A relevant LCA methodology adapted to biomass-based products

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Abstract: *The Life Cycle Assessment (LCA) methodology is commonly employed to assess the performances of the different uses of biomass, which is supposed to play an important role in both mitigating climate change and reducing dependence on fossil fuels. The range of LCA results is however very wide and prevents from having reliable and accurate results for policymaking.*

In order to better understand such discrepancies in results, this work reviews the LCA methodology and issues, and carries a sensitivity analysis on every LCA parameter, either assumption or data. Non-specific methodological elements appear to be of major importance for LCA results: allocation rule influence is quantified to range from 48 to 82%, and system boundaries one from 0 to 93%. Input data play also an important role in results discrepancy, especially for GHG emissions. Local specificities can influence the final results by 53 to 118% and N_2O uncertainties by 31 to 67%. This calls for agreements about LCA methodology depending on its application, limitations of geographical coverages and integration of the best scientific knowledge about N_2O dynamics.

Finally the soil integration shortcoming is pointed out. Variations of soil carbon quantities due to land use changes can be very important and overwhelm GHG savings induced by biofuels use. This parameter is however lacking in LCA methodology applied to biomass-based products.

Keywords: *LCA methodology; biomass; biofuel; soil carbon.*

Difficulties in LCA of biomass-based products

The promotion of biomass to energy use is generally based on two potential advantages: biomass may reduce the consumption of fossil materials and so mitigate climate change, and since it is a local resource it may decrease the energy and raw material dependence on materials from other parts of the world. Life Cycle Assessment (LCA) is a valuable methodology to assess the performances of biomass uses; most of environmental assessment tools, from simplified ones, such as *Bilan Carbone* (Ademe, 2007) in France, to the most detailed ones, such as the CML guidelines (Heijungs et al., 1992; Guinée et al., 2001), were created from LCA methods.

The range of LCA results when applied to biomass-based products is however wide and leads to contradictory policymaking decisions, from moratorium to promotion. First and second-generation biofuels, that is to say from agriculture and forestry, have been the more assessed biomass-based products in recent years. Figure 1 shows the ranges of LCA results for different biofuels, in terms of primary energy and greenhouse gases (GHG) saved compared to fossils fuels, obtained in 2004 from a review of more than 60 studies (Quirin et al., 2004): some results, such as primary energy savings for ethanol from sugar beets can be in a ratio of 1 to 5.

This work aims at giving a better understanding of such discrepancies and identifying a relevant way to apply the LCA methodology to biomass-based products, in order to get more reliable and accurate figures than actual ones. To reach this goal, first the LCA methodology is reviewed and its major issues identified, then the analysis of two biofuel case studies (ethanol from wheat and methyl ester from rapeseed) are presented in order to determine the influence on results of the selected methodology and data quality in LCA.

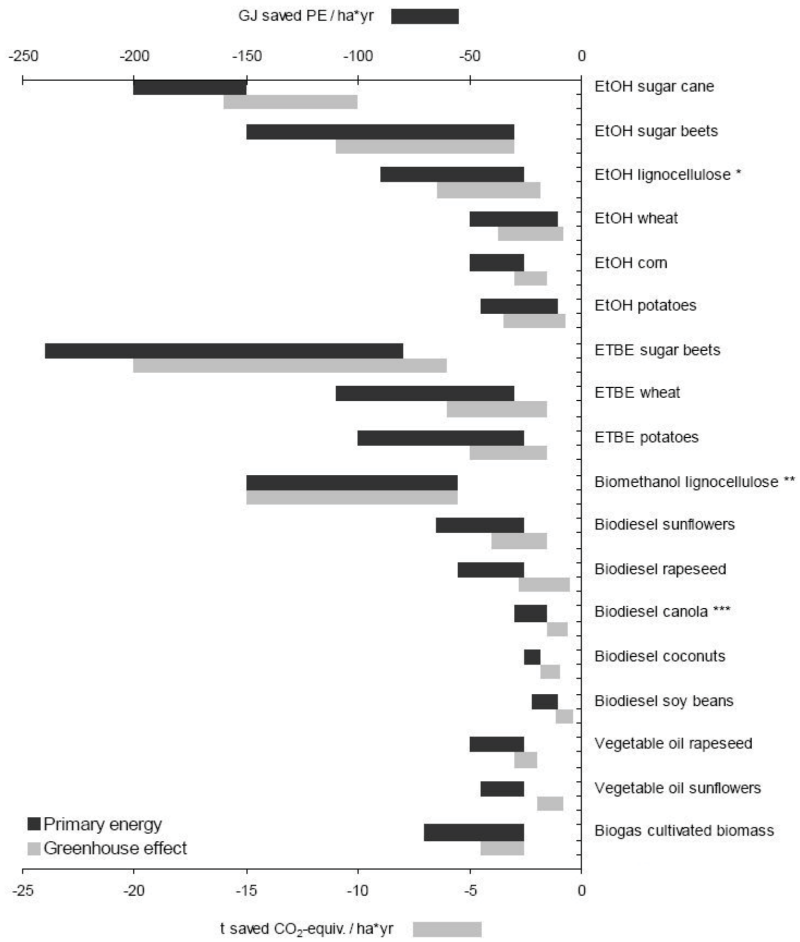

Figure 1. Primary energy and GHG savings of some first and second-generation biofuels, compared to their fossil counterparts; results from an IFEU review (Quirin et al., 2004)

Review of the LCA methodology

LCA is an assessment methodology of the environmental performance of a product, which can be a good as well as a service. The fundamental principle of this technique is to study the environmental impacts of the product during its whole lifecycle, or “from cradle to grave”, it is to say from the extraction of raw materials to its final elimination.

LCA first appeared in the 1970s, due to the issues raised after the oil crisis. Many contributions have been done in the 1990s, and finally came in the late 1990s to a standardization of LCA. These standards were reviewed in 2006, leading to two international standards: ISO 14040:2006 (ISO, 2006a) for general public and ISO 14044:2006 (ISO, 2006b) for practitioners.

Carrying an LCA study

The international standards ISO 14040:2006 and ISO 14044:2006 define the specific lexicon, set the four execution phases of an LCA study and describe their constitutive elements. These four execution phases are: *goal and scope definition*, *inventory analysis*, *impact assessment* and *interpretation*. Their consecutive achievement is logical but as some problems met in later phases must be solved in previous ones, carrying an LCA study is quite an iterative process.

The description below of the LCA methodology is made from a review of these standards and some valuable guidelines (Curran, 2006; Guinée et al., 2001; Pennington et al., 2004; Rebitzer et al., 2004; Udo de Haes et al., 1999a; Udo de Haes et al., 1999b).

Goal and scope definition

The first phase of a study is essential to the whole LCA consistency. The practitioner must set out the goal of the study: *why*, *for which* and *for who* it is done. He must also describe all the assumptions and choices made for the study. Among them two elements are very specific to this first phase of an LCA: *system boundaries* and *functional unit*.

In order to make clear what the expression “from cradle to grave” means for the studied product, the practitioner must fully describe the product system. He must name the elements which are taken into account, or ‘included into the system boundaries’, and the ones which are not. If an element is assumed to be negligible, the reasons have to be explained.

In order to help the data management and to allow an easy comparison between different system products, a functional unit must be defined. This unit has to be representative of the product system. In case of biofuels, the energy content is generally acknowledged as a representative unit, though a liquid fuel quality can not be limited to this characteristic. In case of crop production in general, it can be discussed if the functional unit should be the weight, the protein content, the sugar content, the cultivated area, etc.

Inventory analysis

This second phase consists in providing the needed information of the system flows. The first concern when collecting data is the *data quality*, especially their representativeness to the geographical and time coverage defined in the goal and scope definition phase.

One of the major LCA issues occur during the inventory phase: *allocation*. This problem appears when a process has more than one single product. The LCA practitioner must then allocate the process impacts between the products in order to determine the impact relating to the product of interest. Many options can be considered but they can be sorted into two types of solutions: allocation based on an indicator, or system expansion.

When applying an allocation based on an indicator, the process impacts are divided between the products in compliance with a specific indicator of the products. This indicator could be a physical one, such as weight or energy content, or an economical one, such as market value.

When applying the system expansion approach, the practitioner must identify, for each by-product P_1 which is not the product of interest P_0, an equivalent product P_1’. The impacts of the system will first be fully allocated to the product of interest P_0. Then the impacts saved by the substitution of the product P_1’ by the by-product P_1 will be subtracted to obtain the final impact of the product of interest. This method principle is presented in figure 2.

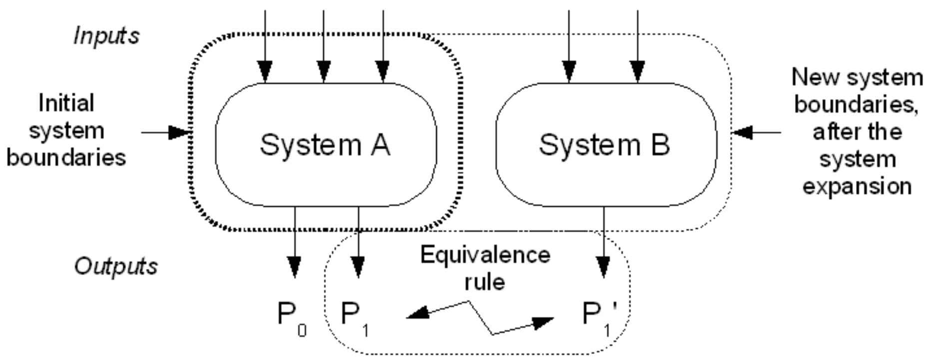

Figure 1 – Application of the system expansion approach to figure out an allocation issue

Impact assessment

The point of this third phase of an LCA study is to translate the flows from the inventory phase, whose amount can reach several hundreds, into a few well-chosen indicators. This allows a better understanding of the environmental impact of the product under study. Three main stages make up this phase: the *selection of impact categories and category indicators*, the *classification* and the *characterisation*.

First the relevant impact categories for the LCA goal and scope have to be chosen, for instance depletion of resources, climate change, eutrophication or human toxicity. For each of these categories, an indicator must be chosen; it can be a mid-point indicator, of scientific relevance but poor environmental understanding, such as kg CO_2 equivalents for climate change, or an end-point indicator, of environmental relevance but poor scientific reliability, such as damage to crop production for climate change.

Then each substance taken into account in the inventory phase must be assigned to one or several impact categories. During this classification stage, special attention must be paid to the possibility of double counting of substances.

Finally characterisation models are aimed at translating the substance flows into contributions to category indicators. These models must take into account so far as possible the fate and exposure of these substances, and the threshold effects.

As a facultative step, it is possible to reduce again the amount of indicators by normalizing, grouping and weighting the indicators obtained after the characterisation.

Interpretation

The last phase of an LCA study consists in giving an answer to the issue defined in the goal and scope definition phase. Beyond the interpretation of the results of the impact assessment phase, their reliability and accuracy must be established by checking the consistency of assumptions and data with the goal and scope of the study, and by carrying sensitivity and uncertainty analysis.

Major issues of the LCA methodology

The major issues of the LCA methodology can be identified from the previous review as given in table 1. This can be useful to keep in mind when reading any LCA study.

Table 1 – Major issues of the LCA methodology

Phases	Major methodological issues
Goal and scope definition	System boundaries
	Functional unit
Inventory analysis	Data quality according to the scope of the study (in terms of geographical and time coverages)
	Allocation rule
Impact assessment	Point level of indicators (mid-point or end-point)
	Characterisation models
	Value choices for normalisation and weighting
Interpretation	Sensitivity analysis

An assessment of biofuels LCA parameters influence on the results

Many LCA results are now available for biofuels though very often limited to energy consumption and GHG emissions. Since the discrepancy of evaluated biofuel performances is wide, they are an interesting case study of LCA methodology application to biomass-based products. Two specific biofuels have been chosen for the amount and transparency of available results and the importance of their production in Europe: ethanol (EtOH) from wheat and methyl ester (ME) from rapeseed.

Working methodology

Five European LCA studies were considered: CCPCS '91 (Bouvet et al., 1991), Ademe '02 (Ecobilan, 2002), GM '02 (Choudhury et al., 2002) JRC '03 (Edwards et al., 2003) and JRC '07 (Edwards et al., 2007). All their data and assumptions were collected and a sensitivity analysis was carried out for each LCA methodological parameter, such as allocation rule or system boundaries, as well as each LCA input data, such as agricultural yield or fertilizer use.

Since an LCA study needs a significant amount of input data, the influence of data on results were aggregated in three categories:

- *local specificity*, which underlines the link between the local characteristics, such as the soil and climate context or agricultural practices, and the system performances,
- *approximations*, which brings together the influence of data assumed to be negligible, and
- *uncertainties*, regarding the measurements of N_2O fluxes from soils.

LCA parameters influence is defined as the ratio between the amplitude of the variation calculated by the sensitivity analysis and the median LCA result for the studied biofuel.

Results

Among the five reviewed studies, each one takes into account rapeseed ME production, and only GM '02 does not consider wheat EtOH production. LCA parameters influence is determined for both primary energy consumption and GHG emissions. Figure 3 presents this work results for the major methodological assumptions and the three data categories.

The three major methodological assumptions identified are:

- the allocation rule,
- the system boundaries, especially whether they include or not the necessary treatments of by-products before use, and
- the alternative use considered in the system expansion approach, it is to say the use for by-products identified to figure out the allocation issues.

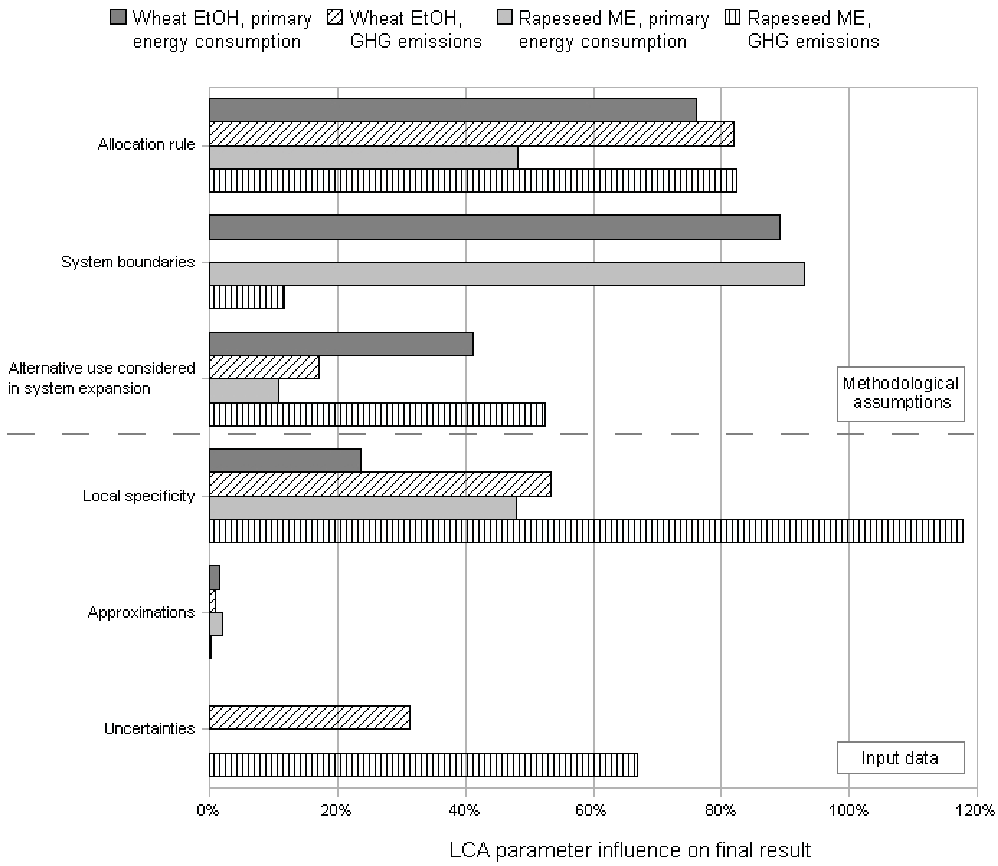

Figure 3. Measurements of the major LCA parameters influence on results for two specific biofuels (wheat EtOH and rapeseed ME)

The allocation rule appears as the major LCA parameter inducing variations in results. Its significant influence, from 48 to 82%, impacts both indicators and both biofuels. Inclusion, or not, of by-products treatment is also a methodological assumption of major importance for energy consumption only; this can be explained by the fact that the energy used for the by-products treatment is generally natural gas, whose GHG emissions are of minor importance compared to other GHG emissions of the product system (other fuels or N_2O). Finally, the influence of the alternative use considered for by-products in the system expansion approach underlines the importance of defining a realistic by-product use scenario to obtain a relevant final LCA result.

Input data analysis shows that:

- local conditions may have a major influence on final results, from 24 to 118%, to such an extent that considering a too wide geographical validity for the study can be harmful to the relevance of results,
- N_2O uncertainties are of major importance for the GHG results accuracy,
- rapeseed ME seems more sensible to input data variations than wheat EtOH; this can however be mainly explained by the lower final results obtained for ME than for ethanol in these studies,
- approximations represent no more than 2% of the results, but some items assumed to be negligible in these studies, such as agricultural buildings and machinery, should be integrated according to a study from the European Commission which underlines that this assumption relevance was quite different for agricultural systems than for industrial ones (Audsley et al., 2003).

Shortcomings in the common approach of biomass-based products

Beyond the better understanding of the origins of discrepancy of LCA results, this review of LCA studies for biofuels allowed to identify common shortcomings in these studies implying living systems. Soil integration in actual studies is especially very poor.

Soil seems to be seen in living systems LCA in the same way as machines in industrial systems LCA, it is to say a base for production. Changes in soil quality can however appear depending on the agricultural practices and on land use. This matter is especially of great importance for the GHG emissions indicator. Variations in soil carbon quantities represent indeed high amount of carbon (Arrouays et al., 2002; Freibauer et al., 2004), which can easily exceed the GHG savings induced by a replacement of fossil fuels by biofuels. For instance Arrouays et al. evaluated the soil carbon loss due to the substitution of grasslands by cultivation area to 92 ± 26 $tCO_{2\text{-equivalent}}$ / ha, among which 80% in 25 years (Arrouays et al., 2002), whereas IFEU collected GHG savings due to biofuels ranging from 1 to 20 $tCO_{2\text{-equivalent}}$ / ha / yr (see figure 1) (Quirin et al., 2004).

This shortcoming of soil integration in LCA should worsen if results about other impacts than energy consumption or GHG emissions are aimed to be provided (Audsley et al., 2003; Milà i Canals et al., 2007).

Conclusions and perspectives

LCA methodology appears in this work as the major source of discrepancy in the assessments of biofuels environmental performances. Agreements have to be found about typical methodological issue such as allocation rule, whose influence on results can reach 80%, depending on LCA goal and application. In particular the proposal of the 23rd January 2008 for the European directive on the promotion of the use of energy on renewable sources pointed that allocation issues should be managed with the system expansion approach for 'policy analysis purposes' and with allocation based on energy content 'for regulatory purposes' (Commission of the European communities, 2008).

Specific recommendations for application of LCA methodology to biomass-based products can however be made from this work in order to improve the reliability and accuracy of available results: limiting the geographical coverage to more homogeneous agricultural areas, and integrating the most accurate data available on N_2O fluxes. Indeed, according to this work, local specificity influence can go past 100% in specific cases and N_2O uncertainties represent 30 to 70%.

Finally new elements of the LCA methodology itself have to be developed. Soil integration is especially a key element to obtain a reliable assessment of land use and land use change.

References

Ademe, 2007. Bilan Carbone, Calcul des facteurs d'émissions et sources bibliographiques utilisées, Version 5.0. Ademe - MIES, Paris.

Arrouays, D., Balesdent, J., Germon, J.-C., Jayet, P.-A., Soussana, J.-F., Stengel, P., 2002. Stocker du carbone dans les sols agricoles de France ? Rapport d'expertise, INRA.

Audsley, E., Alber, S., Clift, R., Cowell, S., Crettaz, P., Gaillard, G., Hausheer, J., Jolliet, O., Kleijn, R., Mortensen, B., Pearce, D., Roger, E., Teulon, H., Weidema, B., van Zeijts, H., 2003. Harmonisation of environmental life cycle assessment for agriculture. Final report, Concerted Action AIR3-CT94-2028, European Commission.

Bouvet, J., Leroudier, J.-P., Leprince, P., Herz, O., 1991. Rapport des travaux du groupe de travail n°1. Rapport, Commission Consultative pour la Production des Carburants de Substitution.

Choudhury, R., Wurster, R., Weber, T., Schindler, J., Miller, M., Brinkman, N., Armstrong, A., Rickeard, D., Jersey, G., Kerby, M., Kheshgi, H., Robbins, J., Cadu, J., Le Breton, D., Dautrebande, O., 2002. GM Well-to-wheel analysis of energy use and greenhouse gas emissions of advanced fuel/vehicle systems - A European study. Report, GM, LBST, BP, ExxonMobil, Shell, TotalFinaElf, Ottobrunn.

Commission of the European communities, 2008. Proposal for a directive on the promotion of the use of energy from renewable sources. Directive of the European parliament and of the council, version 15.4, Brussels.

Curran, M.A., 2006. Life cycle assessment: principles and practice. Report EPA/600/R-06/060, EPA, Cincinnati.

Ecobilan, 2002. Bilans énergétiques et gaz à effet de serre des filières de production de biocarburants. Rapport final, ADEME / DIREM.

Edwards, R., Griesemann, J.-C., Larivé, J.-F., Mahieu, V., 2003. Well-to-wheels analysis of future automotive fuels and powertrains in the European context. Well-to-tank report, CONCAWE, EUCAR, JRC.

Edwards, R., Larivé, J.-F., Mahieu, V., Rouveirolles, P., 2007. Well-to-wheels analysis of future automotive fuels and powertrains in the European context. Well-to-tank report, CONCAWE, EUCAR, JRC.

Freibauer, A., Rounsevell, M., Smith, P., Verhagen, J., 2004. Carbon sequestration in the agricultural soils of Europe, Geoderma, 122, 1-23.

Guinée, J., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Sleeswijk, A., Suh, S., Udo de Haes, H., de Bruijn, H., van Duin, R., Huijbregts, M., 2001. Life cycle assessment - An operational guide to the ISO standards. Final report, CML, Leiden.

Heijungs, R., Guinée, J., Huppes, G., Lankreijer, R., Udo de Haes, H., Sleeswijk, A., Ansems, A., Eggels, P., van Duin, R., de Goede, H., 1992. Environmental Life Cycle Assessment of products. Guide, CML, TNO and B&G, Leiden.

ISO, 2006a. Environmental management -- Life cycle assessment -- Principles and framework. ISO 14040:2006.

ISO, 2006b. Environmental management -- Life cycle assessment -- Requirements and guidelines. ISO 14044:2006.

Milà i Canals, L., Bauer, C., Depestele, J., Dubreuil, A., Freiermuth Knuchel, R., Gaillard, G., Michelsen, O., Müller-Wenk, R., Rydgren, B., 2007. Key elements in a framework for land use impact assessment within LCA, International Journal of Life Cycle Assessment, 12, 1, 5-15.

Pennington, D., Potting, J., Finnveden, G., Lindeijer, E., Jolliet, O., Rydberg, T., Rebitzer, G., 2004. Life cycle assessment - Part 2: Current impact assessment practice, Environment International, 30, 5, 721-739.

Quirin, M., Gärtner, S., Pehnt, M., Reinhardt, G., 2004. CO_2 mitigation through biofuels in the transport sector. Main report, IFEU, Heidelberg.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B., Pennington, D., 2004. Life cycle assessment - Part 1: Framework, goal and scope definition, inventory analysis, and applications, Environment International, 30, 5, 701-720.

Udo de Haes, H., Jolliet, O., Finnveden, G., Hauschild, M., Krewitt, W., Müller-Wenk, R., 1999a. Best available practice regarding impact categories and category indicators in life cycle impact assessment, International Journal of Life Cycle Assessment, 4, 2, 66-74.

Udo de Haes, H., Jolliet, O., Finnveden, G., Hauschild, M., Krewitt, W., Müller-Wenk, R., 1999b. Best available practice regarding impact categories and category indicators in life cycle impact assessment, International Journal of Life Cycle Assessment, 4, 3, 167-174.