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Ex-ante LCA of emerging technologies

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Abstract

Life cycle assessment (LCA) is a method that has been applied on numerous different types of product systems. Most of these LCA studies concern full-market existing systems. In our common search for a more sustainable society, new technology systems are proposed of which the environmental sustainability still needs to be proven. These emerging technologies often only function at lab- or pilot-scale, and process data are also only available at these scales, and not at observed full-market scales. Performing LCAs of emerging technology systems poses challenges because relevant observations are lacking with regards to the projected final system, projected unit process data, projected characterization factors of new chemicals, etc. These challenges are increasingly recognized and addressed by the LCA community. In this contribution we discuss these challenges, with a special focus on ongoing research and recent developments.

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Keywords: Ex-ante LCA; emerging technology; scenario; upscaling

1. Introduction

The existence of ISO-standards [1] for life cycle assessment (LCA) has contributed to strengthening its scientific reputation and widespread use. LCA practice has evolved, however, separately from the standards, and over the years methodological developments and practical applications have given rise to multiple approaches and modes of LCA. Despite differences in methodological choices and type of systems under assessment, the majority of LCA studies conducted in the past two decades analyze an existing system ex-post. Every technology system assessed with LCA exists in a network of connected technologies, or, in other words, makes use of an intricate network of interlinked processes. The need for sufficient data for background (or generic) processes, as well as for foreground (or system-specific) processes, determined that LCA studies have traditionally been ex-post analyses of well-defined systems.

Ex-post LCA studies can provide valuable inputs to decision-making. However, applying changes to technological systems that are fully operational comes with considerable cost. This clashes with a commonplace notion in technology design and development: decisions taken early in the process have far reaching influences on the future and success of a technology [2]. These choices have implications for both functional aspects and environmental impacts of technology systems. Technology developers should therefore get early-on support of quantitative tools – when important decisions can still be made without major disruptions – to understand the implications of design choices on the anticipated environmental performance of a technology. This can prevent avoidable environmental burdens, reduce costs, avoid regrettable investments and substitutions, and anticipate changes in environmental regulations.

Recent developments in the literature have started to move away from the trend of analyzing systems ex-post that so much has marked the first decades of LCA practice. Of particular interest are new methodological proposals and studies that use scenarios in LCA to assess the projected future of emerging technologies [3], and to assess the large-scale implementation of technologies (see e.g. [4]). The application of LCA in this so-called ex-ante fashion allows testing alternative policy interventions, putting claims of environmental sustainability to the test, and supporting early design improvements and sound investments.

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The aim of this contribution is to highlight the benefits of using ex-ante LCA for technology development, and to analyze the main aspects that distinguish ex-ante LCA practice from conventional LCA studies. We focus on the early-on assessments of emerging technologies, i.e. technologies for which there is just an experimental proof of concept, a validation in the lab, or pilot plant. For all approaches that deal with such technologies, and that deal with speculations on the future of technologies, we will use in this contribution the admittedly broad definition of ex-ante LCA [5]. The typical practice in such assessments involves evaluating the technology system at scale, i.e. using multiple scenarios that detail a future in which the technology system operates at full operational scale. Scenarios are used in the ex-ante application to estimate and simulate alternative futures of e.g. full-market penetration, and maximum efficiency.

Ex-ante LCA does not predict the future. Rather, it explores the future by assessing a range of possible scenarios that define the space in which the technology may operate. This will allow verification of design options that could steer the technology towards a preferred future state, and allowing for a fair comparison with incumbent technologies that will also have evolved. Conducted in this fashion, the ex-ante assessment provides preliminary results that can guide the design and development processes, and that do become a stepping-stone towards improved environmental performance.

In the remainder of this contribution we will focus on the specificities of ex-ante LCA. In particular, we will start by providing a brief screening of the literature on some applications that fall under this category. In section 3, we will, then, highlight the specific features that differentiate ex-ante assessments from common LCA practice, with a focus on methodological aspects and data needs that were highlighted in recent ongoing research. In section 4, we will touch upon the experience of other disciplines in dealing with emerging technologies and upon the commonalities with ex-ante LCA. An outlook on the benefits of performing ex-ante LCA closes the paper.

2. A definition of ex-ante LCA and a brief review of applications

Let us start with a definition. We define ex-ante LCA studies those that:

- scale-up an emerging technology using likely scenarios (e.g. using expert help, extreme views, learning curves for similar technologies) of future performance at full operational scale;
- compare the emerged technology at scale with the evolved incumbent technology.

This definition helps us screening the literature for relevant contributions, although a complete systematic review of the ex-ante literature is outside of the scope. We will briefly focus here on the classification of a number of studies that will help to detail the main specific features of ex-ante LCA. Following the definition, a number of approaches and modes of conducting LCA follow under the umbrella-definition of ex-ante LCA, as the terminology used in the literature on the matter is not homogeneous, as reported in Table 1 below.

Table 1. Selected literature on ex-ante LCA

Type of assessment	Main focus	Examples in the literature
Prospective	The approach studies future technological systems and their environmental implications, as opposed to retrospective ex-post studies dealing with existing information and technologies	[6–9]
Consequential	This approach models the effects determined by changes in the technology landscape, e.g. as a consequence of the introduction of a new technology, or as a consequence of changes in policies	[10,11]
Dynamic	The term stresses the importance of improving the accuracy of LCA by addressing the temporal component not only of technological developments, but especially of emissions and the related impacts	[12,13]
Anticipatory	A specific focus is placed on integrating in the assessment techniques of decision-theory that should allow for the explicit inclusion of the values of decision-makers in the analysis	[14,15]
Mixed	Applications falling in this category combine criteria and features that cross the boundaries of the single types above defined	[16–18]

The classification here reported defines a number of operational modes of conducting ex-ante LCA, which, despite differences in the specific focus of the analysis, generally fall within the definition that we provide. Excluded from the list above are those studies that limit the analysis to the comparison of a lab-scale technology with an incumbent, without any definition of scale-up scenarios.

3. Specific features of ex-ante LCA

What defines an emerging technology, as mentioned, is its early-stage of development. In the literature, terms such as *emerging*, *early-on*, *novel*, *early-application*, *lab-stage*, *pilot* are used interchangeably. Of importance for the assessment, is the comparative nature of the ex-ante LCA study. The analyst would have to identify in the current technological landscape the best available technology performing a similar function as the emerging one. We define that as the incumbent technology. The incumbent is typically technology at a later stage of the development curve, i.e. has already passed the pilot stage, or has achieved a considerable level of market penetration. The incumbent performs the specific function under assessment in a way that makes it preferable to others available (e.g. it is cheaper, more efficient, and has lower environmental impacts). The developers of the emerging technology will likely have already identified the incumbent, but help may be required from the analyst to screen alternatives. Ideally, at this stage of the analysis the LCA analyst should collaborate closely with the technology developers, to allow for a back and forth transfer of information. This approach is well described in the ex-ante analysis of technologies allowing the recovery of metals from e-waste by Villares et al. [19]. On the one hand, the LCA analyst will provide information on the full spectrum of environmental impacts of specific technological designs, as compared to the incumbent technology (or technologies; see Fig. 1 below). The technology developers would likely intervene on the design choices, and improve where possible on the environmental performance.

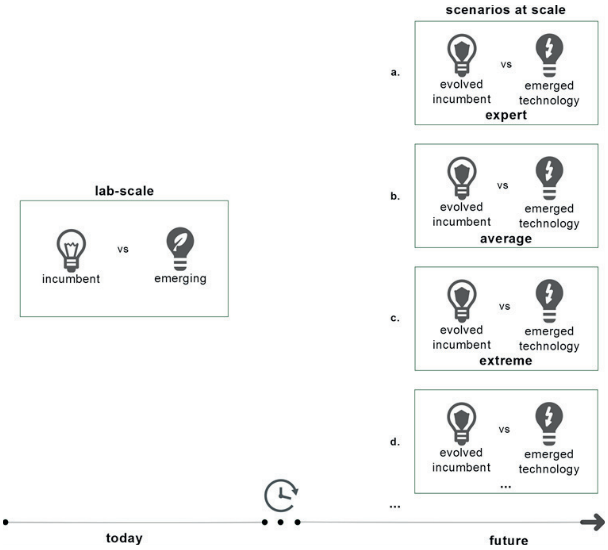

Fig.1. Ex-ante LCA of emerging technologies

The notion of time becomes important in the later stages of the process. Once the design is considered satisfactory, the analysis moves on to assessing the potential future performance of the emerging technology as compared to the incumbent. The former will have changed, and moved along its development curve. Thus, the emerging technology will have now emerged, i.e. it exists at operational scale. Once at scale, the performance aspects of the technology will also change, thus the ex-ante analysis will have to account for such changes. These could directly, among others, relate to the increased economies of scale [20]. The LCA analyst will draft a number of consistent scenarios with different likelihood. These scenarios will allow comparing the emerged technology with the incumbent. A point of attention that is specific to ex-ante LCA is the fact that the incumbent, although at a later stage of the development process, will also have changed. Depending on the window of time in the future considered in the analysis, also the incumbent will have benefited from performance improvements. The scenarios will, then, also take into account that the incumbent has evolved.

Scenario modelling in ex-ante LCA uses the concepts of multiple futures and system thinking [21], and builds upon existing practice in general technology development theory [22]. Each scenario that the analyst builds represents a possible future state of the considered technological systems (i.e. the technological system of the emerging technology, and that of the incumbent) with a specific timeframe. Depending on the type of selected scenario, the analyst would either move only a few time steps (e.g. months) into the future, or leap forward faster (e.g. 10-20 years). Alternative formal or intuitive representations of the future can be used to model scenarios. Technology developers and other topical experts can be directly involved in the process of definition of scenarios [23]. experts in the specific domain of application of the technology, the so-called expert scenarios. Scenarios can also be drafted taking into consideration extreme situations, such as extremely positive performance as a result of learning curves, advantageous market conditions, and favorable policy interventions and rebates, in a what-if exploration of alternatives [24]. Further explorations of scenarios in the context of LCA are available in [25].

The above features de facto differentiate ex-ante LCA from common practice in ex-post LCA studies. In the following, we try to analyze some specific methodological differences, in order to better highlight what the differences mean for the daily ex-ante practice. Some of the problems that we highlight here are not only specific to ex-ante LCA, but become more critical in the context of ex-ante LCA. For a more extensive discussion on this topic, we refer to Hetherington et al. [26] van der Giesen et al. [27], and Villares et al. [19].

3.1. Functionality

Even though the emerging technology would likely not be a one-to-one replacement of existing ones, it will rarely perform an entirely new function. The emerging technology would rather improve and innovate on a specific function that is already performed by an incumbent technology. For a technology to be successful, its performance will have to provide, at least, a sizable improvement on the performance of the incumbent. Improvements on the incumbent could focus e.g. on the improvement of efficiency, on the reduction of impacts, or on the reduction of the material inputs to provide the specific function. We can draw a relevant example from ongoing research on new photovoltaic cells. Despite considerable investments, silicon-based photovoltaic cells (i.e., the incumbent) have not reached efficiencies above 25 %. Significantly higher conversion efficiencies of up to 45% can be reached with multi-junction cells using e.g. as semiconductors nanowires of gallium and indium (i.e., the emerging technology; more information on nano-tandem.ftf.lth.se). At times, the emerging technology could have unique properties that make the comparison with existing technologies less straightforward [28]. The right choice of the incumbent strictly relates to the function, and thus the application area of a technology. The matter of functionality is not trivial, as the concept of functional unit is the basis of a meaningful comparison across technological systems in LCA.

For the case of ex-ante LCA, such a comparison may require special attention if performed at an early-stage, due to, among others, scale issues and technology uncertainties [26]. Additionally, practice has shown that technology developers need several iterations of analyses before finally settling one or more specific functions for the technology under assessment. Thus, this requires the LCA analyst to carefully reconsider the incumbent every time the main function(s) of the technology are modified in the process. A change in the function of the emerging technology may actually result as a response to the results of a comparative ex-ante study showing the emerging as performing worse than the selected incumbent. As a consequence, the technology developer may decide to switch to another function hoping for a better environmental performance. This decision on its turn has implications for the ex-ante analysis, e.g. in terms of functional unit, selection of system boundaries, and co-products. Let us consider, as an example, the case of a technology aiming at producing a liquid fuel from solar power, as described by van der Giesen et al. [29]. A number of functions, and incumbents, could be identified from the plethora of available technologies, such as batteries for storage, fossil-based liquid fuels, or technologies using solar energy to produce electricity to power vehicles.

When moving on to the evaluation of the scaling-up process, the matter of the adequate selection of a functional unit remains of fundamental importance for the development of scenarios, and the selection of the desired future states of the technologies under assessment. The matter of the specific timeframe considered in the development of the specific scenarios also comes into play at this stage. Multiple functional units representing different functions and/or timeframes may be chosen at this stage to ease decision-making.

3.2. Data

By definition, amongst other methodological complications, emerging technologies require ad hoc strategies to deal with data availability. Primary data are scarce, and only little representative of real-world conditions of full-fetched deployment. Data would be at this stage representative of the lab-scale, or pilot-scale conditions, thus affecting the usefulness of the results. The case of missing data would not only be specific of the foreground processes, but likely also influence the relevance and reliability of background data. LCA data can hardly keep the pace with innovation and technology development. Typically used LCA databases would have to be carefully analyzed and deconstructed, at the expenses of the time required for the analysis, to verify whether they are still representative. Similarly, assumptions and changes in these datasets would have to be mapped and transferred, if applicable, also to case of the incumbent.

The criticality of data is further exacerbated by the need to scale-up the data to the potential future of the technology. Learning curves, economies of scale, secondary data, and, at times, realistic assumptions need to be used to fill data gaps for lacking foreground data [30]. Additionally, the help of the technology developers and other domain expert would be key to identify most representative data, or alternative sources of data. For instance, Piccinno et al. [31] use stoichiometric balances and other physico-chemical relationships as an approach to derive data for a novel chemical synthesis process. In this way, the analyst uses specific features of an existing technology, for which data are known, to synthetically derive foreground data for the emerging technology under assessment.

Care should be paid at all stages of the data collection process to adequately address the variability and uncertainty in the results of the ex-ante exercise, and to adequately match similar data for the emerging and incumbent technologies also when conducting statistical simulations. The use of distribution functions, rather than point values, has proven in practice to be beneficial if combined with multiple simulations, and an adequate explanation of the meaning of results. The analysis of the variability and uncertainty of the results should be combined with the identification of the main inputs to the ex-ante LCA model determining the output variability by means of a sensitivity analysis [32]. Next, LCA analysts could try and improve the knowledge on those specific inputs in collaboration with the technology developers.

3.3. Impact Assessment

While the breadth and depth of LCA impact assessment models have drastically grown in the last decade, technology development has also outpaced such models. This translates in a list of unclassified and uncharacterized flows, which cannot be accounted in the life cycle impact assessment phase of the ex-ante LCA study. While these may be deemed negligible in a comparative context with shared background and foreground data at a first glance, the lack of specific characterization models or characterization factors does have an impact on the potential of intervening early in the design process to avoid environmental burdens [33]. The lack of impacts, due to the sheer lack of models, can also provide the self-ensuring feeling that the emerging technology performs better than the incumbent. In order to obviate to such problem, ongoing research is working on increasing the coverage of impact assessment models (see e.g. [34]), and using synthetic data models to fill-in data gaps (see e.g. clicc.ucsb.edu).

4. Ex-ante LCA and other disciplines

With the objectives above set out, ex-ante LCA joins a plethora of methods and a variety of disciplines that deal with the assessment of technologies. A number of learning elements could be drawn from looking at those disciplines and collaborating with the relevant expert. Let us take a brief excursus outside of the LCA domain.

In the book the Nature of Technology [35], Arthur tries to understand what technologies are and how they evolve. Interestingly enough, without ever referring to LCA, Arthurs greatly stresses the importance of the functionality of a new technology, and also highlights how new technologies exist from innovating on a combination of existing ones, and on making use of a set of physical phenomena [35]. The matter of functionality and functions well links to the way LCA operates. Here, as earlier detailed, we also extensively talk about functions and connectedness of technological systems. The concept of structural deepening that Arthur introduces is also highly relevant for ex-ante LCA. According to Arthur [35], the early versions of technologies are crude, and go through iterative steps until they finally operate as required by the developers, or until they overcome certain limitations. Such limitations can also be related to environmental performance of the technology, thus can be overcome using ex-ante LCA.

We can identify another important connection with the influential theory of diffusion of innovations of Rogers [36] , which seeks to explain why innovations and new technologies, in particular, eventually are adopted and become established. The theory identifies in a number of social prototypes the type of humans favoring diffusion of a technology. These include, for instance, innovators and early adopters. The application of ex-ante LCA can be seen as a means to increase early in the development process of a technology the possibility to reach as many early adopters as possible, driven by the environmental benefits of an emerging technology iteratively improved with the support of LCA. The types of landscape that favor technological change are also a well-studied matter in the field of transition management. In particular, Hekkert et al. [37] identify a set of functions that support innovation. In particular, ex-ante LCA can be seen as contribution to the function of innovation related to knowledge development. At this stage, mechanisms of learning are put in place to support innovation processes, such as the transition to sustainable technologies [38]. Ex-ante LCA can be seen as one of these learning mechanisms. Technological innovation also has economic repercussions that should be separately dealt with in a Techno-Economic Assessment (TEA; see e.g. [39]).

Another focus of the field of technology studies regards the potential to describe transition pathways, and the socio-technical system changes determined by technologies. While the focus of typical studies in this field is retrospective, the main idea is to identify, once again, the optimal conditions that allow technologies to emerge. The socio-technical landscape is the object of the such analyses, and, in particular, the possibility of technologies to emerge from niche-innovations to dominant positions [40]. The application of ex-ante LCA can be studied in this context as determining a flywheel effect that would speed up the process of emergence, thanks to the possibility to intervene early, and to directly influence the design process.

Let us conclude this digression into related scientific disciplines with an excursion into the field of archaeology. Archaeologists that study ancient technologies and artefacts often use the so-called *chaîne opératoire* method (i.e. operational sequence) [41]. The method allows reconstructing the techniques used and the chronological ordering of the different steps required to produce a technology. Using this methodological tool, archaeologists can understand the processes and construction of technologies and tools, better determine the evolution of tool technology, and understand the development of ancient cultures and lifestyles. Critics of the chaîne opératoire argue that it is subjective because it is based upon the analyst's personal experience and intuition. Also, they further claim that it is not a replicable or quantifiable approach to data collection [41]. Even though the goals of this analysis may look different, the practice of ex-ante LCA is not that far apart, and the remarks of critics similar. By applying ex-ante LCA, we also deal with scarce data, have to deconstruct a technology, have to identify its potential uses, and have to make assumptions about the potential future contexts of use, and other relevant social implications. The analogies are uncanny and should be further explored.

5. Outlook and sketch of a research agenda

In this contribution, we tried to sketch the main elements of ex-ante LCA practice. We focused on the benefits of conducting ex-ante LCA, on main points of attention, and on the linkages between LCA and other disciplines. All of these elements require further research. Specific applications of ex-ante LCA to a diverse set of technologies will most likely require new solutions to the problems that we briefly touched upon here. Finding new solutions will be an iterative trial and error process. Ongoing research tells us that sharing clear information about the complexities of the modelling undertaken with technology developers and other stakeholders greatly benefits the design and development process of a technology. The inherent variability and uncertainty of the results will not nullify the effort. Ex-ante LCA has the potential to influence technological development and sustainable innovation more than the science of LCA has ever done in the past. Following-up on the emerging technologies under scrutiny along their development curve will allow us to further verify in practice whether our support was indeed a fundamental component of success.

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