Journal of Cleaner Production 259 (2020) 120904

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A critical view on the current application of LCA for new technologies and recommendations for improved practice

Coen van der Giesen [a, *], Stefano Cucurachi [a], Jeroen Guinée [a], Gert Jan Kramer [b], Arnold Tukker [a]

[a] Institute of Environmental Sciences (CML), Leiden University, Einsteinweg 2, 2333 CC, Leiden, the Netherlands
[b] Copernicus Institute of Sustainable Development, Utrecht University, Princetonlaan 8a, 3584 CB, Utrecht, the Netherlands

ARTICLE INFO

Article history:
Received 20 November 2019
Received in revised form
10 February 2020
Accepted 2 March 2020
Available online 6 March 2020

Handling editor: Panos Seferlis

Keywords:
Life cycle assessment
Ex-ante LCA
Technology assessment
New technology
Emerging technology
Research & development

ABSTRACT

LCA is a well-known assessment tool that identifies and provides insights on the environmental impacts of products and services over their lifecycle. The guidance provided by the existing manuals typically applies to modelling and assessing environmental impacts ex-post, meaning that information is available from empirical experience after products have been commercially in use for extended periods of time. This information is not available if LCA is applied in an ex-ante manner before a technology is commercially deployed at scale. We identify the major challenges of applying LCA in an ex-ante manner and propose a route forward in dealing with these challenges that combines intuitions from other disciplinary fields. The first challenge is how to model consistent future foreground systems for the incumbent and new technology systems. Learning curves and scenario approaches are the way forward. The second challenge is how to model future background systems. Here a solution is to transform existing LCI databases towards future contexts, informed by the Integrated Assessment Models (IAMs) that provide scenarios in line with the Shared Socioeconomic Pathways (SSPs). Finally, uncertainty in ex-ante LCA is of a different nature as in ex-post LCAs. The main difference with conventional LCA studies is the highly uncertain information for the future. To acknowledge this. considerate attention should be attributed to the discussion on these uncertainties, both in the design of the assessment and the data used. Responsive evaluation can play a supportive role here. This will increase the transparency and efficacy of the results because the relevant stakeholders and experts are involved. In this way technology designers and other stakeholders derive insights on the influence of design choices or contextual factors (that are important, but hard to influence) on the potential environmental impacts of their foreseen technology.

1. Introduction

Research, development, deployment and widespread diffusion of new environmentally sound technologies is a major route towards achieving sustainability (United Nations, 2017). To support the research and development of claimed environmentally sustainable technologies, international research frameworks such as the European Horizon 2020 program (European Commission, 2017) demand the application of quantitative methods, such as life cycle assessment (LCA) (Wender et al., 2014b).

LCA is a well-known policy support tool that identifies the environmental impacts of products and services over their lifecycle (Hellweg and Milà i Canals, 2014). The consolidated practice of conducting LCA studies for innumerable product systems for over three decades also makes LCA the preferred option for assessing the potential environmental impacts of new technologies.

The execution of conventional LCAs is guided by the ISO 14040–14044 standards (International Organization for Standardization (ISO), 1997) for which practical guidance is given in various LCA manuals (Baumann and Tillman, 2004; Curran, 2012; European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010; Guinée et al., 2002). The guidance provided by the existing manuals has been typically applied to modelling and assessing environmental impacts ex-post, meaning after products have been commercially in use for extended periods of time and information and data are available

* Corresponding author.
E-mail address: vandergiesen@cml.leidenuniv.nl (C. van der Giesen).

https://doi.org/10.1016/j.jclepro.2020.120904

from empirical experience. The ISO standard could and should also be used when LCA is applied in an ex-ante manner. Ex-ante is defined as before a product or technology is commercially deployed at scale (Tecchio et al., 2015) and information and insights on the topic under assessment are not (yet) readily available. Using LCA in an ex-ante manner should allow anticipating potential avoidable environmental impacts as well as avoid environmental lock-ins. It promises the assessment of the potential environmental impacts of a technology at an early stage of its development curve when little information is available and greater and less costly opportunities to change can still be gauged. Guided by the results of LCA studies, technology developers can take appropriate action at an early stage of the development of a technology to prevent investments in those technologies that will eventually prove to have a higher environmental impact.

Performing the ex-ante exercise introduces additional challenges. These include the lack of representative information for the product systems under study, the lack of a clear vision into the future of the technological landscape in which the technology will operate, and the lack of direct access to representative data for lab-scale processes. Some of these challenges have been identified long ago. Frischknecht et al. (2009) questioned the fitness of standard LCA to assess the potential impacts of future technologies already in 2009,. More recent reviews of the challenges of using LCA to inform early research decisions are also available now (Arvidsson et al., 2017b; Cucurachi et al., 2018; Hetherington et al., 2014).

Despite the existing efforts in the literature to categorize studies, there are no structured guidelines to perform ex-ante LCA which link the ex-ante challenges to the classical ISO framework for LCA (International Organization for Standardization (ISO), 1997). While an update of methods and concepts is necessary, the framework and the standard phases of LCA (i.e. goal and scope definition, inventory, impact assessment, interpretation) can be enriched with additional guidance for doing ex-ante LCA. Our work complements the framework of Buyle et al. (2019), which reviewed ex-ante LCA studies with a focus on technology development, technological learning and technology diffusion.

Hence, with this paper we aim to integrate the challenges and recommendations for ex-ante LCA identified in the literature into the ISO LCA structure in order to provide guidance for the execution of ex-ante LCA studies. This research is built up around the following research questions:

1. How can ex-ante LCA be defined and positioned in other forward-looking approaches to LCA (see section 2)?
2. Which challenges in ex-ante LCA can we identify in case studies and by deductive reasoning that are different from ex-post LCA practices (see section 3)?
3. What solutions can be thought of to deal with these challenges (see section 4)?
4. And concluding: what additional guidance can be provided on this basis when performing an ex-ante LCA study according to the ISO guidelines (see section 5)?

2. Defining ex-ante LCA

A growing number of studies apply LCA to new, emerging or future technologies and product systems. A variety of approaches and modes of conducting forward-looking LCA that can be applied for these assessments is reported in the literature. An overview and summary of these approaches can be found in Table 1.

Consequential LCA's main focus is on quantifying the potential environmental impacts that accompany a change in policy. LCSA tries to include all dimensions of sustainability since next to environmental impacts, the introduction of a new technology will also have a considerate impact on the economy and society. Dynamic LCA tries to take into account that the world is dynamic and development will most likely choose a different path than one can anticipate at the start of development. Anticipatory LCA stresses that conventional LCA is always performed with hindsight and is not easily attributed to assess future developments, and in addition states that stakeholders should be included in the process to obtain more valuable results. Prospective LCA and ex-ante LCA seem to be similar labels for the same exercise and might be seen as umbrella terms under which practices from other approaches could be used.

Table 1 illustrates that it is not easy to discern between different modes of LCA used for future technology assessment. And following the notion by Suh and Yang (2014) that "no model is perfect and the question is whether it provides useful insights (..) given questions and available data" we do not aim to identify a single best term. A discussion or categorization of best approaches has little merit since all modes have their own, often overlapping, strengths and weaknesses depending on the analysis for which they are applied.

For the purpose of this paper we prefer to define and use the term ex-ante LCA because it gives a clear focus on the analysis at hand. Using the term "ex-ante" makes clear that the assessment is performed before market introduction of a technology, where for example a prospective LCA can also be performed on an established technology to see its environmental impacts in a defined future. Hence, leaving aside epistemological and semantic differences, in this paper we use the term **ex-ante LCA** to refer to *performing an environmental life cycle assessment of a new technology before it is commercially implemented in order to guide R&D decisions to make this new technology environmentally competitive as compared to the incumbent technology mix.*

3. Challenges for performing ex-ante LCA

3.1. Introduction

Using deductive reasoning based on a review of the relevant literature, this section analyzes which typical challenges ex-ante LCA faces. We conducted a literature search in *Web of science* (Thomson Reuters, n.d.) using the following keywords[1]: "dynamic LCA", "prospective LCA", "ex ante LCA" and "anticipatory LCA". The combination of keywords delivered 112 hits. The titles, keywords and abstracts of these papers were screened on the question if an LCA for technology development was performed, which led to a reduction of the list to 54 papers. After this, the abstracts of these papers were analysed in more detail to see if the paper would discuss methodological challenges. In this way, we ended with 26 papers listed in Table S1 of the Supporting Information.

Interestingly, publications that, in our view, provide crucial insights in this field, such as Hetherington et al. (2014) and Cucurachi et al. (2018) did not surface in this search despite the structured approach we applied. It seems that the novelty of this field and the multitude of terms used still inhibits a proper, structured meta-analysis for ex-ante LCA. After having reviewed about half of the selected papers we noted however, that reviewing additional papers did not lead to identification of additional challenges and solutions in ex-ante LCA. We therefore feel confident that our selection of papers provides a good overview of issues in this field.

The selected studies were analysed on their discussion of challenges, difficulties and bottlenecks in performing the

[1] "dynamic LCA" OR "prospective LCA" OR "ex ante LCA" OR "anticipatory LCA" OR "dynamic life cycle assessment" OR "prospective life cycle assessment" OR "ex ante life cycle assessment" OR "anticipatory life cycle assessment".

Table 1
Selected literature on forward-looking LCA, adapted from Cucurachi et al. (2018).

Type of assessment	Definitions or descriptions given in literature
Consequential LCA	Consequential LCA provides understanding on "the potential effects of policies on market responses to support environmental decision making" (Kätelhön et al., 2016). "[T]o provide information on the environmental burdens that occur directly or indirectly as a consequence of a decision (usually represented by changes in demand for a product)" (Guinée et al., 2018).
Lifecycle sustainability analysis (LCSA)	Life cycle sustainability analysis proposes a transdisciplinary framework of methods and in principle broadens the assessment to include social and economic impacts, and deepensto include more than just technological relations e.g. by scaling up the technology to society wide implementation. This may imply making future scenarios, but not necessarily looking into innovative technologies (Guinée et al., 2011; Hu et al., 2013; Van Der Giesen et al., 2013).
Dynamic LCA	"The analysis of individual technologies must consider the extremely dynamic development. This concerns the development of products and their production processes as well as their technical performance and the development of background systems." (Pehnt, 2006) This approach focusses on including the dynamics of parameters that are expected to change over time and to compare different development pathways (Alfaro et al., 2010).
Anticipatory LCA	Takes a forward-looking (not retrospective assessment) and engages stakeholders to inform critical modelling decisions and increase credibility and relevance of results. Anticipatory LCA can be defined as"non-predictive and inclusive of uncertainty, which can be used to explore both reasonable and extreme-case scenarios of future environmental burdens associated with an emerging technology." The aim is to identify the most relevant uncertainties and engaging research and development decision makers to guide research and development and innovation. (Wender et al., 2014a).
Prospective LCA	"An LCA is prospective when the (emerging) technology studied is in an early phase of development (e.g. small-scale production), but the technology is modelled at a future, more-developed phase (e.g. large-scale production)" (Arvidsson et al., 2017a). Prospective LCA integrates forecasting methods in its approach (Hummen and Kastner, 2014). See also (Mendoza Beltran et al., 2018; Miller and Keoleian, 2015)
Ex-Ante LCA	In ex-ante LCA an environmental analysis of a technology that is typically still in its R&D phase is performed (Hesser et al., 2017b; Schrijvers et al., 2014; Tecchio et al., 2015) to guide R&D. Villares (Villares et al., 2017, 2016) stresses the ex-ante application of LCA, meaning before (ex-ante) market introduction (Roes and Patel, 2011).

assessment in practice. We review such challenges below following the LCA phases discerned in the ISO 14040 standard. Some of the challenges found can also be relevant for ex-post LCA, but have more prominence when an ex-ante LCA is performed. We will eventually see that similar challenges occur across different LCA phases. Section 4 discusses potential remedies for the challenges encountered. Most remedies provided by the selected studies make (implicit) use of scientific disciplines and concepts that are often not necessarily the strengths of the LCA practitioner (e.g. scenario development).

3.2. Goal and scope definition (GSD)

Methodological choices in any form of assessment or research are determined by the goal of the study and the research questions asked (Hetherington et al., 2014; Miller and Keoleian, 2015; Zijp et al., 2015). In order to understand the merit of any assessment, choices and research questions should be clearly defined. The ISO standard prescribes to define the goal and scope of the study as a first step (International Organization for Standardization (ISO), 1997). When using scenarios in LCA, the GSD is the place where these scenarios need to be framed (Pesonen et al., 2000).

3.2.1. Goal (and research question)

The starting premise for ex-ante LCA studiesis that new technologies are developed to improve the *status quo* situation by implementing a new technology in the technology mix. These new technologies will likely compete with well-established mature technologies (Frischknecht et al., 2009) and a comparison with these incumbent technologies should be part of the assessment. The inherent goal of any ex-ante LCA is therefore to compare the future potential environmental performance of the new technology, vis-a-vis one or multiple incumbent technologies (Hetherington et al., 2014) in order to gain insights on the further developments of these not-yet-introduced technologies and guide upcoming efforts in research and development of the new technology. Therefore we see technology developers as the main audience for these studies although they could also be insightful for policy makers.

Scope (temporal, geographical, functional unit and alternatives, choice for impact categories).

Making a balanced comparison of technologies requires a consistent modelling framework for all lifecycle phases and boundaries conditions (Bauer et al., 2015). Specific attention points in ex-ante LCA include:

- Temporal and geographical scope. An obvious implication of assessing technologies before market implementation is that ex-ante LCA studies should consider a hypothetical future commercial state (e.g. technological performance, market situation) of the technology under assessment (Frischknecht et al., 2009). One has to be particularly explicit in defining at what moment in the future what level of maturity and what level of market penetration the novel technology may reach. One might even consider how the introduction of the new technology might influence the existing market. Defining a specific moment in time is an essential step to provide a balanced comparison between new and incumbent technologies. As a result, an explicit temporal scope will also have implications on how the competing incumbent technology and background systems are modelled.
- Functional unit and alternatives. It is often a challenge to comprehensively define its foreseen function of new technologies and, based on that, the incumbent technology (Hetherington et al., 2014). Although one of the strengths of LCA is that assessments are based on functionality (service) and not on a specific product. Defining this function and related functional unit is however, a big challenge in ex-ante LCA (Aldaco et al., 2019; Hesser, 2015; Peters and Weil, 2017). Such a challenge is complicated by the necessity to identify the alternative technologies that compete in providing the same function or functions (Arvidsson et al., 2017a). An example of such challenge is reported in Van Der Giesen et al. (2014), in which a total of four functions were defined for solar fuels produced from CO2. In that study it is clearly shown that an unambiguous function (or reason) to produce solar fuels is hard to define. Hence, the choice for the functional unit needs a more careful deliberation than is common practice in classical ex-post LCA. Moreover it

might even happen that a technology identified as “the alternative” might not be the future incumbent (Arvidsson et al., 2017b).

- Choice for impact categories. Ex-ante LCA usually aims to analyse if the new technology can have (expected or projected) environmental gains over the incumbent technology. However, since the properties of the new technology are not yet well known and experience in practice is absent or low, full insight in all the relevant impact categories may not yet exist. Challenges with impact categories for new technologies and materials are identified and will be discussed under Life Cycle Impact Assessment below.

In sum, in the goal and scope definition in ex-ante LCA has the following additional challenges compared to regular, ex-post LCA:

1. At what moment in time is the new technology to be expected to be operational at which level of maturity?
2. How does the functional unit need to be defined so that the new and the incumbent technology provide the same (similar) functionality?
3. What is the incumbent technology?

3.3. Inventory (LCI)

Unavailability of life cycle inventory data is a common hurdle encountered in ex-post LCA, which is often overcome by making use of secondary data in combination with a sensitivity analysis. To limit the time and resources of the LCA practitioner a distinction is made between *foreground data*, data that is gathered by the LCA practitioner and *background data*, data that is taken from existing LCI databases. For ex-ante LCA studies we expect that foreground data is collected to describe and model the new technology and the incumbent. Background data is required to represent the context of the study, usually consisting of data for upstream supply chains necessary for the emerging and incumbent technologies to perform the selected functions, which can also include socio-economic considerations. While a technology developer typically has limited influence on the background system, manipulation in the face of consistent modeling might be needed.

Foreground data, is usually not readily available for new technologies (Frischknecht et al., 2009). The available data and knowledge is specific for the case and context at hand (Gavankar et al., 2014; Hospido et al., 2010) and is highly subjective to a variety of factors that cannot be controlled (Miller and Keoleian, 2015). Existing LCI databases are based on historic data and the new technology under study is not available therein (Kunnari et al., 2009a; Wender et al., 2014b). The data that are available most likely originate in lab experiments or pilot projects and are therefore not representative of operational scales (Arvidsson et al., 2014; Gifford et al., 2016; Hesser et al., 2017a; Schulze et al., 2018). One should be aware that a comparison between the new technology with the incumbent, for which data at industrial scale is available, should not be done without first making apparent the assumptions and scenarios about the future of these technologies (Hetherington et al., 2014; Piccinno et al., 2015; Tecchio et al., 2015).

Inventory data for the new technology can be collected from scientific articles, patents, collected via expert interviews, or can be found in unpublished lab results or through process simulation (Arvidsson et al., 2017b). These data however, mainly provide proof of principle for a new technology and are far from representative for future commercial scale operation. It might be necessary to manipulate whatever data is available to hypothetically represent the future situation. In this context, using assumptions (e.g. based on learning curves) is unavoidable (Villares et al., 2016). Data representing commercial scale operation is most likely to be available for the incumbent technology given the more advanced level of development of the incumbent over time. Further optimization of performance for such technologies f can be expected in the future. An additional difficulty here is that the available data for both systems most probably does not automatically allow comparable systems boundaries. This demands for a hypothetical expansion of the system boundaries of one of the systems by the practitioner (Hetherington et al., 2014) and will obviously also contribute to significant uncertainties about how such a new technology will perform in the future.

B*ackground data*, should represent the future situation for when the new technology is defined to be commercially operational. This is highly relevant, since background processes usually make up to 99% of all unit processes in a product system and only occasionally fall below 95% (Wernet et al., 2016). This means that the impacts caused by background processes are of considerable influence on the outcomes of an LCA study. Several authors have stressed that changes over time in background systems (e.g. in the competing technology as well as in the technological landscape) should also be taken into account (Arvidsson, 2013; Frischknecht et al., 2009; Sanden et al., 2005). A temporal mismatch between back- and foreground systems is to be avoided (Arvidsson et al., 2017b), which can only be facilitated by a clear definition of the temporal scope in the GSD of the study. The data used for modeling the background system should represent the future operational playing field and be consistent for the same scope defined for the technology and incumbent(s) under study. A challenge here is that available background data, like the ecoinvent database (Swiss Centre for Life Cycle Inventories, 2010), are commonly assumed to be representative for the current situation while data is clearly already outdated.

In some cases, forward-looking LCA studies do not explicitly compare a specific new technology with an incumbent technology as such, but want to assess the environmental impacts of a proposed sustainable future. A good example of this is the work of Hertwich et al. (2015) and Berril et al. (2016) who perform ‘integrated life cycle assessment of long-term, wide-scale implementation of electricity generation from renewable sources’ (Hertwich et al., 2015) using IEA scenarios. Where this approach is different from our definition of ex-ante LCA (the goal is not to guide R&D of a specific new technology), it provides very useful insights on how to deal with future changes for the incumbent and background system. At the same time these studies show the importance of assessing new technologies on wider economic scales and go beyond the limitations of the functional unit to assess economy-wide implications. Estimating the potential market share of new technologies over time may be relevant in ex-ante LCA and should at least be considered when making claims on the future performance of new technologies.

In sum, the Inventory phase in ex-ante LCA has the following additional challenges compared to regular, ex-post LCA:

1. How will new technological systems develop into the future, perform under the scope defined and is representative LCI data available?
2. How will incumbent technological systems develop into the future, perform under the scope defined and is representative LCI data available?
3. How do background systems and their performance develop over time, perform under the scope defined and is representative LCI data available?
4. What is the potential market share of the new technology in the future?

3.4. Impact assessment

In ex-ante LCA studies it is important to realize that potential environmental impacts of new technologies are not automatically covered by the existing impact categories commonly used in ex-post LCA studies described in the LCA handbook (Guinée et al., 2002) or in the ReCiPe life cycle impact assessment method (Huijbregts et al., 2017). Recent ex-ante LCA studies of new technologies and new materials stress the great limitation of the lack of characterization factors at the life cycle impact assessment (LCIA) phase of LCA studies (Deng et al., 2016; McKone et al., 2011; Tufvesson et al., 2012; Wender et al., 2014b). The absence of suitable impact categories and specific characterization factors may mask the true environmental performance of a new technology compared to the incumbent technology, as many biosphere flows with a potential environmental impact are left unclassified due to a lack of adequate models and data. Hetherington (2014) stresses that environmental impact assessment methodologies will lag behind the formation of new materials with potential impacts in the environment. A good example of this is the upcoming interest in nano-technology. It has been recognized that properties of nano-technoloy are not yet well known and that considerate efforts should be put in developing methods to assess the environmental impacts on the environment (Guineé et al., 2017).

In sum, the Impact Assessment phase in ex-ante LCA has the following additional challenges compared to regular, ex-post LCA:

1. Can the new technological systems display unexpected new impacts not yet covered in LCIA?
2. Can characterisation factors relevant for the incumbent and new technical systems change over time?

3.5. Interpretation

The inherent necessity of making assumptions and high uncertainty surrounding modeling choices that have to be made makes that the outcomes of an ex-ante LCA study should not be regarded as a final result, but rather as a possible implication a technology can have under a specific set of assumptions (Villares et al., 2017). It is even said that ex-ante LCA provides a set of answers and not the answer, it rather provides a structure for debating and guiding research and development with all necessary stakeholders involved (Frischknecht et al., 2009). The execution of an ex ante LCA should thus be regarded as a process and not a product in itself (Wender et al., 2014b). Absolute outcomes should be regarded as indicative (Kunnari et al., 2009b) or preliminary (Pehnt, 2003), and should be used to inform decision making with the warning that decision-makers should use their wisdom and experience when using the results (McKone et al., 2011). So how can we interpret the results we get from performing an ex-ante LCA?

One issue that plays up more with new technologies in early development stages is that classical uncertainty analysis used in LCA which focuses on the 'known unknowns' may be insufficient. We simply do not know what the future will look like. Classical uncertainty analyses (in LCA) assume complete information on the (LCI) systems under assessment. Further the impact categories and characterization factors are known and uncertainties can be measured. Quantifying uncertainties for future situations enters another dimension of uncertainty (see section 4.4), and we should be careful not to "add a surrogate quantified layer to the already evidently ambiguous generated information related to the scenarios and development paths considered" (Villares et al., 2016). For ex-ante LCA it is a challenge to deal with this advanced dimension of uncertainty.

Connected to the issue of increased uncertainty is that new technologies more likely exhibit 'unknown unknowns' than mature technologies. An example of this issue is the introduction of biofuels and the use of micro-plastics. Before being commercially available, these technologies were seen as a huge step forward in terms of potential and innovation, only to find out their negative and pervasive impacts years later. The question is if we could not have been more considerate during research and development of these technologies, a question that goes far beyond the focus of ex-ante LCA, but at least deserves consideration.

In sum, the Interpretation phase in ex-ante LCA has the following additional challenges compared to regular, ex-post LCA:

1. How can the increased uncertainty around modelling new technologies in the future be dealt with?
2. How can the possibility that new technologies will display unkown unknowns be dealt with?

4. Methods, techniques and approaches supportive to performing ex-ante LCA

4.1. Introduction

While section 3 identified challenges by phase in the LCA process, it is clear that certain challenges come back in different stages of the LCA. For instance, the GSD phase needs to specify at which moment in time the new technology is operational, while in the Inventory phase an estimate of future performance needs to be made. This all relates to the issue of modelling consistent future foreground systems. To identify methods, techniques and approaches supportive to performing ex-ante LCA, we cluster the challenges into three main focus points that methods for ex-ante LCA need to address specifically and discuss them in the subsequent sections (see SI; Table S2 for a full explanation of relations):

1) Modelling consistent future foreground systems
   a) Modelling the incumbent technology into the future (future LCI data);
   b) Modelling the new technology into the future (future LCI data and potential market share).
2) Modeling consistent future background systems
3) Dealing with the uncertainty in ex-ante LCA
   a) Covering uncertainty around the future incumbent technologies;
   b) Covering uncertainty around the future of new technologies;
   c) Dealing with potential 'unknown unknowns' with regard to e.g. impact categories.

4.2. Modelling consistent future foreground systems

When a new technology is benchmarked against the incumbent it is important that modelling choices consistently represent the compared systems, including the background system at a time that the new technology is supposed or expected to be commercially operational (Bauer et al., 2015). The LCA practitioner needs to be aware and take into account that these three parts of the model might be at different levels of development. Knowledge and data on these three parts are most likely only available on different scales of operation and, in addition, depend on the level of development of the technologies themselves.

At the time of execution of an ex-ante LCA, the new technologies are typically in their technology or development trajectory (see Fig. 1). It will likely take a considerable amount of time to get from

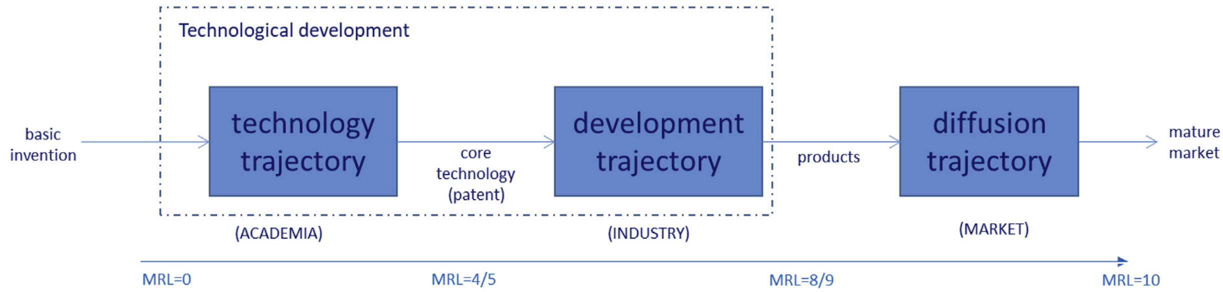

Fig. 1. Innovation trajectories and development over time based on Hirooka (2006).

patent to market introduction. Only at this point does the new technology start to compete with the incumbent. Based on historic data, this period can be defined at up to 25 years, although this time frame seems to decrease for newer technologies (Hirooka, 2006). After market penetration it will take a similar amount of time for the technology to become mature (Kramer, 2009). When comparing new technologies to incumbent technologies, it is very important to take into account their level of development and that considerable time is required before technologies operate at similar (comparable) scales. To account for this in ex-ante LCA we build on work done by Gavankar et al. (2014), who discuss the role of technology maturity in LCA and introduced the concept of Technology Readiness Levels (TRL) and Manufacturing Readiness Levels (MRL) to the field of LCA. They stress that the outcomes of LCA studies on emerging technologies should be represented in relation to their scale of operation because the environmental impact at lower levels (kW scales) is most likely not linearly scalable to higher levels (GW scales), while the new technologies proposed are intended to perform at those higher scales. We stick to the concept of MRL because technology readiness only implies that a technology is feasible, but does not provide information to whether the technology is ready for large scale manufacturing or operation. It is easy to understand that technologies with a low MRL (~5) encounter larger uncertainties when modelled to be at their hypothetical full scale and that modelling incumbent technologies with a typical MRL of 10 have much lower uncertainties.

Ex-ante LCA studies are by definition based on a hypothesized state of operation (Hospido et al., 2010), or even on more than one stylized or extreme state that allows the illustration of differences between specific technological options (Arvidsson, 2013; Sanden et al., 2005). The main challenge is defining the states of the compared technologies consistently by making similar choices on the anticipated operation and scale-up of the technology from the lab to its industrial state. The subjective choices, individual preferences and perceptions of the practitioners and of the technology developers are an integral part of the modelling process and are also bound to be affected by the inherent changes in basic socio-economic conditions over time (Frischknecht et al., 2009).

4.2.1. Selecting and modelling the incumbent technology into the future

Selecting the incumbent technology should be based on (similar) functionality as is common in LCA. However, new technologies often have multiple functionalities that often are not found simultaneously in one existing (incumbent) technology (mix). It is therefore important to be very clear on the intended application of a new technology, although this is often an uncertainty. Keeping this implicit and qualitatively discussing multiple intuitive functions makes it very hard if not impossible to perform a fair assessment. Moreover, this approach does not allow to give insights in the potential implications of certain design choices. Choosing the potential application of a technology could be guided by the public discourse, but could also be determined by available data for the insights desired. At least a clear statement on this needs to present. For example, Van Der Giesen et al. (2014) explicitly choose to compare fuels produced form CO_2 to existing diesel fuels where, based on other possible functionalities discussed in the paper, also a choice for carbon capture and sequestration could have been made. It is clear that a single best incumbent is hard to define, however, organizing stakeholder discussions to identify the incumbent technology for the assessment enables making the assessment as insightful as possible.

Even after a product is at MRL 9 or 10 it is still possible that minor advances and developments take place. It might be possible that the incumbent technology, typically operational at an MRL of 10, will have developed further at the time that the new technology will start entering the market. In their future scenario work Hertwich et al. (2015) used a combination of industry roadmaps, technology learning curves and expert consultation to arrive at substantiated performance data for technologies that are already on the market. These sources provide a first solid base to integrate potential further development of the incumbent technology to be aligned with the scope defined for the ex-ante LCA study.

4.2.2. Modelling a new technology at scale into the future

The big question for modelling a new technology at the same scale as the incumbent is how to base a full scale model of the technology on the available knowledge from the lab and the technology trajectory. The use of technology learning curves that describe technology progress in terms of “decreasing costs as a function of accumulating experience with that technology” (McDonald and Schrattenholzer, 2002) or “as a function of cumulative production” (Bergesen and Suh, 2016) unfortunately seems not directly applicable for new technologies since market-based experience with these new technologies simply does not exist. However, experience with similar technologies might provide an idea for further technology development in combination with basic laws of physics and critical expert input. One should, however, be informed that a learning curve “hardly represent[s] a physical law, but rather describe[s] a persistent empirical phenomenon with still significant uncertainties surrounding both the estimation of specific learning rates and their extrapolation in scenarios” (McDonald and Schrattenholzer, 2002).

Another way is to combine learning curve insights with knowledge and experience on ‘upscaling’ from the field of e.g. chemical engineering, for which considerate expertise is required. Piccinno et al. (2016) provide a framework with which LCA practitioners with limited chemical engineering knowledge can obtain a first estimate about the impacts a chemical produced at an industrial scale when only laboratory scale data is available. The authors stress that the framework is only applicable to existing technologies and not for new technologies in the future. Another contribution to including upscaling in LCA was provided by Caduff (2014) who investigated the use of scaling factors from cost engineering and power-law relationships and applies this to energy technology. Also here the scaling factors are based on empirical experience with existing technologies. Thus, it is hard to say if this approach is applicable to new technologies in early stages of development.

Parvatker and Eckelman (2019) reviewed eight different upscaling methods that are used in chemical engineering to fill up data gaps in LCA. Also these methods do not take into account any future developments. Although these approaches are not equipped to look into the future, they might provide a starting point for defining scenarios. Including scenarios analysis is found to be crucial in up-scaling exercises since it makes the influences of assumptions and uncertainty transparent (F Piccinno et al., 2016). It even seems that the methods ranked by Parvatker and Eckelman (2019) are indicative of application at certain MRL levels and are also in line with levels of uncertainty encountered (see Fig. 2).

Concluding, we can say that extensive guidance for modelling new technologies in the future exists (in e.g. the field of chemical engineering). A remaining question is how we can perform some form of upscaling in other fields like nano-, energy or food technology. For now the only option seems to be to organize a structured discussion with experts on the future expectations and potential of new technologies. The practitioner should not expect the perfect and correct answer, but gather enough information to investigate different hypothetical routes of development through the use of scenarios.

4.3. Modelling future background systems

It has already been identified that existing ex-ante LCA studies do not necessarily take into account developments in the background system, while it is important that "a temporal mismatch between back- and foreground systems in prospective LCA studies should be avoided" (Arvidsson et al., 2017a). We already showed the importance of choices in background systems for the final outcomes of the study in section 3.3. In practice, the foreground system is modelled at a future state while for the background system, one assumes the current (even outdated) temporal state (Mendoza Beltran et al., 2018). The question is, how to take time into consideration so that fore- and background systems cover the same temporal scope?

A common and fruitful approach for dealing with time and future systems in LCA is to make use of scenarios (Pesonen et al., 2000). Several studies attempt to integrate time to account for potential future developments in the fore- and background systems (Krishna Manda et al., 2015; Nordelöf et al., 2014; Spielmann et al., 2005). Even though these studies show that it is essential to integrate a time dimension in the assessment, most existing projects attempting to do so encounter challenges. The scenarios used are often inconsistent and lack transparency, technology maturity is often not accounted for and reproducibility of these scenarios is difficult because of large amounts of data needed and tracing assumptions made during scenario generation (Mendoza Beltran, 2018). To overcome these, Mendoza et al. (2018) propose to explicitly discern between scenario generation and scenario assessment (following Fukushima and Hirao (2002)). For scenario generation they build on the Shared Socio-economic Pathways (SSPs) developed by the climate change research community and constructed with Integrated Assessment Models (IAMs) (van Vuuren et al., 2014). For the evaluation of these scenarios they combine the market shares for e.g. energy technologies as predicted by IAMs with LCA data from databases like ecoinvent 3 (Wernet et al., 2016).

Mendoza et al. (2018) show that it is feasible to implement technology scenarios calculated with IAMs into LCI databases for the electricity sector. The challenge remains to develop similar future background LCI databases for other sectors that are closely linked to future sustainable technology development. The approach taken is new and therefore not yet common practice. It would be very beneficial to develop or expand on existing LCI databases like ecoinvent to represent potential future situations via clearly defined scenarios. Integrating these scenarios is a project in itself, so externally developing scenarios that address critical future parameters should be a point of focus for further development of ex-ante LCA practices.

As long as IAM based LCI background data are not available, practitioners should at least attempt to be transparent about potential temporal mismatches between back- and foreground system and the implications of that on the outcomes of the study. As is commonly done, one can assume that the current background data is also representative for a defined future, or one can assume that the background system does not change over time and is constant.

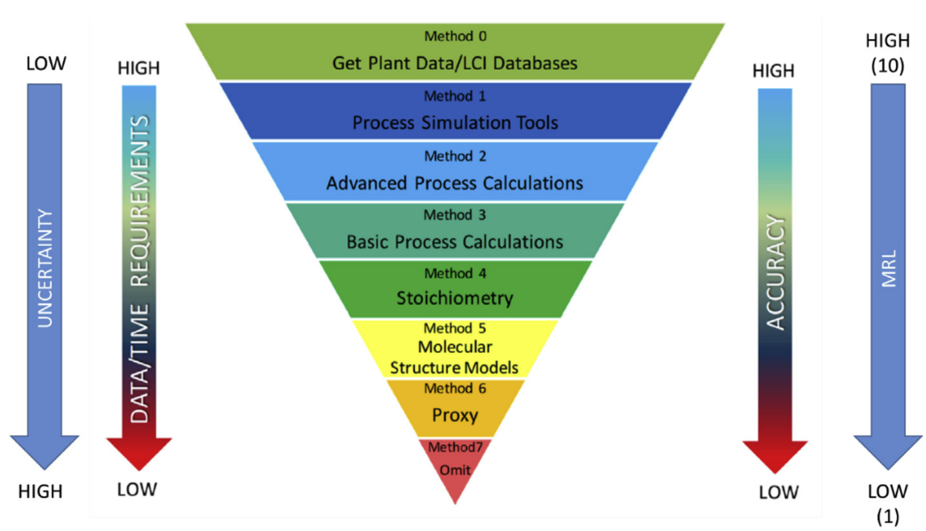

Fig. 2. Hierarchy of methods in LCI data generation adapted from Parvatker and Eckelman (2019).

This might however, result in huge errors as shown by Cox et al. (2018). Therefore, a thorough discussion on the impact of such modelling decisions on the outcomes should be included. Another option is to use the NEEDS database ("The NEEDS Life Cycle Inventory Database," n.d.), which has its focus on energy. This consistent database is outdated because it is based on ecoinvent 1.3 and does not use the scenario approach as proposed by Mendoza et al. (2018). However, taking all limitations in mind and providing a proper discussion on the use of this database could allow for an ex-ante LCA study in which the temporal mismatch between back- and foreground data is covered.

4.4. Dealing with uncertainty in ex-ante LCA

It is obvious that studies assessing technologies in the early stage of their development deal with higher levels of uncertainty than technologies that are already implemented. This includes issues that have been termed 'unknown unknowns' and that cannot easily be covered by traditional, quantitative uncertainty assessments that are now applied in state of the art LCAs. The field of technology assessment therefore came up with concepts such as post-normal science (Funtowicz and Ravetz, 1993) and indeterminacy (Wynne, 1992) to capture a broader view on uncertainty. Mendoza Beltran (2018) used the typology of Wynne (1992) to position her PhD thesis as being mainly focused on quantifiable risks and uncertainties. We use Wynne's typology pragmatically, being a rather straightforward typology discerning a) risk (system parameters and probabilities are known), b) uncertainty (system parameters are known, but not the probability distributions), c) ignorance (neither system parameters nor probabilities are known) and d) indeterminacy (the future development is inherently undetermined).

The four types of uncertainty can respectively be assigned to high development and early development stages of the technology under assessment (see Fig. 3). Conventional ex-post LCA studies and incumbent technologies in ex-ante LCA typically deal with technologies at a high MRL level. If the behaviour of the technology is well known, the chance of ignorance or indeterminacy is low and the more traditional fields of risk and uncertainty have to be covered. The LCA community has developed state of the art methodologies that can be applied here. These are Monte-Carlo simulations to deal with parameter uncertainty, or scenarios to deal with uncertainties related to methodological choices, see e.g. Mendoza Beltran (2018). In principle, such approaches can also be used to address e.g. changes in characterisation factors due to e.g. changing background concentrations as discussed in section 3.4.

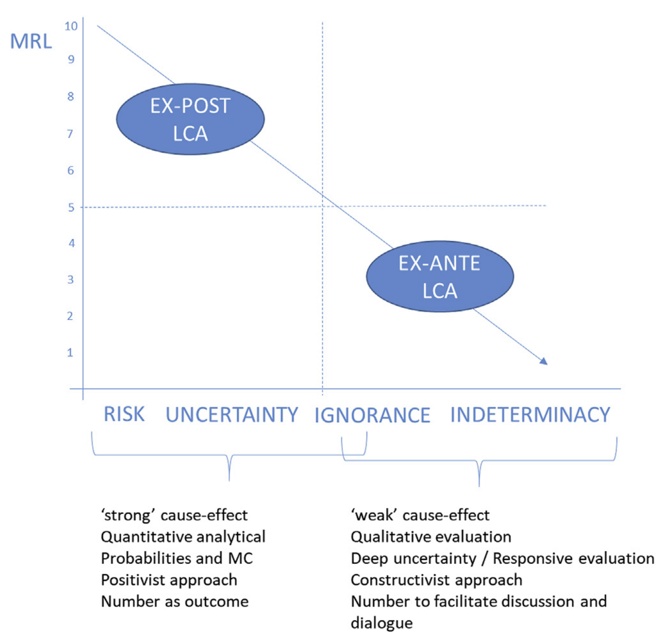

Fig. 3. Relation between MRL, uncertainty and type of LCA assessment.

Ex-ante LCA must somehow deal with the problems of ignorance and indeterminacy for the assessment of new technologies. This is a field where the LCA community has a limited track record, in part since it requires a somewhat different view on the role of science. A so-called positivist view on science assumes that the world can be fully known, which fits well with the quantitative approaches including the assessments of uncertainty that the LCA community is so familiar with. A more constructivist view on science assumes that the world cannot be fully known, leading to the acknowledgment that overarching views exist, using different parts of available knowledge, combined with certain, often implicit, differences in interpretation.

To give the subjects of ignorance and indeterminacy a sound place in decision making, various strands of science have developed the following approaches. Authors such as Hamarat et al. (2013), Kwakkel and Pruyt (2013) and Maier (2016) have coined the concept of 'deep uncertainty', which is defined as "uncertainty for which experts do not agree on models to describe interactions among a system's components, and subsequently do not agree upon (exact causal structures) corresponding probabilities and possible outcomes" (Tegeltija et al., 2018). The remedy is to "think about the future in terms of multiple plausible futures rather than probability distributions" (Maier et al., 2016). In essence this approach is still somewhat fitting in the positivist tradition in the sense that it is deemed possible to define and quantify specific scenarios capturing the elements of ignorance and indeterminacy. Policy and social scientists however, seek the solution in embarking on more participatory approaches that deliberately encourage to uncover different, but plausible perspectives or framings of the possible risks and impacts of the new technology. An illustration of this is the 'Fourth Generation Evaluation" proposed by Guba and Lincoln (1989) who propose to bring this about in a *hermeneutic dialectic process* which is done in a *responsive evaluation* in 4 steps:

1. Identify stakeholders and collect their claims (any assertion favourable to the evaluand), concerns (any assertions unfavourable to the evaluand) and issues (any state of affairs about which reasonable persons may disagree) on the evaluand;
2. Claims, concerns and issues are presented to other stakeholder groups for response and discussion;
3. Unresolved claims, concerns and issues steer additional needs for information that need to be collected by the evaluator;
4. Negotiations using information added in step 3 to arrive at a consensus ("as each group copes with the construction of all the others, their own constructions alter by virtue of becoming better informed and more sophisticated" (Guba and Lincoln, 1989)).

To some extent this reflects the classical peer-review in LCA, but it is also obvious that in this case the panel will not only consist of technical specialists. The panel will consist of stakeholders that are likely to have (highly) opposing views and therefore allow the identification of potential ignorance and indeterminacy. This will help to counter the (usually positive) biases of the developers of the new technology as well as bring potential drawbacks of a new technology to light at an early stage when it is still possible to adjust the technology for the better. In the end it is not about being right, but about aiding the design of new sustainable technologies in the best possible way.

5. Discussion and conclusions

In this paper we investigated how to perform an environmental assessment of potential new technologies that are still in their R&D phase. We identified the main challenges in comparison with conventional ex-post LCA practices and propose practical remedies for coping with these challenges. We chose to use the term ex-ante LCA and defined this as *performing an environmental life cycle assessment of a new technology before it is commercially implemented in order to guide R&D decisions to make this new technology environmentally competitive with the incumbent technology mix*.

Having started from this definition, we conclude that a fixed way of performing an ex-ante LCA does not exist and that the challenges defined here as well as suggestions proposed are also applicable to other modes of LCA like consequential and prospective LCA which are discussed in section 2. Choosing a method depends on the question at hand. We found different questions in literature that are assessed by different forward-looking LCA approaches using different terminology. In this paper we specifically looked at a method to environmentally assess a new technology in order to guide research and development. Where such an assessment can provide important insights for R&D one should be careful not to reach a verdict on a new technology before it has been implemented.

The challenges and proposed potential remedies for ex-ante LCA based on the former sections are summarized in Table 2. Modelling future foreground systems for the incumbent and new technology is a first challenge, which includes e.g. estimates of learning curves and scenarios for future market penetration. Although not the direct focus of this paper, a further investigation on the relationship between incumbent and marginal technology, the latter being common practice in consequential LCA approaches, could bring up interesting practices for defining the incumbent technology. Future background systems could be modelled by imposing futures as predicted by Integrated Assessment Models on Life Cycle Inventory databases, but this is not yet widely done. The main difference with conventional LCA studies however, is the highly uncertain information for the future. To acknowledge this considerable attention should be paid to the discussion on these uncertainties both in the design of the assessment as for the data used. This can be done in the form of *responsive* or *third generation evaluation,* which resembles the traditional LCA peer review procedure, but is different since it involves a much wider set of actors, and a more specific assessment of their claims and concerns on potential future impacts. This will increase the transparency and efficacy of the assessment because the relevant stakeholders and experts are involved. In this way technology designers and other stakeholders derive insights on the influence of design choices or contextual factors (that are important, but hard to influence) on the potential environmental impacts of their foreseen technology.

The main recommendation for ex-ante LCA that we can give is of a scientific philosophical nature. In order to perform an ex-

Table 2
Challenges and suggested remedies for ex-ante LCA.

LCA phase	Challenge	Potential Remedy	Explanation
Goal and scope definition	At what moment in time is the new technology to be expected to be operational at which level of maturity?	Responsive evaluation Expert involvement	It is unclear when and where a new technology will be applied in the future or how it will exactly be designed. Defining a clear scope however, sets the base for many modelling choices that need to be made for the assessment.
	How does the functional unit need to be defined so that the new and the incumbent technology provide the same (similar) functionality?	Responsive evaluation expert involvement scenarios	The application of new technologies is a question for the future and can only be proposed with high uncertainty, sometimes multiple functions need to be defined.
	How can the incumbent technology be defined?	Responsive evaluation expert involvement	The application of new technologies is a question for the future and can only be proposed with high uncertainty. Existence of multiple functions makes defining the right incumbent uncertain.
Life cycle inventory	How will new technological systems develop into the future, perform under the scope defined and is representative LCI data available?	Upscaling techniques, Responsive evaluation expert involvement scenarios	Data is often only available at lab scale for the current moment, How this will play out in the future is uncertain.
	How will incumbent technological systems develop into the future, perform under the scope defined and is representative LCI data available?	Technology learning curves technology road maps Responsive evaluation expert involvement scenarios	Data is often available at full scale, but incumbent technologies might slightly improve or change over time.
	How will background systems and their performance develop over time, perform under the scope defined and is representative LCI data available?	Combining LCI databases with IAM scenario Responsive evaluation expert involvement scenarios	Background data is available for a different scope and not always include newer technologies or socio-economic change.
	What is the potential market share of the new technology in the future?	Responsive evaluation expert involvement scenarios (IAMs, IEA, IPCC)	Which market share a new technology will occupy in the future is highly uncertain.
Impact assessment	Can the new technological systems display unexpected new impacts not yet covered in LCIA?	Responsive evaluation expert involvement scenarios	Existing (base-line) impact categories might be irrelevant for the future or different, yet undefined, impacts will become relevant.
	Can characterisation factors relevant for the incumbent and new technical systems change over time?	Responsive evaluation expert involvement scenarios	Characterisation factors for impact categories defined above might change based on new insights and research
Interpretation	How can the increased uncertainty around modelling new technologies in the future be dealt with?	deep uncertainty responsive evaluation scenario modelling expert involvement	In conventional (ex post) LCA uncertainties that go beyond risks and uncertainty are not acknowledged systematically, although doing so might provide valuable information for R&D efforts.
	How can the possibility that new technologies will display unkown unknowns be dealt with?	Responsive evaluation expert involvement	Not acknowledged systematically in conventional (ex post) LCA, but relevant for new technologies intended to contribute to a sustainable future.

ante LCA the assessment requires a shift from a positivist to a more constructivist approach. Ex-ante LCA studies encounter such high uncertainties and require considerate assumptions that need to be based on debate rather than on fixed statements that are gratuitously presented as correct. In this way ex-ante LCA finds a perfect application in guiding the discourse along the R&D path by providing structure following the ISO norm and quantifications that enable a proper discussion on design choices and potential future scenarios of new technologies. Practical experience in taking this more constructivist approach is still limited, needs to be further developed and can only be obtained by application of the suggested solutions in real case studies. This is the aim for our ongoing case study work and we are looking forward to seeing the experience and insights of other research in this developing field.

Performing an ex-ante LCA study should follow the ISO norm, but would also require departing from the standard by increasingly involving stakeholders (Tsoy et al., 2019) as well as disciplines and skills[2] for which the conventional LCA practitioner is not typically equipped. It should however, not be the goal that the LCA practitioner masters these disciplines, rather that the discourse between the different disciplines is properly managed. Instead of performing a critical review after the LCA study one should invite the proper critical scientists on all modelling choices that need to be made, by incorporating for example the practice of *responsive evaluation*. Moreover, there is a great need for *background databases* that can be used in modelling future technologies. Research on integrating IAMs and LCI databases, which was initiated by Mendoza (2018), should definitely be followed up. Lastly, practices to deal with 'higher' less defined uncertainties (ignorance and indeterminacy) should be investigated, for which a good starting point is the concept of *deep uncertainty*.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Coen van der Giesen: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing - original draft. **Stefano Cucurachi:** Conceptualization, Investigation, Methodology, Writing - review & editing. **Jeroen Guinée:** Conceptualization. **Gert Jan Kramer:** Conceptualization, Supervision. **Arnold Tukker:** Supervision, Writing - review & editing.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The authors would like to thank Ilana Becher for text and language editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.120904.

[2] Responsive evaluation/Technology expert involvement/Scenarios/Upscaling techniques/Technology learning curves/technology roadmaps/Combining LCI databases and IAMs/Deep uncertainty/general morphological analysis.

References

Kätelhön, A., Bardow, A., Suh, S., 2016. Stochastic technology choice model for consequential life cycle assessment. Environ. Sci. Technol. 50, 12575–12583.

Aldaco, R., Butnar, I., Margallo, M., Laso, J., Rumayor, M., Dominguez-Ramos, A., Irabien, A., Dodds, P.E., 2019. Bringing value to the chemical industry from capture, storage and use of CO 2 : a dynamic LCA of formic acid production. Sci. Total Environ. 663, 738–753. https://doi.org/10.1016/j.scitotenv.2019.01.395.

Arvidsson, R., 2013. How to make policy-relevant life cycle assessments of future products? - lessons learned form nano materials. In: The 6th International Conference on Life Cycle Management in Gothenborg.

Arvidsson, R., Kushnir, D., Sandén, B.a., Molander, S., 2014. Prospective life cycle assessment of graphene production by ultrasonication and chemical reduction. Environ. Sci. Technol. 48, 4529–4536. https://doi.org/10.1021/es405338k.

Arvidsson, R., Janssen, M., Nordel, A., 2017a. Environmental assessment of emerging technologies recommendations for prospective LCA 22. https://doi.org/10.1111/jiec.12690.

Arvidsson, R., Tillman, A.-M., Sandén, B.A., Janssen, M., Nordelöf, A., Kushnir, D., Molander, S., 2017b. Environmental assessment of emerging technologies: recommendations for prospective LCA. J. Ind. Ecol. 1–9. https://doi.org/10.1111/jiec.12690, 00.

Bauer, C., Hofer, J., Althaus, H.-J., Del Duce, A., Simons, A., 2015. The environmental performance of current and future passenger vehicles: life Cycle Assessment based on a novel scenario analysis framework. Appl. Energy 157, 1–13. https://doi.org/10.1016/j.apenergy.2015.01.019.

Baumann, H., Tillman, A.M., 2004. The Hitchhiker's Guide to LCA: an Orientation in Life Cycle Assessment Methodology and Application. Studentlitteratur, Lund, Sweden.

Bergesen, J.D., Suh, S., 2016. A framework for technological learning in the supply chain: a case study on CdTe photovoltaics. Appl. Energy 169, 721–728. https://doi.org/10.1016/j.apenergy.2016.02.013.

Berrill, P., Arvesen, A., Scholz, Y., Gils, H.C., Hertwich, E.G., 2016. Environmental impacts of high penetration renewable energy scenarios for Europe. Environ. Res. Lett. 11, 014012 https://doi.org/10.1088/1748-9326/11/1/014012.

Buyle, M., Audenaert, A., Billen, P., Boonen, K., Van Passel, S., 2019. The future of ex-ante LCA? Lessons learned and practical recommendations. Sustainability 11, 5456.

Caduff, M., Huijbregts, M., Koehler, A., Althaus, H.-J., Hellweg, S., 2014. Scaling relationships in life cycle assessment. J. Ind. Ecol. 18, 393–406. https://doi.org/10.1111/jiec.12122.

Cox, B., Mutel, C.L., Bauer, C., Mendoza Beltran, A., Van Vuuren, D.P., 2018. Uncertain environmental footprint of current and future battery electric vehicles. Environ. Sci. Technol. 52, 4989–4995. https://doi.org/10.1021/acs.est.8b00261.

Cucurachi, S., Van Der Giesen, C., Guinée, J., 2018. Ex-ante LCA of emerging technologies. In: Procedia CIRP. https://doi.org/10.1016/j.procir.2017.11.005.

Curran, M.A. (Ed.), 2012. Life Cycle Assessment Handbook - A Guide for Environmentally Sustainable Products. Scrivener Publishing, Salem, Massachusetts.

Deng, Y., Li, J., Qiu, M., Yang, F., Zhang, J., Yuan, C., 2016. Deriving characterization factors on freshwater ecotoxicity of graphene oxide nanomaterial for life cycle impact assessment. Int. J. Life Cycle Assess. 1–15. https://doi.org/10.1007/s11367-016-1151-4.

European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010. ILCD handbook - general guide for life cycle assessment - detailed guidance, international reference life cycle data system (ILCD) handbook. https://doi.org/10.2788/38479.

European Commission, 2017. Horizon 2020 - THe EU framework programme for research and innovation [WWW Document]. https://ec.europa.eu/programmes/horizon2020/. accessed 12.15.16.

Frischknecht, R., Büsser, S., Krewitt, W., 2009. Environmental assessment of future technologies: how to trim LCA to fit this goal? Int. J. Life Cycle Assess. 14, 584–588. https://doi.org/10.1007/s11367-009-0120-6.

Fukushima, Y., Hirao, M., 2002. A structured framework and language for scenario-based Life Cycle assessment. Int. J. Life Cycle Assess. 7, 317–329. https://doi.org/10.1007/BF02978679.

Funtowicz, S.O., Ravetz, J.R., 1993. Science for the post-normal age. Futures 25, 739–755. https://doi.org/10.1016/0016-3287(93)90022-L.

Gavankar, S., Suh, S., Keller, A.a., 2014. The role of scale and technology maturity in life cycle assessment of emerging technologies: a case study on carbon nanotubes. J. Ind. Ecol. 19, 51–60. https://doi.org/10.1111/jiec.12175.

Gifford, M., Chester, M., Hristovski, K., Westerhoff, P., 2016. Reducing environmental impacts of metal (hydr)oxide nanoparticle embedded anion exchange resins using anticipatory life cycle assessment. Environ. Sci. Nano 3, 1351–1360. https://doi.org/10.1039/C6EN00191B.

Guba, E.G., Lincoln, Y.S., 1989. Fourth Generation Evaluation. SAGE Publications Inc.

Guinée, J., Gorrée, M., Heijungs, R., 2002. Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards. Kluwer Academic Publishers.

Guinée, J., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., Rydberg, T., 2011. Life cycle Assessment : past , present and future. Environ. Sci. Technol. 45, 90–96. https://doi.org/10.1021/es101316v.

Guineé, J.B., Heijungs, R., Vijver, M.G., Peijnenburg, W.J.G.M., 2017. Setting the stage for debating the roles of risk assessment and life-cycle assessment of engineered nanomaterials. Nat. Nanotechnol. 12, 727–733. https://doi.org/10.1038/NNANO.2017.135.

Guinée, J.B., Cucurachi, S., Henriksson, P.J.G., Heijungs, R., 2018. Digesting the

alphabet soup of LCA. Int. J. Life Cycle Assess. 23 https://doi.org/10.1007/s11367-018-1478-0.
Hamarat, C., Kwakkel, J.H., Pruyt, E., 2013. Adaptive robust design under deep uncertainty. Technol. Forecast. Soc. Change 80, 408–418. https://doi.org/10.1016/j.techfore.2012.10.004.
Hellweg, S., Milà i Canals, L., 2014. Emerging approaches, challenges and opportunities in life cycle assessment. Science 344, 1109–1113. https://doi.org/10.1126/science.1248361.
Hertwich, E.G., Gibon, T., Bouman, E.A., Arvesen, A., Suh, S., Heath, G.A., Bergesen, J.D., Ramirez, A., Vega, M.I., Shi, L., 2015. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. Proc. Natl. Acad. Sci. Unit. States Am. 112, 6277–6282. https://doi.org/10.1073/pnas.1312753111.
Hesser, F., 2015. Environmental advantage by choice: ex-ante LCA for a new Kraft pulp fibre reinforced polypropylene composite in comparison to reference materials. Compos. B Eng. 79, 197–203. https://doi.org/10.1016/j.compositesb.2015.04.038.
Hesser, F., Mihalic, M., Paichl, B.J., Wagner, M., 2017a. Injection moulding unit process for LCA: energy intensity of manufacturing different materials at different scales. J. Reinforc. Plast. Compos. 36, 338–346. https://doi.org/10.1177/0731684416674565.
Hesser, F., Wohner, B., Meints, T., Stern, T., Windsperger, A., 2017b. Integration of LCA in R&D by applying the concept of payback period: case study of a modified multilayer wood parquet. Int. J. Life Cycle Assess. 22, 307–316. https://doi.org/10.1007/s11367-016-1173-y.
Hetherington, A.C., Borrion, A.L., Griffiths, O.G., McManus, M.C., 2014. Use of LCA as a development tool within early research: challenges and issues across different sectors. Int. J. Life Cycle Assess. 19, 130–143. https://doi.org/10.1007/s11367-013-0627-8.
Hirooka, M., 2006. Innovation Dynamism and Economic Growth. Edward Elgar Publishing. https://doi.org/10.4337/9781845428860.
Hospido, A., Davis, J., Berlin, J., Sonesson, U., 2010. A review of methodological issues affecting LCA of novel food products. Int. J. Life Cycle Assess. 15, 44–52. https://doi.org/10.1007/s11367-009-0130-4.
Hu, M., Kleijn, R., Bozhilova-Kisheva, K.P., Di Maio, F., 2013. An approach to LCSA: the case of concrete recycling. Int. J. Life Cycle Assess. 18, 1793–1803. https://doi.org/10.1007/s11367-013-0599-8.
Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y.
Hummen, T., Kastner, F., 2014. Evaluating Existing Methodological Approaches for Prospective LCA at Early Technology-Development Stages.
International Organization for Standardization (ISO), 1997. ISO14040 Environmental Management - Life Cycle Assessment - Principles and Framework.
Kramer, G.J., 2009. No quick switch to low-carbon. Energy 462, 3–5.
Krishna Manda, B., Worrell, E., Patel, M.K., 2015. Prospective life cycle assessment of an antibacterial T-shirt and supporting business decisions to create value. Resour. Conserv. Recycl. 103, 47–57. https://doi.org/10.1016/j.resconrec.2015.07.010.
Kunnari, E., Valkama, J., Keskinen, M., Mansikkamäki, P., 2009a. Environmental evaluation of new technology: printed electronics case study. J. Clean. Prod. 17, 791–799. https://doi.org/10.1016/j.jclepro.2008.11.020.
Kunnari, E., Valkama, J., Keskinen, M., Mansikkamäki, P., 2009b. Environmental evaluation of new technology: printed electronics case study. J. Clean. Prod. 17, 791–799. https://doi.org/10.1016/j.jclepro.2008.11.020.
Kwakkel, J.H., Pruyt, E., 2013. Exploratory Modeling and Analysis, an approach for model-based foresight under deep uncertainty. Technol. Forecast. Soc. Change 80, 419–431. https://doi.org/10.1016/j.techfore.2012.10.005.
Maier, H.R., Guillaume, J.H.A., van Delden, H., Riddell, G.A., Haasnoot, M., Kwakkel, J.H., 2016. An uncertain future, deep uncertainty, scenarios, robustness and adaptation: how do they fit together? Environ. Model. Software 81, 154–164. https://doi.org/10.1016/j.envsoft.2016.03.014.
McDonald, A., Schrattenholzer, L., 2002. Learning curves and technology assessment. Int. J. Technol. Manag. 23, 718–745. https://doi.org/10.1504/IJTM.2002.003035.
McKone, T.E., Nazaroff, W.W., Berck, P., Auffhammer, M., Lipman, T., Torn, M.S., Masanet, E., Lobscheid, a., Santero, N., Mishra, U., Barrett, a., Bomberg, M., Fingerman, K., Scown, C., Strogen, B., Horvath, a., 2011. Grand challenges for life-cycle assessment of biofuels. Environ. Sci. Technol. 45, 1751–1756. https://doi.org/10.1021/es103579c.
Mendoza Beltran, A., 2018. When the background matters: using scenarios from integrated assessment models in prospective LCA. J. Ind. Ecol. submitted.
Mendoza Beltran, A., Cox, B., Mutel, C., van Vuuren, D.P., Font Vivanco, D., Deetman, S., Edelenbosch, O.Y., Guinée, J., Tukker, A., 2018. When the background matters: using scenarios from integrated assessment models in prospective life cycle assessment. J. Ind. Ecol. 1–16. https://doi.org/10.1111/jiec.12825, 00.
Miller, S. a, Keoleian, G. a, 2015. Framework for analyzing transformative technologies in life cycle assessment. Environ. Sci. Technol. 49, 3067–3075. https://doi.org/10.1021/es505217a.
Nordelöf, A., Messagie, M., Tillman, A.M., Ljunggren Söderman, M., Van Mierlo, J., 2014. Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? Int. J. Life Cycle Assess. 19, 1866–1890. https://doi.org/10.1007/s11367-014-0788-0.
Parvatker, A.G., Eckelman, M.J., 2019. Comparative evaluation of chemical life cycle inventory generation methods and implications for life cycle assessment results. ACS Sustain. Chem. Eng. 7, 350–367. https://doi.org/10.1021/acssuschemeng.8b03656.
Pehnt, M., 2003. Assessing future energy and transport systems: the case of fuel cells Part I: methodological aspects. Int. J. Life Cycle Assess. 8, 283–289. https://doi.org/10.1007/BF02978920.
Pehnt, M., 2006. Dynamic life cycle assessment (LCA) of renewable energy technologies. Renew. Energy 31, 55–71. https://doi.org/10.1016/j.renene.2005.03.002.
Pesonen, H., Ekvall, T., Fleischer, G., Huppes, G., Jahn, C., Klos, Z., Rebitzer, G., Sonnemann, G., Tintinelli, A., Weidema, B., Wenzel, H., 2000. Framework for scenario development in LCA. Int. J. Life Cycle Assess. 5, 21–30. https://doi.org/10.1007/BF02978555.
Peters, J.F., Weil, M., 2017. Aqueous hybrid ion batteries – an environmentally friendly alternative for stationary energy storage? J. Power Sources 364, 258–265. https://doi.org/10.1016/j.jpowsour.2017.08.041.
Piccinno, F., Hischier, R., Seeger, S., Som, C., 2015. Life cycle assessment of a new technology to extract, functionalize and orient cellulose nanofibers from food waste. ACS Sustain. Chem. Eng. 3, 1047–1055. https://doi.org/10.1021/acssuschemeng.5b00209.
Piccinno, Fabiano, Hischier, R., Seeger, S., Som, C., 2016. From laboratory to industrial scale: a scale-up framework for chemical processes in life cycle assessment studies. J. Clean. Prod. 135, 1085–1097. https://doi.org/10.1016/j.jclepro.2016.06.164.
Piccinno, F., Hischier, R., Seeger, S., Som, C., 2016. From laboratory to industrial scale: a scale-up framework for chemical processes in life cycle assessment studies. J. Clean. Prod.
Roes, A.L., Patel, M.K., 2011. Ex-ante environmental assessments of novel technologies – improved caprolactam catalysis and hydrogen storage. J. Clean. Prod. 19, 1659–1667. https://doi.org/10.1016/j.jclepro.2011.05.010.
Sanden, B.A., Jonasson, K.M., Tillman, A., 2005. LCA of emerging TECHNOLOGIES : a methodological framework. In: LCM 2005, pp. 5–8. Barcelona.
Schrijvers, D.L., Leroux, F., Verney, V., Patel, M.K., 2014. Ex-ante life cycle assessment of polymer nanocomposites using organo-modified layered double hydroxides for potential application in agricultural film. Green Chem. 16, 4969–4984. https://doi.org/10.1039/c4gc00830h.
Schulze, R., Abbasalizadeh, A., Bulach, W., Schebek, L., Buchert, M., 2018. An ex-ante LCA study of rare earth extraction from NdFeB magnet scrap using molten salt electrolysis. J. Sustain. Metall. 4, 493–505. https://doi.org/10.1007/s40831-018-0198-9.
Spielmann, M., Scholz, R., Tietje, O., Haan, P. De, 2005. Scenario modelling in prospective LCA of transport systems. Application of Formative scenario analysis. Int. J. Life Cycle Assess. 11.
Suh, S., Yang, Y., 2014. On the uncanny capabilities of consequential LCA. Int. J. Life Cycle Assess. 19, 1179–1184. https://doi.org/10.1007/s11367-014-0739-9.
Swiss Centre for Life Cycle Inventories, 2010. Ecoinvent data V2.2 [WWW Document]. ecoinvent data V2.2. http://www.ecoinvent.org/.
Tecchio, P., Freni, P., De Benedetti, B., Fenouillot, F., 2015. Ex-ante Life Cycle Assessment approach developed for a case study on bio-based polybutylene succinate. J. Clean. Prod. 1–10. https://doi.org/10.1016/j.jclepro.2015.07.090.
Tegeltija, M., Oehmen, J., Kozin, I., Kwakkel, J., 2018. Exploring deep uncertainty approaches for application in life cycle engineering. Procedia CIRP 69, 457–462. https://doi.org/10.1016/j.procir.2017.12.006.
[WWW Document], n.d The NEEDS Life Cycle Inventory Database. http://www.needs-project.org/needswebdb/.
Thomson Reuters. n.d. Web of Science [WWW Document]. webofknowledge.com. accessed 12.15.16.
Tsoy, N., Prado, V., Wypkema, A., Quist, J., Mourad, M., 2019. Anticipatory Life Cycle Assessment of sol-gel derived anti-reflective coating for greenhouse glass. J. Clean. Prod. 221, 365–376. https://doi.org/10.1016/j.jclepro.2019.02.246.
Tufvesson, L.M., Tufvesson, P., Woodley, J.M., Börjesson, P., 2012. Life cycle assessment in green chemistry: overview of key parameters and methodological concerns. Int. J. Life Cycle Assess. 18, 431–444. https://doi.org/10.1007/s11367-012-0500-1.
United Nations, 2017. Sustainable development knowledge platform [WWW Document]. https://sustainabledevelopment.un.org/topics/technology. accessed 12.15.16.
Van Der Giesen, C., Kleijn, R., Kramer, G.J., Guinée, J., 2013. Towards application of life cycle sustainability analysis; towards application of life cycle sustainability analysis. Rev. Métall. 110, 31–38. https://doi.org/10.1051/metal/2013058.
Van Der Giesen, C., Kleijn, R., Kramer, G.J., 2014. Energy and climate impacts of producing synthetic hydrocarbon fuels from CO2. Environ. Sci. Technol. 48, 7111–7121. https://doi.org/10.1021/es500191g.
van Vuuren, D.P., Kriegler, E., O'Neill, B.C., Ebi, K.L., Riahi, K., Carter, T.R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R., Winkler, H., 2014. A new scenario framework for Climate Change Research: scenario matrix architecture. Climatic Change 122, 373–386. https://doi.org/10.1007/s10584-013-0906-1.
Villares, M., Işıldar, A., Mendoza Beltran, A., Guinee, J., 2016. Applying an ex-ante life cycle perspective to metal recovery from e-waste using bioleaching. J. Clean. Prod. 129 https://doi.org/10.1016/j.jclepro.2016.04.066.
Villares, M., Işıldar, A., van der Giesen, C., Guinée, J., 2017. Does ex ante application enhance the usefulness of LCA? A case study on an emerging technology for metal recovery from e-waste. Int. J. Life Cycle Assess. https://doi.org/10.1007/s11367-017-1270-6.

Wender, B.A., Foley, R.W., Hottle, T.a., Sadowski, J., Prado-Lopez, V., Eisenberg, D.a., Laurin, L., Seager, T.P., 2014a. Anticipatory life-cycle assessment for responsible research and innovation. J. Responsible Innov. 1, 200–207. https://doi.org/10.1080/23299460.2014.920121.

Wender, B.A., Foley, R.W., Prado-Lopez, V., Ravikumar, D., Eisenberg, D. a, Hottle, T. a, Sadowski, J., Flanagan, W.P., Fisher, A., Laurin, L., Bates, M.E., Linkov, I., Seager, T.P., Fraser, M.P., Guston, D.H., 2014b. Illustrating anticipatory life cycle assessment for emerging photovoltaic technologies. Environ. Sci. Technol. 48, 10531–10538. https://doi.org/10.1021/es5016923.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.

Wynne, Brian, 1992. Uncertainty and environmental learning Reconceiving science and policy in the preventive paradigm. Global Environ. Change 2, 111–127. https://doi.org/10.1016/0959-3780(92)90017-2.

Zijp, M., Heijungs, R., van der Voet, E., van de Meent, D., Huijbregts, M., Hollander, A., Posthuma, L., 2015. An identification key for selecting methods for sustainability assessments. Sustainability 7, 2490–2512. https://doi.org/10.3390/su7032490.

Alfaro, J.F., Sharp, B.E., Miller, S.A., 2010. Developing LCA techniques for emerging systems: Game theory, agent modeling as prediction tools. In: Proceedings of the 2010 IEEE International Symposium on Sustainable Systems and Technology. https://doi.org/10.1109/ISSST.2010.5507728. ISSST 2010.