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CRITICAL REVIEW

Future scenarios and life cycle assessment: systematic review and recommendations

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Abstract

Purpose Future scenarios and life cycle assessment (LCA) are powerful tools that can provide early sustainability assessments of novel products, technologies and systems. The combination of the two methods involves practical and conceptual challenges, but formal guidance and consensus on a rigorous approach are currently missing. This study provides a comprehensive overview of how different topic areas use future scenarios and LCA in order to identify useful methods and approaches, and to provide overall recommendations.
Methods This study carried out a systematic literature review that involved searching for peer-reviewed articles on Web of Science, Scopus and Science Direct, utilising a rigorous set of keywords for future scenarios and for LCA. We identified 514 suitable peer-reviewed articles that were systematically analysed according to pre-defined sets of characteristics for the combined modelling of future scenarios and LCA.
Results and discussion The numbers of studies combining future scenarios and LCA increase every year and in all of the 15 topic areas identified. This combination is highly complex, due to different sequences in the modelling between future scenarios and LCA, the use of additional models and topic area-specific challenges. We identify and classify studies according to three archetypal modelling sequences: input, output and hybrid. More than 100 studies provide methods and approaches for combining future scenarios and LCA, but existing recommendations are specific to topic areas and for modelling sequences, and consensus is still missing. The efficacy of many studies is hampered by lack of quality. Only half of the articles complied with the LCA ISO standards, and only one quarter demonstrated consistent knowledge of future scenario theory. We observed inconsistent use of terminology and a considerable lack of clarity in the descriptions of methodological choices, assumptions and time frames.
Conclusions and Recommendations The combined use of future scenarios and LCA requires formal guidance, in order to increase clarity and communicability. Guidance should provide unambiguous definitions, identify minimum quality requirements and produce mandatory descriptions of modelling choices. The goal and scope of future scenarios and LCA should be in accordance, and quality should be ensured both for the future scenarios and the LCA. In particular, future scenarios should always be developed contextually, to ensure effective assessment of the problem at hand. Guidance should also allow for maintaining current modelling complexity and topic area differences. We provide recommendations from the reference literature on terminology, future scenario development and the combined use of future scenarios and LCA that may already constitute preliminary guidance in the field. Information collected and recommendations provided will assist in a more balanced development of the combined use of future scenarios and LCA in view of the urgent challenges of sustainable development.

Keywords Life cycle assessment · LCA · Future scenarios · Foresight · Prospective · Ex-ante · Archetypes

1 Introduction

Sustainable development involves challenges that are urgent and global, such as climate change, clean energy provision and responsible consumption and production. The urgency of these challenges requires that governments,

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companies and experts across all sectors assess the sustainability of their policies, products and solutions as early as the planning stage (Griggs et al. 2013; United Nations 2015; Sala et al. 2020). Sustainability assessment models offer a 'rehearsing space' for addressing the numerous aspects connected to sustainable development, responsible innovation and development strategies (e.g. environmental, economic, social) (Wender et al. 2014a, b; Matthews et al. 2019). Life cycle assessment (LCA; ISO 2006a, 2006b) addresses environmental aspects of sustainable development and can allow for a systematic early assessment of the environmental sustainability of solutions at different scales. For example, a small-scale LCA can provide an early quantification of the potential environmental impacts of emerging products or technologies (Thonemann and Schulte 2019). On the medium scale, an LCA can support the scaling-up and integration of novel products or technologies in existing and future systems (Vega et al. 2019). Some authors use LCA also on a large-scale system level, where LCA is used to evaluate national and regional solutions, such as energy provision, transportation, as well as water and waste management (Guven et al. 2018; Glensor and María Rosa Muñoz 2019; Martin-Gamboa et al. 2019). On all scales, the time horizon of sustainability assessment studies is in the order of decades into the future. For example, an assessment of a new technology may include development, implementation, operation and end-of-life; effects of policies, such as Sustainable Development Goals, and may aim 15 to 30 years into the future (United Nations 2015). However, the LCA's ISO standard does not offer explicit guidance on modelling future and long-term solutions (Hospido et al. 2010; Matthews et al. 2019), and many of such studies addressing future solutions are often not well conceived and fall short in describing long-term structural and technological developments.

Modelling products and systems that do not yet exist in LCA involves practical challenges. For example, assessing emerging products and technologies and their scale-up requires information on future functionality and operative data that may not be available yet (Villares et al. 2017). Likewise, assessing the scale-up and integration of technologies and solutions requires data and information on potential future large-scale developments (Mendoza Beltran et al. 2018), as well as decisions on accounting for potential future environmental impacts (Hellweg et al. 2003). Such practical challenges and uncertainties can be very different according to the topic area of the LCA. For example, assessments focusing of emerging technologies may depend mostly on data uncertainties in the foreground system (as defined by European Commission 2010), while the outcome of the assessment of novel waste management solutions depends just as much on the potential interactions and developments of the background system in which the new technologies will operate.

Uncertainty in LCA is assessed through different methods; for example, sensitivity and uncertainty analyses can quantify data uncertainties, and 'scenario analysis' can assess epistemic uncertainties from potential modelling choices and future developments (e.g. Groen et al. 2014). Furthermore, they can also help quantify 'known unknowns' with statistical methods. However, data—and especially future developments related to future products and systems—are 'unknown unknowns' and may require a more structured framework on top of quantifying sensitivity and uncertainty with statistical methods. At an early development stage, not only uncertainty but also data especially may not be available, and potential future operational background scenarios may be numerous and highly uncertain (Michiels and Geeraerd 2020). In this situation, scenario analysis can systematically address epistemic uncertainty. Rehearsing plausible options and quantifying potential environmental impacts may be more meaningful and accurate than aiming at higher-precision results with early and uncertain data.

Future scenario analysis (also known as foresight or future studies) is an established management-engineering method for exploring future situations in corporate strategy, political transition and natural resource management (Bohensky et al. 2011; see conceptual framework for future scenarios in section 2.1). Today, future scenarios are experiencing renewed popularity in strategic decision-making and change management in the context of global environmental challenges, and many authors suggest combining future studies and sustainability assessments to address sustainable development challenges (Hojer et al. 2008; Arushanyan et al. 2017b; Fauré et al. 2017). As such, future scenarios can offer the structured framework for addressing the epistemic uncertainty of LCAs of future products and systems (Mendoza Beltran et al. 2018). For example, Fukushima and Hirao (2002) and Spielmann et al. (2005) are early and prominent examples of the application of future scenarios in an LCA to address numerous alternatives, uncertain conditions and unpredictable systemic future developments.

Despite the implicit future-oriented feature of an LCA (Arvidsson et al. 2018; Buyle et al. 2019b), a combination of the future scenario and LCA methodologies presents conceptual and methodological challenges that have been addressed by several LCA experts over the years. Primarily, modelling future products and systems in LCA involves decisions on the life cycle inventory (LCI) modelling approach that affect the type of data used for the assessment. Data differ if the study aims to account for potential future impacts (attributional approach) or to assess potential future consequences induced by a future product or system (consequential approach; ISO 2006a). SETAC's 'Working Group on Scenario Development in LCA' discussed the sometimes tacit future-oriented purpose of LCA and introduced the concept of 'prospective LCA', which was defined consequential and aimed at describing the consequences of changes (Weidema et al. 2004). SETAC's scenarios differed according to scale and time horizon: 'what-if' (short- or medium-term horizon, small-scale systems) and 'cornerstone' (long-term horizon, large-scale systems) (Pesonen et al. 2000). However, the later LCA's ISO standard neither assigned specific LCI data modelling approaches to future scenarios nor addressed time horizon issues in LCA. The ILCD Handbook (European Commission 2010) contradicted previous guidance on future scenarios (Ekvall et al. 2016), advising the use of attributional modelling for micro-level decision support with short- (1–5 years) and mid-term (5–10 years) time frames, and consequential for macro-level decision support with mid- and long-term frames (more than 10 years), rather than basing the modelling choice on changes or consequences. The data modelling approach for future-oriented LCAs still divides experts, and formal guidance is currently missing (De Camillis et al. 2013; Thonemann et al. 2020).

Consequently, LCA practice has had to develop outside the standards, thereby giving rise, in different topic areas, to multiple approaches in order to address future-oriented issues (Cucurachi et al. 2018; Moretti et al. 2020). Such examples are the use of economic input-output tables, hybrid input-output and process-based LCAs, the integration of LCA with regional and global energy models and the use of dynamic LCA (Dandres et al. 2012; Wender et al. 2014a; Pauliuk et al. 2017). A series of authors have used and updated SETAC's definition of prospective LCA (Hospido et al. 2010; Arvidsson et al. 2018), while others have created new definitions and terminology for future-oriented LCAs, leading to a proliferation of definitions, concepts and methods (Buyle et al. 2019b). For example, Wender et al. (2014a, b) introduced 'anticipatory LCA', while in the field of emerging technologies, several authors refer to 'ex-ante LCA' (Villares et al. 2017; Cucurachi et al. 2018). Therefore, the lack of formal guidance may have led to the formulation of approaches in different topic areas that already combine the future scenario and LCA methodologies and which can help solve the practical and methodological challenges of future-oriented LCAs. A few authors have carried out literature reviews with the purpose of finding such existing approaches and providing recommendations, but only for emerging technologies (Cucurachi et al. 2018; Arvidsson et al. 2018; Buyle et al. 2019b; Moni et al. 2020; Thonemann et al. 2020; Tsoy et al. 2020; van der Giesen et al. 2020). Others have addressed temporal issues in LCA separately, but with little focus on future scenarios (Beloin-Saint-Pierre et al. 2020; Lueddeckens et al. 2020).

The goal of this study is to provide a systematic review of existing peer-reviewed articles combining the future scenario and LCA methodologies, across all topic areas. The aim of the literature review is to establish a clear overview of the status of the combination of the two methodologies, in light of the urgent sustainability assessments required by global sustainable development challenges. This literature review provides the general characteristics of the included studies (e.g. year, country and topic area; section 3.1) and carefully analyses the individual methodological and practical choices of the LCAs (section 3.5) and future scenarios (section 4.2). We provide an assessment of the methodological and practical modelling aspects affected by the long-term perspective of the studies and combined use of future scenarios and LCA (section 5). On this basis, we identify and evaluate potential archetypal modelling approaches (section 7.), specific topic area modelling preferences (section 3.5) and existing methods and approaches (section 3.6). Finally, we discuss shortcomings and potential research gaps (section 4), in order to provide recommendations for the future combined use of LCA and future scenarios in different topic areas and on different scales (section 5).

2 Methods

This section provides an overview of (i) future scenario concepts and methods and (ii) criteria adopted for the systematic literature review. A clear understanding of future scenario theory, methodology and terminology is fundamental for identifying meaningful review criteria (Arvidsson et al. 2018; Buyle et al. 2019b).

2.1 Conceptual framework: future scenarios

Future scenarios are not forecasts or predictions of the future (Meristö 1989; Harries 2003). The concept is based on the belief that it is not possible to describe the future as a single, precise image; rather, several plausible alternative visions are needed to describe the range of possible futures (IPCC 2000; Siddiqui and Marnay 2006; Wiek et al. 2006). Scenarios are a 'rehearsing space' intended to highlight central elements of possible futures and draw attention to important key aspects that will affect future developments (Schnaars 1987; Wiek et al. 2006; Kosow and Gaβner 2008).

Within foresight practice, a future scenario is defined as an internally consistent description of a future situation, including the path of development leading to that situation (Kosow and Gaßner 2008). Understanding important aspects and causal connections in the studied system, and describing development from the present to the future, is considered an integral and fundamental part of future scenarios (Meristö 1989; Bood and Postma 1997; Rasmussen 2011). For this reason, they are useful especially for decision support and policymaking (Godet 2000). Common examples are found applied within global climate and energy reports, or shared socioeconomic pathways (e.g. O'Neill et al. 2014; International Energy Agency 2016).

The formulation of a future scenario can follow numerous foresight approaches (Jarke 1999; Godet 2000). However, the scenario-building process unfolds in a similar way across the different approaches and is typically characterised by five iterative phases. Figure 1 provides an overview of the generic approach (left column area) and the terminology for each future scenario building phase (right area). This terminology is subdivided according to the length of the time horizon of the future scenario (from left to right).

First, the goal and scope definition of the future scenarios (Phase 1, Fig. 1) is fundamental for the identification of the future scenario type. Börjeson et al. (2006) introduced well-known definitions of scenario types: (i) predictive (probable future, what will happen?), (ii) explorative (possible future, what can happen?) and (iii) normative (preferable future, how can a specific target be reached?). Predictive and explorative scenarios look forward into the future (arrow in Fig. 1 from the present to the future), while normative scenarios start from a desirable point in the future and look into potential pathways from the present on how the target can be reached (Robinson 2003). The scenario funnel in Fig. 1 represents the range of possible futures identified by the scenario-building process. Phase 2 involves identifying important case-specific aspects in the present situation and assigning future values (or descriptions of the future state) to these important features. The important aspects can be identified both with quantitative (e.g. sensitivity analysis) or qualitative techniques (e.g. workshops, participatory methods) (Harries 2003). Phase 3, future scenario development, involves combining the identified important aspects values into consistent sets (scenarios), sometimes with additional techniques (e.g. models). Phase 4 identifies a number of consistent scenarios from those identified in Phase 3. Many authors suggest limiting the number of scenarios, ideally to three or four (Schnaars 1987; Meristö 1989; Wollenberg et al. 2000). Finally, scenario transfer involves applying the scenarios to the specific case (Phase 5).

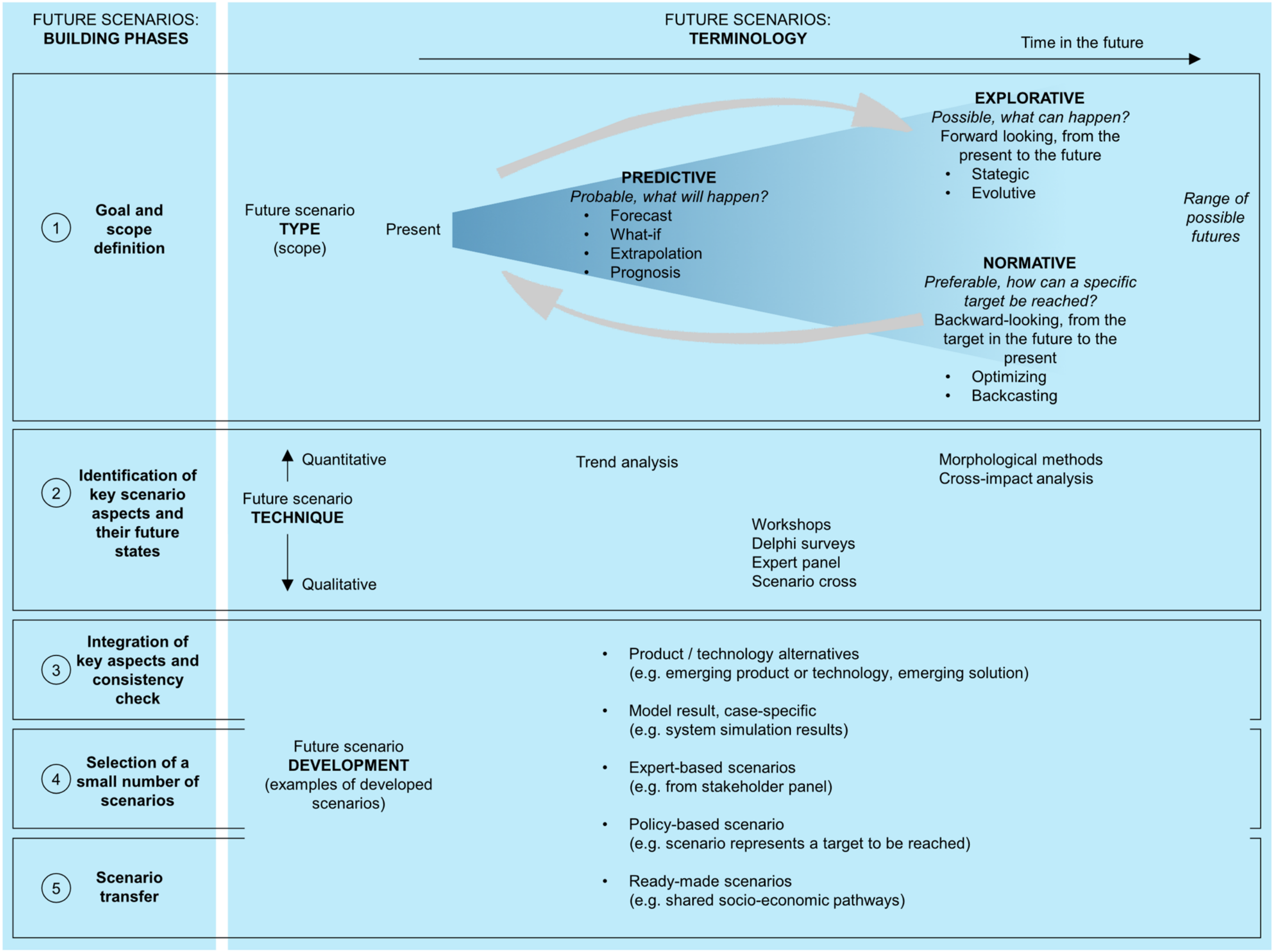

Fig. 1 Overview of future scenario (foresight) building phases and respective terminology. The terminology is subdivided according to scenario-building phases and time horizon (based on Ringland and Schwartz 1998; Godet 2000; Börjeson et al. 2006; Kosow and Gaßner 2008 and Rasmussen 2011

2.2 Literature review criteria

The literature review adopted a systematic approach involving a clear review scope (2.2.1), a structured method for the selection of studies (2.2.2) and a definition of unambiguous evaluation criteria (2.2.3). Full details on the review approach are available in the Supplementary Material (SM).

2.2.1 Review scope

The review focused on peer-reviewed journal articles including both future scenarios and LCA. Focus was placed on peer-reviewed literature, to ensure as best as possible the quality of the adopted methods and results. Only studies explicitly focusing on future scenarios and stating a future-oriented or prospective nature were included e.g. 'future time horizon', a 'future technology', a 'prospective study'. Studies comparing scenarios (e.g. technological alternatives) while only implicitly assuming that they may occur in the future were not included. Life cycle costing (LCC) studies addressing only economic aspects were excluded from the review, while studies assessing costs in parallel with environmental aspects were included (see Martinez-Sanchez et al. 2015). The review included LCI modelling as well as full LCIAs covering one or multiple impact categories.

2.2.2 Selection of studies

The systematic literature review approach involved searching for a specific set of keywords in literature databases. The set of keywords included one keyword for future scenario (e.g. 'future scenario', 'foresight', 'prospective') used jointly with one keyword for LCA (e.g. 'LCA', 'life cycle assessment'); full details on the database query language are available in the SM. Only peer-reviewed articles in English were included. The literature search resulted in 2643 articles from three databases: Web of Science (1068 articles), Scopus (989) and Science Direct (586), all retrieved in January 2020.

After grouping all of the retrieved articles, a large number of double-counted and off-topic articles were identified e.g. due to different approaches for archiving individual studies in the three databases and articles using the acronym 'LCA' for purposes other than life cycle assessment (e.g. in other scientific fields). Double-counted and off-topic articles were discarded, leaving 1208 unique articles for the next reviewing step. These articles were screened for compliance with the scope of the literature review, resulting in 514 articles to be included in the systematic review process. The large number of non-compliant articles reflects that many included the 'LCA' and 'future scenario' keywords without actually including content related to future scenarios and the LCA methodology. For example, often, the term 'future scenarios' was used to highlight the urgency of a study, to provide further study perspectives, expected developments or policy targets. Some articles referred to technological alternatives as 'future scenarios' in the abstract, while not reflecting this in the methods. 'LCA' studies often included the life cycle of resources, metals or land availability, accounting for their lifetime but not for their emission inventory. At the end of the review process, we ran the literature review search again in order to retrieve articles published during the review process and selected and included in the review 30 articles from 2020 according to their methodological relevance for future scenarios and LCA when relevant to the discussion on the outcomes of the review.

2.2.3 Review criteria

We reviewed the 514 articles according to the following predefined criteria:

- General characteristics (e.g. publication year, journal, topic area, country, location of search keywords in article and study type);
- LCA characteristics and proxies for quality (e.g. mention to ISO standards/ILCD Handbook, documentation of modelling approach and choices, LCI/LCA modelling characteristics and number of scenarios);
- Future scenario characteristics as summarised in Fig. 1 (e.g. documentation of future scenario methodology, modelling techniques, scope and time horizons);
- Approach used for the combined use of the LCA and future scenarios (e.g. modelling sequence, approach for identification key aspects of future scenarios, parts of the LCA model affected and total number of scenarios).

For each criteria group (e.g. general characteristics, LCA characteristics), we identified a predefined set of review criteria, which were also used for proxy-indicators for the quality of the studies, as well as LCA and future scenario knowledge (summarised in Table 1) and set out predefined possible answers, which were used to compile the literature review results (see SM).

3 Results

The following sections report the main findings from the review. The SM provides the full quantitative results for all literature review criteria and every one of the 514 articles.

Table 1 List of criteria used for the literature review, subdivided into criteria groups, and an indication of outcome types. The complete list of possible outcomes for each criterion is available in the SM

Criteria groups	Review evaluation criteria
General characteristics	• Publication year • Journal name • Topic area (macro-topic and sub-topic according to journal classification) • Country (country affiliation of first author) • Location of keywords (title, abstract, keywords) • Article type (method or framework-oriented article, case study)
LCA characteristics	• ISO 14040-14044 standard mentioned • Description of goal, scope, functional unit • Impacts assessed (e.g. climate change, acidification) • Data quality included • LCI/LCIA • Modelling approach (process-based, input-output, hybrid) • LCI modelling approach (e.g. attributional, consequential) • Costs included • Infrastructure/capacity included • Number of LCA scenarios (as defined by Pesonen et al. 2000)
Future scenarios characteristics (see Fig. 1)	• Reference foresight theory and keywords (section 2.1) • Future type (as defined by Börjeson et al. 2006) • Scenario-building technique (e.g. quantitative, qualitative) • Scope of scenario (e.g. product or technology alternative, policy) • Representation of the future (e.g. discrete scenarios) • Presence of baseline scenario • Time horizon of the study • Presence of multiple time horizons • Number of future scenarios
Characteristics of the combined use of LCA and future scenarios	• Modelling sequence (e.g. future scenarios before LCA) • Use of additional models and type (e.g. simulation tools) • Method of identification of important aspects (e.g. quantitative) • Location of important aspects (e.g. in future scenario, in LCA) • Time modelling (static, dynamic e.g. Fukushima and Hirao 2002) • Part of LCA model affected (e.g. functional unit, foreground LCI data, background LCI data) • Presence of sensitivity and/or uncertainty analysis • Additional scenarios used for sensitivity analysis • Total number of scenarios (including LCA, future and sensitivity analysis scenarios) • Presence of proposed approaches for the use of future scenarios and LCA

3.1 General characteristics of the studies

Figure 2 provides the year of publication of the 514 articles included in the review, subdivided according to research topic areas. The number of articles published over time, and in particular in the most recent years, indicates a current growing interest in combining future scenarios and LCAs, with around half of the articles published between 2017 and 2019.

Topic areas. Interest in the combined use of future scenarios and LCA is not limited to one specific topic area. The articles belonged to 126 journals with different topic areas and targeted a wide range of research fields and applications. Most of the articles combining LCA and future scenarios typically involved environmental aspects of decision-making in the fields of management and environmental engineering or environmental sciences (196 articles). In these topics, frequent journal titles were the *Journal of Cleaner Production* (77), the *International Journal of Life Cycle Assessment* (49) and the *Journal of Industrial Ecology* (28). Since a large number of articles focused on renewable energy transition (166, see Fig. 2), *Applied Energy* was also one of the most frequent journal titles (34 articles). In recent years, we observed a marked increase in articles focusing on civil engineering (sustainability of management of materials in construction and cities, 37 articles), manufacture engineering (sustainability aspects related to new products and technologies, 35) and sustainability assessment of policies (42).

Geographical location. Interest in the use of future scenarios and LCA does not belong to a specific country or 'research school'. The articles originated from 46 countries, mostly from Europe (315 articles). Some countries consistently contributed with publications over time, such as the USA (58), the United Kingdom (50), Switzerland (37) and

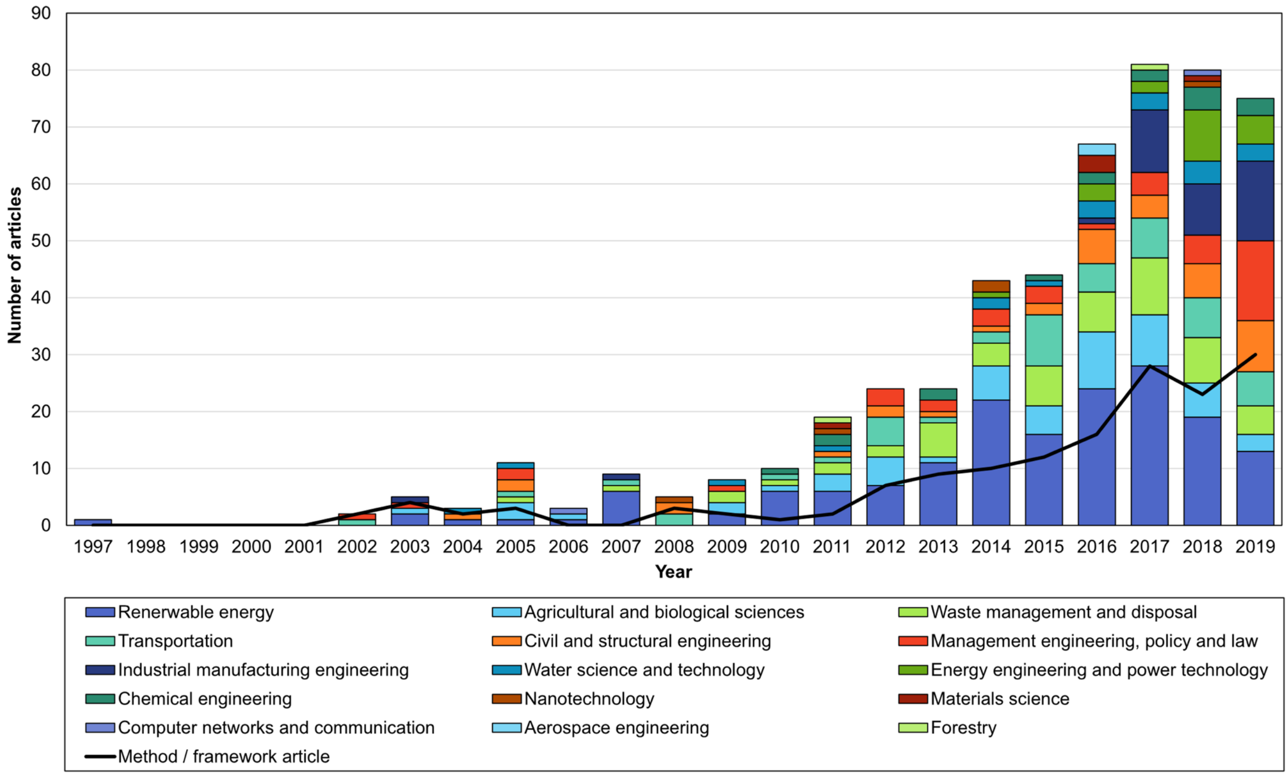

Fig. 2 Year of publication of the 514 articles included in the review subdivided according to pre-defined topic areas. The black line indicates the number of articles proposing a method or an approach for the combined use of future scenarios and LCA over the years covered by the literature review. Details in the SM

Sweden (34). Other countries provided most of their contributions in most recent years, as in the case of China (40), Spain (25), Italy (18), the Netherlands (15) and Brazil (10). Developing countries increased their contribution by 55 articles in the last 3 years.

Novel approaches. Most of the articles applied future scenarios and LCA on a case study (359 articles). In numerous cases, and due to the lack of formal guidance, the authors of the studies formulated case-specific approaches in order to combine future scenarios and LCA. We retrieved 155 articles providing novel approaches, 139 articles used a new approach on a case study, while 16 articles focused on providing a method or an approach with no case study (see Table S5 in the SM for a complete list). Figure 2 (black line) shows that articles providing novel methods or approaches for future scenarios and LCA consistently increased in the last period, with around 30 publications per year. We discuss selected prominent topic area approaches and recommendations in section 3.5, including selected articles from 2020. We examined the 498 articles containing a case study for their modelling choices for future scenarios and LCA (sections 3.5–4.6).

3.2 LCA characteristics

The characteristics of the LCA applied in the reviewed literature are presented with respect to the type of LCA, quality of the LCA and the impact assessment.

Type of LCA. While traditionally the focus of LCA experts is on whether future LCAs should be attributional or consequential, our analysis of the retrieved articles showed that in practice very few studies explicitly state the modelling choice adopted for LCI modelling. This was also highlighted in a recent review by Moretti et al. (2020). The articles rarely disclosed or discussed the LCI modelling approach, which we deducted based on the overall description of modelling choices (please refer to SM, Section 2.2). About 60% of articles applied an attributional modelling approach, while 35% applied consequential modelling. The remaining articles utilised LCA metadata from other studies. Ekvall et al. (2005), Mattila et al. (2012), Sandin et al. (2013) and Jones et al. (2017) represent relevant discussions for LCI data modelling, whilst Buyle et al. (2019a, b) investigated the use of attributional and consequential modelling in ex-ante LCA. A decline in the use of the consequential approach was also observed, from 30% in 2015 to 20% in 2019, as already evidenced by Frischknecht et al. (2017). Regarding the modelling approach, 88% of the studies were process-based, 2% input-output and 10% were process-based and input-output hybrids. The individual articles assessed on average two to five LCA scenarios, representing product, technology or systems alternatives.

Quality of LCA. In general, we observed that the quality of a large share of the LCA studies did not comply with the ISO standard, irrespective of the topic area. Only half of the identified articles referred to the LCA ISO standards (52%), while only 3% referred to the ILCD Handbook (European Commission 2010). References to ISO increased in recent years. Clear descriptions of the goal, scope and functional unit occurred only in 60% of the studies, whilst 76% that referred to the ISO standard also described the goal, scope and functional unit. Only 49% of the articles addressed the quality of the data with respect to the goal and scope, mostly as statements regarding data representativeness. Studies such as Gallagher et al. (2015), Mann et al. (2014), Niero et al. (2015a, b) and Vieira and Horvath (2008) specifically addressed data quality, for example by assigning uncertainty to the data. While attention to data quality increased during the period, only half of the studies identified the most sensitive aspects in the model with sensitivity or uncertainty analyses (47%).

Impact assessment. The majority of articles (99%) used midpoint LCIA indicators. Amongst the ILCD recommended impact categories (please see SM for criteria), 87% of the articles addressed climate change, while about 45% included resource depletion (water, energy, resources) and 37% acidification. Articles including references to ISO standards and transparent descriptions of the goal, scope and functional unit generally assessed multiple impact categories. Overall coverage of impact categories appeared to increase throughout the period. Parallel life cycle costings (LCCs), supplementing the traditional environmental LCA (environmental LCC), were included in 34% of the articles. Capacity and infrastructure-related impacts were included in more than half of the articles (56%), indicating that a considerable number of studies evaluated potential changes in infrastructure and its capacity during the assessment of the future scenarios (e.g. Pehnt 2003a, b).

The numerous examples of poorly defined goals, scopes and functional units, as well as non-transparent LCI data modelling approaches, suggest a potential low quality to the LCA part of the reviewed articles. In turn, this may limit the interpretation and application of the results with respect to future scenarios, as also indicated by De Camillis et al. (2013). See the SM for examples of good LCA practice from the articles reviewed.

3.3 Future scenarios characteristics

The characteristics of the future scenario approach used in the reviewed literature are presented in terms of foresight methodology, future scenario types and time horizons, as well as other identified key aspects.

Use of the foresight methodology. Despite using foresight keywords, most of the articles did not follow future scenario principles or the SETAC guidelines for the formulation of scenarios. Reference to acknowledged foresight literature or the use of the future scenario terminology reported in section 2.1 herein occurred in only 27% of the articles. The use of future scenario keywords without applying its principles undermines the communicability of LCA results to foresight experts, and little attention to the future scenario formulation may limit the representativity of the assessment and its learning outcomes. When used, future scenario-building techniques strengthened scenario formulation and understanding of the system being assessed e.g. for Giurco et al. (2011), Bocken et al. (2012) and Meylan et al. (2014). The studies highlight, for example, how back-casting scenarios can be combined with industrial ecology principles applied to energy systems, how foresight and a streamlined LCA can be combined for the assessment of future technologies and how the participatory approach can be used to design effective waste management solutions. Fukushima and Hirao (2002), Spielmann et al. (2005) and Mendoza Beltran et al. (2018) are examples of scenario development consistent with the foresight theory. The studies thoroughly describe the scenario development process, which complies with the procedure described in section 2.1. The studies also provide the basis for a solid scenario development framework that can be successfully applied outside their specific application areas.

Future scenario types and time horizon. The studies only occasionally explicitly addressed the type of future scenario used, which we often deduced from the description and the formulation of the scenarios. Figure 3 summarises the scenario types, time horizon and formulation. Most of the scenarios were explorative (51%) and predictive (42%). Normative scenarios (7%) occurred in articles referencing an acknowledged future scenario theory, mostly within policy assessment and waste management. The most frequent time horizon was between 30 and 50 years into the future (210 articles), therefore aiming at much farther time horizons than those addressed by ILCD. Mid- and long-time horizons characterised explorative and normative scenarios, and 39% of the articles included multiple time horizons e.g. for an intermediate period shorter than the overall temporal scope of the study. A scenario for the baseline year was included in 72% of the studies. On the other hand, an equally large share of articles (181) did not state the time horizon of the study. This happened more often in predictive scenarios, where the future scenarios represented mostly product or technology alternatives, for example, in studies on emerging technologies. Fauré et al. (2017) also highlighted the missed reporting of time horizons in future sustainability assessment studies, whilst Beloin-Saint-Pierre et al. (2020) discussed how the lack of a precise temporal definition partly derives from the lack of consensus on how to define temporal scopes.

Identification of key aspects. For the majority of the studies, the key aspects characterising the scenarios were quantitative (398) e.g. the scenarios involved a definite set of values describing a technology, product or solution in a specific time in the future. We observed an increase in quantitative scenario formulation in recent years e.g. for product or technology alternatives at the research and development stage (31% of the studies). Otherwise, the scenarios were based primarily on expert knowledge (32%) or using additional modelling tools (18%), as in the case of explorative scenarios. Another 12% of the studies used already available scenarios (e.g. from International Energy Agency or IPCC reports), and 7% were based on policies or political targets (mostly normative scenario types). Half of the studies formulated three to five distinctive future scenarios, represented as discrete scenarios in the majority of articles (97%), while only a few represented the future as uncertainty distributions.

3.4 Future scenarios and LCA in practice

The following paragraphs describe modelling features observed when future scenarios are modelled with LCA (5) and provide archetypal modelling approaches based on observed modelling sequences between future scenarios and LCA (7.).

3.4.1 General modelling features

General modelling features are presented in terms of the modelling sequence, additional models employed, identification of key aspects, transparency and time representation.

Modelling sequence. Studies where future scenarios are first developed and then subsequently evaluated with an LCA account for only 39% of the total, indicating that the actual modelling sequence in current studies presents higher complexity in terms of not only the sequence between

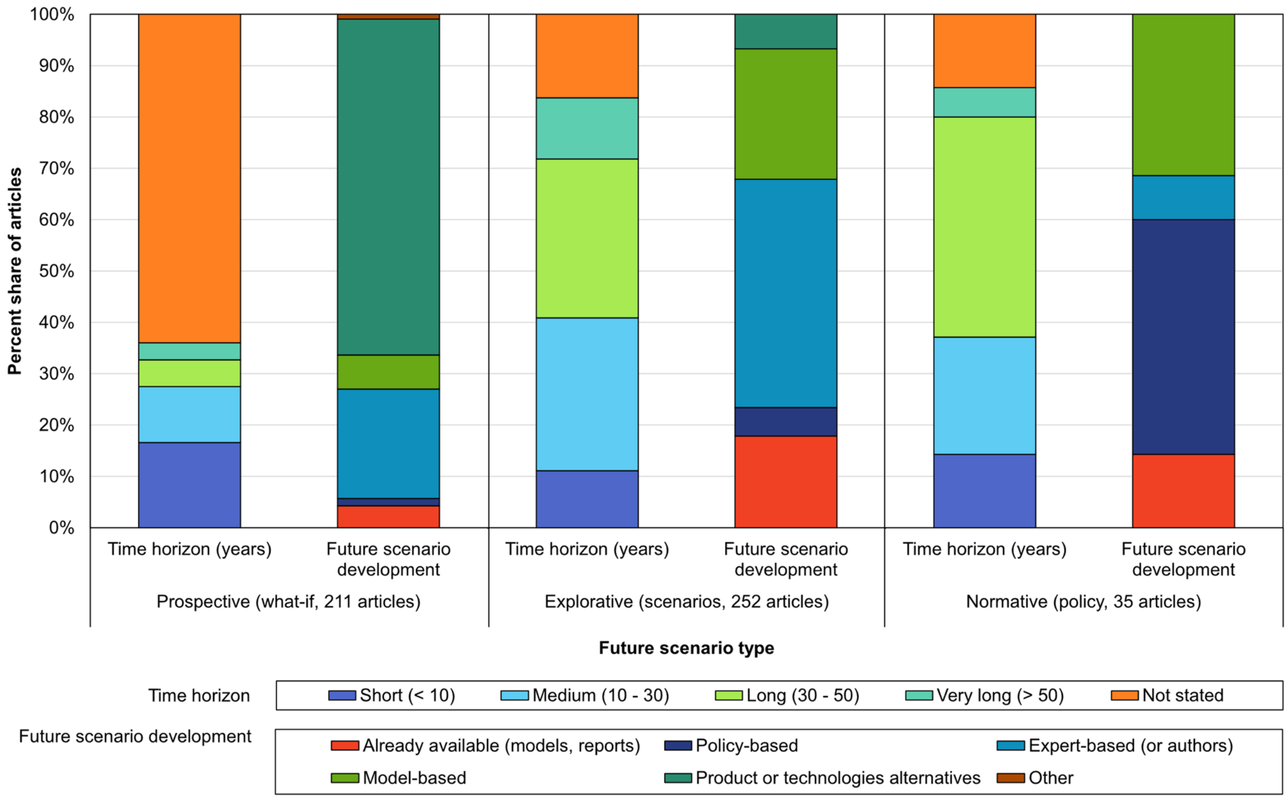

Fig. 3 Percentage of reviewed publications subdivided according to type of future scenario (predictive, explorative and normative) and, within each future scenario type, the percentage share of time horizon and future scenario development. The figure refers to the 498 articles containing case studies

future scenario development and LCAs but also the use of additional models. Future scenarios did not always precede an LCA. Future scenarios represented a development and interpretation of previous LCA results in 7% of the articles (e.g. Andersen et al. 2007; Pehl et al. 2017). Moreover, in 27% of the articles, a subsequent LCA evaluated future scenarios developed from LCA results, in an iterative procedure (e.g. Giurco et al. 2011; Cox et al. 2018; Thonemann and Schulte 2019). We provide more insight into the modelling sequences in the next section 2.2.3.

Additional models. Irrespective of the sequence used, 41% of the studies used additional models and modelling tools, before or between future scenario development and an LCA. The additional models were numerous and could affect, for example, scenario development, the identification of future values for key aspects in the scenarios assessed or the interpretation of LCA results. Examples include case-specific models (such as stochastic emission models), material flow analysis (static or dynamic MFA, SFA), GIS applications, partial and global optimisation models, external databases (e.g. GREET), economic models (cost benefit analysis, market trend analysis, input-output models, etc.), market-based databases (e.g. THEMIS, MARKAL, GEMIS), energy system models (e.g. TIMES), risk assessment models and foresight-specific models (trend analysis, grey forecasting, etc.). The SM provides a complete list of the additional models used in the reviewed studies. LCAs involving such additional models often presented less clearly defined goal, scope and functional units. De Camillis et al. (2013) and Mendoza-Beltran el al. (2018) highlighted this lack of consistency and transparency when using additional models.

Identification of key aspects. The sequence between future scenarios, LCAs and additional models also affected the location and identification of the key aspects of the future scenario for the study at hand. The majority of studies (67%) identified case-specific, important aspects qualitatively, for example, indicating those that are usually important in a specific application area. In total, 33% of the studies based their identification of important scenario aspects on quantitative methods and data, such as simulation models or ad-hoc sensitivity analysis. For 40% of the studies, the important factors were associated with technology alternatives and future scenarios, which were then assessed in a subsequent LCA model.

Missing sensitivity and uncertainty analyses. A high number of studies (46%) identified key aspects from the LCA results, albeit rarely involving sensitivity (33%) and uncertainty analyses (17%). Sensitivity and uncertainty analyses are required from the ISO standards for a balanced interpretation and use of LCA results. However, the observations from this review highlight how rarely sensitivity and uncertainty analyses occur in practice. The importance of parameters in LCA models varies greatly between case studies due to the interaction of sensitivity and uncertainty, and sensitivity and uncertainty should never be defined a priori (e.g. 'key aspects' prior to the study), and should consistently be analysed (Bisinella et al. 2016). The review process highlighted that, when applied to the LCA model, sensitivity and uncertainty analyses facilitated a more appropriate determination of important aspects and the discussion of the effects of implementing future scenarios.

Transparency. In general, the most common feature of the reviewed case studies was a lack of transparency with respect to the modelling choices taken when combining future scenarios and LCAs. A future technology and solution may change its functionality during the long time horizon of the study, or the larger-scale system in which the technology operates may develop from its initial conditions. Developments can also affect capacities, infrastructures or costs. Nevertheless, in the reviewed studies, future scenarios most often affected only selected parts of the LCA model. In 95% of the studies, future scenarios involved technological features of the LCA model's foreground systems (Fig. 4) and involved background system characteristics in only 41% of cases. Even when the time horizon was mid- and long-term, future scenarios only involved the foreground part of the LCA system and neglected aspects in the background system, as shown in Fig. 4 and as earlier voiced by Arvidsson et al. (2017) and Mendoza-Beltran et al. (2018). In 6% of the studies, future scenarios influenced the applied impact assessment methods and weighting, whilst they affected infrastructure in 45% of studies, corresponding to 71% of cases where infrastructure was modelled. This indicates that infrastructure was included primarily when temporal developments in related capacities and impacts were specifically in focus. In 8% of the studies, specific characteristics of the functional unit were allowed to vary over time e.g. the evolution of waste composition or a transport fleet over the time horizon (Tchertchian et al. 2016; Arushanyan et al. 2017a).

Time representation. The majority of the studies represented time in a static way, as a snapshot of a future point in time (69%), while 31% represented time dynamically. Dynamic studies made comparatively fewer references to ISO standards and less well-defined goal, scope and functional units than static studies. In addition, they frequently employed metadata and had a higher occurrence in LCAs addressing infrastructure capacities and costs, generally involving explorative and normative future scenario types modelled via additional models. When time representation was dynamic, the scenarios were often represented continuously, by uncertainty distributions. Dynamic time representation was applied over long periods with well-defined future time horizons.

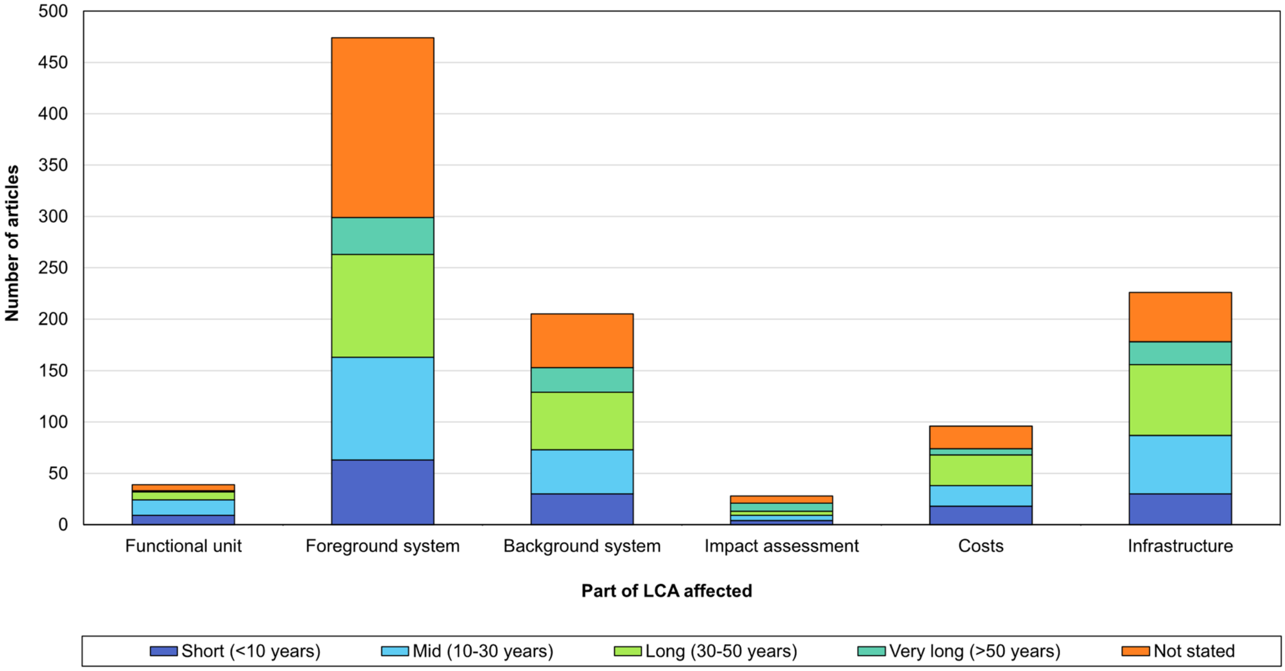

Fig. 4 Number of reviewed publications subdivided according to the part of the LCA model affected by the future scenario and time horizon of the studies. The figure refers to the 498 articles containing case studies

3.4.2 Archetypes

We identified three types (or archetypes) of modelling approaches from the reviewed articles: (i) input 'I', where LCA results were used as the basis for defining the future scenarios, (ii) output 'O', where future scenarios were first defined and then assessed by LCA, and (iii) hybrid 'H', where LCA results were used to define important aspects of future scenarios which were later analysed in an LCA. The archetype names refer to the position of the LCA with respect to the future scenario. The subdivision of the studies according to archetype allows for clearly distinguishing between the model structure and sequence of choices rather than by topic area or application. The use of archetypes and grouping the studies was particularly useful for their systematic review, because it compensated for the lack of clarity in the assumptions and choices in the study.

Sub-archetypes. Within the three main archetypes ('I1', 'O1' and 'H1'), we identified more subtypes according to the presence and the position in the modelling sequence of an additional model. For example, an I archetype, in which an additional model follows the LCA and precedes the future scenario, was named 'I2'. These archetype and subtype names were assigned to each of the reviewed articles and allowed for classifying the studies according to their modelling choices, irrespective of their research field or type of additional model used. Figure 5 illustrates the three generic archetypes as well as possible identified variations, and the number of studies assigned to these variations. Relevant examples of studies per archetype are indicated below.

Input. For the input archetype, the future scenario often constitutes the result of the study. The basic I archetype (I1) is represented by studies such as Rasmussen et al. (2005), Andersen et al. (2007), Bocken et al. (2012) and Chen et al. (2015). These studies applied an LCA as a tool for mapping the technological domain and to generate the knowledge needed for defining future scenarios, and they represent relevant examples of good practice in scenario development. The LCA results could also be further elaborated, in order to constitute the starting point of a future scenario. For example, Giarola et al. (2013) used an additional model after the LCA to assist in defining the future scenario (I2), while Acosta-Alba et al. (2012) used an additional model after the future scenario to optimise or organize the results (I3).

Output. The output archetype represents the most straightforward concept of combining future scenarios with LCA. Good examples of the basic O archetype (O1) are the studies by Hospido et al. (2010), Meylan et al. (2014) and Dijkman et al. (2016). Additional models can be applied before, between or after the future scenarios and the LCA. Vandepaer et al. (2019) and Leão et al. (2019) included an additional model before the future scenario to identify important scenario aspects (O2), while Gibon et al. (2015), Albers et al. (2019) and Allacker et al. (2019), for instance, used an additional model between the future scenario and

ARCHETYPE		STRUCTURE	OBSERVED IN THE LITERATURE REVIEW					
Main	**Sub-type**		**Number of publications**	**LCA ISO**	**Foresight literature**	**Predominant future scenario type**	**Predominant time horizon**	**Scenario technique and location of key factors**
I - INPUT	**I1**	**Definiton**: LCA used to contextually identify environmental indicators/values that are later used to create scenarios outside the LCA framework. **Example**: Chen et al. (2015) LCA → FUTURE SCENARIO	16	50 %	38 %	Predictive, technology alternative	Not stated	Quantitative future, quantitative key factors from LCA results
	I2	**Definiton**: See archetype I1. The LCA results are treated with an additional model before being used to formulate the future scenarios. **Example**: Giarola et al. (2013) LCA → Additional model → FUTURE SCENARIO	9	44 %	22 %	Explorative, model based	Mid-term (10-30 years)	Quantitative future, qualitative key factors from external model
	I3	**Definiton**: See archetype I1. The future scenarios are subsequently utilized as input of an additional model. **Example**: Acosta-Alba et al. (2012) LCA → FUTURE SCENARIO → Additional model	11	27 %	36 %	Explorative, model based	Long term (30-50 years)	Quantitative future, quantitative key factors from LCA results
O - OUTPUT	**O1**	**Definiton**: The future scenarios are formulated outside the LCA framework and are directly tested in the LCA model. **Example**: Meylan et al. (2014) FUTURE SCENARIO → LCA	195	64 %	21 %	Predictive, technology alternative	Not stated	Quantitative future, quantitative key factors within scenarios
	O2	**Definiton**: See archetype O1. The future scenario is based on results from an additional model. **Example**: Vandepaer et al. (2019) Additional model → FUTURE SCENARIO → LCA	25	68 %	28 %	Explorative, model based	Mid-term (10-30 years)	Quantitative future, quantitative key factors from external model
	O3	**Definiton**: See archetype O1. The future scenarios are elaborated/used as input with/to an additional model before being implemented in the LCA. **Example**: Allacker et al. (2019) FUTURE SCENARIO → Additional model → LCA	88	38 %	31 %	Explorative, expert based	Long term (30-50 years)	Quantitative future, quantitative key factors within scenarios
	O4	**Definiton**: See archetype O1. The results of the LCA are used/further elaborated within an additional model. **Example**: Azapagic et al. (2016) FUTURE SCENARIO → LCA → Additional model	18	59 %	18 %	Predictive, expert based	Not stated	Quantitative future, quantitative key factors within scenarios
H - HYBRID	**H1**	**Definiton**: LCA used to contextually identify environmental indicators/values that are used to create scenarios outside the LCA framework. The future scenarios are then tested in an LCA model. **Example**: Niero et al. (2015b) LCA → FUTURE SCENARIO → LCA	82	57 %	32 %	Explorative, expert based	Not stated	Quantitative future, quantitative key factors from LCA results
	H2	**Definiton**: See archetype H1. The LCA results are treated with an additional model before being used to formulate the future scenarios. **Example**: Cox et al. (2018) LCA → Additional model → FUTURE SCENARIO → LCA	20	55 %	25 %	Explorative, model based	Mid-term (10-30 years)	Quantitative future, quantitative key factors from external model
	H3	**Definiton**: See archetype H1. The future scenarios are elaborated/used as input with/to an additional model before being implemented in the LCA. **Example**: Heeren and Hellweg (2019) LCA → FUTURE SCENARIO → Additional model → LCA	34	47 %	38 %	Explorative, model based	Long term (30-50 years)	Quantitative future, quantitative key factors from LCA results

◂**Fig. 5** Archetypal combinations between LCAs, future scenarios and additional models. The three main archetypes (input (I), output (O) and hybrid (H)) are subdivided into sub-types and observed corresponding numbers of publications, references to the LCA ISO standard or acknowledged foresight theory. The table reports the most frequent distinctive features of the sub-types, based on the 498 reviewed case studies

the LCA (O3). Wender et al. (2014b) and Azapagic et al. (2016) used the additional model after the LCA (O4).

Hybrid. The third archetype (Hybrid) summarises the cases that utilised an LCA as both the input and the output of a future scenario. Relevant examples of the basic H archetype (H1) are the studies by Fedele et al. (2014), Meinrenken and Lackner (2015), Niero et al. (2015b) and Roos et al. (2016). Rauner and Budzinski (2017) and Cox et al. (2018) utilised an additional model between the first LCA and the future scenario (H2). Lastly, some articles utilised additional models between the future scenario and the second LCA (H3), as in the case of Du et al. (2010), Bohnes et al. (2017) and Heeren and Hellweg (2019).

Simple and complex archetypes. The most abundant archetype was O1 (39%), followed by O3 (18%) and H1 (16%). The presence of types other than O, and the substantial share of H, indicates that future scenario LCAs should not be understood only as O types, as they have been conceptualised until recently e.g. in De Camillis et al. (2013). Higher compliance with the LCA ISO standard was observed in simple archetypal configurations (such as O, I1 and H1 types), which also presented the highest use of the consequential approach for LCI data modelling. All the remaining types contained fewer references to the ISO standard. On average, I and H types referenced acknowledged foresight theory more than O types. Simple O type configurations (especially O1 and O3) presented predictive future scenarios representing a specific product or technology alternative with short (and often not stated) time horizons, and in general, they presented higher-quality LCAs. Conversely, complex archetypes (e.g. I3, H3 and O4) used more explorative and normative scenarios based on expert opinions or additional models, usually with well-defined mid- and long-term horizons.

Number of scenarios. Interestingly, when a baseline or business-as-usual scenario was included, it was investigated parallel to the future scenarios in the O types, but separately in the I and H types. In the I and H cases, the present-time scenario usually constituted the preliminary LCA study. Generally, the I types showed the highest variability between the number of LCAs and future scenarios, the latter of which were based on the LCA results, but most often resulted in a different number of future scenarios. A lower number represented optimised future scenarios (e.g. Chen et al., 2015), while a higher number illustrated future scenarios based on combinations of key aspects from the starting LCA (e.g. Bocken et al., 2012). For the O and H types, the number of LCA scenarios most often corresponded to the number of the preceding future scenarios. However, for all archetypes, the total number of scenarios would increase if the studies included additional sensitivity analysis by scenario analysis (epistemic uncertainty).

Scenario evaluation. The best scenario development practices were noted generally in the I and H archetypes. The scenario evaluation defined by Fukushima and Hirao (2002) reached a further level of completeness with the H archetypes, where the effect of introducing the future scenario was quantitatively assessed by comparing the results of the preliminary LCA with the effects caused in the subsequent LCAs. O4 and H3 archetypes most often make use of additional models for further interpretation of the results, for example for rank ordering and for considering more sustainability assessment criteria, as in the case of multi-criteria decision analysis (MCDA).

3.5 Topic area differences

The reviewed articles covered topic areas ranging from small-scale technology development, such as new products and emerging technologies at low technology readiness levels (TRLs), to medium-scale and large-scale development. Small-scale development generally involves the fields of industrial manufacturing engineering, chemical engineering and nanotechnology. Finally, large-scale development is mostly connected to the topic areas of energy and power technology and renewable energy solutions.

Amongst the reviewed 498 case studies across different topic areas, we did not observe a prevalent archetypal modelling approach, except for the transport sector, which used the hybrid archetype in almost half of the articles. All topic areas presented on average a few references to acknowledged foresight theory. However, examples of good modelling practice occurred in all topic areas, generally when both the LCA complied with ISO standards and the future scenarios presented a good knowledge level for foresight, as in the relevant examples reported in 3 There were some tendencies within case studies in the different topic areas. Articles focusing on agricultural and biological sciences and civil and structural engineering presented the highest-quality knowledge level in relation to LCA. The energy and transport sectors included the highest numbers of hybrid LCAs, due to the considerable use of external economic databases and input-output matrices to describe large-scale developments. For the same reason, this topic area most often used metadata for LCI data modelling. Infrastructure was included in 70% of the studies within energy, transport and engineering, with considerably lower occurrence within other sectors. In addition, these sectors had the highest share of scenarios with probability distributions and dynamic time representation, the highest number of scenarios and the longest investigated time horizons.

The scale and the focus of the assessment were determined with respect to differences in systems modelled with an LCA; for example, small-scale applications are characterised by bottom-up modelling. Furthermore, the foreground system of the LCA focuses on the emerging technology or the novel system solution, while the energy system characterises the background system in which technology and the system will operate. On the other hand, when the focus falls on assessments in large-scale system development, such as energy system development at a regional level, the energy system itself and the share of the power technologies constitute the foreground system. Most often, energy, transport and engineering studies used top-down approaches based on the use of macro-economic models and data. These approaches allowed for modelling large-scale changes with a more simplified vision and organisation of model components, in comparison with the more detailed process-based, bottom-up models that were often used in other sectors on small and medium scales e.g. waste management. However, top-down approaches often decreased the transparency of the studies, for example, with respect to the goal, scope and functional unit definitions. In particular, definitions of LCI data modelling approaches were often missing within energy and transport studies. The reconciliation between top-down and bottom-up approaches has been discussed in Brand et al. (2012) and Dandres et al. (2012) for the transport and energy sectors.

3.6 Topic area methods and approaches

The literature review retrieved 16 articles containing methodological recommendations or reviews, as well as 139 studies containing a novel method or approach applied to a case study. However, not all of the retrieved approaches were strictly related to the combined use of future scenarios and LCA, as they also focused on specific aspects of the application at hand with a long-term component. For example, Jørgensen et al. (2015) provided recommendations on how to model temporary carbon storage in long-term LCAs, while Núñez et al. (2015) focused on spatially and temporally based characterisation factors. In total, we identified 113 articles providing approaches that can be generally useful for the combined use of future scenarios and LCAs, with an additional 22 articles providing useful methodological advancements and recommendations from 2020. The identified articles totalled 125 and are reported in Table 2, and they are subdivided according to the general scale of innovation in terms of focus, topic area and archetype.

Large scale. The topic area that presented the largest number of proposed methods and approaches is energy, with 32 publications. O archetypes are the most common in this topic area, and the scale of innovation is usually large, for example, with additional national, regional and global models. The focus of the approaches here mostly falls on coupling LCAs with energy system modelling (partial and global equilibrium models) in O3 archetypes (Gibon et al. 2015; Garcia-Gusano et al. 2017), as well as with multi-criteria decision analysis-based (MCDA) frameworks in O4 archetypes (Azapagic et al. 2016).

Medium scale. Management engineering articles deal with environmental sustainability assessment in general, albeit in different applications. There are 25 approaches in this topic area, and they can have a varying scale, ranging from product assessment to methodology at a regional level. Table 2 reports nine articles with general recommendations on long-term LCAs (Pesonen et al. 2000), temporal issues in LCAs (Beloin-Saint-Pierre et al. 2020; Lueddeckens et al. 2020) and LCI modelling approaches (Moretti et al. 2020). This topic area presents relevant examples of the use of foresight and scenario development, as highlighted in section 4.2. Articles in the middle-scale development topic areas (agriculture, building, transport, waste and water management sectors) pay equally balanced attention to aspects in the foreground system (development of new solutions) and the interaction and development of the background system in which they will operate (Erlandsson and Levin 2004; Levis et al. 2014; El Chami and Daccache 2015; Mastrucci et al. 2016; Göswein et al. 2020).

Small scale. Industrial manufacturing engineering and chemical engineering articles focus on small-scale technological development and provide numerous amounts of high-quality publications providing guidance for sustainability assessments for emerging technologies at low TRL. This topic area presents the most complete approaches and practical recommendations on the combined use of future scenarios and LCAs. Cucurachi et al. (2018), Thonemann et al. (2020) and van der Giesen et al. (2020) identified the challenges of conducting LCAs of emerging technologies for each phase of the LCA, while Moni et al. (2020), Thonemann et al. (2020) and van der Giesen et al. (2020) provide recommendations for each of the challenges identified. In particular, Buyle et al. (2019b) and Tsoy et al. (2020) provide concrete recommendations on scenario development techniques and upscaling methods, focusing on technology development, learning and diffusion.

4 Discussion

The review revealed a large variety of approaches for the combined use of future scenarios and LCA, but it also showed highly varying quality in relation to the studies.

Table 2 Summary of the number of proposed methods and approaches for the combination of LCAs and future scenarios, with the respective references, retrieved by the literature review. The listed 125 articles are those ascribable to an archetypal structure and to a topic-specific area, or they provide general methodological recommendations. In total, there were 155 retrieved frameworks, and they are listed in full in the SM (Table S5)

	Topic area	GENERAL / REVIEW	ARCHETYPES										Total
			INPUT			OUTPUT				HYBRID			
			I1	I2	I3	O1	O2	O3	O4	H1	H2	H3	
									Decision analysis and robust interpretation				
LARGE SCALE (SYSTEM DEVELOPMENT)	Renewable energy, energy and power technology	-	1 Chen et al. (2015)	1 Giarola et al. (2013)	1 Pehl et al. (2017)	3 Miller et al. (2013); Santoyo-Castelazo and Azapagic (2014); Buyle et al. (2019a)	1 Xu et al. (2020)	9 Dandres et al. (2012); Dale and Bilec (2014); Menten et al. (2015); Gibon et al. (2015); Bergesen and Suh (2016); Beck et al. (2018); Some et al. (2018); Albers et al. (2019); Singlitico et al. (2019)	6 Wender et al. (2014b); Azapagic et al. (2016); Gumus et al. (2016); Kluczek (2019); Nock and Baker (2019); Moslehi and Reddy (2019)	5 Pehnt (2003a, b); Giurco et al. (2011); Hertwich et al. (2014); Cao et al. (2016)	2 Rubio Rodriguez et al. (2013); Rauner and Budzinski (2017)	3 Garcia-Gusano et al. (2016, 2017); Arvesen et al. (2018)	**32**
MEDIUM SCALE (TECHNOLOGY AND SYSTEM DEVELOPMENT)	Management engineering, policy and law	8 Pesonen et al. (2000); Weidema et al. (2004); Arushanyan et al. 2017b; Buyle et al. (2018); Beloin-Saint-Pierre et al. (2020); Lueddeckens et al. (2020); Michiels and Geeraerd (2020); Moretti et al. (2020)	2 Rasmussen et al. (2005); Bocken et al. (2012)	-	1 McKellar et al. (2013)	2 Fitch and Cooper (2005); Cluzel et al. (2014)	2 Vega et al. (2019); Leão et al. (2019)	6 Yang and Chen (2012); Lan et al. (2012); Heijungs et al. (2014); Kobayashi et al. (2017); Lin et al. (2019); Luderer et al. (2019)	2 Matthews et al. (2019); Sansa et al. (2019)	4 Fukushima and Hirao (2002); Hellweg et al. (2003); Lehmann and Hietanen (2009); Roos et al. (2016)	-	1 Martin-Gamboa et al. (2019)	**28**

Table 2 (continued)

Topic area	GENERAL / REVIEW	ARCHETYPES										Total
		INPUT			OUTPUT				HYBRID			
		I1	I2	I3	O1	O2	O3	O4	H1	H2	H3	
								Decision analysis and robust interpretation				
Agricultural and biological sciences	-	-	-	-	3 Hospido et al. (2010); Rothwell et al. (2016a, b)	-	6 Garcia-Quijano et al. (2005); Verones et al. (2012); Vazquez-Rowe et al. (2014); El Chami and Daccache (2015); Cosme and Niero 2017); Marvuglia et al. (2017)	-	2 Fedele et al. (2014); Niero et al. (2015b)	-	-	**11**
Civil and structural engineering	2 Su et al. (2017); Hossain et al. (2020)	-	-	-	3 Vieira and Horvath (2008); Collinge et al. (2013); Hasik et al. (2019)	2 Williams et al. (2012); Su et al. (2020)	2 Erlandsson and Levin (2004); Allacker et al. (2019)	3 Schlegl et al. (2019): Göswein et al. (2020): Mastrucci et al. (2020)	1 Wiprächtiger et al. (2020)	-	1 Heeren and Hellweg (2019)	**14**
Transportation	-	-	-	-	2 Tchertchian et al. (2016); Rocco et al. (2018)	1 Mendoza Beltran et al. (2018)	1 Brand et al. (2012)	-	3 Contadini et al. (2002); Spielmann et al. (2008); Meinrenken and Lackner (2015)	2 Bauer et al. (2015); Harris et al. (2018)	1 Bohnes et al. (2017)	**10**
Waste management and disposal	1 Meylan et al. (2018)	-	-	-	3 Moora and Lahtvee (2009); Meylan et al. (2013); Villares et al. (2016)	-	3 Levis et al. (2013, 2014); Münster et al. (2013)	-	1 Salemdeeb et al. (2018)	1 Mastrucci et al. (2017)	-	**9**
Water science and technology	-	-	1 Venkatesh et al. (2011)	-	1 Lundie et al. (2004)	-	2 Loubet et al. (2016); Bixler et al. (2019)	-	-	-	-	**4**

Table 2 (continued)

	Topic area	GENERAL / REVIEW	ARCHETYPES										Total
			INPUT			OUTPUT				HYBRID			
			I1	I2	I3	O1	O2	O3	O4	H1	H2	H3	
									Decision analysis and robust interpretation				
SMALL SCALE (TECHNOLOGY DEVELOPMENT)	Industrial manufacturing engineering	8 Villares et al. (2017); Arvidsson et al. (2018); Cucurachi et al. (2018); Buyle et al. (2019); Moni et al. (2020) Tsoy et al. (2020); van der Giesen et al. (2020); (van der Hulst et al. 2020) Thonemann et al. (2020)	-		1 Smith et al. (2019)	-	-	1 Peng et al. (2019); van der Hulst et al. (2020)	2 von Gleich et al. (2008); Blanco et al. (2020)	1 Chopra et al. (2019)	1 Yokota et al. (2003)	-	**14**
	Chemical engineering	1 Piccinno et al. (2016)	-	-	-	1 Patel et al. (2013)	-	-	-	1 Thonemann and Schulte (2019)	-	-	**3**
	Total	**20**	**3**	**2**	**3**	**18**	**6**	**30**	**13**	**18**	**6**	**6**	**125**

Together, these may limit the usefulness and applicability of the results. The main critical issues identified in the review are discussed in the following sections. Then, we provide recommendations for a more transparent and effective combined use of future scenarios and LCA.

4.1 Lack of formal guidance

Currently, no formal guidance exists for the combined use of future scenarios and LCA, and the little and general guidance on addressing future scenarios in the LCA ISO standard allows for considerable freedom. SETAC's initiative for providing a framework had a specific focus on the future scenario methodology and foresight, but it had little follow-up: only 15 of the articles retrieved in this review referred to the SETAC framework initiative. The LCI modelling approaches and respective time horizons suggested in the ILCD Handbook focus on time horizons that are considerably shorter than the typical time horizons observed in the articles retrieved by this literature review. Due to this methodological gap, authors across all topic areas had to develop their own methods and approaches to carry out their long-term sustainability assessments.

4.2 Archetypal approaches and modelling sequences

The lack of a framework gave rise to different ways of combining future scenarios and LCA. For example, a future scenario is assessed with an LCA (output archetype), or a future scenario is created from an LCA study (input archetype), which can also be further assessed with an LCA (hybrid archetype). These archetypal combinations demonstrate that different choices and sequences for future scenarios and LCA provide different types of results (e.g. a future scenario for I archetypes and an LCIA for O and H types), thereby allowing high flexibility in terms of specific research fields, goals and scopes. This flexibility is further enhanced by the variety of additional models that can be introduced in the modelling sequence. In particular, Table 2 shows how different topic areas and different scales of innovation have separate focuses and need case-specific scenario development approaches.

Methods, approaches and recommendations developed in different topic areas still do not fill the methodological gap on the combined use of future scenarios and LCA. The literature review retrieved more than 100 articles containing topic- and case-specific approaches and recommendations in this regard (Table 2 and Table S5, SM), and the approaches and recommendations retrieved provide excellent topic-specific guidance, such as the most recent Thonemann et al. (2020) and van der Giesen et al. (2020) papers for LCAs of emerging technologies, or the decision support framework proposed by Azapagic et al. (2016). Amongst recent literature, some articles refer to the recommendations made by Arvidsson et al. (2018) for prospective studies. However, the topic-specific methods and approaches retrieved in Table 2 lack consensus. Existing recommendations may be difficult to generalise outside their specific topic area, especially when linked to fixed archetypal modelling sequences, and use topic-specific additional models.

4.3 Low LCA quality

The review showed that future scenarios and LCA are used in combination in many topic areas for assessing innovative solutions and supporting decision-making. In addition, specific needs within topic areas have led to the combined use of LCA and additional models, on top of future scenarios. While this is a promising signal for the widespread use of LCA methodology and sustainability assessment in general, the use of the LCA methodology should follow its standardised approach and provide transparent reporting of the choices made, yet many of the peer-reviewed articles retrieved did not comply with the LCA's quality criteria. For example, a large number of studies did not describe the goal, scope and functional unit or address multiple impact categories. Moreover, most studies did not discuss the quality of the data with respect to the goal and scope or carry out sensitivity and uncertainty analyses in the interpretation phase, and most of the articles did not state the LCI modelling approach, which should be stated irrespectively of whether the LCA focuses on a future scenario. These observations emphasise the general need for more transparent and rigorous LCA reporting as well as peer-review process.

4.4 Low foresight knowledge

Future scenario methods are not standardised methodologies, and scenario development can follow different approaches (Fig. 1). However, amongst the reviewed articles, references to future scenario theories and approaches were rare, which suggests that the retrieved articles employed future scenarios as a general concept, rather than following a systematic procedure. Future scenarios addressed in the studies were most often 'options' assessed with the LCA methodology, and the studies did not pay specific attention to the future scenario development phase. From a foresight perspective, these are potentially missed opportunities for obtaining a deep understanding of the problem at hand, using future scenario methods. A systematic foresight procedure requires the study to address the goal and scope of the future scenario, to define a specific intention for the scenario process and to identify a precise time horizon. The scenario process also stresses on defining case-specific key aspects contextually and using different techniques. For example, qualitative techniques involving stakeholders' opinions can provide a backbone for quantitative data, as shown by Meylan et al. (2015).

4.5 Low consistency assessment

In output and hybrid archetypes, future scenarios are assessed with an LCA. However, the review revealed little consistency between the future scenario and LCA modelling approach, or in the clarity of reporting the assumptions made. Of concern is that the goal and scope of future scenarios and LCA were often developed separately. When the studies used additional models, consistency between the assumptions behind the models and the goal and scope of the future scenarios and the LCA were not discussed. Few articles stated the reasons for choosing a specific additional model or method for generating future scenarios, and they did not discuss the appropriateness of the chosen method. Furthermore, they did not state precisely the temporal scope of the study or provide a clear statement on the parts of the LCA affected by the long-term modelling. For example, few studies mentioned potential variations in the functionality of the system being assessed. In particular, even in long-term studies, we observed that they rarely discussed the rationale for not including potential changes in the background system, or capacities and infrastructure. A prominent shortcoming in the retrieved studies is the lack of a systematic procedure for evaluating the assessed scenarios. Often, these scenarios were not developed contextually but paid attention to selected case-specific aspects, indicating difficulties in assessing whether the chosen future scenarios sufficiently investigated the problem at hand.

Lack of clarity in defining conceptual aspects, aligned with a lack of consistency amongst approaches within a study, directly translates into practical challenges such as quantitatively delineating the functionality of the future system being assessed, selecting consistent and representative data for the foreground and background system and addressing temporal issues in the character of the environmental impacts. Functionality choices, data consistency and data modelling approaches, as well as impact assessment methods, were rarely addressed in the reviewed articles.

Lack of sensitivity and uncertainty analyses was common amongst the reviewed literature. Future scenario methods are techniques that not only allow for systematically developing and rehearsing future situations but also increase knowledge of the assessed system. Few articles made proper use of the future-scenario development techniques and framework illustrated in Fig. 1 with the purpose of addressing uncertainties in the studied system. When scenarios are developed and directly evaluated with an LCA, as in the case of O archetypes, the lack of sensitivity and uncertainty analyses leads to an incomplete interpretation and use of the scenario development process. Without proper interpretation of the consequences of introducing the scenario in LCA modelling results, scenarios are only 'blindly applied'.

4.6 Ambiguous use of terminology

The lack of guidance and the general low compliance with the LCA ISO standard and future scenario methods, together with a number of case-specific approaches, in turn generate considerable confusion regarding not only methodological phases and good practices but also the terminology in use. In cases where both the LCA and future scenarios did not comply with LCA standards and foresight theory, both LCA and foresight terminology have been applied inconsistently. For example, keywords such as 'what-if', 'prospective' and 'predictive' were used with different meanings than intended in acknowledged foresight theory. The use of 'what-if' for foreground scenarios, as suggested by SETAC, can potentially be confused with probable 'what-if' scenario types (Börjeson et al. 2006), which are bound to a specific foresight goal and short time frames. Another example of potentially confused terminology is the case of 'prospective LCA' (Pesonen et al. 2000; Weidema et al. 2004), in that the use of 'prospective' in the ILCD Handbook is in conflict with the definition provided by SETAC for such an LCA (Ekvall et al. 2016). In the articles retrieved, 'prospective' was associated with both attributional and consequential approaches with short time frames, probably due to its resemblance to the 'predictive' scenarios term, thereby suggesting the need to pay special attention to such terminology within future official guidance. The inconsistent use of the term 'scenario' itself in an LCA represents a prominent example. 'Scenarios' are used to denote technological alternatives without specifying the context in which they are compared, but scenarios can also be used to evaluate uncertainty associated with the choice of alternatives (scenario analysis), often not distinguishing whether foreground only or also background conditions are changing. Moreover, 'scenarios' are used both for present and future points in time. The use of clear and consistent terminology between future scenarios and LCA is of the utmost importance, in order to convey to experts in the foresight and LCA fields the methods applied and the results obtained, and thus assuring unambiguous communication of long-term sustainability assessment studies.

5 Recommendations

The highly diverse nature of the applications of future scenarios and LCA observed in the literature suggests that rather than trying to identify a single procedure applicable to all cases (e.g. De Camillis et al., 2013), guidance should maintain the current complexity and freedom for modelling choices within LCA, future scenarios, their combined use and their sequence. Complexity is required by the specific different needs of the many topic areas where future scenarios and LCA are applied. This is in line with foresight theory, whereby creativity is a fundamental aspect for the quality and usefulness of the future scenario process. Nevertheless, when future scenarios and LCA are combined, the usefulness of the results also depends on the clear understanding of the modelling choices taken. For example, rather than binding LCI data to one specific modelling approach, guidance on combining future scenarios and LCA should focus on facilitating the transparency, quality and communicability of modelling choices. First of all, guidance can increase the transparency and communicability of studies by providing a common and unambiguous language for future scenarios and LCA, for example, with clear terminology definitions. In this case, guidance should identify minimum quality requirements for the future scenario and LCA methodologies and list mandatory methodological aspects, in order to declare for the combined use of future scenarios and LCA. Quality requirements refer not only to the LCA's standardised method and to foresight approaches but also to the development of future scenarios that effectively and systematically assess the problem at hand. Future scenarios should be developed contextually, identifying key characteristics and potential evolutions thereof to make sure that those assessed with an LCA sufficiently cover potential future environmental issues.

5.1 Terminology

Future guidance needs to establish unambiguous definitions and a clear terminology for future scenarios and LCA, for example, the collection of definitions provided in the recent review studies of Moni et al. (2020), Tsoy et al. (2020) and van der Giesen et al. (2020), and ensures that definitions are in accordance with the future scenario theory.

There is an urgent need for a clear definition of 'scenario' to be shared between LCAs and foresight (Fig. 1), such as 'a set of aspects describing a specific situation at a specified time'. Within an LCA, a scenario describes the situation to be assessed therein; furthermore, it is a set of input values, associated LCI process data (foreground system and background system) and LCIA context. Scenarios can be used on any time horizon to evaluate the effects of epistemic uncertainty with scenario analysis, by selectively changing some aspects of the LCA model, in order to represent an alternative situation from the starting LCA model. When time has an explicit future horizon, the scenario becomes a future scenario, in which case any LCA element affected by the future time horizon should be unambiguously stated, in order to facilitate transparency and communicability. Useful definitions of 'scenario' in a future scenario-LCA context are provided by Pesonen et al. (2000) and Mendoza Beltran et al. (2018).

As suggested by SETAC, a distinction can be made between future scenarios affecting the foreground system and those affecting aspects of the background system and the LCIA phase. For example, the use of 'what-if', 'cornerstone', 'umbrella' or 'range' scenarios (Pesonen et al. 2000; Weidema et al. 2004, Arvidsson et al 2018; Meylan et al. 2018) could be beneficial, albeit by paying special attention to the use and communication of the terms 'what-if' or 'prospective', which should be in accordance with future scenario theory and terminology (Fig. 1).

5.2 Goal and scope definition

Goal and scope should always be clearly stated and preferably be in accordance with the future scenario and the LCA, in order to identify the most suitable future scenario type for the goal of the study (Arushanyan et al. 2017a, b). An LCA is a standardised procedure, so the goal and scope definition should follow ISO (2006a, b). The studies should therefore comply with ISO quality standards, for example, by assessing more than one impact category. The future scenario type should then be selected according to the goal and scope of the study (e.g. according to the types identified by Börjeson et al. 2006). Moreover, a clear definition of the temporal scope is necessary for unambiguously identifying the time horizon, which should also be clearly stated. Time issues in the LCA model should be addressed as early as the goal and scope definition stage, following the comprehensive checklist provided by Beloin-Saint-Pierre et al. (2020). The researcher should then decide and clearly state the archetypal sequence between the intended future scenarios and LCA (Fig. 5). Different archetypes provide different results, and the aim and result type should be identified as early as the goal and scope phase. Moreover, the goal and scope phase should include decisions on the use of additional models and a discussion of the consistency of the model's assumptions, system boundaries and data employed at this point.

5.3 Future scenario development

The process of scenario development occurs in the same way, irrespective of the archetypal modelling sequence chosen in the goal and scope phase. Developing future scenarios following foresight approaches ensures a systematic assessment of the problem at hand (left column in Fig. 1). Studies should document the future scenario development process, for example, by describing how important scenario aspects are identified (e.g. qualitatively or quantitatively, with the use of additional models) and whether this is done contextually. Scenario development should occur in close collaboration with specialists and stakeholders in the case-specific field, in order to ensure meaningful coverage of the problem at hand. Collaboration with specialists and stakeholders ensures transparency and scope alignment also when using additional models for defining and modelling future scenarios (Frischknecht et al. 2017). In addition, studies should define what the developed future scenarios represent. It is especially important to reflect on whether changes of the background conditions and the interaction with the system studied are relevant in the specific context of said study. Finally, studies could provide an early quantification of the number of scenarios assessed, and make a clear distinction with additional scenarios used for extra sensitivity analysis.

5.4 Future scenarios in LCA

Modelling of future scenarios in LCA replete with its conceptual and practical challenges occurs in output and hybrid archetypes, where future scenarios are assessed in a subsequent LCA model. Studies should clearly state the methodological choices taken, such as parts of the LCA model affected by the future scenario (functionality, foreground system, background system and capacity).

Practical challenges, such as data selection for LCI modelling and techniques for modelling the foreground system and background system, can be very topic area- and scale-dependent. However, approaches developed in different areas and on different scales can already be extremely useful for solving specific practical challenges within and especially across topic areas. The rows in Table 2 provide a useful and rich collection of state-of-the-art approaches and recommendations, subdivided according to archetypal modelling structure. Across topic areas, the columns in Table 2 can be used for organising recommendations according to archetypal modelling structure. Moreover, approaches and recommendations retrieved from different scales of technology and system development provide extremely useful information for solving practical challenges related to future scenario modelling in an LCA. Small-scale approaches offer useful recommendations for modelling novel technologies, especially where functionality is uncertain and data is scarce. For example, small-scale technology development studies such as industrial manufacturing engineering and chemical engineering can provide useful approaches for functionality issues and foreground system data modelling approaches, such as the scale-up techniques for emerging technologies summarised by Piccinno et al. (2016), Buyle et al. (2019b) and Tsoy et al. (2020). Medium-scale approaches provide useful information for modelling interactions between a novel technology or a unique combination of technologies and the surrounding system in which they operate. Integration of technologies in existing and potentially developing surrounding system conditions is well represented in medium-scale studies, such as those found in the waste management field. Large-scale approaches provide recommendations for modelling national and regional large-scale systems, for example, in the energy sector. While these systems constitute the foreground system in their topic area, these large-scale studies can constitute potential background system developments in many small- and medium-scale studies.

Between the identified archetypes, the hybrid archetype is the most promising, in that it offers the possibility to base the selection of important scenario aspects on a preliminary (baseline) LCA. In particular, when sensitivity and uncertainty analyses are carried out as part of an H type modelling sequence, this facilitates considerably more insight into the important aspects that are decisive for the modelling outcome and the early identification of environmental hotspots when applied in the research and development phase (Villares et al. 2017). This approach may be significantly more effective than simply applying a priori defined future scenarios. Finally, the interpretation phase can be strengthened further by using additional models in collaboration with stakeholders, for example MCDA approaches.

5.5 Interpretation of the results

The combined use of future scenarios and LCA occurs primarily due to the need to develop and rehearse a future situation, for which we wish to quantify potential sustainability. Interpreting the results obtained, and evaluating the potential sustainability of a future situation and its potential future alternatives, thus requires a starting point of comparison, which can be a baseline scenario in the present or in the future. Result interpretation should thus ensure that the study discusses differences in sustainability results induced by the different scenarios and their ‘unknown unknowns’. Systematic interpretation of the results should include sensitivity analysis, in order to identify the most sensitive input values and processes in the modelled scenarios, aligned with uncertainty analysis for their potential variability.

It is important not only to evaluate and discuss changes induced by the future scenario with respect to the present but also to discuss whether the developed scenarios and the results obtained sufficiently rehearse the research questions identified in the goal and scope of the study. The scenario development should follow a systematic procedure and be formulated contextually and with the help of stakeholders in the field. In this way, the developed scenario can better cover the case-specific issue and identify potential developments that are more meaningful to assess with an LCA, rather than quantifying sensitivity and uncertainty with statistical methods provided by a poorly defined scenario.

LCA results are generally uncertain, especially when related to products and systems that do not yet exist. However, the combined use of future scenarios and LCA calls for a more flexible and foresight-oriented interpretation of the LCA results. As pointed out by Villares et al. (2017), due to temporal uncertainties, we should not see results as absolute but rather as serving the purpose of identifying potential environmental hotspots, advising on directions for sustainable technological development and raising questions on environmental features and alternative perspectives.

6 Conclusions

Existing literature counts more than 500 peer-reviewed articles combining future scenarios and life cycle assessment (LCA) in a variety of applications and topic areas. The numbers of articles increase every year in all topic areas, and they focus on sustainability challenges ranging from small-scale innovation (emerging products and technologies) to medium-scale systems (such as new solutions for transportation, waste management, building sectors) and large-scale and global systems (such as energy provision). Due to a lack of formal guidance for long-term assessments in the LCA ISO standard, more than 100 articles tried to provide a method or approach to assess future scenarios in an LCA. The approaches and recommendations provided in the literature are very useful in the specific topic areas, but they are difficult to generalise, due to the specific needs and scopes of the different applications and subjects.

Irrespective of the topic area and application, the articles lacked transparency in both the practical and the conceptual modelling choices taken, even when a formal framework did exist, as in the case of the LCA ISO standard. In general, only a few articles took advantage of the future scenario (foresight) methodology, in order to develop scenarios in a consistent way and to use the scenario development part of the assessment to increase knowledge of the specific topic area application. Modelling future situations is inherently uncertain, and yet a lack of systematic interpretation or assessment of the effects of the future scenarios in LCA modelling, for example, using sensitivity and uncertainty analyses, was observed.

The systematic review of case studies highlighted the complexity in the modelling sequence between future scenarios and LCA that previous literature did not address. We observed three main archetypal combinations: ‘input’, when future scenarios are developed from key aspects retrieved from a preliminary LCA, ‘output’, when future scenarios are developed and evaluated with an LCA and ‘hybrid’, when future scenarios developed from key aspects from a preliminary LCA are evaluated with a subsequent LCA. The archetypes differ further according to the presence of additional models in the modelling sequence, and these modelling differences can be a further obstacle to a formulation of a generic framework for the combination of future scenarios and LCA, which were mostly conceived in the literature as ‘output’.

Due to the diversity and complexity found by our systematic review, we believe that future formal guidance should provide recommendations that still allow for topic area and modelling sequence differences. We recommend ensuring the transparency of the combined use of the LCA and future scenario methodologies, starting from the goal and scope definition, and then moving on to the modelling sequence (archetype choice) and life cycle inventory (LCI) modelling. We provide herein relevant and noteworthy examples of good practice in terms of future scenario development combined with LCA, as well a systematic overview of 125 existing methods and frameworks that can help practitioners in different topic areas and on different scales of innovation in their future-oriented assessments. Small-scale technology development articles provide solid recommendations for building LCIs for technologies and products that that are still under development. Medium-scale applications, such as for transport and waste management, provide suggestions on how to model novel solutions characterised by a strong interaction with the background systems in which they operate. Large-scale system development assessed in the energy technology field is useful in retrieving methods for large system overviews, in order to supply data for the future background systems in which emerging technologies and medium-scale solutions will operate. Finally, we highlight relevant examples of interpretation and decision analyses linked to specific archetypes, amongst which the hybrid archetype represents the most promising modelling sequence for combining future scenarios and LCA, since it ensures consistent scenario development and the systematic evaluation of scenario effects on the LCA model.

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Declarations

Competing interests The authors declare no competing interests.

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