Introduction

Life Cycle Assessment (LCA) is a method to assess environmental impacts of cradle-to-grave chains connected to products or services. It compiles and evaluates the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO, 1996). The environmental inputs and outputs include emissions, but also the use of resources such as land, water and minerals. Traditionally, this analysis is done at the micro-level and uses a static, steady-state approach. Recently, the LCA field has started to broaden its horizon. Life cycle thinking is now also used at a higher scale level, for forward-looking analyses and for assessing social and economic impacts. This broadened field of science is nowadays indicated as Life Cycle Sustainability Assessment, which is rather a framework than a method in itself. The development of quantitative methods for LSCA is now in full progress. This may open up possibilities to account for nexus issues in a more dynamic and integrated way. In this chapter, we briefly describe the LCA method and outline the potential of this method to address resource nexus issues. Then we will explore the possibilities of LCSA to include more of these aspects. We conclude by a summing up of the strengths and limitations of the LCA approach in addressing the resource nexus.

The LCA method

Environmental Life Cycle Assessment (LCA) of products and services is a method that has been developed over nearly 50 years. The first studies that are now recognized as (partial) LCAs date from the late 1960s and early 1970s (Assies, 1992; Guinée et al., 2011). Since then, an ISO standard has been published (ISO, 1996; ISO, 2006), and several LCA guides and handbooks have been produced (ILV et al., 1991; Lindfors, 1992; Grieshammer et al., 1991; Heijungs et al., 1992; Vigon et al., 1993; Lindfors et al., 1995; Curran, 1996; Hauschild and Wenzel, 1998; Guinée et al., 2002; Baumann and Tillman, 2004; EC, 2010; Curran, 2012; Klöpffer and Grah, 2014) providing general guidance and specific guidelines for practical LCA studies.

According to the ISO Standard, the method consists of four phases (see Figure 5.1).

In the goal and scope definition, the purpose of the LCA study is stated and a choice is made for the functional unit: the basis for comparing different product or service systems fulfilling the
same function. These choices, among others, determine the further work: system boundaries, data collection, impact assessment, etc.

The next phase is the Life Cycle Inventory (LCI) analysis. In this phase, the product system is specified. In LCA the system is typically cradle-to-grave: it includes all processes related to the production, use and waste management of the product or service. In the LCI phase, the system boundaries are established and economic and environmental flows of all unit processes in the chain leading up to the functional unit are quantified. The LCI can be considered as the most demanding part of the LCA since representative data need to be collected for all unit processes of the product system. Unit processes are specified according to environmental inputs (resources), economic inputs (products, services, energy and materials), environmental outputs (emissions) and economic outputs (products, goods, services and waste to be processed). To make up the flow chart of the product system, these unit processes are linked up into chains. Several LCI databases are available (see e.g. www.rivm.nl/Onderwerpen/L/Life_Cycle_Assessment_LCA/Databases). Usually, specific “foreground” data are added to tailor the LCA to the needs of the user. One of the methodologically most influential steps within the LCI phase refers to allocation: the treatment of multifunctional processes. It has been established that different ways of allocation can lead to widely different outcomes (see for example van der Voet et al., 2010). The choice for allocation is therefore a critical one. Unfortunately, the ISO standard is not unambiguous here: ISO offers a hierarchy of different methods to solve multifunctionality but the hierarchy can be interpreted in different ways in practice. We will show examples of how the choice for allocation can be relevant for resource nexus issues as well. The result of the life cycle inventory phase is the inventory table showing all the environmental interventions associated with a product system (Guinée et al., 2002).
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The next phase is the Life Cycle Impact Assessment (LCIA). In this phase, all extractions from and emissions to the environment are evaluated and aggregated into potential contributions to environmental impact categories. There are many ways of doing this. A general distinction is made into “midpoint” methods and “endpoint” methods. The midpoint methods translate the extractions and emissions into a potential contribution to a number of environmental impact categories, such as global warming, resource depletion, human toxicity and ecotoxicity. Multipliers are used, in LCA called characterization factors, expressing a particular environmental intervention in terms of a common unit, for example, Global Warming Potentials (GWPs) expressing global warming gases in CO₂-equivalents representing the midpoint infrared radiative forcing. The endpoint methods try to translate all emissions and extractions into impacts on human and ecosystem health, and on natural resources. To some extent, midpoint and endpoint methods can be translated into each other as, for example, shown by the ReCiPe (Goedkoop et al., 2013) and IMPACT2002+ (Jolliet et al., 2003) methods. A very controversial step in the LCIA is weighting: by giving weights to the different impact categories, a single score can be obtained for the product or service system’s environmental performance, which can be used for comparison with other systems. The ISO standard objects to the use of weighting in comparative assertions.

Present developments in LCA go in several directions:

- Finetuning the LCIA by adding new impact categories or refining existing ones;
- Developing LCA into a forward-looking tool by using consequential LCA or adding scenario techniques to attributional LCA (Spielmann et al., 2005; Hertwich et al., 2014);
- Adding context, for example via hybrid LCA or IPAT LCA: encompassing the LCA system into a model of the total economy to discover side-effects via broader economic mechanisms;
- Attempting to include more spatial and temporal differentiation, both in the LCI and the LCIA;
- Developing uncertainty and sensitivity analyses to comment on the robustness of the LCA outcomes, including data uncertainty as well as variability due to methodological choices;
- Broadening LCA into LCSA: Life Cycle Sustainability Analysis. This development is treated in a little more detail below.

Life Cycle Sustainability Analysis

LCSA is a new and potentially very relevant research field, which may in the end encompass many other methods of analysis. A generally accepted definition of LCSA is not yet available, but nowadays there is a small body of studies claiming to be LCSA studies. An up-to-date overview of the literature is provided by Guinée (2016). This publication also contains a discussion on LCSA definitions. LCSA is perceived as a framework and not as a specific method (Guinée et al., 2011). The idea of cradle-to-grave chains is maintained, but applied in a broader way than just to environmental impacts related to micro-level product or service systems. The whole development stems from the need for a life cycle approach to apply to other, broader types of questions than can be answered with the classic LCA.

Generally, the following aspects are included in the notion of LCSA:

- Broadening the scope by including social and economic impacts: adding Life Cycle Costing and social LCA to the environmental LCA to cover the three pillars of sustainability in one framework;
• Broadening the spatial scale by life cycle thinking to larger systems such as sectors or national economies that may change society’s metabolism as a whole;
• Broadening the temporal scale by forward-looking analysis: Life Cycle Scenario Analysis uses life cycle thinking in forecasting or backcasting scenario analysis to overcome the usually narrow focus and cover a broader array of relevant changes;
• Deepening the analysis by including economic and behavioural relations within the system besides technical relations.

To this end, other more macro-scale models are used, for example environmentally extended input–output models (see Chapter 9). Aspects such as the rebound effect, indirect effects of changes in technology via income effects, also require the use of macro-level models in addition to LCA models (Hertwich, 2005; Hofstetter et al., 2006; Thiesen et al., 2008; Girod et al., 2011; Druckman et al., 2011; Font Vivanco and van der Voet, 2014). A more elaborate treatment can be found in Guinée (2016). This whole area of research might become very relevant for nexus issues as well.

**LCA and the resource nexus**

In LCA, resource extraction and energy use is specified over the full life cycle of the product or service. We therefore know the complete resource requirements of certain products/services. This information can also be used to calculate “footprints” (see Chapter 8). At the micro-level, such footprints are essentially LCA studies with a single focus, such as water or land use, energy use, or GHG emissions in the case of the carbon footprint (ISO, 2012; BSI, 2008), related to the product or service.

This means that LCA can be used to specify the resource intensity of products/services. This is relevant information to quantify the resource nexus. By appointing 1 kg of a certain resource as the functional unit, it is possible to calculate resource and energy requirements to produce 1 kg of this resource. The LCA is then used in the cradle-to-gate mode, ignoring the application and the end-of-life phase of the resource. Kleijn et al. (2010, 2011) take such an LCA approach in specifying the linkages between energy and metals. This is elaborated in more detail in Chapter 28. Similarly, linkages between energy and water and energy and materials are explored by Graedel et al. (2015) (see Figure 5.2) and by Eckelman et al. (2013). Linkages between water and materials are also investigated on an LCA basis, a.o. by Norgate and Haque (2010) (see Figure 5.3). They specify their results in terms of MJ per kg produced material, or kg copper per MJ produced: the energy intensity of material production, or the material intensity of energy production.

This is a first step in the analysis of the resource nexus. A next step is then to identify places where the linkages are mutual or reciprocal. For example, to produce copper we need electricity, and to produce electricity we need copper. Thus, feedback loops are identified and to some extent quantified. The concept of the Energy Return on Investment (EROI) is used as an indicator for such a feedback loop, which can be calculated based on LCA outcomes (Fthenakis et al., 2011). The EROI specifies how much MJ of energy is required to produce 1 MJ of energy. The EROI is used mostly in the assessment of alternative fossil resources such as shale oil or gas from fracking (Hall et al., 2014), but also in the assessment of renewable energy technologies (see Figure 5.4). The same can also be done, for example, with environmental technologies: to reduce GHG emissions implies having extra GHG emissions related to building and applying the equipment (Singh et al., 2011).
Figure 5.2  Water requirement of energy technologies according to different authors
Source: Graedel et al. (2015)

Figure 5.3  Energy requirement of metal production as a function of ore grades
Source: Norgate and Haque (2010)
With LCA, therefore, we can map the resource intensity of and the linkages between resource usage for a particular product or service system as a steady state (steel needed for electricity production, electricity needed for steel production). This is without doubt very useful information in the analysis of resource nexus phenomena. What cannot be done with LCA is to map the intensity and linkages under changing circumstances, for example as a consequence of degrading ore grades. Therefore, the dynamic nature of the linkages and the influence of feedback loops on those linkages is probably better investigated by other assessment methods. One of the characteristics of LCA, in section 5.2 is the need for allocation in case of multifunctional processes. This need for allocation is also present in case of circular processes: waste recycling and secondary production. Although allocation is essential to having model outcomes in LCA, and probably in some other methods as well, it is not helpful for insight in the dynamics of the resource nexus. It is also a major source of variability in LCA outcomes.

Apart from unit process data (Henriksson et al., 2015), uncertainty and variability in calculating resource intensities arises mainly from allocation choices (Mendoza et al., 2015), allocation being a methodological step that is always required in cases of transforming waste into resources again. Examples can be found in the areas of bio-based energy and of metal production. In the case of metal production, mining delivers ores which usually contain many different metals. Not in all cases is it clear which metal is the “main” product and which are co-products or by-products. Some metals are even produced completely as by-products, or originate mainly from waste-treatment processes. In some cases, metals could be co-produced but are not for economic reasons, and then may be recovered later. In such cases, how to allocate the extractions and emissions related to the production processes? Using partitioning based on mass means the by-products have very little impacts allocated to them. Resource and energy intensity of by-products then would always be low. Using economic proceeds does justice to the driving forces but means the allocation changes whenever (relative) market prices change. Such difficulties arise, and need to be solved somehow, when calculating resource and energy intensities of metals.

In the case of bio-energy, allocation occurs especially when waste streams or by-products such as corn stover, flax shives or wheat stems are used to make fuel or generate electricity. This

Figure 5.4 EROI for discoveries for the US oil and gas industry. The inset is the same data plotted on a different scale.

Source: Guilford et al. (2011)
can be ‘solved’ by declaring such by-products to be waste. In that case, the resource and energy intensity is zero. Allocating on a mass basis usually means that very large parts of the burden are allocated to the bio-energy, usually rendering it useless because it is worse than fossil fuels. Economic allocation makes more sense, but is again unstable with fluctuating (relative) prices. A method often used here is ‘avoided burden’: by producing bio-energy in addition to food crops, the production of fossil energy is ‘avoided’ and the hypothetical emissions of fossil energy production may be subtracted from the emissions of the bio-energy production. As it leaves the path of thinking in supply chains, this method is not applicable for calculating resource intensities in the framework of a resource nexus analysis. Allocation thus is a complicating factor, but such issues invariably arise when dealing with complex chains and networks of supply, even while aiming to focus on one resource or product only. They will show up in the analysis of the resource nexus as well.

Thus, we can conclude that resource and energy intensities of resource production, both single and reciprocal, can be calculated using the traditional, steady-state LCA. Allocation may be a complicating factor and some allocation methods lead to meaningless results in the analysis of the resource nexus. The need for allocation however will arise in all cases we address a system within a wider context, and therefore has to be dealt with.

However, the dynamics of the linkages and the way they influence each other cannot be specified with LCA. Another issue is the upscaling of the information to encompass larger systems than just the micro-level functional unit. LCA is typically not suitable for that. It may be that the broader LCSA can capture these aspects. This will be explored in the next section. Figure 5.5 shows an example of the influence of allocation on LCA outcomes for the case of biofuels.

These are just first insights, following from a brief overview. To identify the contribution that can or cannot be made by LCA in studying the resource nexus in more detail and with

![Figure 5.5](image-url)

**Figure 5.5** Outcomes of four different allocation procedures in nine biofuel Life Cycle Assessment case studies, in percentage improvement compared to fossil fuels, for greenhouse gas emissions (cases 1–8) and energy requirement (case 9)

*Source: van der Voet et al. (2010)*
more rigour, it is important that the developing field research into the resource nexus should first develop clear definitions of the resource nexus itself, the consequences and impacts related to it, and related indicators measuring these impacts. LCA (and other assessment methods) may then supply these indicators (e.g., as part of the LCIA phase) as long as the indicators don’t ask for input information that LCA cannot provide, or require too much spatial and/or temporal details. If the information requirements are too high for LCA, LCA developers may decide to adapt those indicators again to the constraints of LCA, but will then never be able to assess the resource nexus problem comprehensively. This is very similar to the relation between LCA and human and ecosystem health risk assessments, studies of biodiversity or climate science. They are different fields of science: LCA doesn’t develop risk assessment, climate change or biodiversity models, but it will try to apply models and indicators developed by scientists and experts of these fields as far as possible and sensible, and possibly involving some adaptations.

**LCSA and the resource nexus**

*Extending LCA to include social and economic impacts*

The resource nexus is about connections between resources. In LCA, resource extraction is specified, as well as emissions to the environment. In the LCIA, resource extraction is translated into rather straightforward characterisation factors related to resource depletion for individual resources. This does not really add to insight in the dynamic nature of the linkages between resources. The field is developing, however, and there are some ideas that are interesting from a resource nexus point of view (see van Oers and Guinée (2016) for an overview). Vieira et al. (2012) for example propose to use ore grade degradation as an indicator for scarcity.

Expanding LCA to include economic and social impacts may allow for a more sophisticated treatment of resource extraction. There are some attempts to include resource criticality into the LCA framework (Drielsma, Russel-Vacari et al., 2016; Schneider et al., 2015). Resource criticality is typically a topic that is unrelated to environmental issues, but is very relevant when LCA is expanded to include economic impacts. These developments are quite new and have not yet crystallised out into generally accepted impact factors. One pitfall to be avoided is to introduce economic driving forces as environmental impacts. That would turn the train of thought around in an unfortunate direction. An example is introducing GDP as an indicator for environmental pressure. No doubt GDP correlates heavily with environmental pressure, but the information is meaningless in a context where society aims at reducing environmental impacts while maintaining economic growth. To use price information as an indicator in LCA may lead to similar results (Guinée et al., 2011; Drielsma, Allington et al., 2016). It is imaginable that resource nexus issues have social aspects that could be included in an LCSA framework. We are not aware of any attempts so far.

This direction of development may open up possibilities to include a larger array of impacts in the analysis of the resource nexus. That in any case could be useful. It is too early to be able to conclude which specific additions would be applicable and would make sense.

*Increasing the spatial scale of application*

A second aspect of LCSA is the scale level: from the micro-level of the individual product or service to a relevant system at the regional, national, continental or global scale. Enlarging the scale level is certainly relevant for the resource nexus. At the micro-level there is never a problem; therefore, much of the relevance of the resource nexus operates at the regional or global scale. Analysing the resource nexus at such a larger scale level with LCSA means preserving the
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Life cycle idea, but extending or complementing the ‘classic’ LCA tool. Some attempts have been made to quantify the resource nexus at the global level. Mostly this has been done by upscaling micro-level intensities: for example, multiply the MJ/kg data of the energy intensity of material production with the number of kilograms produced in one year worldwide. In UNEP (2013) the conclusion is drawn that at the global level 7–8% of total global energy consumption is used for metals production, the majority of that for iron and steel. Graedel et al. (2015) conclude that the energy–water linkage is asymmetric: “about 1% of the total global energy production is needed for water, whereas tens of percents of global water use are involved in energy production”. Such explorations show the importance of the resource nexus and put it into a global level perspective, adding to the already existing global sustainability agendas. This upscaling is justified for past situations, although data needs are considerable and the uncertainties high. For future situations and emerging technologies this is not straightforward.

At the regional level, many attempts have been made to explore nexus issues. These are discussed in Chapters 26–31. However, a life cycle perspective is not often used in these studies.

So far, there has been no standard use of models for quantifying the nexus at larger scale levels. Models such as multiregional–environmentally extended input–output analysis or Material Flow Analysis could be used to highlight aspects of the resource nexus at the higher scale level. These are discussed in Chapters 7 and 9 of this volume. Both allow for a life cycle perspective, although this is not automatically the case. MR–EE–IOA models are used, for example, to calculate water or carbon footprints at the larger scale level of national economies (see Chapter 8). Material Flow Accounting is also used at the level of national economies, but falls short on the life cycle perspective. The more versatile Material Flow Analysis can include the life cycle perspective but has a very narrow view in other respects (see Chapter 7).

Forward-looking analysis: including the time dimension

The resource nexus is not static, but has many dynamic aspects. Even the rather straightforward resource or energy intensities change over time as a result of improving efficiencies or otherwise changing technologies. The whole modus of resource use, including all interdependencies, changes over time. Not just technology, but also consumption patterns and industrial production change, thereby leading to modified or even completely new relations between different types of resources.

A relevant question is whether improved/extended LCA models could address the dynamics of the nexus. There is an increased attention for forward-looking analysis in the LC(S)A community (Spielmann et al., 2005; Hertwich et al., 2014; Koning et al., 2015). Relevant aspects include, among others:

- Changes in background processes for the linked resources. An example of that is the question, posed by German federal governments, whether the ‘Energiewende’ has consequences for the usefulness of improvements in the built environment aimed at a reduction of energy use. Measures such as thermal insulation do reduce energy use, but the potential to reduce GHG emissions is very limited when the energy system is renewable. Such dynamics can be captured by LCA time series with changing ‘background data’ for the energy system. This could be called a quasi-dynamic analysis: a series of (static) LCAs of subsequent years, together providing a simulated time series.
- Changes or assumed changes in production processes of the resources. Such changes can be captured adequately with LCA time series, and will lead to changed resource or energy efficiencies. Here we deal with uncertainties related to economies of scale, and sometimes with uncertainties related to the conversion from lab and pilot data to real-world data. Such
uncertainties are inherent to explorations of future situations and must be dealt with in one way or another anyway. They are not limited to LC(S)A.

- Changes in resource scarcity or criticality. Resource availability may change in the future. It may grow less, as more and more resources are ‘used up’. It may also grow better, in case substitutes are found for some specific resources and when the share of secondary production increases, reducing the demand for virgin resources. To assess such dynamics, LCA is not a suitable tool. LC(S)A may not be much better in that respect. The other way around, it means that any scarcity or criticality related characterization factors used in LC(S)A need to be updated frequently to remain relevant.

Conclusions

Life Cycle Assessment is a relevant tool for analysing the resource nexus. As is shown in this chapter, it is excellently suited to calculate resource or energy intensities, which are essential information for the resource nexus. These intensities can be used to calculate footprints at the micro-level.

Life Cycle Sustainability Analysis offers options to upscale the information on intensities or footprints. LCSA is a framework rather than a method. It therefore does not offer a recipe for analysis, but it does allow both for a more forward-looking analysis and for an exploration of change in the interrelations between resources. It also allows including the economic and social dimension of sustainability, which may be relevant for analysing the resource nexus. Methods to do so are in development, and are partly described in other chapters of this book.

Although LC(S)A can include resource scarcity in its array of impact categories, it is not suitable to analyse the phenomenon of resource scarcity or criticality itself. LCSA can add certain aspects of dynamics, if strictly defined and bounded. The main advantage, even at the macro-level, is the technological detail involved linked to the idea of the life cycle. With the LCA framework, however, it is not possible to assess feedback loops, so the dynamics of the linkages themselves remain unaddressed. Other tools are better suited to do that.

In all, LCA is able to have a limited but essential contribution to the analysis of the resource nexus. The broader framework of LC(S)A has more potential. The life cycle approach should be an integral, although in itself not sufficient, part of the analysis of any resource nexus.

Note

1 According to ISO 14044, a unit process represents the smallest portion of a product system for which data are collected in an LCA.

References


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