Terminology for future-oriented life cycle assessment: review and recommendations

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COMMENTARY AND DISCUSSION

Terminology for future-oriented life cycle assessment: review and recommendations

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Abstract

Purpose Some future-oriented life cycle assessment (LCA) terms, particularly prospective and ex-ante, show notable increase in use in publications over the last decade. However, scholars have pointed out that it is currently unclear exactly what these terms mean and how they are related. This paper aims to explain defining differences between future-oriented LCA terms and provide terminology recommendations.

Methods Existing definitions of future-oriented LCA terms were reviewed and analyzed. Workshops were held where defining differences of future-oriented LCA terms were discussed.

Results Temporal positionality and technology maturity appear to be two critical aspects of future-oriented LCA. Prospective and ex-ante LCA are similar, with the possible difference that ex-ante LCA always involves an increase in technology maturity in the future. Considering the notable similarities, it seems reasonable to converge terms to mitigate field fragmentation and avoid terminology confusion.

Conclusions To denote LCA studies with a future temporal positionality, we recommend using the term prospective LCA, defined as "LCA that models the product system at a future point in time relative to the time at which the study is conducted". Furthermore, since technology maturity is clearly a critical aspect for prospective LCA, we recommend prospective LCA studies to clearly define the maturity of the technologies modeled in the production system.

Keywords Prospective · Ex-ante · Retrospective · Anticipatory · Emerging technologies

1 Introduction

Life cycle assessment (LCA) comprises several subtypes stemming from specific aims and methodological choices. Guinée et al. (2018) referred to the set of all such subtypes as "the alphabet soup of LCA". Continuing that metaphor, we here consider a spoonful of that soup, namely that of future-oriented LCA types, i.e., LCA types that explicitly consider the future. Most LCA studies consider product systems as they are at the approximate time of the assessment, but an increasing number of studies are now considering products at a potential future time (Thonemann et al. 2020). Often, some technologies involved in the product systems of such products are currently immature but are assessed at a future time when they have become more mature. Several terms to denote such LCA studies have been proposed, such as prospective LCA, ex-ante LCA, and anticipatory LCA. As shown in Fig. 1, some of these terms (prospective and ex-ante) show notable increases in use in publications over the last decade.

However, several studies have pointed out that it is currently unclear exactly what these terms mean and how they are related. Buyle et al. (2019) write that "[f]or modes of LCA that do account explicitly for possible future states, the terminology is also far from homogeneous. […] So, subtle but not consistent differences can be found between prospective, anticipatory, and ex-ante LCAs." Similarly, Bergerson et al. (2020) write that "[t]he diversity of terms

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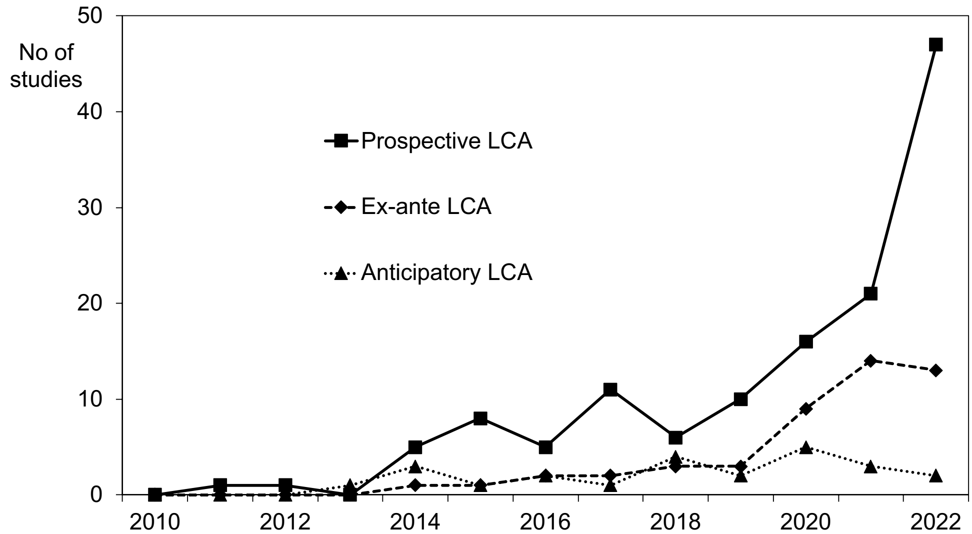

Fig. 1 Results from a Scopus search 2023–05-09 on three future-oriented LCA terms in title, abstract, and keywords, including different spellings. Example: "prospective LCA" OR "prospective life cycle assessment" OR "prospective life-cycle assessment"

mirrors the wide range of available methods and disparate language employed across the LCA community. In some cases, different terms refer to similar approaches, and in others, the same term is interpreted differently by different research groups." Cucurachi et al. (2018) also note that "the terminology used in the literature on the matter is not homogeneous". Adrianto and Pfister (2022) seem to consider prospective and ex-ante LCA effectively equivalent: "Prospective/ex-ante LCA attempt to resolve these issues by adapting early-stage processes in the environmental assessment of modelled future systems". This strategy of considering future-oriented LCA terms (in particular prospective and ex-ante) equivalent can be seen in other works as well (Moni et al. 2020; Pallas et al. 2020; Joyce and Björklund 2022; Sander-Titgemeyer et al. 2023). Another approach is to suggest they are "similar" but not necessarily equivalent (van der Giesen et al. 2020). Despite the claimed similarity between prospective and ex-ante, different studies often select one (van der Hulst et al. 2020) or the other (van der Giesen et al. 2020) term to use as the main term in their work. This disparity is also reflected in some proposed definitions of prospective, ex-ante, and anticipatory LCA (Table 1). For example, the definition of prospective LCA by Arvidsson et al. (2018) is similar to the definitions of ex-ante LCA (Cucurachi et al. 2018; van der Giesen et al. 2020), while other definitions

Table 1 Examples of previous definitions of prospective, ex-ante, and anticipatory LCA

Term	Definition	Source
Prospective LCA	"[LCA] studies […] looking *forward* at *future* environmental impact."	Sandén and Karlström (2007)
Prospective (or future-oriented) LCA	"[A] systematic assessment of *future* events and developments in society, technology, economy and policy that in the *long-term* could considerably influence the product system (and/or functional unit) and its conditions and hereby the environmentally relevant flows."	Olsen et al. (2018)
Prospective LCA	"[LCA] estimating *future* life-cycle environmental impacts using scenarios"	Guinée et al. (2018)
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 modeled at a *future*, **more-developed phase** (e.g., **large-scale** production)."	Arvidsson et al. (2018)
Ex-ante LCA	"[LCA] studies […] 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."	Cucurachi et al. (2018)
Ex-ante LCA	"[A]n environmental [LCA] 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."	van der Giesen et al. (2020)
Anticipatory LCA	"[A] *forward-looking*, non-predictive [LCA] tool that increases model uncertainty through inclusion of prospective modeling tools and multiple social perspectives."	Wender et al. (2014a)

Italic terms relate to temporal positionality, and **bold** terms relate to technology maturity of prospective LCA do not mention new or emerging technologies (Sandén and Karlström 2007; Guinée et al. 2018).

To mitigate this unclear situation, this paper aims to explain defining differences between future-oriented LCA terms and provide terminology recommendations. Below, the method is first described, followed by a review of definitions where differences are explained, and finally, recommendations are provided.

2 Method

Existing definitions of prospective, ex-ante, and anticipatory LCA were first reviewed and analyzed. Definitions of antonymic and related terms, such as retrospective and ex-post LCA, were also considered. We also considered frameworks describing the LCA terms or aspects of these without providing formal definitions, such as Bergerson et al. (2020), Buyle et al. (2019), and Thonemann et al. (2020). A series of workshops was held within the author group, where defining differences of future-oriented LCA terms were discussed. Important input to the work was also received at a digital seminar organized by the Prospective LCA Network (https://prospectivelcanetw.wixsite.com/prospectivelcanet) on the 17th of February 2023 and at a presentation at the SETAC Europe 33rd Annual Meeting in Dublin (Arvidsson et al. 2023).

As can be seen in Table 1, there are two central and recurring types of words in the definitions. First, several terms relate to the temporal positioning of the study, such as “future”, “forward”, “before”, and “long-term”. Second, several terms also relate to the maturity of the technology studied, such as “new”, “emerging”, “early phase”, “small scale”, and “large scale”. Therefore, we focus the discussion in this paper on temporal positionality (Sect. 3) and technology maturity (Sect. 4), which appear to be two critical aspects of future-oriented LCA. We also explain how previous definitions of future-oriented LCA terms (prospective, retrospective, ex-ante, ex-post, lab-scale, anticipatory and, to some extent, dynamic) can be related to these aspects.

3 Temporal positionality

Many definitions and descriptions of prospective, ex-ante, and anticipatory LCA include the temporal position of the analyst in relation to the product system assessed (Sandén and Karlström 2007; Wender et al. 2014b; Arvidsson et al. 2018; Cucurachi et al. 2018; Guinée et al. 2018; Olsen et al. 2018; Thonemann et al. 2020), which can be referred to as temporal positionality. When performing an LCA, the analyst is positioned at a certain time, i.e., in the ever-advancing ‘now’.[1] Historically, LCA studies have often modelled the product system at a recent past time (t_p) relative to the time at which the study is conducted (sometimes with a slight *de-facto* time lag due to a lack of updated inventory data). Such studies have been referred to as retrospective (Sandén and Karlström 2007). Although less common, it is also possible to model product systems at a more distant time in the past, not because of slightly outdated data but with the deliberate intention to assess historical impacts, which has been referred to as historical LCA (Bruhn et al. 2023). An example of a retrospective historical LCA case study is Kristensen et al. (2015), who assessed variations in climate impacts from dairy cattle production in Denmark from 1900 to 2010. Increasingly, though, LCA studies have begun to model product systems at a future point in time (t_f) relative to the time at which the study is conducted, which has been referred to as prospective LCA (Sandén and Karlström 2007; Guinée et al. 2018; Olsen et al. 2018). Such a future time is sometimes specified (e.g., 2050) and sometimes more vaguely described (e.g., ‘in the future’, ‘in a few decades’).

Before turning to technology maturity, a brief remark about temporal positionality and what has been labelled dynamic LCA can be made. In most LCA studies, the whole product system is time-integrated to a certain point in time.[2] Dynamic LCA is instead time-resolved, which means that parts of the system can be positioned at t_p (e.g., the extraction of raw materials for a building) while other parts might be positioned at a future time t_f (e.g., the demolition of the building) (Levasseur et al. 2010). Considering time-resolved product systems is particularly relevant for product systems that extend over longer times, such as forest products that need many decades to grow and may have product lifetimes that are even longer (Peñaloza et al. 2019). Emissions happening over such a resolved time period can then be time-stamped in the inventory analysis and combined with characterization factors for the corresponding time in the impact assessment (Levasseur et al. 2010). Regardless of whether an LCA takes on a retro- or prospective perspective, the significance of such time-stamping is evident, but is not further discussed in this work.

4 Technology maturity

Technology maturity is also mentioned in many definitions and descriptions of studies referring to prospective, ex-ante, and anticipatory LCA (Wender et al. 2014a; Villares et al.

[1] Observe that the reader of the study (perhaps a decision maker) may be at yet a different temporal position, experiencing a different ‘now’ than the analyst.

[2] This applies also to input–output LCA, in which all product flows and related elementary flows of an economy are assumed to occur within 1 year close to the contemporary time (1–5-year time lag) (Suh and Huppes 2005; Steubing et al. 2022).

2017; Arvidsson et al. 2018; Cucurachi et al. 2018; Bergerson et al. 2020; Thonemann et al. 2020). Indeed, maturity is an important aspect of technologies. All technologies first undergo a formative phase when they are immature, subject to early research and development, and may start to be used in niche applications. Then, they may enter a growth phase of rapid technology development and diffusion, after which they reach a saturated, mature state in terms of development and performance and finally decline as other technologies take over (Grübler 1998).[3]

LCA studies can consider product systems containing technologies that are either mature or immature (or possibly in some intermediate state between mature and immature). Some studies have proposed definitions and frameworks of prospective LCA in which immature technologies are placed in a future when they have become more mature, e.g., Arvidsson et al. (2018) and Thonemann et al. (2020). This has also been referred to as ex-ante LCA, where ex-ante means before the event, i.e., before technological maturity, commercialization, and large-scale production (Cucurachi et al. 2018; van der Giesen et al. 2020). This technology is then modelled with parameters reflecting its environmental performance in a future mature state. In practice, it is often only a certain currently immature focal technology in the foreground system that is upscaled to maturity in the future, while the rest (i.e., the vast majority) of the product system was already mature in the past and thus modelled as such also in the future. The antonym of ex-ante LCA, ex-post LCA, has been used to denote LCA of technologies that have already become mature at a past time (Cucurachi et al. 2018). Ex-post LCAs thus satisfy the definition of retrospective LCA by Sandén and Karlström (2007). An LCA can also consider immature technologies without modelling them as mature, which has been referred to as lab-scale LCA (Pallas et al. 2020). Comparing results from a lab-scale LCA to results for mature technologies is problematic, but lab-scale LCA can be useful for identifying hotspots at early stages of technology development and directing efforts of technology developers to those (Pallas et al. 2020).

Another future-oriented LCA term that considers technology maturity is anticipatory LCA, which, like ex-ante LCA models, currently immature technologies in the future (Wender et al. 2014a, b). In addition, anticipatory LCA puts a strong focus on stakeholder participation in methodological choices related to system boundaries, functional unit, impact category selection and weighting. This is done to increase the social engagement and credibility of the LCA and to avoid privileging certain stakeholders (Wender et al. 2014b), building on the anticipatory governance concept from the broader field of science and technology studies (Guston 2014).[4]

Technology maturity typically increases with time, which can be quantified by technological readiness levels (TRL) and manufacturing readiness levels (MRL) or considered in qualitative terms, e.g., 'pilot scale', 'large scale' and 'commercial scale' (Arvidsson et al. 2018; Buyle et al. 2019; Tsoy et al. 2020; van der Giesen et al. 2020; van der Hulst et al. 2020). As Bergerson et al. (2020) pointed out, technology maturity and the maturity of the technology's market (i.e., market diffusion) can be considered two separate aspects of maturity. However, they often evolve in parallel over time since market formation is an important factor in the development of a technology (Bergek et al. 2008).

Since both temporal positionality and technology maturity can be quantified, it is possible to consider them as dimensions in a two-dimensional space (Thonemann et al. 2020). Figure 2 illustrates how the terms prospective, retrospective, ex-ante, ex-post, and lab-scale LCA can be positioned in such a space based on previous definitions and descriptions.

5 Recommendations

Future-oriented LCA terms are gaining popularity (Fig. 1), but there is a high degree of similarity between future-oriented LCA terms (Table 1). As shown in the discussions in Sects. 3–4, prospective and ex-ante LCA are similar, with the possible difference that ex-ante LCA always involves an increase in technology maturity in the future, which some prospective LCA definitions do not entail. Considering the notable similarities, it seems reasonable to converge terms to mitigate field fragmentation and avoid the terminology confusion described by several scholars (Buyle et al. 2019; Bergerson et al. 2020). We suggest that temporal positionality is the most fundamental aspect of a future-oriented LCA study, which sets the scene for all further definitions of the scope. This includes technology maturity since a TRL cannot be meaningfully defined without considering the time at which the product system is positioned, as well as other modelling choices. To denote LCA studies with a future temporal positionality, we recommend using the term prospective LCA, defined as:

[3] This process is often referred to as the 'technological life cycle', but we avoid this term as to not confuse it with the 'product life cycle' considered in LCA.

[4] However, a recent description of anticipatory LCA emphasizes several additional aspects beyond temporal positionality and technology maturity, such as global stochastic uncertainty analysis, presenting preference ordering of options rather than impact quantification, and performing normalization and weighting (Seager 2023).

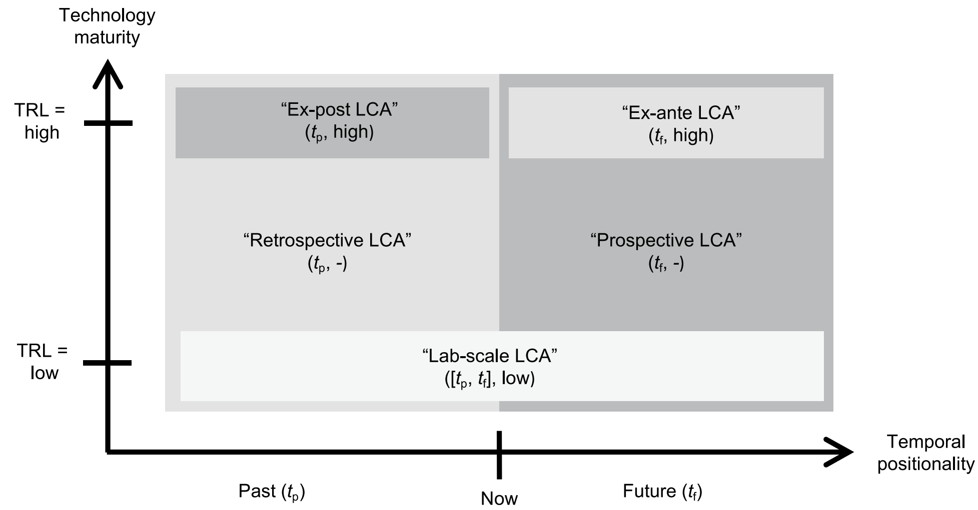

Fig. 2 Schematic illustration of how five LCA terms have previously been defined and described along the two dimensions, temporal positionality and technology maturity. TRL = technology readiness level

"*LCA that models the product system at a future point in time relative to the time at which the study is conducted*",

in accordance with some previous definitions (Sandén and Karlström 2007; Guinée et al. 2018). The term retrospective LCA is recommended to denote:

"LCA that models the product system at a recent or distant past point in time relative to the time at which the study is conducted",

in line with Sandén and Karlström (2007). In both prospective and retrospective LCAs, the temporal positioning should preferably be specified in more detail, e.g., to a specific year (e.g., 2050) or time span (e.g., 2040–2050).

This recommendation is similar to the proposal by Guinée et al. (2018) to refer to all LCA with scenarios of potential futures as "explorative LCA" (XLCA). However, the term prospective LCA is preferred here since prospective literally means "forward-looking", is the currently most used term for future-oriented LCA (Fig. 1), and has been used since at least 2005 (Sandén et al. 2005; Spielmann et al. 2005), long before the terms ex-ante and anticipatory were used in LCA.[5]

Technology maturity is clearly a critical aspect for prospective LCA, as is evident from Sect. 4 and several definitions in Table 1. We therefore recommend prospective LCA studies to clearly define the maturity of the technologies modeled in the production system, as also recommended by, e.g., van der Hulst et al. (2020). The specification could be in terms of TRLs or MRLs, or more qualitatively. There is an analytical benefit to keeping temporal positionality and technology maturity as two separate aspects of the scope: while many prospective LCA studies have focused on currently immature technologies (Arvidsson et al. 2018), others might want to consider only already-mature technologies at a future point in time, e.g., investigate the effect of changes in background systems without differences in the maturity of the foreground system.[6]

In addition to the temporal positionality and technology maturity, several other critical aspects should also be reported in the scope when performing prospective LCA. A non-exhaustive list of such aspects can include:

- Technology selection: Which technologies are modelled at the future time? Here, thinking beyond near-future technologies and considering more long-term technologies with high potential is recommendable (Arvidsson et al. 2023).
- Technology upscaling: Which approaches are applied for upscaling in prospective LCA of immature technologies? Here, guidance can be found in the decision tree by Tsoy et al. (2020).
- Scenario development: How are future scenarios constructed? Here, guidance can be found in, e.g., the SMPL approach by Langkau et al. (2023).
- Background data: To what extent does the background data match the temporal positioning of the foreground system? Here, prospective LCA databases such as Premise can be used to alter background system data according to specified scenarios (Sacchi et al. 2022).

[5] In addition, Guinée et al. (2018) excluded attributional LCAs modeling future situations from the XLCA term, although this is likely the currently most common future-oriented LCA study. The term prospective LCA as defined here includes such studies.

[6] An example of such a study is Voglhuber-Slavinsky et al. (2022), who deliberately considered only future changes in the background system of an already mature product (apple juice).

- Life cycle impact assessment: To what extent is the impact assessment tailored to assessing the impacts of product systems in the future? Here, work has so far been done for a few impact categories, e.g., water scarcity (Baustert et al. 2022) and ozone depletion (van den Oever et al. 2023).
- Stakeholder interactions: How and to what extent are stakeholders involved in the prospective LCA? Here, guidance can be sought in anticipatory LCA descriptions (Wender et al. 2014a, b).

To summarize, we recommend that LCAs modelling the product system at a future point in time (relative to the time at which the study is conducted) are referred to as *prospective*, while additional critical aspects of the study should be clearly reported in the scope, including technology maturity. Hopefully, this can lead to consistent communication of future-oriented LCA studies, i.e., prospective LCA.

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Declarations

Conflict of interest The authors declare no competing interests.

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