advanced recycling process was shown to be only significant on a recycling level, but negligible if the system boundaries also included the battery production. Another critical point which was raised by Jan Tytgat is the choice of proxy data, if no exact data for, e.g., certain production of metals is available. This issue can lead to large discrepancies in the results, which are often not transparently reported. The use of proxy data is frequently the case if the LCA practitioner runs into confidentiality problems or difficulties in obtaining the required data. Possible reasons for this can include, for instance, recovery rates, which are hard to obtain because of commercial reasons and because many people are involved in the data collection. LCA project leaders need to have the authority to motivate colleagues and external partners to deliver their data contribution within a tight timeline. Another important point is the communication of the LCA results, including their interpretation. GWP is "fashionable" but should not be used as a stand-alone indicator. For the extraction and recovery of metals in particular, ecotoxicity is a "must" to report, and other suitable indicators such as biodiversity require further attention and development. Apart from these limitations, Umicore sees LCA as a powerful tool to enhance the motivation for improvement and to provide a valuable service to customers.

5 Short presentations

Amélie Orthlieb (Holcim, Switzerland) presented a comparison of two treatment options for discarded wind mill rotor blades in Germany. The two processing alternatives encompassed a cement kiln in northern Germany and a nearby MSWI. The assessment was performed using a set of LCA tools developed at ETH Zurich (Boesch et al. 2009) and it was assumed that the EoL rotor blades substitute brown coal in the clinker production. The MSWI option consisted of a grate furnace with electricity (η=6%) and heat (η=14%) recovery. The results with respect to contribution to global warming indicated that, whereas the direct emissions from the MSWI exceed the benefits generated from energy recovery, the substitution of brown coal (including supply chain) in clinker production results in a net environmental benefit. It was concluded that streamlined LCA tools enable Holcim and its stakeholders to better understand and evaluate the effects of coprocessing of waste in cement kilns and to compare the effects of alternative waste treatment options.

Anne Himeno (Bluehorse Associates, France) talked about the importance of including the prevention of food losses when assessing the impacts of food packaging. The study was performed with Carbonostics, an LCA tool for food products that allows users to capture waste at every stage of a product's life cycle and to assess the impact of food loss along the supply chain. The results of the study suggest that the environmental impacts of food waste occur both through additional volume of waste requiring treatment and additional food volume being produced and that there is an urgent need to better model food loss in life cycle assessment studies.

Annina Gaschen (Neosys, Switzerland) presented an evaluation of best available technologies in after-treatments of municipal solid waste incineration residues (e.g., filter ashes and slag). The assessed technologies were FLUREC, NEUTREC, and PLASMOX. The study revealed the dilemma of the correct timeframe for the assessment of landfilled after-treatment residues. A shorter timeframe (e.g., 100 years) only considers leaching of a tiny fraction of heavy metals; an unlimited timeframe makes the assessment of the landfilling process obsolete as the entire amount of the persistent metals will reach the environment. Therefore, she supported to apply a 60,000-year timeframe for such studies, according to Doka and Hischier (2005).

6 Conclusions

In order to make fair and consistent environmental assessments of waste treatment alternatives, differences in scope definitions, low data quality, and subjective weighting in the impact assessment have to be minimized. Waste prevention, the first pillar of the waste hierarchy, is often not considered in EoL-LCA but represents an important aspect for providing a holistic environmental perspective. The prevention of waste generation, however, generally requires that the entire product life cycle is considered in order to capture the resulting change in impacts of the preceding life cycle phases. High-quality data for waste treatment and recycling life cycle inventories is frequently missing or lacking in transparency due to confidentiality issues. New inventory items have to be developed to account for emerging waste materials, such as nano-materials. The timeframe of element exchanges in the environment and technosphere is crucial for a fair environmental assessment. Dynamic LCA can address this issue by introducing the temporal dimension in LCA. On the other hand, this raises the question of how to assess impacts separated in time (Hellweg 2001). To serve decision making, the numerous environmental indicators require clear guidance for their appropriate use and full transparency in the report of results and assumptions made. Many of the aforementioned points now become part of EoL-LCA tools. New approaches are currently being developed and implemented (hybrid LCA, optimization, etc.) in order to provide better support for collection or treatment processes or entire waste management systems.

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