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

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1

Chapter 1

Introduction

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Toward Sustainability Through Technology

1. Introduction – Toward Sustainability Through Technology

Research, development, deployment and widespread diffusion of new environmentally sound technologies is a major route towards achieving sustainability (United Nations 2017; Giovannini et al. 2015). In the Emissions Gap Report 2018 by the UNEP it is made clear that current efforts to reduce GHG emissions to keep global warming below 1,5 degrees Celsius by 2030 are not sufficient. By 2030 GHG emissions should be 25% lower than in 2017 to stay below a 2 degree temperature rise and even 55% lower to keep this rise below 1,5 degrees Celsius. According to UNEP, the key component to reach climate targets is to be found in the acceleration of innovation and increased investments in new technologies (Olhoff and Christensen 2018).

The relation between technology and sustainability has some paradoxical features. Technology can be seen as both the cause and the remedy for detrimental environmental change, but it also allows for monitoring this environmental change and can be seen as liberating humanity from environmental constraints (Grubler 2003).

In the scientific field of industrial ecology, technology is regarded as the most important factor for reducing environmental impacts of anthropogenic action. Industrial ecology's "master equation" (Graedel and Allenby 2010), which is derived from the IPAT equation (Ehrlich and Holdren 1971, 1972), is conceptually used to show the connection between environmental Impact (I) and the product of Population (P), Affluence (A) and technology (T).

$$\underset{\text{[impact]}}{(\boldsymbol{I})\boldsymbol{mpact}} = \underset{\text{[capita]}}{(\boldsymbol{P})\boldsymbol{roduction}} \times \underset{\text{[consumption / capita]}}{(\boldsymbol{A})\boldsymbol{ffluence}} \times \underset{\text{[impact / unit of consumption]}}{(\boldsymbol{T})\boldsymbol{echnology}}$$

The world population is expected to increase to around 8 billion people in 2040 (Randers 2012) and peak at 10,9 billion in 2100 (UN DESA 2019). This increase in population is hard to stop or redirect, although an improvement in education and healthcare in countries with lower income levels will limit the amount of children being born and will slow down population increase in the coming decades (Rosling et al. 2019).

Also an increase in affluence can be expected. Affluence is often expressed in GDP and GDP growth is the focus of most national policies. Virtually all authoritative economic forecasts used for economic policy assume GDP growth in the next decades. In addition, one of the Sustainable Development Goals of the United Nations is reducing poverty and inequality in the world which will make that people in poor and lower income countries will increasingly become more wealthy. This increase in affluence will show a trade off in increased environmental impacts (Scherer et al. 2018).

When Population and Affluence will increase and have positively connection to Impact, it is up to influencing the factor technology to reduce the impacts per unit of consumption to decrease the environmental impacts (Scherer et al. 2019; Chertow 2001, 13). We need to keep in mind here that, in the equation, Technology has a negative connection Impact. Meaning, that an increase in (improvement of) Technology decreases impacts per unit consumed.

This reasoning can also be found in the "Global Materials Resources Outlook to 2060" by the OECD. It reports that an increase in population and affluence will drive an increase in demand for goods and services that also involve higher material intensities(OECD 2018). It further states that "more than half of all GHG emissions are related to material management activities and the fossil fuel use in these activities also leads to larger energy related emissions from material and resource use" (OECD 2018). The International Resource panel of the UN adds that materials do not only have a large influence on GHG emissions, but also contribute to over 90 per cent of biodiversity loss and water stress" (Oberle et al. 2019). Both organizations point to technological improvements to slow the growth in future material demand and reduce global materials intensity to reduce environmental impacts (Oberle et al. 2019, 9; OECD 2018).

1.1 The challenge of technology development

1.1.1. S-curves and the technology life cycle

When hopes are put on developing and improving technology to reduce global environmental impacts, we need to know how technology development works and how we can develop technologies that actually address the environmental challenges we are facing. The development of technology is often described by the use of s-curves in which technology performance is plotted against time (Figure 1.1). It shows that technology development is not linear and unlimited, but rather goes through several stages in which the rate of development changes over time.

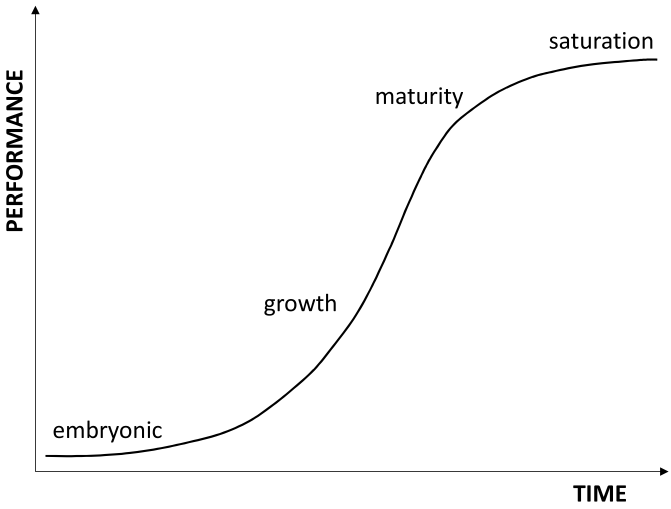


Figure 1.1: Technology development s-curve, based on Grubler (2003).

Using s-curves in combination with biological analogies can help to explain how technology develops through different phases in its life cycle (Grubler 2003). At the start we see a slow embryonic phase of exploration, research and development. In this phase production volumes and market shares are low because the focus is on demonstrating viability. Because of learning effects for both producers and consumers the applicability of a technology becomes clearer, its viability becomes more certain, and innovation becomes less risky. This is when a technology enters a period of growth in which performance improve faster. A technology enters a phase of maturity as costs and prices start decreasing. In this phase competition is driven by cost reduction rather than improvement of performance (Grubler 2003; Hirooka 2006, 128). Finally the pace of performance slows even further down as the market becomes saturated, and costs for further improvement the technologies' performance become too high.

1.1.2. Understanding the technology life cycle via innovation trajectories

Where s-curves help in providing a general picture of the life cycle of technologies, they do not provide details on what exactly happens in the different life cycle phases and how this might be influenced. More detail can be found in the work of Hirooka (2006) who uses empirical data to explain what happens in different development phases of technology development. He introduces the concept of *innovation paradigm* in which three consecutive trajectories for innovation and technology development can be discerned: the technology trajectory, the development trajectory and the diffusion trajectory. These consecutive (slightly overlapping) trajectories also follow the shape of an s-curve (see figure 2).

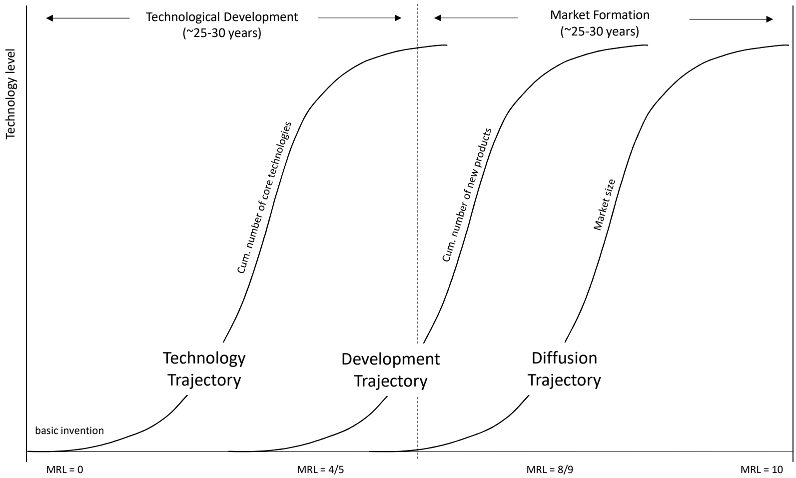


Figure 1.2: **Innovation Paradigm: three consecutive trajectories in technology development, based on Hirooka (2006).**

Hirooka (2006) explains that technology develops from idea or basic invention through development of core technologies to products that gain market share. He discerns two consecutive phases (left and right side in Figure 1.2) called *technological development* and *market formation*. The phase of market formation is the main focus in the scientific field of technology dynamics and has been extensively described by e.g. Geels (2002) and Hekkert (2007). Insights in the phase of technology development are however less commonly available.

The more tangible output of technology development can be found in the form of patents and is applied in new products. Hirooka defines technology development as "the phenomenon of knowledge transfer from one person to another in the field of human society" (Hirooka 2006, 130). Within technology development one can discern two trajectories. First, the technology trajectory, in which academic and industrial research institutes convert ideas into core technologies and patents. Second, the development trajectory in which these core technologies and patents are deployed into useful and marketable products.

The main insights from Hirooka's work for this thesis are the timeframes that he assigns to technology development. The time required for technology development is around 25-30 years, after which another period of 25-30 years is needed for full market formation. Using these time frames in combination with the description of different MRL phases (see box 1) we can construct a general technology development timeline that includes the different innovation trajectories and MRL scores (figure 1.2).

Box 1 - Connecting innovation trajectories to Technology (TRL) and Manufacturing Readiness Levels (MRL)

Technology Readiness Level (TRL) are used to indicate the level of development of a technology. From its original use, TRLs also found their way to other organisations like the U.S. Department of Energy (U.S. Department of Energy 2011). TRL was originally developed and introduced by the National Aeronautics and Space Administration (NASA) to assess the maturity of a technology and its fitness to be used in space.

The concept of TRL has been expanded into Manufacturing Readiness Levels (MRL). MRLs do not assess "just the maturity of a technology but also that of components and subsystems from a manufacturing perspective" (Gavankar et al. 2014). For the assessment of newt technologies it is important view these in their (intended) systems of use. This thesis will therefor use MRL as indicator to indicate the level of development of the technologies discussed.

Innovation Trajectory	**Technology Development stage**		**Technology Readiness Level (TRL)**	**Manufacturing Readiness Level (MRL)**
Technology trajectory	Conceptual development	1	Basic principles observed	Implications identified
		2	Formulation of concept	Basics identified
		3	Proof of concept	Proof of concept
		4	Validation in Laboratory	Laboratory sample
Development trajectory	Technology development	5	Components in representative (simulated) environment	Prototype components in simulated environment
		6	Prototype in representative (simulated) environment	Prototype system in simulated environment
	Engineering development	7	Prototype in operational environment	Prototype in production environment
	Small scale production	8	System qualification	Ready for small scale production
Diffusion trajectory		9	Technology ready	Transition to full scale production
	Mass production	10	n/a	Lean mass production

1.1.3 Technology development in practice

To come up with a practical approach for the environmental assessment of new technology we need more insight and further understanding of what happens in the technology development phase in a more practical sense. In other words, we need to know and understand what technology developers do and how they approach research and development so that the outcomes and insights of an assessment can be applied in the development of technology that will indeed provide an improvement for reducing environmental impacts.

Brian Arthur (2009) explains that technologies can be defined at different levels (see Figure 1.3). At the basis of all technology lies *science*, which allows us to fundamentally understand natural phenomena, e.g. the photovoltaic effect. If a natural phenomenon is 'captured' and can be 'steered in some sort of way', this is done by an *individual technology*, e.g. a PV cell. According to Arthur technology ultimately provides some sort societal functionality by "capturing natural phenomena that are orchestrated under human agency" (Arthur 2009). We will need to involve more technologies in tandem put a natural phenomenon is to good use. This groups of technologies we need for this are called *bodies of technologies*, e.g. PV technology or solar technology to provide us with renewable and clean energy. PV technology consists of PV cell but also of aluminum mountings and electronic convertors. When we talk about our reliance on technology for a sustainable future we are actually talking about *technology as a whole* without being specific.

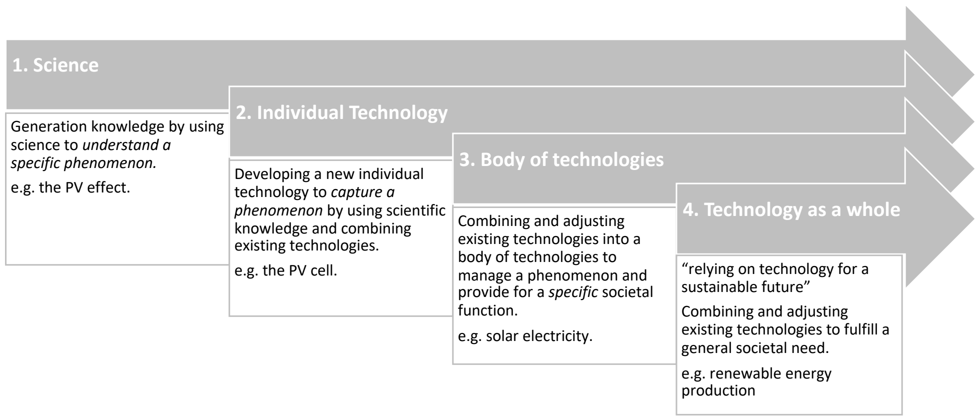


Figure 1.3: Different definition levels for technology, after Arthur (2009).

It is unavoidable not to mix up these different levels when discussing the development of technology. The different definition levels however also illustrate the process of technological evolution from idea to application and product. In practice existing technology is often used to develop new technologies that are better in managing natural phenomena or capturing new ones or put them to better use. Technology developers use the available stock of technologies and combine technologies from different levels in order to construct a new technology. This is a recursive process called *combinatorial evolution.* In this process suitable parts and functionalities of existing technologies from different levels are combined. "The initial version of a technology has a functional physical form and can only be pushed so far before some parts of its system run into a barrier that restrains it" (Arthur 2009). To overcomes these barriers technology developers apply other existing technologies that are taken from the total stock of technologies. This process of improving technology in small steps by introducing solutions to overcome internal design is called *structural deepening*. In essence technology is created out of itself and the larger the amount of available building blocks in the total stock of technology the bigger the chance for success and the faster development goes.

The processes of combinatorial evolution and structural deepening are daily practice for R&D engineers. When developing better technologies that have lower impacts on the environment it is important to understand that it is not only about getting the technology to work, but getting the technology to work in an environmentally sound manner. Different decisions to overcome design barriers will have different impacts on the technical performance and on the environmental consequences of these technologies. The possibility to assess pending decisions concerning combinatorial evolution and structural deepening during the R&D process is important so that a balanced choice can be made in the design of new technologies.

1.2 Technology development and time constraints

While the urgency in new technology development to face climate challenges is eminent it is just as important to realize that development and implementation of new technologies takes a considerable amount of time, especially when this technology has to replace old (unsustainable) technologies and has to fulfill a significant share of a functional and societal demand. "For global environmental transformations such as climate change, the long time-scale of technological change complicates decision making. The time-scale for pervasive technology approximates the time-scale of global environmental change. If climate change proves extremely serious, and we wait to act, it will be too late to implement the massive economic and technological changes required to reduce impacts." (Grubler 2003, 354)

Research on technology development time-frames mainly has mainly been done for the market formation phase. Kramer and Haigh (2009) have shown that it takes about 30 years for energy technologies to develop from introduction to the market to occupying about 1% of the world's energy mix. This 1% might be considerable when taking an economic look at global market shares but might only be a drop in the ocean for averting climate change for which established technologies with much higher market shares need to be improved or replace.

Hirooka (2006) has shown that developing a new technology from scratch until it finds its way in a product which provides for considerate market share can take 50 to 60 years. Fortunately not all technologies have to be developed from scratch although and when climate goals are set for 2030 we see that completely new ideas and technologies will not be able to contribute to those goals.

R&D of technology is subject to a phenomenon known as the Collingridge dilemma, which says; "when change is easy, the need for it cannot be foreseen; when the need for change is apparent, change has become expensive, difficult and time consuming" (Collingridge 1980). So in early phases of development is easy to make changes in design but we do not know the implications of a new technology until it has put to use. This is indeed a dilemma, when do we make the necessary changes? The inherent nature of a dilemma is that a way out is not possible using logic reasoning but is simply driven on personal choices. Assistance in making such choices might be found in early assessment of a technology's potential impacts by investigating different design choices, while keeping in mind that making the perfect decision is impossible.

Developing greener, cleaner and more efficient technologies (using fewer resources or using them more efficiently) has been and will be the focus of many research projects. It forms the backbone of many EU sustainability policies and research projects. To support the R&D of such environmentally sustainable technologies, international research frameworks, such as the European Horizon 2020 program (European Commission 2017), demand the application of life cycle assessment (LCA). Some examples of these research projects are as follows: Carbon4PUR (carbon4pur.eu) is a project in which it is investigated if CO_2 can be used as a resource for building insulation and coatings; The Sitasol project (sitasol.com) investigates new technologies to produce tandem solar cells; The Nano Tandem project (nano-tandem.ftf.lth.se) investigates the use of nano-technology in the production of tandem solar cells and pursues a balanced view on the environmental advantages and disadvantages of using nano-materials. All these projects use LCA to guide technology development. The research presented in this thesis was initiated in the Dutch, NWO funded, Biosolarcells project. This project focused on fundamental research on artificial photosynthesis and included an early stage assessment of environmental value propositions of solar fuels (Biosolarcells 2011).

1.3 Technology assessment and LCA

The scientific field of technology assessment (TA) develops methods to assess the potential implications of the introduction of a new technology in society. The aim of this field is TA is to "broaden and positively influence technology development processes by addressing potential innovation obstacles or impacts as early as possible rather than assessing ex-post the impacts of more-or-less finalized products."(Baumann 2017, 38). It tries "to reduce the human costs of trial and error learning in society's handling of new technologies, and to do so by anticipating potential impacts and feeding these insights back into decision making, and into actors' strategies." (Schot and Rip 1996). It also provides a context-relevant overview of potential practical consequences of the introduction of a new technology that serves as a base for communication about this technology and strategies for technology implementation" (Fleischer and Grunwald 2008).

TA usually applies qualitative narrative methods to present prospective sociotechnical scenarios informed via face to face interviews with stakeholders (Baumann 2017, 40). Overall technology assessment can be defined as a form of policy research that examines short- and long-term consequences (e.g. societal, economic, ethical and legal) of the application of technology (Banta 2009).

TA is mainly informative for policy makers by providing insights in potential concerns and opportunities of a new technology in a desired sustainable society (Rip 1998). It is a qualitative approach that focusses on informing society at large about potential socio-economic impacts and risks. It is therefore limited in informing technology developers or in technology design because it tends to be qualitative and lacks practical quantitative assessment of potential impacts of design choices. Life Cycle Assessment (LCA) in principle is a more suitable method for such comparative quantitative environmental assessments. However experience with performing forward looking assessment is still limited in the field of LCA.

The standard approach to LCA is described in box 2 below. The main strength of LCA is that it takes a systems approach which allows for identifying *problem shifts*; the shift of environmental impacts to different life cycle phases or to different environmental impacts as the result of a change in practice. E.g. the introduction of the electric car shifts CO_2 emissions from the car to the power plant. Or by reducing CO_2 emissions shift the problem to increasing demand for rare earth metals, needed in batteries and electric engines.

Conventionally, LCA is mostly used to evaluate technologies that already exist, are mature and are used in established markets (Fleischer and Grunwald 2008). LCA therefor uses general data that are based on the past performance of technologies. LCA until now did do not incorporate information of the future ahead and has therefore been kept outside the field of prospective TA (Fleischer and Grunwald 2008). One objective for contemporary TA to better address the sustainability challenge of technology development is to include and "develop LCA methodologies which allow the integration of (uncertain and incomplete) prospective knowledge" of new technologies under development (Fleischer and Grunwald 2008).

Table 1.2 lists some differences and characteristics of current approaches of TA and traditional LCA the required characteristics for forward looking LCA. TA and LCA should however not be considered competitors for technology assessment but should be seen as complementary. LCA should be tailored to include a forward looking perspective so that it can provide valuable insights for technology development. Developing such a forward-looking LCA method for the assessment of potential environmental impacts of new technologies is the main ambition of this thesis.

Table 1.2: Comparison of TA and LCA for early technology assessment.

Characteristic	Technology assessment	Traditional LCA	Needed for forward looking LCA
Research method	Qualitative	Quantitative	Quantitative
Research focus	Socio-economic impacts	Environmental impacts	Environmental impacts
		Life cycle or systems perspective	Life cycle or systems perspective
Research scope	Prospective	Retrospective	Prospective
Level of abstraction	High level of abstraction long cause effect chain	Low level of abstraction short cause effect chain	Low level of abstraction short cause effect chain
…	-	Comparative	Comparative
Goal	Policy support	Policy support	Technology design support
Research basis	Scenarios and probabilities	Empiric data	Expectations
Uncertainty	High but manageable uncertainty	Manageable uncertainty	High uncertainty

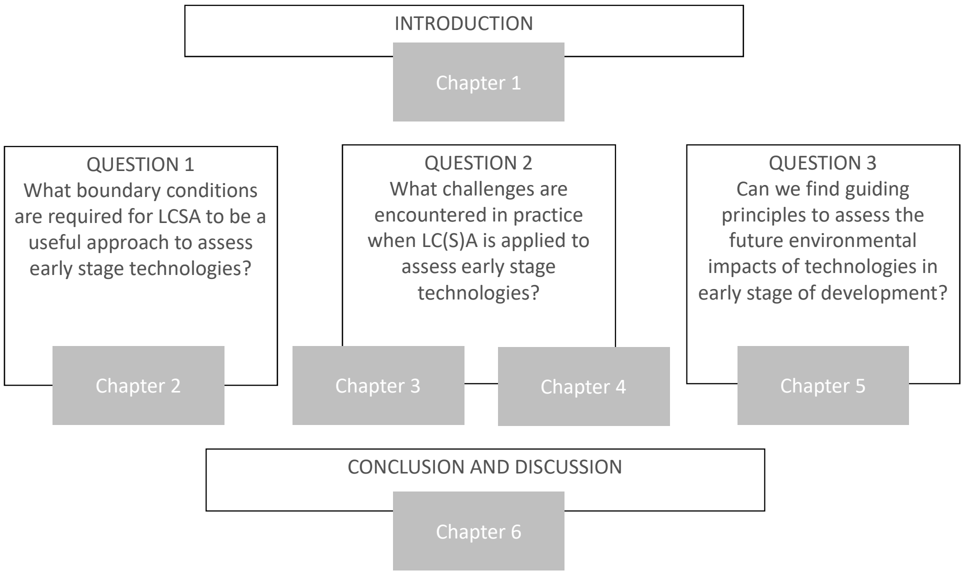


Figure 1.4: Thesis outline.

1.4 Aim, research questions and thesis outline

We identified a need to assess the potential future environmental impacts of technologies in the early stage of development. The aim of this thesis is 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.

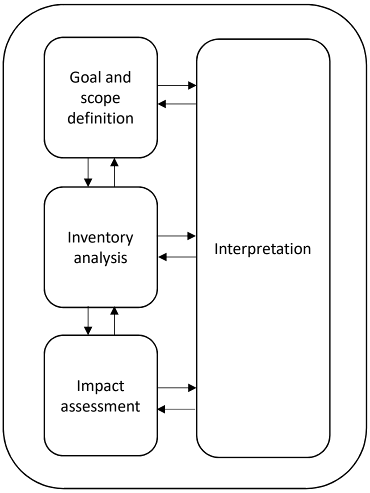
The research performed to propose a forward-looking LCA method to assess new technologies on their potential environmental impacts was guided by three research questions (see Figure 1.4).

At the start of this thesis trajectory, life cycle sustainability assessment (LCSA) was the most comprehensive form of LCA available. A logical point of departure for this thesis was therefore to start with investigating the applicability and usefulness of LCSA for the assessment of new energy technologies. Chapter 2 presents the research to answer question 1: "*What boundary conditions are required for LCSA to be a useful approach to assess early stage technologies?*" Since shortcomings of the LCSA approach were found, the decision was made perform two LCA case studies concerning two technologies in early stages of development: the production of fuels from CO_2 (chapter 3) and the use of two CO_2 capture technologies to reduce CO_2 emissions from coal powered electricity generation (Chapter 4). Experience and insights from these case studies help to answer question 2: “*Which challenges are encountered in practice when LC(S)A is applied to assess early stage technologies?*” Putting the insights from these case studies side by side with a broader literature review of existing studies performing forward looking LCA forms the basis for answering question 3: “*Can we find generalizing principles to assess the future environmental impacts of technologies in early stage of development?*” Finally, chapter 6 presents the answers to the research questions and adds broader insights and recommendations for the future.

Box 2 - Principles of Life Cycle Assessment (LCA)

LCA is used to compile all physical inputs (for example, energy and resources) and outputs (e.g. CO_2 emissions) and calculates the connected environmental impacts of a product system throughout its life cycle. There is a standardized procedure to perform an LCA, which can be found in the ISO 14040 - 14044 series issued by the International Organization for Standardization (ISO).

LCA comprises four iterative phases as presented in the figure on the right.



Goal and scope (GSD)
In the first phase of LCA the practitioner determines the goal and scope; why is this study done, how will the results be used (goal)? And what is the study about? (scope)

Life cycle inventory phase (LCI)
In the second phase of an LCA the practitioner makes a flowchart of the system in which all relevant processes are displayed. Then all extractions from and emissions to the environment are collected and quantified. The result of the LCI phase is an inventory table in which all exchanges between the system under assessment and the natural environment are shown.

Life cycle impact assessment (LCIA)
In the third phase of an LCA different predefined methods are used to group and aggregate the inventory data into environmental impact categories, e.g. greenhouse gas emissions like CO_2 and CH4 contribute to climate change. Other impact categories can be toxicity or resource use.

Interpretation
In the last phase of an LCA the outcomes from the previous phases are interpreted. Here it is possible to identify which processes contribute most to specific impacts, which is called a hotspot analysis. The practitioner also checks the potential influence of methodological choices, data-quality and uncertainty on the outcomes. These should also be reported to make sure that the work performed is in line with the goal and scope of the study.