Life cycle assessment-based guidance for development of new energy technologies

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Summary

The development of new environmentally sound technologies is seen as a key route towards achieving sustainability. Also technology is regarded as the most important factor in the scientific field of industrial ecology for reducing environmental impacts of anthropogenic action. Developing greener, cleaner and more efficient technologies (using fewer resources or using them more efficiently) has therefore increasingly become the focus of many research projects that include the need to assess the potential future environmental impacts of technologies in the early development stages. The aim of this thesis was to develop a forward-looking assessment method based on LCA that can be used to integrate early insights in potential environmental impacts in R&D, with a specific focus on new energy technologies.

The research performed was structured around three complementary and successive research questions:

1. "What boundary conditions are required for LCSA to be a useful approach to assess early stage technologies?" (chapter 2)
2. "Which challenges are encountered in practice when LC(S)A is applied to assess early stage technologies?" (chapter 3 and 4)
3. "Can we find generalizing principles to assess the future environmental impacts of technologies in early stage of development?" (chapter 5)

At the start of the thesis research trajectory, life cycle sustainability assessment (LCSA) was the most comprehensive form of LCA available. A logical point of departure for this thesis was to therefore start with investigating the applicability and usefulness of LCSA for the assessment of new technologies (question 1). Since shortcomings of the LCSA approach were found, the decision was made to perform two LCA case studies concerning two technologies in early stages of development to investigate the challenges that are encountered in practice when performing an LC(S)A study (question 2). Finally, all insights were combined in formulating a general approach to guide upcoming ex-ante LCA studies (question 3).

Chapter 2 answers question 1 and explores the boundary conditions for the LCSA framework to be useful in the early assessment of new technologies. The conclusion of chapter 2 is that LCSA as a holistic, open method is not specific enough for performing a dedicated ex-ante LCA of novel technologies. An LCSA study should be initiated with a broad, but relevant system description. A missing thorough system description leaves ample room to manoeuvre in discussing the efficacy of a new technology, but

hampers the execution of a strict assessment. This makes it difficult to give developers of new technologies precise guidance on pathways with which the environmental impacts of such new technologies can be minimized. Starting the assessment with a thorough system description enables answering questions on a new technology's potential impact in a concrete manner that provides insights for further R&D of these technologies.

Chapter 3 reports an LCA case study on the production of fuels from CO_2. There is an increasing interest in using CO_2 as a resource to produce a new form of liquid hydrocarbon fuels. When these fuels are produced by solely using solar energy, they are labelled as solar fuels and claimed to be sustainable. Chapter 3 takes a quantitative approach to investigate some of the sustainability claims concerning solar fuels. The life cycle performance of various classes of solar fuel processes using different primary energy and CO_2 sources were analysed. It was concluded that producing liquid hydrocarbon fuels starting from CO_2 by using existing technologies requires much more energy than existing fuels. An improvement in life cycle CO_2 emissions is only found when solar energy and atmospheric CO_2 are used.

Chapter 4 reports an LCA case study in which mono-ethanolamine (MEA) based post-combustion-capture (PCC) of CO_2 with a new technology called humidity-swing-based DAC (HS-DAC). Most carbon capture and storage (CCS) envisions capturing CO_2 from flue gas by using post combustion capture where DAC is deemed unviable because of the higher energy associated with CO_2 capture at low atmospheric concentrations. Chapter 4 looks beyond the capture process alone and shows that given suitable temperature, humidity, wind and water availability, HS-DAC can be largely passive and therefore HS-DAC can complement MEA-PCC in suitable geographies. In addition HS-DAC also enables CO_2 capture independent of time and location of emissions and van re-capture background GHG emissions from fossil-based electricity beyond flue stack emissions.

The main insights from executing the case studies in **chapters 3 and 4 answer question 2**. First, for setting up an ex-ante LCA study, more effort and resources should be attributed to defining the function or future application of a new technology when performing an ex-ante LCA. The basis of any LCA model lies in defining system functionality and the functional unit. A simple rule of thumb in the field of LCA says that the function of a system should be chosen as close as possible to the "end use". In practice, this might require expanding the system boundaries to define a system in which all (or most) attributes of the technology under assessment are taken into account. The process of defining the technologies' application provides insights in its context consisting of competing technologies, but also (auxiliary) technologies required to make the new technology function as defined. Although the future application of a new technology might be uncertain, providing a strict definition to start with provides the foundation to investigate this uncertainty further, give insights in the technological system and navigate the technology developers to taking a systems perspective.

Second, applying a systems view to assess potential impacts of different alternatives is often not straightforward in technology development. This insight is based on various critiques on the case studies during journal review processes and informal discussions at conferences. It was often brought forward that the case study results reported only support the obvious (e.g. that making fuels from CO_2 indeed demands more energy input than conventional fuels). Another recurring remark was that the analysis was performed on a supposedly wrong or suboptimal system of technologies for the production of solar fuels, or for using direct air capture to capture CO_2 from the atmosphere. Instead of providing insights based on the knowledge available, some saw the studies as being biased. These critiques seem to be founded in common engineering practices in which the conventional stand is about getting a technical system to work. This automatically leads to optimizing specific process parameters such as process efficiencies and process production yields. These are then translated as having the lowest economic cost per ton CO_2 captured. It could be argued - or at least should be investigated from a systems perspective- whether a lower process efficiency also provides a lower systems efficiency which is necessary to improve the status quo situation. As a consequence of this experience it is recommended to put more effort in expanding the classical engineering approach and practice to include taking a systems view.

Chapter 5 answers question 3 by listing methodological challenges and providing potential remedies or a route forward for dealing with these challenges. The first challenge is how to model consistent future foreground systems for the incumbent and new technology systems. Learning curves and scenario approaches are the way forward. The second challenge is how to model future background systems. A solution here to transform existing LCI databases towards future contexts informed by the Integrated Assessment Models (IAMs) that provide scenarios in line with the Shared Socioeconomic Pathways (SSPs). Finally, uncertainty in ex-ante LCA is of a different nature as in ex-post LCAs. The main difference with conventional LCA studies is the highly uncertain information for the future. To acknowledge this, considerable attention should be attributed to the discussion on these uncertainties, both in the design of the assessment and the data used. Responsive evaluation can play a supportive role here. This will increase the transparency and efficacy of the results because the relevant stakeholders and experts are involved. In this way, technology designers and other stakeholders derive insights on the influence of design choices or contextual factors (that are important, but hard to influence) on the potential environmental impacts of their foreseen technology.

Chapter 6 concludes that methodological challenges that are already common in conventional LCA are emphasized even more in ex-ante LCA and that ex-ante LCA is about the process not the numerical outcomes per se. It is the experience gained during the assessment that provides the insights, while the numbers used and numerical outcomes of the assessment help in explaining these insights. The experience gained from this research provides the following recommendations to improve the existing practice of ex-ante LCA. First, there is a need for experience in using scenarios that allow representation of new energy technologies and incumbents in a foreseen future. Second, to obtain representative future background data there is a need for further integrating the use of Integrated Assessment Modelling and LCI databases. Third, future assessments encounter increased levels of uncertainty. It should be investigated how to deal with these, for which a good starting point seems to be integrating responsive evaluation in the process of ex-ante LCA and investigating the possibilities of using the concept of deep uncertainty.