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► To cite this version:

Véronique Bellon-Maurel, Lynda Aissani, Cécile Bessou, Laurent Lardon, Eléonore Loiseau, et al.. What Scientific Issues in Life Cycle Assessment Applied to Waste and Biomass Valorization? Editorial. Waste and Biomass Valorization, Springer, VAN GODEWIJCKSTRAAT 30, 3311 GZ DORDRECHT, NETHERLANDS, 2012, <10.1007/s12649-012-9189-4>. <cirad-00771298>

HAL Id: cirad-00771298

<http://hal.cirad.fr/cirad-00771298>

Submitted on 8 Jan 2013

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This is the author version of the “Waste and Biomass Valorization” article

“What Scientific Issues in Life Cycle Assessment Applied to Waste and Biomass Valorization? Editorial “
DOI: 10.1007/s12649-012-9189-4

The final publication is available at www.springerlink.com

What scientific issues in Life Cycle Assessment applied to waste and biomass valorization? Editorial.

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Abstract

Whereas Life Cycle Assessment (LCA) is more and more used for assessing the environmental load of waste management systems and of biomass production and valorization systems, various scientific issues are still to be dealt with. The purpose of this paper is to enlighten these scientific issues and to describe the current attempt to overcome them. The method used has been to go through the steps of the LCA standardized framework (ISO 14040) and to outline at each step the points that could be improved and still deserve research efforts. The various identified issues are: in step 1 (goal and scope), the choice of attributional/consequential modelling, the difficult choice of the functional unit due to the highly multi-functional nature of such systems, the allocation choices and the need for spatial differentiation; in step 2 (inventory), the thorny issue of modelling such complex systems and properly estimating field emissions; in step 3 (impact assessment), the lack of appropriate impacts (such as odours) in current LCA impact categories; in step 4 (interpretation and use), research efforts are needed to understand and facilitate the way actors take over and use LCA multi-criteria results. A transversal issue, i.e. uncertainty characterization and reduction, is also analyzed. These various scientific bottlenecks are currently under study; some are handled by this “Waste and Biomass Valorization” special topic, which includes a selection of papers presented in 2011 at the Ecotech&Tools conference (Montpellier, France).

Keywords: Lifecycle Assessment, LCA, Waste, Biomass, Allocation, Spatialization, Decision, Complex system

1. Introduction

Life Cycle Assessment (LCA), which has a standardized framework (ISO 14040), is widely used in industry as an environmental assessment method. It quantifies the negative aspects (impacts) of a system against its benefits in terms of functional units (or FU). Thanks to its multi-criteria approach, it allows us (i) to identify the main sources of environmental impacts, (ii) to avoid pollution transfers between impact categories or lifecycle stages, and (iii) to provide elements for decision support (choice of practices or equipment that have less impact, criteria for product eco-labeling...). But this method still has many shortcomings when applied to biological products, bio-production chains, water and land management issues. To meet the resulting challenges, the Ecotech&Tools conference (Environmental & Integrated Assessment of Complex Systems - Biosystems, Water, Land Management) was first held in December 2011. A part of the conference was dedicated to LCA applied to biomass/waste valorization systems.

LCA has gained acceptance in biomass/waste valorization systems as a tool for environmental assessment used for innovation management and decision making [5-6]. For waste management, some authors [7,6] note that LCA provides a more detailed and better environmental analysis than those advocated by the Framework Directive No. 2008/98/EC on waste, which ranks waste disposal methods. However, the use of LCA to evaluate waste or biomass valorization scenarios requires some methodological fine-tuning to take into account the specificities of these systems. The above systems may be regarded as complex biotechnical entities: they involve complex biological processes, which are highly variable and sometimes poorly understood, they raise the question of the status of the material to be recovered (is it a waste or secondary raw materials) and they involve spatial systems with open media which are difficult to model. Consequently, these systems raise methodological research issues close to the ones generated by complex biotechnical systems [8]. Other papers have already pointed out the unresolved or emerging issues of LCA methodology, such as [1-2] and [3]. This editorial article focuses especially on those most especially encountered with waste and biomass valorization (for instance, as there is no special emphasis on boundary and cut-off issues in waste and biomass valorization systems, this aspect, although important in LCA, will not be described hereafter). The articles gathered in this special topic provide snapshots of these scientific challenges that we introduce in this editorial paper.

2. The Life Cycle Assessment method.

The LCA method comprises four phases (ISO 14040):

- Phase 1 - Objectives and functional unit: this phase deals with defining the objectives and consequently the functional unit, making the methodological choices (e.g. modeling framework) and setting the system boundaries.

- Phase 2 – Inventory: in this phase, an inventory of emissions and consumptions due to the studied system to generate a FU is built up based on a model of the process/system.

- Phase 3 – Characterization: this phase concerns the conversion of inventory data into impacts (e.g. greenhouse gas emissions, acidification, eutrophication, ecotoxicity etc.).

- Phase 4 – Interpretation: in this phase, LCA results are analyzed, criticized (i.e., qualified and explained, etc.) and finally used.

In each phase, methodological issues arise when applying LCA to biotechnical systems (Figure 1). These issues are raised, with varying degrees of urgency, when biomass and waste valorization is considered.

3. Research questions related to Phase 1 - Objectives and functional unit.

The first difficulty to be overcome when working on biomass/waste valorization systems concerns the choice of the conceptual model. This is one of the concerns that Guinée et al [3] characterized as “the translation from functional unit- based to real-world improvements”. Indeed, two approaches stand out in the literature for modeling systems in LCA: the “attributorial” and the “consequential” approaches. The scope and objectives of the study determine the choice of the most appropriate approach for conducting the LCA [9]. The “attributorial” approach is traditionally used for standard “process-LCA” where all the production processes are modeled. This approach is very descriptive [10]. The “consequential approach” can be used to consider the consequences of the realization of the studied scenario on its background, including production of raw materials and energy, transport mode, etc. This approach is commonly used when the studied scenario can have huge impacts on another system. It therefore requires a certain expertise in economic science in order to model the effects on other markets. This is often the case when energy or raw material markets are being dealt with, or when production/consumption patterns may drastically change [4]. As waste and biomass valorization systems may directly and notably influence energy and raw material markets (e.g. biofuels), the issue of consequential/attributorial choice is particularly crucial. The choice of the modeling approach also has notable implications on how the results are interpreted [4]. For decision making, it is advisable to carry out both approaches and to analyse the differences between both, provided that the level of uncertainty is acceptable [11].

Valorization chains are multi-functional, i.e. they seek to satisfy several objectives, and this adds another layer of difficulty to the task in hand. This is the case, for example, in waste treatment as one is simultaneously attempting to eliminate and/or reduce waste while also producing energy or a secondary raw material. Such systems do not only provide a “waste treatment” function but also a function aimed at

enhancing their potential as an energy and/or material source. Therefore, the definition of a F.U. and system boundaries is by no means a straight-forward task for such multifunctional systems [12,1]. The issue being: should one try to aggregate them under a single unit (monetization) or should one define a "panel" of functional units and report emissions / consumption flows for each FU [13]? To make the comparison of these multifunctional systems feasible and relevant, defining a unique FU, which would be common to these different systems, should be considered. The standard approach is to define "waste management" as the main function and the functions linked to valorization (energy and material recovery) as co-functions, as they provide services which are very different from the main function. As the valorization process is closely linked to the treatment process, both are considered indivisible. The commonly accepted rule that enables these various co-functions to be taken into account is the rule of substitution or boundary extension [14]. The substitution rule deals with assigning to the co-function the environmental loads generated by the classical process which would provide an equivalent level of service. Substitution involves extending the system boundaries, either by adding to the main function (i.e. waste management) the environmental burdens of the classical process equivalent to the co-function (e.g. energy production) or by subtracting them, which is the most popular approach [7,15]. The imputation rule of substitution by subtraction introduces the notion of avoided impact, which is computed as a negative impact on the results.

As outlined by [1], we face a third methodological difficulty, i.e. the issue of allocation, which particularly concerns the waste and biomass valorization sectors. Allocation deals with assigning to the raw material entering the process the "amount" of environmental burden that has been generated by its production. As waste is an unwanted end-of-life residue with zero or negative economical value, the common assumption for waste entering treatment process is that no environmental load should be allocated to it; this is called the "zero burden" hypothesis [16]. But when wastes undergo treatment for partial recovery of potential energy or matter, they acquire an indirect economic value. Therefore, the issue of status of waste and residue is raised: should we still consider waste/residue as "left-overs" to be eliminated or as co-products? The "zero burden" hypothesis could be rejected if, with growing raw materials and energy shortages, the economic value of waste and residue changed. Another question then pops up: "shouldn't a system modeled in LCA be released from these conventions and economic situations?"

The final challenge offered by these types of systems is their requirement of a spatial approach, which breaks with the integrative way in which standard LCA accounts for impacts (for each impact category, the values are summed wherever the impact takes place). Waste management or biomass production/processing chains are characterized by a geographical concentration of their foreground activities i.e., activities linked to waste/biomass collection and processing. This specific characteristic justifies the need for a spatially differentiated approach to assess local impacts - such as eutrophication and damage to human health. Spatial

differentiation can be achieved, firstly, at the inventory level (identification of waste/biomass residue resources and of their energy potential) and secondly at the impact characterization stage by taking into account the characteristics of the “pollution source/impacted medium” couple in the computation of the local impacts [17]. Methodologies of spatial differentiation may feature attempts to couple Geographic Information Systems (GIS) and models for calculating emissions and their environmental fate [18].

4. Research questions related to Phase 2 – Inventory

As pointed out by [12] "Life cycle assessment is a system analysis method as indicated by the occurrence of multidisciplinary, teleological features, the presence of large (complex) systems and handling of a systems model, and the existence of case studies and their iterative nature. "

The model construction phase is critical for complex systems. The model must be representative of the system from the LCA point of view (that is to say, to allow the calculation of emissions/consumption flows) and must be supplied with available data. If one of these assumptions were not validated or if the model generated excessive uncertainty levels, it would be of little use. Research focuses on inventory refinement, i.e. in characterizing and reducing these uncertainties. It is therefore crucial to build more accurate models by:

- concentrating efforts on the inventory of sensitive processes (this is the approach used in building hybrid LCA);
- representing and characterizing process variability, instead of providing average models;
- increasing our knowledge of the process and therefore refining emission factors (i.e. factors converting activity data into emissions) through more accurate emission models.

These three points will be developed below.

** The first approach is to adapt the scale to work holistically on background processes -on which the stakeholder has no influence- and to zoom in on the most sensitive parts of the system. Indeed, when industry- or economy- wide scales are considered, the standard LCA analytical approach is no longer viable because of the complexity of the studied object; approaches as input/output matrices [19] based on data related to inter-sector economic transactions [11] are proposed as alternatives but are also faced with numerous challenges [20-21]. Another way is to combine the advantages of the two first approaches (i.e. process-LCA and input/output methods) in the form of a hybrid LCA [20], in which the aggregated data of the input/output approach are replaced, for the biggest flows, by data generated by "process" approaches.*

** A second approach is to better model system variability instead of hiding it using averaging. Variability is indeed one of the uncertainty components, i.e. the stochastic one, the second one being epistemic uncertainty*

which is due to a lack of either knowledge or process data. In agricultural – i.e. biomass - production systems, emission variability is due to the variability of agricultural practices and/or soil and climate conditions. In this case, variability is managed by building up typologies of production systems (e.g. intensive agriculture, organic farming, etc.) and the LCA is then carried out for each of these types. The rate of uncertainty reduction is all the greater when inter-type variance is significant. In systems where dynamics has a notable influence (such as systems involving energy production and consumption), it is essential to integrate the time dimension in the model in order to obtain meaningful results, even if today this practice is not compulsory in LCA. Such an approach has already been proposed by [22] or by [23] in the framework of Symbiosis project on the production of energy from algal biomass grown using waste water and extra CO₂ available from neighboring industries. Finally, in order to succeed in modeling the process under study, particularly in the recovery processes, it is crucial to go beyond the feasibility of the physical modeling by using social science approaches in order to understand the human influence on the physical interactions, as advocated by [3]. This is the field of industrial ecology (IE), which allows the generation of plausible scenarios both in terms of physical flows and human interactions, when it is combined with LCA [24] [25].

** A third approach attempts to reduce epistemic uncertainty* by increasing our knowledge of either production processes (to obtain more accurate activity data) or emission processes (to obtain more accurate emission factors). In agriculture, field emission inventories are primarily based on statistical models [26], on complex mechanistic models (as proposed by Langevin et al to model emissions from liquid manure fertilization [27]) or simplified operational models (eg SALCA) providing ultra-simple emission factors. The challenge is to find a model of the emission factor that would be comprehensive enough to represent the process, but simple enough to limit the number of parameters. In agriculture, it has been shown that less than 10 key parameters (application settings and pedo-climatic parameters) could provide a satisfactory representation of emissions due all the agricultural operations [28].

5. Research questions related to Phase 3: Development of causal chains linked to specific environmental impacts

Despite progress on new specific impact categories in recent years [29-30], several impacts (such as biodiversity, specific land uses (sea-use), emerging pollutants, impact of pesticides and fertilizers, odors, etc.) are still not satisfactorily represented in LCA. This is due either to the absence of this indicator in the range of indicators of classical product-LCA, or to unsatisfactory models of characterization factors (which convert the flow of pollutant into an impact value). But one of the significant advances of LCA would be its ability to give a spatial dimension to the impacts, and particularly to so-called site-specific impacts

(eutrophication, ecotoxicity, toxicity...). By allocating a spatial significance to an impact, the vulnerability of the medium encountering pressure, is taken into account. This means that the assessment shifts from a “potential” to a “probable” impact [31,30]. This is particularly important if public decision-makers wish to use LCA to assist them with decisions having local impacts. Usetox [32] is one of the most successful advances in the spatialization of impacts. It characterizes factors such as emission, exposure and toxicity. It would be useful to take advantage of its framework to develop other impact categories which have local impacts and are relevant to WMS (odours, noise etc).

6. Research questions related to Phase 4: Interpretation and use.

Although there is no specific research issue to be addressed relating to the interpretation stage, challenges do arise when trying to use LCA multi-criteria results of LCA in a decision-making processes. The latter may be very complex when social groups are involved regarding the systems under study, unlike for product-oriented LCA where output decisions are in the hands of an eco-design specialist. This situation is often encountered when dealing with waste/biomass valorization systems. As LCA outputs are presented in the form of vectors of mid-point or end-point impacts, explaining them to a public audience can be a very tricky exercise. Social sciences are therefore called upon to investigate and assist social appropriation of the LCA results, for example through public debate [33-34].

7. Cross-cutting issue: uncertainties

Uncertainty in LCA is crucial when comparing scenarios, as decision-making must integrate not only the value obtained but also uncertainty. This requirement permeates the whole LCA process. In general, as explained by [35], the methodological choices made for the study boundaries (step 1), or for the lifecycle impact assessment method or LCIA (Step 3) are the main factors of uncertainty because they directly influence the results. Several methods are available for LCIA (Eco-indicator, Edip, impact 2002+, impact world +...) and, whatever the choice, the final result will be affected. In addition, models for computing characterization factors may be imprecise and not always adapted to the situation experienced. This is confirmed by [36] who, for waste processing research, studied all the methodological issues that could lead to LCA results discrepancies (for certain impacts, it can reach 1400%). As seen above, the model (Step 2) is the third factor generating uncertainty as the model must be a trade-off between completeness and data availability. Besides, methods to propagate uncertainties may also affect the value of the final uncertainty. The possibility theory can be used to better deal with both variability-based uncertainty and epistemic uncertainty and therefore to reduce the final uncertainty. This has been demonstrated by several authors working on biofuels [37-38]

8. Conclusion

LCA can not be optimized using the classical standardized method when applied to complex systems such as those used for biomass production or waste valorization. New research avenues have been put forward, and some of them, issued from presentations made at Ecotech&tools conference, are published in Waste and Biomass Valorization: Halog & Bichraoui [39] enlarged the LCA approach to other modeling tools such as system dynamics, materials flow analysis and agent-based modelling to assess the sustainability of an industrial eco-park in Maine; Pradel et al. [40] and Dufossé et al [41] describe methods for improving the accuracy of inventories for agricultural operations; both are based on the use of appropriate emission models for nitrogen emissions; Marchand et al [42] develop a new pathway to take odour into account when waste treatment processes are dealt with; Schlieff et al [43] assess how far LCA can contribute to public debate in decision for waste treatment processes.

These examples show that the fields of research in LCA applied to these systems are vast and may call upon multiple disciplines. The challenges involved will be addressed over the coming years.

ACKNOWLEDGEMENTS

The authors thank the other members of ELSA pole for their advice and suggestions. We are also grateful to the Languedoc Roussillon for its financial support and to Interreg Sudoe (Ecotech-Suode project) for its funding in LCA research.

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