INTEGRATING ECONOMIC MECHANISMS INTO LIFE CYCLE ANALYSIS: WHAT TO CONSIDER AND HOW

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ABSTRACT

A research project has been recently started to evaluate the environmental performances of an innovative tyre recycling system by means of the life cycle assessment (LCA) methodology, comparing the new technology with a more conventional solution involving the use of tyres as fuel in a cement kiln. The technology analysed, developed under the 7th Framework Programme project "TyGRE" (High added value materials from waste tyre gasification residues) consists of the gasification treatment of waste tyres and the utilization of the carbon-rich char fraction obtained, together with glass cullet, for the synthesis of ceramic materials (SiC) and the energy recovery of syngas.

For a more accurate and comprehensive environmental assessment of the new technology, it is important to identify and analyse the markets affected (e.g.: waste tyres, cement, glass, SiC, as first order markets), the involved quantities and the related substitution mechanisms. Indeed, the introduction of a new technology in a market sets off multiple dynamics with the surrounding systems, at the environmental, economic and social level. If dealt with in its wholeness, this problem would pose several methodological challenges; nevertheless, even if we narrow the question to the environmental analysis, problems are still far to be solved from both the conceptual and computational viewpoints. A pure environmental assessment would leave the surrounding system in which a product/process is embedded out of consideration. However, in some circumstances this simplification is not acceptable. Working on the environment-economy interface, the question "Which is the environmental impact of technology X?" would be rephrased into "Which are the environmental consequences due to the introduction of technology X in the market?"

This paper described an analysis performed within the Life Cycle Sustainability Analysis (LCSA) framework, which was proposed in the 6th Framework Programme project CALCAS (Co-ordination Action for innovation in Life-Cycle Analysis for Sustainability). LCSA is a structure that works with a plethora of disciplinary models and guides selecting the proper ones, given a specific sustainability question. A three-phase work method has been developed for the application of the framework: i) *Framing the question*, i.e. identification of question and object of the analysis; ii) S*election of appropriate methods and models* to perform the analysis; iii) *Application of the methods and interpretation of results*.

This paper discusses the general approach to the Life Cycle Sustainability Analysis, focusing on its first step, i.e. framing the question, and suggesting an approach to structure this phase, in which both qualitative and quantitative analyses should be used. Our research suggests that in this phase an iterative approach should be used, which combine experts' judgment with analytical tools. Regarding the latter, more than one tool

could provide useful insights: for this reason, during the project different analytical approaches will be tested. It appears also necessary to translate the approach to the framing of the question into practical guidelines, easily extendible to other systems besides the technological ones.

INTRODUCTION

The phrase "Sustainability Assessment of Technologies" is used to define a harmonised approach aimed at evaluating the sustainability (environmental, economic and social aspects) of future and existing technologies. Over the past decades many different approaches and methods have been developed for assessing the different aspects of sustainability. Each has its own strengths and weaknesses and is able to address a specific sustainability aspect: tools for environmental assessments, tools for economic modelling and assessments, approaches for sociological analyses, approaches for integrated assessments, methods and tools for futures studies, and participatory approaches. Nevertheless, none of them is able to deal with the problem in its wholeness, to cover all the complexities of the problem; this mainly because an overall method capturing all the complexities and dimensionalities of sustainability is not achievable. An interdisciplinary and multidimensional approach is required to deal with multiple effects in different domains, like forecasting of system behaviour and technology evolution, normative choices, uncertainties and risks, just to cite some.

CALCAS project dealt with these aspects and delivered a Life Cycle Sustainability Analysis framework (LCSA) (Heijungs et al. 2010), a structure that works with a plethora of disciplinary models and guides selecting the proper ones, given a specific sustainability question (Guinée et al. 2010). The framework is aimed at linking life cycle sustainability questions to the knowledge needed for addressing them, and makes use of several methods and models which have to be selected according to a specific sustainability question. The main characteristics of the framework (Figure 1), with respect to LCA, are the following:

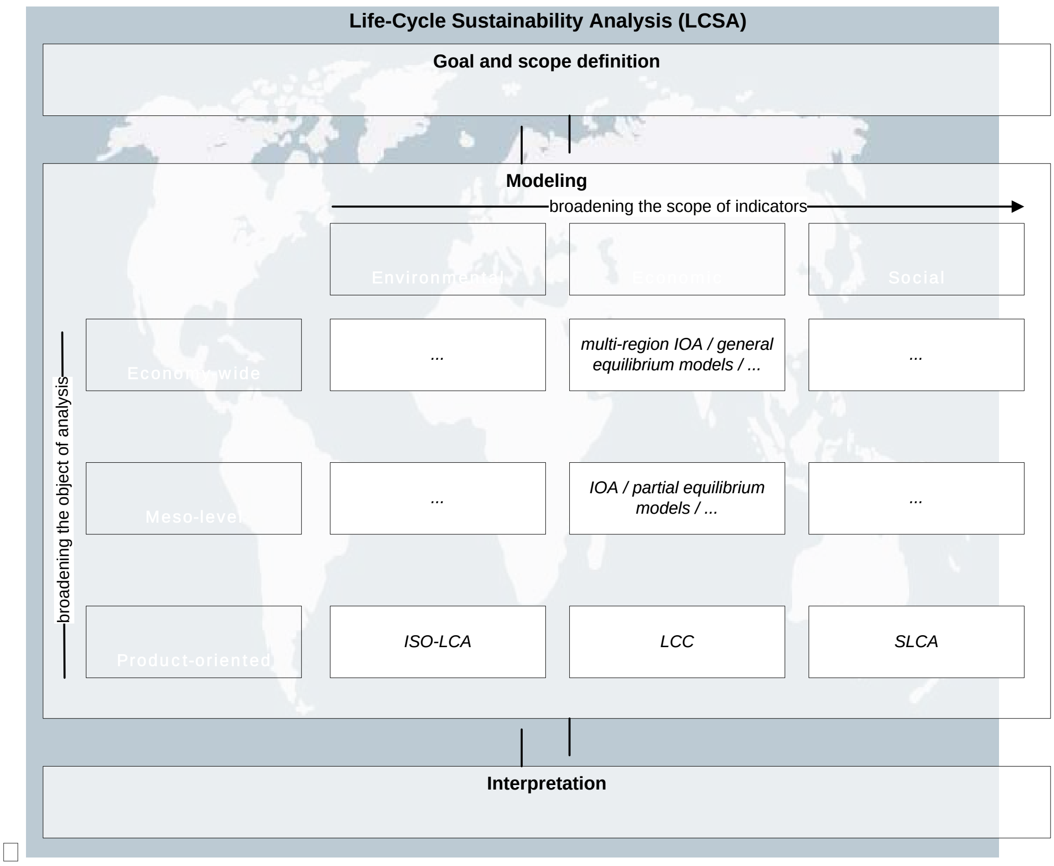

Figure 1: LCSA framework (source: Guinée et al. 2010)

- It broadens the scope of indicators and/or the object of the analysis. Broadening can be achieved by extending the number of environmental indicators, or by going beyond the focus on environmental aspects and including also the economic and social ones. Another example of broadening is the shift of the object of the analysis from individual product systems to sectors, baskets of commodities, markets or whole economies.
- It deepens the scope of mechanisms and/or a particular mechanism. Deepening can be achieved by going beyond the focus on technological and environmental mechanisms and including also physical, social, economic, cultural, institutional and political ones (Heijungs et al. 2010). On the other side, deepening means also further sophisticating the modelling, for example adopting spatially differentiated models.

Central question in the LCSA framework is how to frame and link questions for sustainability decision-making support to the most appropriate life-cycle-based methods and models. Indeed, different types of sustainability questions exist, which have been grouped in three categories (Zamagni et al. 2009):

- Product-oriented level. Products are defined according to the ISO 14040 series standards and thus comprise any goods or services. Examples of questions:
  - Should I fill my car today with gasoline or with E85[1]?
  - Is Jatropha-based biodiesel from plants cultivated on set-aside land at a Brasilian farm for local use more sustainable than fossil-based diesel?
- Meso level. It refers to groups of products and technologies, basket of commodities, recycling systems, etc. Examples of questions:
  - Should Sweden (or Denmark; or Iceland; or China) shift to 25% biofuel for road transport? At which time horizons?
  - Should the richest countries endorse on a path to biofuels as the major fuel for mobile applications in the medium term of two decades?
- Economy-wide level. It refers to national economies or other macroeconomic systems including the EU and the world. Examples of questions may include:
  - Should the world economy endorse on a path to biofuels as major fuel for mobile applications?
  - Should we shift to a bio-based society, for both energy and materials?

These brief examples of questions show that a study on biofuels may be carried out at different levels, depending on the main question to answer. Sometimes questions may refer to one level only, while in other cases questions may be translated into one or more questions for each level of the analysis. Moreover, the three levels are not sharply defined, and there may be questions that fall in between two levels.

Guidance should be given by elaborating a procedure which supports the use of the framework. In the following sections the procedure is introduced and the role that science can offer in defining the object of the analysis is highlighted.

[1] Alcohol fuel mixture of approximately 85% denatured fuel ethanol and 15% gasoline/other hydrocarbon by volume

WORKING WITH THE FRAMEWORK

The LCSA procedure articulates into three phases (Buonamici et al. 2009):

1. *Framing the question*, i.e. identification of the question and the object of the analysis (what the problem is, what the system does, what the expected impacts of the decision at hand are). It resembles the Goal & Scope definition of LCA;
2. *Selection of the appropriate methods and models* to solve the problem (analysis of methods and models available and of ways to integrate/combine them);
3. *Application of the methods and interpretation of results*.

As described later and likewise in LCA, the application of the procedure is an iterative process, in which both qualitative and quantitative approaches play a role.

Purpose of our project is to evaluate the environmental consequences due to the introduction of an innovative tyre recycling technology (hereinafter TyGRE technology) in the market, developed under the 7th Framework Programme project "TyGRE" (High added value materials from waste tyre gasification residues)[2]. The assessment has been streamlined considering the following assumptions:

- we focus on the environmental impacts caused by the introduction of a new technology into the market;
- we leave social aspects out of the analysis;
- we consider only economic relations, besides those technological and environmental usually taken into account in a LCA study.

Although usually not much attention is paid in formalizing the "Goal and Scope" phase of an LCA, here we focus on the first phase highlighting the need to make it operational with a specific procedure.

1. The role of economic relations in analyses with an environmental focus

The importance of working at the environment-economy interface has been recognised by different schools of thought, either from an environmental or from an economic angle. Already in 50s and 60s Kapp (1950) and Mishan (1967) warned us about the environmental disruption from economic growth. In 1987 the World Commission on Environment and Development (WCED) said that policy failure in both environment and economic development are the results of neglecting economic and ecological interdependencies by compartmentalised line ministries and agencies (Bartelmus 2008).

Let us consider the case of the development of a new technology, which is the object of our study. Its introduction in the market sets off multiple dynamics with the surrounding systems, giving potentially rise to:

- secondary effects by offsetting resource saving from improved production processes by increased and less expensive consumption;
- secondary effects on other technologies, leading to cheaper production and higher production volume elsewhere.

Clearly in both cases the related environmental impact looks different.

Analysing how the market affects the potential choices and how the market reacts to these choices allows us tracing side effects, which might potentially exert great influence on the overall environmental effects of the system under study.

[2] www.tygre.eu

2. Framing the question

Like in any evaluation problem, whatever the approach or the methodology is, the first aspect we have to deal with is the correct formulation of the question. In our framework, this means identifying at which level we set our analysis: product level, meso level, economy-wide level. Framing the question is a very important activity which, if erroneously done, could lead to an erroneous answer, like the biofuel case demonstrates (Huppes and Ishikawa 2009). The scientific literature does not show evidence of the importance of such an activity and the reasoning that led to the formulation of a question is usually not described. Guidelines are missing and it seems that practitioners rely upon their own knowledge and expertise.

In this phase we have to wonder what the expected impact of the decision at hand is and which is the time frame involved: whether the system analysed is simply replacing other systems on a small scale; or whether the technology used is expected to expand to many more applications on a larger scale. In the latter case, the analysis will probably be transposed into a higher level.

To structure this phase we propose an approach in which both qualitative and quantitative analyses are used. The following main aspects have been identified which can guide the formulation of a question (Table 1):

SUB-PHASE	MAIN ASPECTS TO CONSIDER
Technology characterisation	Technology description Performance characteristics Applications Time frame
Analysis of interrelations with the sourrounding systems	Technological relations Environmental relations Physical relations Economic relations Cultural, institutional and political relations Scale and time frame of the expected changes
Identification of trade-offs	Resources level Consumption level

Table 1: How to guide the phase of "Framing the question"

The process is iterative: first, a qualitative analysis based on experts' judgements is performed, aimed at providing a preliminary characterisation of the aspects listed in Table 1; then, the use of analytic techniques is necessary to identify, in a more precise way, the question and the object of the analysis, as well as the indicators to be adopted.

a. Technology characterisation

Detailed information has to be collected about: how the technology works (technology description); its performances, its foreseen applications and the time frame considered (the time to fully implement the technology on the market and the length of time required to recover the cost of investments). TyGRE is a technology of gasification treatment of waste tyres and utilisation of the carbon-rich char fraction obtained, together with a source of silica, for the synthesis of ceramic materials (silicon carbide -SiC) (via carbothermal process). The syngas obtained from tyres will be used for energy production. The technology, which will be developed at pilot scale, is presently at laboratory scale, thus performance characteristics are still under test (Portofino et al. 2008).

SiC-based products are employed in a number of applications, ranging from the metallurgical industry (used mostly as oxide agent in steel smelting), to the abrasives industry and finally to the electronics and other industries (for example, SiC crystals are the third generation semi-conductor materials, to be potentially used in national defence, space flights, aviation, etc.). In TyGRE, the potential use of SiC for filters for micro- and ultra-filtration is analysed: these are upcoming products that are not yet on the market. Presently the main competitors for SiC filters are manufacturers of ceramic membranes produced mainly from alumina. However SiC has a large number of advantages, in particular it withstands high and low pH values and temperatures, and withstands adhesion much better (Porta et al. 2010).

b. Analysis of interrelations

As already explained at the beginning of this section, we limit our analysis to technological, environmental and economic relations. The first two are those typically considered in any LCA study. Technological relations describe the principal causal relationships that connect the level of two economic activities (Heijungs et al. 2009): these form the central element of the inventory analysis and are typically described in a flow chart. Environmental relations describe all pathways and conversions that a substance released in the environment can be subjected to: they are included in the characterisation steps of the impact assessment.

A simplified attributional LCA study was carried out to identify the environmental hotspots. Two scenarios have been built up to compare different technologies for end-of-life tyres: the first considers the production of SiC from an innovative gasification process of end-of-life tyres, under the hypothesis of using white glass scraps as a source of silica; the second considers the production of electricity from the incineration of end-of-life tyres. Scenario 1 shows the highest environmental impacts. The main hotspots identified will represent the starting point for further refining the analysis (Ansuini 2009).

Economic relations describe the link between a product and the market, in which several interrelated mechanisms occur that have to be dealt with simultaneously. The question how to include economic mechanisms in LCA is not new. In the last years we have witnessed an increasing number of approaches, which can be classified in two main categories:

- consequential approach for systems affected by marginal changes (Zamagni et al. 2010).
- consequential approach for systems affected by non-marginal changes (Dandres et al. 2009)

All the approaches analysed inevitably show shortcomings. The main reason for that is a conceptual one: practitioners apply linear modelling, with a hypothesis of market clearance, to work out answers for non-linear systems. Besides that, in the case of consequential approach still several open questions exist, mainly related to: i) the type of marginal effects (short/long term) to include; ii) the identification of goods for which a change in demand in a life cycle affect the demand in other life cycles; the use of partial equilibrium models (when they are relevant); if and how the concept of experience curves and learning investment should be integrated into LCA and, if so, what approaches should be used in what circumstances (Zamagni et al. 2009).

Regarding TyGRE technology, we approached the problem by making a first qualitative identification of the main markets involved by means of experts' judgment. Cement, rubber, silica and silicon carbide produced via conventional production (Acheson technology) are those identified. Nevertheless, the analysis needs to be further refined with the support of an analytical technique in order to have more precise information related to: i) the economic relevance of the markets directly involved, and the potential penetration in the same markets of the product resulting from the new technology; ii) the identification of the markets which – even if indirectly linked– might affect our system (input markets and other output markets using the same inputs); iii) the technology-penetration scenario, in order to understand if the resulting product (thanks to the specific product characteristics resulting from the application of the new technology) could be employed also in applications not expected yet. Presently, a few different approaches have been considered:

- *Industry sector analysis*. In this regard, industry sector analysis (and, in general, those approaches that can be traced to the structure-conduct-performance paradigm) (Scherer and Ross 1990) could be a first useful framework. This framework proves very useful especially during the collection and systematization of data, and it can provide good results in case-studies; however, it is mainly qualitative and does not seem to be as generalizable as required for a theoretical approach to the problem through a clear and general methodology.
- *Econometric models*. When econometric tools are used, the most obvious option is to selectively assess the effects on a limited number of markets, i.e. that of the main product, those of the environmentally-relevant inputs, and other linked markets based on those inputs. In this case, given the lack of comprehensive data sets, one should prioritise the identification of a set of variables expressing the environmental performance of these markets, as well as the formal specification of a sufficiently general system of relations to be applied in a number of instances.
- *Input/Output Analysis*. The input/output analysis – a tool already known in this field of study - would enable a preliminary assessment of the structural effects of changing levels of consumption of intermediate goods and services based on various assumptions of technology penetration. Of course, the level of detail attainable depends on the size of the matrices provided by the statistical agencies, and the significance of the analysis is limited by the linearity assumption.
- *Dynamic Systems and Complexity*. A further possibility is to refer to the methodological paradigm of complexity. According to this approach, a simulation model could be built where the introduction of a new technology is an exogenous shock in a nonlinear dynamic system (with increasing returns) (Colander 2000; Waldrop 1992). The results could be very useful to evaluate the effects of technology diffusion, the sensitivity of the environmental benefits to the starting conditions, and the presence of emergent properties.
- *"Target costing"*. When a problem is dealt with from the theoretical point of view and with no reference to any specific case, one cannot know in advance the levels of investment needed to obtain the fund inputs (Georgescu-Roegen 1971) required to operate a new technology, being those inputs normally characterized by great uncertainty, especially in the case of process innovations. Starting from this limitation, a final approach could be to assume a target level of penetration of a new technology on the market (i.e., that level of penetration necessary to achieve acceptable economy-wide environmental effects), as well as an acceptable time frame in which this target level should be achieved. One could then proceed to estimate a target price and deduct the cost of flow inputs (framed as dynamic to take into account the likely variation trends) (Ansari and Bell 1997)[3]. This would make it possible to estimate the resources that a new technology can generate on the market and the ability of these resources to meet more or less adequately the investment required in the preparation and adaptation of the production structures present. This information could mainly be suitable for the design of support policies.

[3] This is based on the strategic approach to the introduction of new products on the market, i.e. *Target costing*. For more information Ansari S, Bell J (1997) *Target Costing.* McGraw Hill, New York.

Clearly these approaches differ each other in terms of technology specification, data availability and reliability, complexity of computational structure, general approach (top-down vs bottom-up vs hybrid approaches) and results they deliver. In the next phase of the research project they will be analysed in detail and those which show greater potentialities with respect to our technology system will be selected. Their application will help us defining the right question.

c. Identification of trade-offs

Dealing with sustainability inevitably involves the question of trade-offs. Indeed, the introduction of a new technology in the market can meet already existing needs or hidden ones. In both cases, the structure of consumption is affected: satisfaction of needs usually requires an increase in production and thus in the use of natural resources. The production of SiC with this innovative technology could potentially open up new and unforeseen applications, besides those developed for. If these would extend to a broad scale, the availability of resources could represent a limiting factor. Thus, a preliminary identification and evaluation of trade-offs has to be done, at least in terms of resource availability and patterns of consumption. The screening LCA already performed coupled with the analysis of the markets involved could provide the rational for the identification of trade-offs.

At the end of this process we can better formulate the question of our problem. The initial question “Which are the environmental consequences due to the introduction of an innovative technology for waste-tyres treatment in the market” can be translated in more precise questions:

- Product-level question:
  - Is the production of SiC by end-of-life tyre treatment more environmentally sustainable than the energy production from incineration of end-of-life tyre?
- Meso-level question:
  - Would the technology developed for producing SiC for filters expand towards many more applications in a environmentally sustainable way?
  - To what extent can we meet our need for SiC in a environmentally sustainable way with TyGRE technology?

These preliminary and qualitative analysis suggest that the problem should be set at the meso level, which shows the following characteristics:

- high complexity, due to the several interrelations with the surrounding systems;
- the ceteris paribus assumption does not hold, as the product investigated has influence on other activities elsewhere (Lundie et al. 2008);
- several methods and models exist which can be applied for these level-type question;
- the contribution of different disciplines is necessary since the beginning of the definition of the problems;
- rebound effects need to be evaluated, and can be related to price effects or other secondary effects.

The application of analytical models in the subsequent phase will serve the purpose to validate this first result.

CONCLUDING REMARKS

This paper presents the first outcomes of a research project aimed at developing a framework for the inclusion of economic mechanisms in LCA, in the context of a Life Cycle Sustainability Analysis. The approach described highlights that, besides modelling, the phase of framing the question is one of the most critical. Indeed, it is here that we pose the basis for a proper modelling of the system: here we define the question and the object of the analysis that determine which models and indicators should be adopted. Our research suggests that in this phase an iterative approach should be used, which combines experts' judgment with analytical tools. Regarding the latter, more than one could provide useful insights: for this reason, during the project different analytical approaches will be tested. It appears also necessary to translate the approach to the framing of the question into practical guidelines, easily extendible to other systems besides the technological ones.

The next step of the project will be the selection of models for evaluating the economic effects. The challenge is to find out or develop models which can reconcile the bottom-up and the top-down approach: the first would allow taking into account the specificities of the technology under study; the second would allow a wider overview of the system, capturing the chain of changes and interrelations in which the technology is embedded.

CONCLUDING REMARKS

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