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Sustainability and Future Trajectories: How is Prospectivity Integrated into Life Cycle Sustainability Assessment?

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Abstract. The energy transition and associated objectives like climate change mitigation, economic efficiency, social acceptance and security of supply require technologies that are sustainable. With the help of a Life Cycle Sustainability Assessment (LCSA), such a holistic evaluation of energy technologies can be carried out. This in itself is very complex, since criteria of the different sustainability dimensions have to be compiled and integrated to give an overall result. However, LCSA often only considers the current development status of technologies and not their potential future developments. Particularly in the case of emerging technologies, possible future improvements or even negative impacts may occur in the course of technology development, which could significantly change the initial LCSA results. An early consideration of future developments of technologies in the context of so-called prospective LCSA is therefore highly relevant, but also of high complexity and associated with uncertainties. We evaluated how this complex topic of prospectivity has been dealt with in the LCSA community so far by conducting a literature review. Focusing on LCSA of energy technologies, we present our findings related to commonly used prospective methods and data, the underling motivation of their application as well as research gaps and potentials for further development.

1 Introduction

The approach of Life Cycle Sustainability Assessment (LCSA) has been developed to address the environmental, economic and social impacts of the entire life cycle of a technology. In order to have this holistic view on technologies, a combination of the methods of Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA) is necessary [1]. In addition to the challenge of considering all three dimensions simultaneously, however, another major challenge is to determine "future" or "not yet realized" developments or optimisations of (emerging or mature) technologies as well as their future interactions with other systems. So-called life cycle inventory data such as efficiency,

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lifetime or yield can change over time e.g. due to improved production processes or technical innovations and lead to different environmental, economic and social impacts. Furthermore, the systems or rather system elements (system/actor behaviour) with which the technologies interact as well as their relationships to each other can become different in the future.

In order to deal with these future developments, some authors have tried to include a prospective view into their assessments and use therefore terms like “anticipatory” [2] , “ex-ante” [3], “dynamic” [4], “scenario-based” [5] or “prospective” [6]. Because the definitions for the terms are not consistent, we assume terms as being analogous and consider them under the overarching term of “prospective”. Considering the prospective view in a holistic LCSA, we define prospective LCSA as an assessment that covers the environmental, economic and social consequences and impacts of a technology in interaction with the surrounding system by means of an LCA, LCC, and SLCA, and in addition consciously incorporates changes over time in life cycle data, system/actor behaviour and/or their relationships.

However, the question arises with which approaches and methods a prospective view can be integrated into LCSAs and which challenges are associated with prospective LCSA. A look into the existing literature shows that there are no review articles on the topic of prospective LCSA, but only on prospective LCAs with a focus on environmental aspects. A common topic of these publications is the discussion of suitable methods for a prospective assessment. The mentioned methods include scenario development [3, 6–9], extrapolation (the use of learning curves for efficiencies, cost curves or economies of scale development) [3, 6–9], reviews of policy strategies for interventions or incentives [3, 7], socio-economic storylines [7], market diffusion models [7], document analyses (scientific studies/patents) [6, 8], expert interviews [3, 6–8], process simulations [6–9] or own assumptions [3, 8]. Moreover, in all mentioned review articles the challenges for conducting prospective LCA were identified, e.g. comparability between emerging and mature technologies in terms of technical functionality, data availability and uncertainty. However, the authors did not indicate what kinds of prospective data were used in the analysed articles. They also did not further investigate whether there were differences in the motivation to conduct prospective assessments among the articles reviewed or whether optimisation potentials were identified.

In order to answer these open questions mentioned before and to have a deeper view into ongoing research on prospective LCSA, we conducted an own literature review of existing LCSA studies. In this context, the following research questions emerged in detail:

- What motivated the authors of the reviewed articles to use prospective assessments?
- Which sustainability dimensions did the authors consider in their prospective assessments and what types of prospective data were used?
- Which prospective methods were applied in which frequency?
- Where did the authors see challenges and potential for optimisation of their applied prospective assessments?

2 Methodology

In order to detect articles potentially relevant to the topic, the “Web of Science” database was queried using the search string “life cycle sustainability assessment” within our literature review. In Fig. 1, the whole procedure of literature review is shown.

We limited the search query to the document type of “articles” published from 1970 to 2020. Within this scope, we identified 155 articles. Before systematically analysing the 155 articles, all articles that did not show a prospective view were sorted out in two steps (coarse and fine selection). Consequently, we identified 23 articles which were evaluated on the basis of the frequently recommended content analysis of Mayring [10].

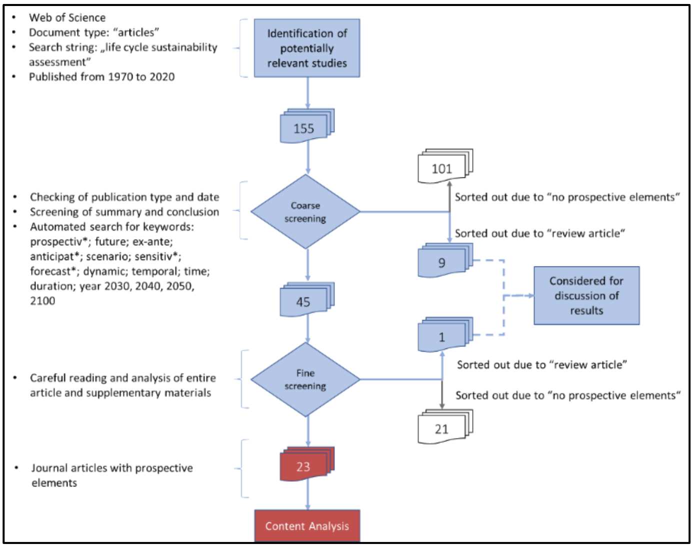

Fig. 1. Procedure of literature review employed in study (own figure)

3 Results

First, all 23 articles were classified according to their research field in order to limit the analysis to the field of energy. Thus, 14 articles with reference to the energy sector could be identified, of which the authors focused on the prospective LCSA of propulsion systems for vehicles in 8 [11–18] and on fuels/energy carriers in 2 articles [19, 20]. 4 studies dealt with the assessment of energy systems, 3 of which refer to countries like Spain or UK [21–24].

3.1 Motivation of authors

Regarding the motivations of the authors to conduct a prospective LCSA, it was found that a majority of the authors considered the possibility of representing changes over time or a dynamic complexity and its effects to be important (cf. [12, 19]). For instance, Kohlheb et al. stated that *"since electricity is an important source of emissions, we scrutinized how much difference a change in electricity mix can produce"* [20] p.7. Furthermore, by considering future changes, most of the authors aimed to provide ex-ante decision support to various stakeholders (esp. policy-makers) (cf. [17, 21]).

3.2 Sustainability dimensions and type of prospective data

In 12 of the 14 articles, impacts related to all three sustainability dimensions were prospectively assessed. Only the authors Kohlheb et al. [20] and Wang et al. [12] have taken impacts just related to the ecological and economic dimension into account. Regarding the type of prospective data, we found that most of the authors (10 articles) changed the "electricity or fuel mix" over time, which had again an effect on the impacts within the different dimensions (e.g. [11, 17, 18, 21]) (cf. Fig. 2). Moreover, data like efficiency or demand for power/technologies were considered over time and had an effect on different economic, environmental and social levels. Focusing more on the economic dimension, in 8 of the reviewed articles the "costs" of energy technologies or systems had prospective character (cf. [23, 24]). Next to the costs, also changes in subsidies (esp. for the use of

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alternative propulsion systems) were considered over time (cf. [11, 12]). Prospective data on matters attributed to the social dimension (efficiency, employment/jobs and worker injuries/fatalities) were only collected in 5 and 3, respectively, articles (cf. [11, 21, 23, 24]).

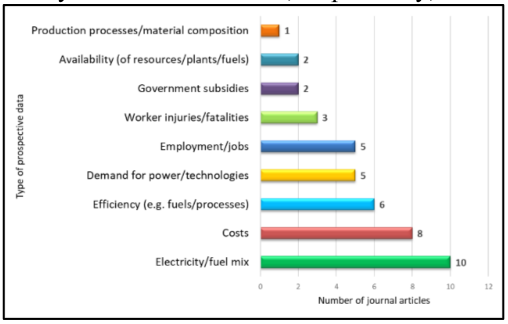

Fig. 2. Type of prospective data used in the reviewed articles (n=14; multiple entries) (own figure)

3.3 Prospective methods

With regard to the prospective methods applied in the reviewed articles, we observed that the authors often combined different prospective methods. Most of the authors (10 articles) used the method of literature review (cf. Fig. 3). Often, they took scenarios from other studies to collect knowledge about the prospective data mentioned in section 3.2. For instance, it is noticeable that the Energy Outlook Reports and Economic Projections, respectively, of the U.S. Energy Information Administration, International Energy Agency, Organisation for Economic Co-operation and Development and International Renewable Energy Agency were mentioned as sources in the articles (cf. [16]) esp. to get information on future energy costs.

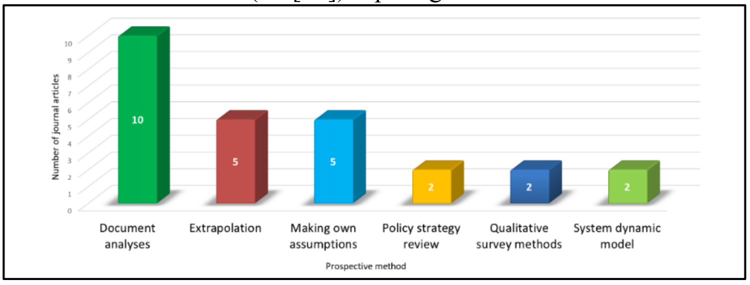

Fig. 3. Prospective methods applied in the reviewed articles (n=14; multiple entries) (own figure)

In five of the 14 articles, the authors applied methods like learning curves/rates and linear estimations/regressions, which we have summarized under the generic term of extrapolation (cf. [12, 16, 21, 23, 24]). E.g., Aberilla et al. stated that *"a regression analysis of published values has been used to estimate direct employment in desalination plants"* ([23] p. 5). Stamford & Azapagic 2014 extrapolated injury rates to the future based on historical trends ([24] p. 202). Moreover, we observed that some of the authors (5 articles) came up with own assumptions without citing sources or methods [11, 14, 17, 18, 20]. For instance, Onat et al. considered two battery charging scenarios related to the electricity mix in their studies; in scenario 1 the electricity mix was based on the existing electricity infrastructure, in scenario 2 on solar power [17, 18]. It is also worth noticing that in two of the articles policy strategies of countries were reviewed to determine prospective data [12, 14]. For instance, Wang et al. [12] considered the future changes of government subsidies and preferential tax policies in China for electric vehicles within the economic dimension, whereas Onat et al. took the 10% electric vehicle market penetration rate set by the government of Qatar into account.

Furthermore, methods like qualitative survey methods and system dynamic models were also applied, but only in 4 articles (cf. [15, 21]).

3.4 Optimisation potential

An additional objective was to find out more about the optimisation potentials formulated by the authors related to the application of their prospective assessments. This should also serve to identify existing research gaps in the field of prospective LCSA (see chapter 4 for details). In 6 studies, the authors mentioned the uncertainties in prospective assessments as a challenge and the need to focus more on this by means of uncertainty analyses [13, 16–18, 21, 24]. The uncertainties apply, for example, to lack of data and the need to make assumptions (cf. [13]), or the use of data that is not spatially or temporally resolved (cf. [17]). For instance, Azapagic et al. pointed out: *"It should be noted that some uncertainties are inherent within future scenarios. In this case, the development of technologies cannot be known with certainty ex ante* […]*"* ([21] p.99). Closely related to the demand for uncertainty analyses is the need to incorporate system dynamics approaches to have a better understanding of the future system behaviour (cf. [14, 16–18]). Other authors criticised the general lack of prospective data and the related research focus on a limited number of indicators (cf. [13, 14, 24]). Finally, we found that some authors considered the integration of less subjective but more generally valid data to be necessary and the application of statistical methods to be useful [12, 19]. On the other hand, the increased integration of stakeholder perspectives and their individual knowledge related to future developments was advocated [24].

4 Discussion and Conclusion

In comparison to the state of the art with focus on prospective LCA presented in chapter 1, we were able to determine that our findings show similarities. Methods such as document analyses, extrapolation, qualitative survey methods or making own assumptions are also used in prospective LCSA. Regarding the use of scenario analyses, we found that scenarios were only taken from other publications or collected by expert interviews, but not carried out as method by the authors themselves. Moreover, types of prospective data were not identified in the state of the art and therefore they cannot be discussed compared to our results. With regard to the challenges and associated optimisation potentials, the handling of any uncertainties and the lack of data could be identified, just as in the prospective LCA studies.

Of course, we must emphasise that our study is associated with uncertainties or limitations. This concerns the scope (e.g. search string as well as type and date of publications) we have selected for the literature query. In addition, as mentioned in the introduction, we developed a working definition that served as a means of identifying LCSA articles with prospective elements within the coarse and fine screening. Both, the actual definition and the interpretation of this definition to select adequate articles, are subjects of subjective judgements. Finally, the articles were only examined for the extent to which their prospective assessments relate to life cycle inventory data. Prospective assessments, e.g. concerning the impact assessment method or the Multi Criteria Decision Analysis were not considered.

With our review article, we are able to fill an important research gap, namely to provide an overview of the use of prospective assessment in the context of LCSA on the field of energy. Compared to other review articles, we were able to gain deeper insight into the types of data that were varied over time and these are particularly data like electricity/fuel mix and costs. With regard to the prospective methods commonly applied, we found that document analyses and extrapolations were mainly used in addition to making own assumption. Scenarios for specific data are often used, but in most cases are extracted from other studies or reports. Furthermore, we identified a particular need for the integration of uncertainty analyses associated with prospective data. For instance, uncertainties like a general lack of data or the need to use data that are not specific to the study´s subject were mentioned. In addition, the demand for system dynamic approaches was expressed in order to be able to better take dynamic changes and feedback into account. Finally, we could draw the conclusion from our analysis that there is still a general lack of a holistic prospective LCSA approach. Often in the reviewed studies, the prospective methods or data were integrated into the LCSA without a systematic approach. It would therefore be beneficial to develop an approach that builds on the already established steps of an LCSA in a structured form to show starting points for a prospective assessment and to suggest possible prospective methods including the integration of uncertainty analyses.

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