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

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Chapter 6

Conclusions
and
General Discussion

6. Conclusions and General Discussion

The aim of this thesis was to find a method that facilitates the integration of potential future environmental impacts in the development of new technologies, with an emphasis on energy technologies. The idea is that having these insights early in the development process will help researchers and developers in making better informed design decisions and prevent that these new technologies show new problems when they are eventually put to use.

In the field of Industrial Ecology, questions on environmental impacts are approached by taking a systems approach. This is also relevant for assessing new technologies because these are not developed or used in isolation, but make up part of a larger technical-economic system. Extensive experience on how to take an analytical systems approach is found in different LCA-based methods. LCA therefore forms the starting point for the method called ex-ante LCA, which is developed in this thesis. The main difference between the conventional LCA-practice is that LCA is normally applied *ex-post*, after a technology is implemented. Here we apply the use of LCA in an ex-ante manner, before a technology is implemented and widespread experience and data is available.

This thesis started by investigating the usefulness of the life cycle sustainability (LCSA) framework, at the time the most comprehensive LCA-based framework available for the assessment of new energy technologies (chapter 2). Since shortcomings in the LCSA approach were found when applied to novel technologies, the following approach was taken in a next step. Two separate LCA case studies assessing new energy technologies with future applications were performed to identify the challenges encountered when LCA is applied ex-ante (chapters 3 and 4). As a final step, recommendations and guiding principles for the further practice of ex-ante LCA were then provided. These were based on learnings from the case studies and a critical review of the current practice of LCA for the assessment of new technologies (chapter 5). This concluding chapter will provide a set of answers to the research questions posed in the introduction, based on the findings reported in chapters 2 through 5.

Guiding research questions covered in this thesis

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)

Further thoughts for future practice and research will be presented in section 6.4. These thoughts are based on experiences in disseminating the knowledge obtained including review processes encountered when getting the research published as well as based on informal discussions with peers at conferences and project meetings. While these insights and thoughts might be merely based on observations and may sometimes be more anecdotal than factual scientific observations, they do provide interesting insights in the daily practice of R&D. Ultimately they are used to outline a set of questions for further developing methods to guide R&D of technologies that are believed to provide a piece of the puzzle in shaping a sustainable future.

6.1 Question 1 - What boundary conditions are required for LCSA to be a useful approach to assess early stage technologies?

There was an ongoing lively discourse on the framework for Life Cycle Sustainability Analysis (LCSA) at the start of this research project,. LCSA was presented as a multidisciplinary framework capable of answering broad sustainability questions related to the life cycle impacts of products and technologies. Chapter 2 investigated if the LCSA approach could also be used to do a sustainability assessment of new technologies and what the boundary conditions are for such an assessment to be useful.

LCSA is intended as a broad framework of different methods with which different questions at different levels of analysis can be answered. The person performing the assessment should choose the method(s) applicable to answer the question posed in the specific case. Most studies applying LCSA lack a clear goal for the assessment and often miss a specific scope, which hinders setting up a clear research approach. Chapter 2 recommends that when used for the purpose of performing an ex-ante LCA, a first step in LCSA should be the definition of a thorough system description. This system description should cover at least the following elements: a technological description, the intended application or function of the technology, the expected market share (technology share in the mix), alternative and/or competing technologies providing the same function and which environmental impacts should be covered.

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 how the environmental impacts of such new technologies can be minimized. This was also the conclusion of a more recent review of sustainability assessment approaches based on life cycles which states that ”the presented holistic approaches for LCSA are either too broad or too narrow for scientific guidance. Therefore, many questions concerning LCSA are still open, e.g., regarding definition of sustainability dimensions and the desire or need for multi-criteria decision-analysis“ (Wulf et al. 2019). Starting the assessment with a thorough system description enables answering questions on a new technology's potential impacts in a concrete manner that provides insights for further R&D of these technologies. The overall conclusion is thus that LCSA as a holistic, open method is not specific enough for performing a dedicated ex-ante LCA of novel technologies.

6.2 Question 2 - Which challenges are encountered in practice when LC(S)A is applied to assess early stage technologies?

Two case studies to assess the environmental impacts of two early stage technologies were performed with the insights from chapter 2 in mind. With these case studies, hands-on experience with the challenges that arise when applying LCA to new technologies was obtained. These insights were used later to formulate guidelines for ex-ante LCA in chapter 5.

6.2.1. Case study 1: Energy and climate impacts of producing fuels from CO_2

An LCA case study that assesses the energy and climate impacts of producing liquid hydrocarbon fuels from CO_2 is reported in chapter 3. In this case study the required technologies in themselves are not specifically new. The different technologies in the system assessed, are however, at different stages of development. For example, using the Reversed Water Gas Shift (RWGS) reaction to produce CO is still in the experimental phase (applying the reaction in the other direction, known as the water gas shift reaction is common practice in steam reforming of fossil fuels). In comparison, post combustion capture of CO_2 has been occasionally applied at an industrial scale and there is abundant experience with the Fischer Tropsch reaction. The combination of the technologies to produce hydrocarbon fuels has not been applied at an industrial scale nor are these fuel types yet available on the market.

The literature review in chapter 3 made clear that this fuel production route is believed to provide a sustainable fuel for the future. The aim of the case study was to scrutinize the broad and abstract claims used to support this belief in a quantitative manner. The claims were quantified by applying conventional LCA, basic physics and chemistry were used to quantify data not readily available in existing LCA databases. The study set up was designed and reported in a transparent manner so that assumptions and the numbers used are easily accessible and the outcomes could support the discussion on the efficacy of these fuels. The main conclusion was 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. Therefore, when looking at currently available technologies, the production of fuels from CO_2 is a very long term niche at best and not the panacea suggested in the recent public discourse (section 3.4 in this thesis).

Since the case study research presented in chapter 3 has been performed, science has progressed and much more research has been done on the environmental gains of using CO_2 as a feedstock for chemicals and fuels. Here we make some additional remarks to put the research performed in context.

To start, in chapter 3 we assumed that in the alternative biofuel production route, the growth of biomass extracts CO_2 from the atmosphere. More recent studies (i.e. Daioglou et al. (2017)) make clear that large quantities of CO_2 are emitted into the atmosphere caused by the initial removal of vegetation when setting up biomass plantations. Although this was not the main focus of the research presented in chapter 3, it should be stressed here that, when taking these more recent insights into account the environmental impact for biofuel production would even be less favourable than presented in chapter 3.

Second, Liu et al. (2020) performed a similar study to ours but uses a hydroxide based process instead of humidity swing DAC process to supply the CO_2. The data for the study performed by Liu et al. (2020) is more elaborate and comes from a real time operating DAC plant, but still arrives as similar conclusions as presented in chapter 5. In addition Liu et al. (2020) also stress the importance of not neglecting the intentional motivation to produce fuels from CO_2, which is obtaining lower GHG emission to the atmosphere. This is an important remark and it was also experienced during the research performed in this thesis. In this context it is important to report that in practice there seems to be no favourable combination of environmental and cost performance (Fernández-Dacosta et al. 2019).

Third, in connection to the functionality discussion presented in chapter 3, other research (Wang et al. 2019) has been focussing on the most efficient use of excess renewable energy (in chapter 5 producing fuels from CO_2 with stranded renewables was one of the potential functions discussed). Wang et al. (2019) prioritize the application of excess renewable energy for useful purposes and find that using it to produce hydrogen as transportation fuel is the most efficient application. Wang et al. (2019) and Liu et al. (2020) contribute to an important discussion here which also shows that is crucial to be clear on the reason why you would produce fuels from CO_2. This discussion is even further investigated in the work performed by Tanzer et al. (2019; 2020). They also stress the need to keep in mind the initial motivation to develop negative emissions technologies or use CO_2 in new products as a GHG mitigation option. It is very important, as encountered in chapter 3 and 4 of this thesis, to clearly define systems boundaries (Tanzer et al. 2020; Tanzer and Ramírez 2019; Fernández-Dacosta et al. 2019) to allow assessing the carbon balance and all proposed properties of new technologies.

6.2.2. Case study 2: Comparing the environmental impacts of HS-DAC and PCC

An LCA case study comparing two CO_2 capture technologies: humidity swing direct art capture (HS-DAC) and post combustion capture (PCC) was reported in Chapter 4. HS-DAC is a new technology still in its development phase that allows the capture of CO_2 from the atmosphere and is not yet applied at an industrial scale. Although different in system setup, its performance is often intuitively compared to PPC which allows the capture of CO_2 at point sources. PCC is much further in development, and although it seems a promising technology for averting CO_2 emissions, it has only been limitedly applied on larger scales, mainly because of political and economic reasons.

In the case study a comparison was made between two systems in which electricity is produced from coal. Either PCC or HS-DAC was used to capture the CO_2 emitted. Defining similar functionalities for both technologies allowed for a fair and structured analysis. The main outcome of the study was that, depending on the right water conditions and the availability of fresh water, HS-DAC seems to be a good complement to PCC. DAC complements PCC in that where PCC allows for capture of only around 70% of life cycle CO_2 emissions of coal fired electricity generation, by that increasing environmental impacts of coal fired electricity generation on average by 30% compared to no capture at all. DAC allows to capture 100% of life cycle CO_2 emissions by increasing environmental impacts by 50% if DAC is driven by coal electricity and just 20% when DAC is driven by PV electricity.

Existing comparisons between PCC and DAC generally provide the concern that DAC's energy requirements are much higher than those of PCC. It will therefore have a far higher cost per amount of CO_2 captured and is therefore too expensive to apply for a sustainable future. What is easily forgotten, however, is that DAC has other favourable properties, such as the possibility to capture CO_2 at its potential storage location, by this eliminating the need for CO_2 transportation via pipelines. In addition, HS-DAC can also be applied for capturing background CO_2 emissions and even making up for non-CO_2 greenhouse gas emissions. These properties would even allow overcoming the restraining political challenges that PCC faces. This case study provides a quantification of some (for now) hypothetical scenarios to investigate the possibilities and restrictions of HS-DAC. It thus facilitates a more balanced discussion on the application and development of HS-DAC that goes beyond process efficiencies CO_2 capture yields per dollar spent.

Looking at research outcomes published after the work done in chapter 4 we now find that humidity swing DAC seems to be a more exotic form of DAC than currently focused on. For direct air capture the more mature technologies at this moment concern the use of hydroxide sorbents or amine minerals (Realmonte et al. 2019). Shortly after publishing the research from chapter 4, David Keith published the first highly detailed description of a hydroxide based DAC paper (Keith et al. 2018). The details in that paper were drawn from commercial experience, where the study performed in chapter 4 was based on basic physics-based calculations and a very first lab scale prototype.

Recent studies on the performance of DAC technology are based on more mature technologies but arrive at similar general conclusions saying that DAC has a definite role in GHG mitigation efforts and will be most contributing when developed and applied alongside other negative emissions technologies (Realmonte et al. 2019; Fasihi et al. 2019; de Jonge et al. 2019).

6.2.3. Insights from the case studies

The main insight from doing these two case studies is that even 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 or even change from a cradle to gate (e.g. capturing CO_2) to a cradle to grave (e.g. producing CO_2 free electricity from coal) assessment to define a system in which all (or most) attributes of the technology under assessment are taken into account. This requirement of expanding system boundaries causes an ex-ante LCA assessment to automatically look beyond the technology under assessment alone and also identifies auxiliary technologies that are required for making a technology perform its function.

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, gives insights in the technological system and navigates technology developers in taking a systems perspective.

Taking a systems perspective is important to not lose sight of the reason why the development of a new technology is initiated in the first place. We need to remember that technology is a means to an end and not a means on itself. For example, technologies that capture CO_2 enable the reduction of CO_2 emissions to the atmosphere caused by fossil fuel use. This reduction is needed to keep temperature rise below 2°C with the ultimate goal to reduce climate change. In the end these technologies are not developed to capture as much CO_2 as possible, which sometimes seems to be the main focus of people involved in developing these kind of technologies.

The insightful challenge of defining the function of a technology is well illustrated in the case study on producing (solar) fuels from CO_2 presented in chapter 3. In the discourse around solar fuels, a combination of intuitive arguments is used to substantiate general claims on the sustainability of these fuels. However, when attempting to quantify these arguments with an LCA, more specific questions concerning the technologies context need to be answered in order to set a running model that makes sense. The separate unquantified arguments to support the case for producing fuels from CO_2 are repeated below, while immediate questions from the LCA practitioner are added.

1. Argument: Solar fuels can be used in the existing energy infrastructure. Immediate LCA questions: But do solar fuels have better environmental performance than incumbent fuel technologies that also use the existing infrastructure? How do we represent the incumbent? How do solar fuels relate to other fuel technologies such as hydrogen or electricity?
2. Argument: Abundant CO_2 and renewable energy can be used to provide scarce hydrocarbon fuels. Immediate LCA questions: Is CO_2 abundantly available for the production of fuels? Which technology do we need to supply sufficient CO_2 of good quality to produce these fuels?
3. Argument: Solar fuels are a way of storing solar energy. Immediate LCA question: Which other energy storage systems exist and how do these perform compared to producing fuels from CO_2?
4. Argument: By producing solar fuels one can offset costs of CCS by making valuable fuels and underground storage of CO_2 only costs money. Immediate LCA question: Is the main goal of CCS not to separate CO_2 from the atmosphere? Are we talking about two different functionalities, making money vs preventing CO_2 from entering the atmosphere, that cannot be compared vis a vis?

Asking these questions is not intended to disqualify the idea of making fuels from CO_2, but is vital in investigating if the production of solar fuels might indeed be a good way to go. Answering these questions would at least identify the conditions under which solar fuels might make a contribution to a sustainable future. Performing an ex-ante LCA with the cooperation of technology developers provides insights by discussing possible applications of foreseen technologies and brings to light the conditions under which a technology is more likely to improve the status quo. It seems, however, that technology developers are not always comfortable with looking beyond the isolated efficacy of their technology alone, while it might be beneficial to at least be aware of other issues that do influence the overall environmental performance of a new technology in the end.

The case study in chapter 4 illustrates the need for attributing sufficient resources to defining a technologies application in its intended system as well. Rejecting HS-DAC to PCC based on costs or energy consumed per unit of CO_2 captured is like rejecting a car with high fuel consumption that seats six people and has big storage space over a smaller car with lower fuel consumption that only seats two people and has only limited storage space. That might be justified when the car's functionality is defined as driving in a city environment. However, when going on a family holiday the higher fuel consumption suddenly becomes less of an issue. It all depends on how you use a specific technology; without making a comparison in functionality, the comparison easily becomes arbitrary and unfair.

Another interesting insight from performing the casestudies is based on various critiques on the case studies during the journal review processes and informal discussions at conferences. It was often brought forward that the case study results report only support the obvious (e.g. that making fuels from CO_2 indeed demand 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 that a lower process efficiency also provides a lower systems efficiency which is necessary to improve the status quo situation. This can however only be investigated by taking a systems perspective. 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.

6.3 Question 3 - Can we find generalizing principles to assess the future environmental impacts of technologies in early stage of development?

Experiences from the case studies described in chapters 3 and 4, supplemented by reviewing existing studies that use LCA to asses new technologies provide valuable insights in the practice of ex-ante LCA. The main challenges for ex-ante LCA and recommendations to overcome these challenges are reported in chapter 5. In this section these findings are generalized with the aim to provide guidance for upcoming ex-ante LCA studies.

The first challenge for ex-ante LCA is modelling consistent future foreground systems for both the incumbent and the new technology. A second challenge is to model a future background systems that is consistent with the foreground system. The final challenge is dealing with highly uncertain information that is inherently connected to forward-looking assessments.

A general recommendation for dealing with these challenges is of a more philosophical nature. In order to perform an ex-ante LCA the assessment requires a shift from a positivist approach - in which one assumes that the world can be fully known by observation- to a more constructivist approach in which one assumes that the world cannot be fully known because of different sources of knowledge that cause differences in interpretation of observations. Ex-ante LCA studies encounter such high uncertainties and require considerate assumptions that it is more informative to base the study performed on debate rather than on fixed statements that are gratuitously presented as correct. The ongoing debate uses and provides information from the LCA model constructed.

It is recommended to follow the existing conventional LCA framework when performing an ex-ante LCA. The following questions should, however, be covered and preferably answered explicitly per LCA phase.

1. Goal and scope phase
    - At what moment in time is the new technology expected to be operational at which level of maturity?
    - How does the functional unit need to be defined so that the new and the incumbent technology provide the same (similar) functionality?
    - How can the incumbent technology be defined?
2. LCI phase
    - How will new technological systems develop into the future, perform under the scope defined and is representative LCI data available?
    - How will incumbent technological systems develop into the future, perform under the scope defined and is representative LCI data available?
    - How will background systems and their performance develop over time, perform under the scope defined and is representative LCI data available?
    - What is the potential market share of the new technology in the future?

3. Impact assessment phase
    - Can the new technological systems display unexpected new impacts not yet covered in LCIA?
    - Can characterisation factors relevant to the incumbent and new technical systems change over time?
4. Interpretation phase
    - How can the increased uncertainty around modelling new technologies in the future be dealt with?
    - How can the possibility that new technologies will display unknown unknowns be dealt with?

Answering these questions might not always be the direct forte of an LCA practitioner and it involves branching out towards other scientific disciplines and practices such as social sciences, responsive evaluation, scenario building, integrated assessment modelling and more advanced techniques to deal with increased uncertainties like the concept of deep uncertainty. Consequently, this means that in an ex-ante LCA project more effort should be attributed to involving the right stakeholders and experts on the additional methods proposed. Different disciplines provide different insights that are all valuable in answering the bigger questions of sustainability. While doing ex-ante LCA it is preferable to investigate these differences and integrate the outcomes as part of an ex-ante LCA study.

Interest in performing ex-ante LCA studies to guide emerging technology has recently increased and a variety of recommendations to perform such studies have been published (Thonemann et al. 2020; Buyle et al. 2019; van der Hulst et al. 2020; Moni et al. 2020). It seems that a lot of research on the same topic has been performed in parallel, showing the need for guidance in performing ex-ante LCA. In general they all come to similar conclusions regarding the challenges of performing ex-ante LCA, which are *comparability* (choosing the functional unit and system boundaries), *data availability* (no data for the future) and uncertainty. Where Moni et al. (2020) and Thonemann et al. (2020) focus on presenting a framework on how to perform an ex-LCA study. Like is done in chapter 5 of this thesis Van der Hulst et al. (2020) and Buyle et al. (2019) focus more on the practical engineering approach development of new technologies and aim for providing knowledge to the technology development process than setting up the perfectly performed LCA study,. They do this by introducing using problem solutions spaces and participatory approaches (Buyle et al. 2019) or by focussing on the knowledge needed and available in the different phases of technology development (van der Hulst et al. 2020). As a final comment all emphasize that there is a need for a database to provide data on upscaling from lab to industrial scale technologies and on new materials that are developed and used for new technologies.

6.4 Reflections and suggestions for future research

This thesis illustrates that using LCA in the R&D stage of new technologies, provides valuable insights in potential environmental impacts of design choices. This thesis shows that methodological challenges that are already common in conventional LCA are emphasized even more in ex-ante LCA. Applying LCA to new technologies without giving these challenges proper attention will not provide any insights to the development of better technology.

The use of LCA for the identification of potential environmental impacts of new technologies is a very new field. Fortunately, more and more methodological experiences are being shared even though a general method for ex-ante LCA does not yet exist. This thesis aimed to provide recommendations on performing such ex-ante LCA by reporting experiences from the assessment of new energy technologies. The set up presented in chapter 5 is a solid starting point for application and further development of this method.

A critical step back is taken below to identify limitations and potential bottlenecks that need to be the focus of further research in this field.

Ex-ante LCA is about the process not the numerical outcomes per se

When reflecting on the relevance of the work presented in this thesis it seems that it is not so much the numerical outcome of the assessment that are important, but rather the insights one gains during the assessment. As stated by Mc Kone et al. (2011) in their LCA research on biofuels "LCA is a process and not a product," a statement that is well known by practitioners inside the LCA community which should also be communicated more explicitly to commissioners of (ex-ante) LCA research and technology developers.

The view on technology development coming from the work performed in this thesis is that the essence of technology development seems to be in developing technical solutions for big problems. The focus is often on getting the technology to work at the lowest possible costs. Presented environmental gains seem to be mainly based on intuition or taken for granted. For example, assuming that using solar energy or CO_2 in a technology is by definition sustainable might be the start of a hypothesis but does not prove this hypothesis to be correct. To investigate a hypothesis like this you need analytical tools that take a systems approach, e.g. LCA. However, if LCA is applied in technology development, it seems to be used to provide a stamp of approval for the technology being developed, not as a critical tool that helps to gain insights.

This can be illustrated using an anecdotal example from the field of artificial photosynthesis. In this technical scientific field, the aim is to develop technologies that produce hydrogen from solar energy and water. In a discussion on the use of iron or platinum as a catalyst to split water into hydrogen and oxygen, the proposal to investigate this in a broader perspective system was ignored because the focus was on obtaining the highest water-splitting efficiency and using indium would provide this high efficiency.

Taking a systems perspective one could have investigated the hypothesis that using iron, although providing lower efficiencies, would be less costly and less disadvantageous for the environment because it is more abundantly available than platinum. It would have been very insightful to investigate if the lower water-splitting efficiency based on using iron catalyst could be compensated by using more production facilities based on iron that in the end could provide comparable quantities of solar hydrogen at potentially lower environmental costs.

One side remark is in place here; technology developers working on new technologies with an MRL < 5 are still focusing on getting the technology to work and the fundamental science involved. Taking a systems perspective to investigate broader implications so early in research probably distracts efforts and resources from this fundamental step. However, using claims about future applications for new technologies are often required to obtain grants to do this research. We should be careful that these claims are not empty and based on intuition alone. It should be acknowledged that when claiming sustainability of a new technology that "for any specific technology, there is no set of design characteristics that would make it sustainable. Rather sustainability of a technology can only be determined through a socio-political process, as the process has to deal with various human capabilities and preferences. Engineers may be uncomfortable with this truth, but we do, both individually and collectively, have to humbly learn to live with this" (Mulder et al. 2011).

Applying ex-ante LCA in technology development almost automatically forces technology developers and all involved to look beyond the pure technological performance of a technology. For the development of technologies intended to make our future more sustainable it is important to take a systems perspective for which ex-ante LCA could be an option. Inviting the use of ex-ante LCA in the R&D process might indeed feel uncomfortable because it does not give one unambiguous answer on which design choices to favour. It could even show that primary intuitive claims on environmental gains turn out to be less favourable when quantified, moreover ex-ante LCA will even provide more questions to answer which hampers quick development of a new technology. However, ex-ante LCA does provide quantification of potential environmental claims and insights in the dependence on the context of a technology. These numbers and insights support making better-informed design decisions. The challenge in practicing ex-ante LCA is to support technology development by investigating solutions for potential barriers, while R&D engineers should allow the process to actually take place by acknowledging the importance for a systems perspective in R&D.

When to apply ex-ante LCA?

Throughout this thesis the question of when and where in the R&D process ex-ante LCA should be deployed has been lingering. The Collingridge dilemma still seems to apply here. If ex-ante LCA is applied too early, it interferes with the fundamental science needed to develop new technologies, if we do this too late, required changes cannot be initiated because of technical lock-inn.

A practical way of answering this question is to make use of the MRL of a technology. A critical note is in place here. In reality, it is not straightforward to assign an MRL level to a technology because in reality technology development does not start from scratch (MRL 1). It starts by combining different technologies at different development levels into a technology for which the application will become clearer when its MRL increases. When the technology up for assessment can be defined as "a body of technologies" (Figure 1.3) using MRL levels seem to be informative and allow for giving practical recommendations.

Ex-ante LCA is best applied to technologies at MRLs between ~3 and ~7. Technologies at an MRL below 3 are mainly subject to fundamental science for understanding basic (natural) principles. In this phase R&D is still far from managing these principles and it is therefore very hard to identify possible applications of the knowledge developed. Since it is fundamental to define the potential functionality of a new technology as a first step in the analysis, performing ex-ante LCA on technologies with MRL < 3 is not recommended. Qualitative discussions on potential application of a technology might, however, provide fruitful insights for shaping expectations. Data is still too uncertain and submerged in the realm of indeterminacy (see section 5.4) in this phase for quantification of environmental claims, and therefore ways to deal with these high uncertainties in ex-ante LCA need to be found.

Knowledge on technologies at an MRL between 3 -7 are becoming more concrete. It is easier to identify potential applications and come up with possible scenarios at these levels also there is still considerable freedom to change specific parts of the design of the technology under development. When MRLs rise above 7, changes in design might have become too difficult.

Future improvements in the application of ex-ante LCA

Having arrived at the end of this thesis, the concluding question is: how do we proceed from here? As presented in chapter 5, there are three practical areas for further research and development of the ex-ante LCA method. 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*.

Overall, it is important to understand that ex-ante LCA is a process in which relevant questions for technology development are dealt with. Answering these questions demands the involvement of the relevant stakeholders and facilitates the necessary discourse that leads to understanding the system in which these technologies are developed. When we understand that system it is also possible to identify the boundary conditions for new technologies to contribute to a sustainable system. Technology developers can influence part of these conditions (choices in materials and supporting technologies), by making changes in design. Other conditions are the subject of governance, in which it might be possible to alter the context of technology development, deployment and use. An ongoing discourse between technology developers and policymakers should therefore always been pursued and LCA can provide valuable input via quantification of certain options under discussion.

A last challenge is to determine who should be responsible for using and guiding the ex-ante LCA process. A good start seems to be LCA practitioners with a multidisciplinary background such as Industrial Ecology. In the end however, main insights come from experiences. To build experience in doing ex-ante LCA technology development projects should be encouraged to use ex-ante LCA and report their experience. This might even help to make engineers more comfortable with taking a systems perspective that is utterly important for developing new technologies that contribute to reaching climate goals.