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Chapter 16

The environmental impacts of resource recovery

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16.1 ENVIRONMENTAL IMPACTS BEYOND LOCAL WATER QUALITY

Resource recovery has significant potential to increase the sustainability in the water sector and reduce its direct and indirect environmental impacts. Nonetheless, pursuing resource recovery does not guarantee a reduction in life cycle environmental impacts, as the inputs required for recovery may have negative environmental consequences that exceed any benefits. For example, the equipment, reactors, chemicals, and energy required to achieve the anaerobic digestion of wastewater sludge may result in net negative outcomes if the adverse environmental impacts associated with the additional consumables and infrastructure outweigh the benefits of the recovered energy. Therefore, robust evaluations of novel processes and wastewater management pathways are required to determine if environmental impacts are actually reduced, to identify opportunities and short-comings of the different options, and to reveal the potential for optimization. Life cycle assessment (LCA) is an example of a tool that helps to facilitate this analysis and discussion.

Generally, evaluations of the environmental impacts of resource recovery should take into account:

(1) The impact of the recovery process itself (e.g., energy and material consumption);
(2) The impact of the recovery on the overall treatment system (e.g., struvite recovery can reduce a wastewater treatment plant's energy demand associated with sludge processing);
(3) The avoided emissions due to the offset of other resources (e.g., recovered ammonia from wastewater as a substitute for nitrogen fertilizer);
(4) Any other emissions, avoided emissions, or changes in the wider system across other sectors (e.g., decreased use of household chemicals as a result of centralized softening of drinking water).

Although this chapter will discuss the characterization of environmental impacts, it is important to note that a reduction in environmental impacts is not inherently more sustainable. This distinction has to do with the definition of sustainability, which does not only include the environmental impacts, but also an evaluation of social and economic aspects (as discussed in Chapters 13–15 and section 16.5 in this chapter).

The chapter is from the book *Resource Recovery from Water: Principles and Application*, Ilje Pikaar, Jeremy Guest, Ramon Ganigué, Paul Jensen, Korneel Rabaey, Thomas Seviour, John Trimmer, Olaf van der Kolk, Céline Vaneeckhaute, Willy Verstraete (Eds.)

16.2 LEARNING OBJECTIVES

At the completion of this chapter you should be able to:

- Explain the difference between a CO_2-footprint and an LCA and the value of environmental impact analyses.
- Perform the key steps required to conduct a well-documented LCA study, and identify the accompanying decisions and challenges that must be overcome.
- Describe the importance of a comprehensive data inventory to enable the characterization of environmental impacts.
- Demonstrate an understanding of things to keep in mind when interpreting LCA results.

16.3 CONCEPTUAL OVERVIEW

Although evaluating the environmental impact of a resource recovery method is crucial, it is not easy to characterize global environmental impacts or compare the impacts of two or more scenarios. Different tools are available to characterize environmental impacts, each with its own advantages and disadvantages. For resource recovery processes, relevant approaches include CO_2-footprint (a.k.a. carbon footprint), water footprint, material flow analyses (MFA), and life cycle assessment (LCA). This chapter will focus on LCA methods, which can also be applied to calculate water and carbon footprints. The water footprint and carbon footprint characterize water use and the greenhouse gas emissions (normalized to carbon dioxide), respectively, associated with a given process (e.g., through transport, energy consumption, or the production of required chemicals). LCA methods, however, can include a broader range of metrics including human health impacts, resource depletion, effects on ecosystem health, and other impact categories.

16.3.1 Life cycle assessment

Environmental issues are increasingly recognized as important factors in decision making. However, the existence of many different categories of environmental impacts makes direct, holistic comparisons across multiple resource recovery alternatives difficult. For instance, one scenario may result in reduced use of chemicals, while another scenario may significantly reduce energy demands: the tradeoffs across alternatives require robust and transparent assessment methodologies.

Upstream and downstream effects, which can relate to the inputs required to operate a treatment process and the potential uses of any recovered products, also complicate environmental impact evaluations. This requires a cradle-to-grave-approach. A higher quality and purity of a recovered product usually results in greater environmental benefits from its use, because such a product can replace more refined primary materials which are often associated with larger environmental impacts. For instance, using calcium carbonate recovered from softening processes to replace milled limestone in glass can result in greater environmental benefits than its use as a substitute for sand in concrete (Palmen *et al.*, 2015). However, the environmental impacts associated with resource recovery (and refinement) must also be considered. For instance, reprocessing a recovered material may consume substantial amounts of additional energy and chemicals, or an impure recovered substance may be sufficient to replace a high-grade chemical without further processing. Therefore, it is crucial to use a cradle-to-grave-approach to compare equally between the proposed and conventional scenario, accounting for these upstream and downstream impacts. LCA is a tool that helps to compare the sustainability of different scenarios in this way, facilitating the discussion of tradeoffs across types of environmental impacts.

16.3.2 Typical LCA steps

An LCA study includes the following phases: goal and scope definition, inventory analyses, impact assessment, and interpretation (ISO 14040:2006). Goal and scope definition is completely determined

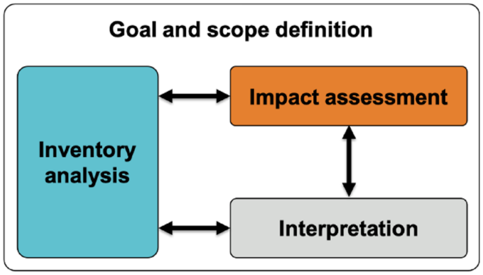

Figure 16.1 Visualization of typical LCA phases. Adapted from ISO 14040.

by the research question. Goals may include determining the environmental impacts of a product or process, comparing the impact of different products or processes, or giving direction to scientific research and development. The case studies in this chapter provide examples of these different applications in the context of resource recovery. Scope definition involves setting the boundaries of the system that will be studied and specifying the functional unit. The functional unit is required to fairly compare across different scenarios. For instance, when comparing different processes to treat wastewater, the functional unit can be the treatment of 1 m^3 of wastewater to a certain effluent quality (Byrne *et al.*, 2017). Ultimately, all environmental impacts must be normalized to the specified functional unit.

The inventory analysis compiles and documents the emissions and resources consumed. An impact assessment is then performed, considering the effects on different impact categories. The emissions and resources are classified according to their relevant impact categories (i.e., those categories on which the emissions and resources exert an impact), and then each emission and resource consumed is characterized (i.e., converted into normalized units of indicators) using impact assessment models (see section 16.3.3).

These steps interact which each other (Figure 16.1). For example, when a certain factor is identified as a hot spot of environmental impacts, it is important to intensify the inventory analysis of this particular assumption. Usually, the inventory analysis – and the determination of its quality – consumes the most time in the execution of an LCA. In all cases, however, it is important to start with the goal and scope definition.

16.3.3 Impact assessment

There are several life cycle impact assessment (LCIA) methodologies available for the translation of emissions and resources into impacts, and these can vary widely in the impact categories they cover. Examples of the most commonly applied methodologies are: CML 2002, Eco-indicator 99, Ecopoints 2006, EDIP 97, EDIP2003, |EPS2000, IMPACT 2000+, LIME, LUCAS, ReCiPe, TRACI, and MEEup (Byrne *et al.*, 2017; ILCD Handbook, 2010). The most suitable methodology will depend on the goal and scope of the LCA, which determines the impact categories that should be included in the analysis and the level at which results should be presented (i.e., endpoint or midpoint indicators). An endpoint method looks at environmental impact at the end of the cause-effect chain (e.g., extinction of species). A midpoint method looks at the impact earlier along the cause-effect chain, before reaching the endpoint (e.g., ecotoxicity). A midpoint indicator focuses on a single environmental problem, such as human toxicity, metal depletion, or particulate formation. The water footprint and carbon footprint are considered midpoint indicators. Endpoints aggregate across multiple environmental issues to make decision making easier, but uncertainty increases with each aggregation step.

For the examples in this chapter, we will use the ReCiPe method. The ReCiPe method analyses three different types of damage at the endpoint level: human health, ecosystem quality, and resources

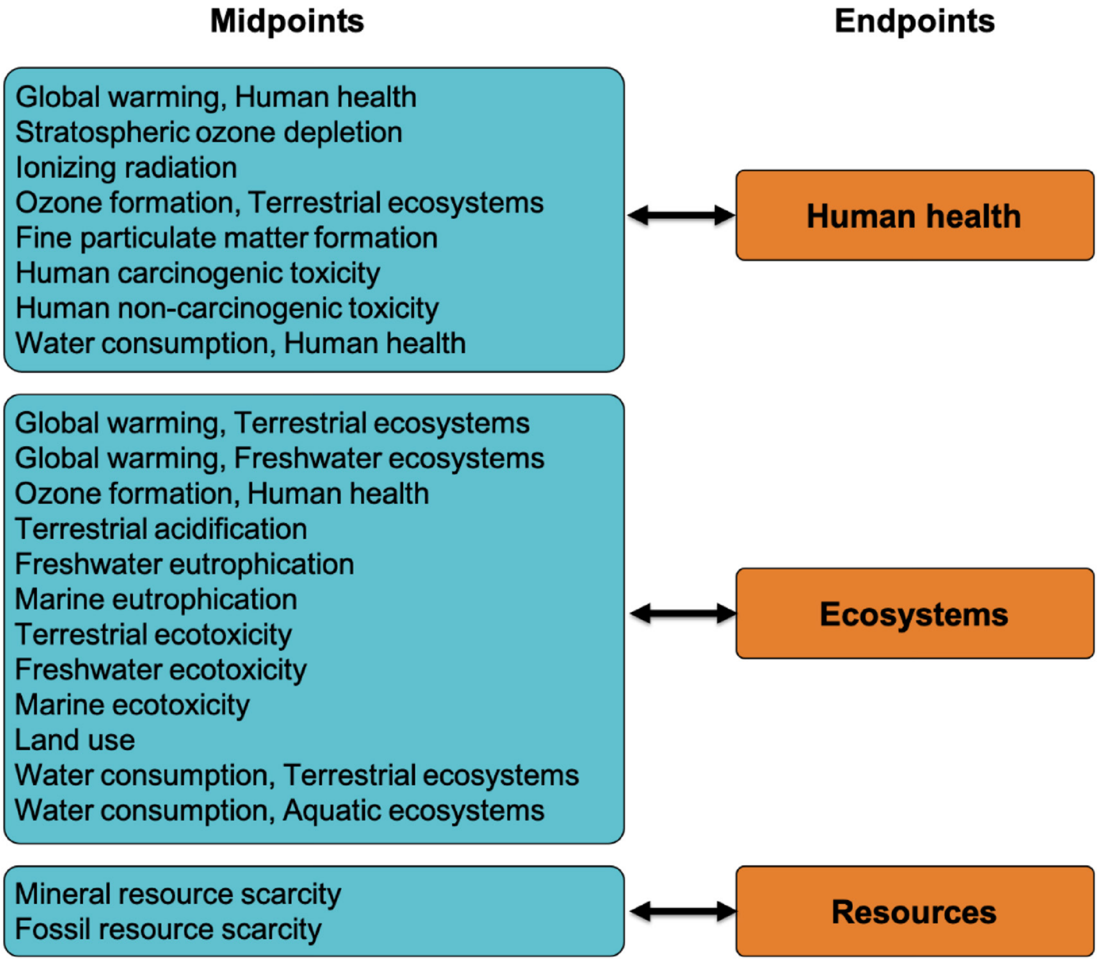

Figure 16.2 Overview of midpoints and endpoints in the ReCiPe method. Adapted from Huijbregts *et al.* (2016).

(Figure 16.2). Each endpoint has a different indicator and unit (Table 16.1). The endpoint scores are calculated from the midpoint scores using weighting and normalization factors.

Analyzing the environmental impacts associated with the ReCiPe method's three endpoints – human health, ecosystems, and resources – still does not provide a single value representing the overall environmental impact. Evaluating a scenario's total environmental impact requires a method

Table 16.1 Overview of endpoint categories and indicators for the ReCiPe method.

Impact Category/Endpoint	Indicator	Unit
Damage to human health	Disability-adjusted loss of life year	DALY
Damage to ecosystem diversity	Number of species lost per year	Yr^{-1}
Damage to resource availability	Increased cost	$

Adapted from Goedkoop *et al.* (2009).

to either navigate tradeoffs across impact categories or to combine all of the endpoint impacts through normalization and weighting. In the ReCiPe method, each endpoint impact can be assigned a certain number of ‘ecopoints’. One thousand ecopoints correspond to the total annual environmental impact of one person in Western Europe (https://www.pre-sustainability.com/download/EI99_Manual.pdf).

16.3.4 LCA standards (ISO standards)

The quality and relevance of LCA studies, and the extent to which they can be applied and interpreted, depends upon the methodology used. Transparent documentation is crucial. The International Organization for Standardization (ISO) published standards to provide guidance on methodological choices, transparency, and rules for reporting. Examples of LCA-related ISO standards are ISO 14040 (Environmental management – Life cycle assessment – Principles and framework) and ISO 14044 (Environmental management – Life cycle assessment – Requirements and guidelines).

At a minimum, ISO standards state that a well-documented LCA should contain the following content and details: approach and method, goal definition, explanation of the scope, description of the evaluated scenario(s), selection of functional unit, description of system boundaries, and details on data collection and methodology (software, database, method, etc.). More specific details can be found in the ISO standards and, as they relate to wastewater management, in a recent review by Corominas *et al.* (2020).

16.3.5 (Avoided) emissions

When resource recovery is applied in the water cycle, it could also avoid environmental impact in other processes and/or sectors. The power to protein concept, in which proteins are made from wastewater resources (Powertoprotein.eu), provides a helpful illustration. The effort to produce protein from wastewater resources occurs within the water cycle, but the environmental benefits would be seen in the food industry, which can reduce its protein production (from cattle or fish, e.g.). Therefore, it is crucial to ensure that the system boundary includes not only the water cycle (where the effort occurs) but also other sectors where the benefits (or costs) may be realized.

In contrast to avoided emissions, resource recovery can also cause additional environmental impacts in other processes. For example, if a WWTP that currently digests sludge to produce biogas installs a process to recover cellulose before the digester, the organic input into the digester will decrease, resulting in lower biogas production (Visser *et al.*, 2016). This reduction in biogas production could result in less on-site electricity and heat production, for instance, potentially requiring pipeline methane or grid electricity to meet the plant’s operational needs. In all cases, any changes in resource consumption must be quantified.

16.3.6 Interpretation

The goal of the LCA study influences interpretation of the results. For example, using a tree structure (Figure 16.5) to perform a hotspot analysis can show which individual process has the largest environmental impact. A mistake often made while interpreting LCA results is to consider only differences in the single aggregated score (e.g., ecopoints in ReCiPe). Only focusing on ecopoints will not indicate which midpoint indicators cause the aggregate environmental impact to change, or which indicator contributes the most to the aggregated score.

When scenarios are compared, one should consider the uncertainty in results stemming from assumptions throughout the execution of the LCA, avoiding overinterpretation of minor differences between scenarios without rigorous characterization of uncertainties. Furthermore, the level of detail can be important in interpretation. When evaluating an overall environmental impact, a value presented in ecopoints may be sufficient, while reporting midpoint level indicators may be required to achieve improvements in specific environmental outcomes (e.g., greenhouse gas emissions). When reporting any LCA findings, transparency about assumptions, midpoint values, uncertainty and sensitivity analyses, and method of weighting (if weighting used) is crucial.

Sensitivity analyses are usually important for interpreting LCA results. Although there are more robust methods for global and local sensitivity analyses, the most commonly employed sensitivity analyses in the literature are one-at-a-time approaches. For instance, a sensitivity analysis may assess how an individual parameter affects the metrics of interest by varying the value of this parameter while holding all others constant. Another option is to investigate best and worst case scenarios. For instance, wastewater collection can occur through a sewer network or through truck transport. While the overall analysis may suggest that the first scenario has lower impacts and is preferred over the second, a sensitivity analyses may reveal that energy is the main contributor within second scenario. If the environmental impact of energy production is expected to decrease in the (near) future, the second scenario may be favorable. The same could be true if an increase in efficiency is expected. As a result, performing robust sensitivity analyses is advisable.

16.4 CASE STUDIES

Depending on the goal of the study, an LCA can be performed at different levels of detail. Therefore, it is important to clearly formulate the goal and scope of the study. Examples of reasons to complete an LCA study include:

- to determine the potential of a certain (resource recovery) concept;
- to direct and focus scientific research of a (resource recovery) concept;
- to calculate the environmental impact of a certain process or product;
- to compare alternatives for a certain scenario.

The first two goals can be achieved by performing a quick scan analysis using LCA, which will be explained in section 16.4.1. The calculation of the environmental impact of a certain process and the comparison between an alternative and a conventional scenario (the final two goals) require an intensive LCA and will be explained in section 16.4.2. As explained in the second example, new insight after the start of the project may have resulted in other choices if this information were known from the beginning.

16.4.1 LCA as quick scan analysis

As mentioned above, the reasons to perform a quick scan analysis could be to investigate the potential of a resource recovery technology or concept, or to further direct and focus scientific research along a specific pathway to reduce environmental impacts. This section demonstrates a quick scan analysis with an example regarding iron flocculants.

As illustrated in Chapter 3 (Table 16.1), iron sludge is formed during the coagulation/flocculation treatment step in drinking water production (Hofman-Caris *et al.*, 2019). If the iron can be recovered, it can be reused as a flocculant in drinking water production or wastewater treatment. Before intensive scientific research on the recovery of iron is initiated, a quick scan analysis can show whether this possibility may decrease the environmental impacts of the process. To this end, only the chemicals required (and their transport) to recover flocculants from iron sludge ('$FeCl_3$ recovered' scenario) are roughly compared with the purchase of a commercial flocculant, including its manufacturing and transport ('$FeCl_3$ commercial' scenario). Also, a third scenario, employing a recycled acid, is investigated as the '$FeCl_3$ recovered green' scenario. The inventory data for these three scenarios is presented in Table 16.2. This analysis will not only help characterize the potential of the suggested concept, but may also identify hot spots for continuation of scientific research. The quick scan LCA analysis used the SimaPro 8.0 software, EcoInvent 3.0 database, and ReCiPe Endpoint E 1.12 method. The functional unit (FU) is the production of 1 kg of flocculant, as the function of both scenarios is to deliver high-quality flocculants.

Figure 16.3 demonstrates that iron flocculants from recovered iron sludge have an environmental impact that is approximately one-third lower than commercial flocculants. In this concept, a virgin

Table 16.2 Inventory data for a quick scan analysis of flocculant recovery from iron sludge with a functional unit of 1 kg flocculant.

FeCl$_3$ commercial	
Iron (III) chloride usage	2.9 kg
Iron (III) chloride transport	0.363 tkm
FeCl$_3$ recovered	
HCl usage	2.61 kg
HCl transport	0.131 tkm
FeCl$_3$ recovered green	
HCl transport	0.131 tkm

hydrochloric acid was used, but if a recycled acid could be applied, the environmental impacts are likely to decrease further. However, the FeCl$_3$ recovered 'green' scenario does not include any impacts from the recycled acid used (with the chosen allocation method). Ultimately, all activities required to isolate HCl from an industrial waste material should be included in the data inventory. At present, however, information about the additional effort required to produce and use a recycled acid are unknown and therefore not included. The actual environmental impact of a resource recovery concept that uses recycled acid will likely fall between the FeCl$_3$ recovered scenario and FeCl$_3$ recovered green scenario. Based on this result, the recovery of iron flocculants from iron sludge is promising, and continued scientific research to better understand the technical aspects appears to be worthwhile. Various research questions could be investigated, such as: What is the safety and efficiency associated

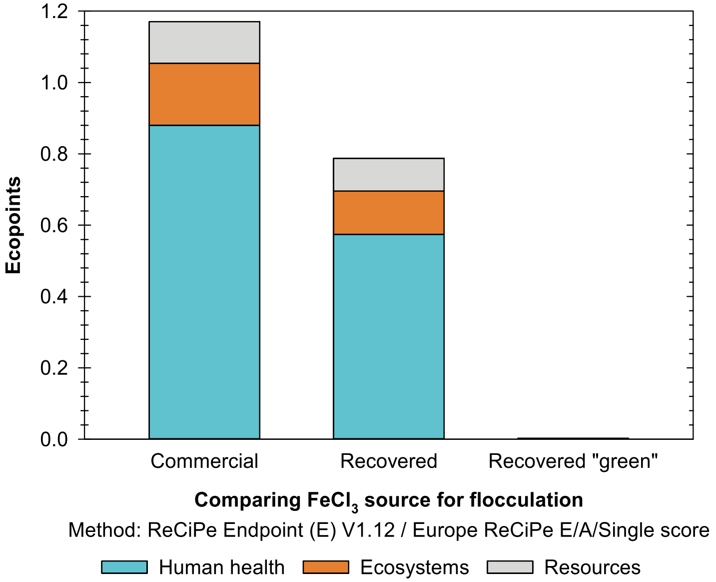

Figure 16.3 A quickscan analysis regarding the reuse of iron sludge as flocculant. Midpoints are represented as: human health (blue), ecosystems (orange) and resources (grey). Note, for the recovered 'green' scenario, any impacts from acid recovery are not included.

with recovered flocculants? Which technical problems may occur, and how can they be solved? The scenario including a recycled acid shows that the impact of the acid represents a hot spot in the total environmental impact. Therefore, efforts to use less acid or a recycled acid should be a focus of continued research. Of course, a more detailed LCA should reevaluate the concept after more comprehensive research has been completed.

16.4.2 An intensive LCA study: Calcite

An intensive LCA study can be conducted to calculate the environmental impact of a certain process/product or to perform a detailed comparison of multiple scenarios. An example regarding calcite (calcium carbonate) will be discussed to demonstrate the function of an intensive LCA study, specifically comparing a conventional system to a proposed future scenario.

In this example, the conventional pellet softening process of a hypothetical drinking water treatment plant is evaluated and compared to a proposed innovative concept. During conventional pellet softening, calcium from the raw water precipitates on a garnet or river sand seeding material. The residual of this process consists of calcite pellets with a garnet kernel. These pellets are used as a substitute for primary materials like sand and low grade crushed or milled limestone. They can also serve as a raw material for limestone products.

In the innovative concept, the garnet seeds are replaced by calcite seeds, resulting in residual pellets that contain 100% calcite. The pure calcite pellets are dried, milled, and sieved at an external location to produce both the calcite seeds and a commercial-grade fine milled limestone product, which is sold to third parties for high-end applications.

The data inventory of the conventional scenario (using garnet as seed) and the innovative concept (using calcite as seed) are presented in Figure 16.4 and Table 16.3, reflecting all process changes that will be evaluated in the LCA.

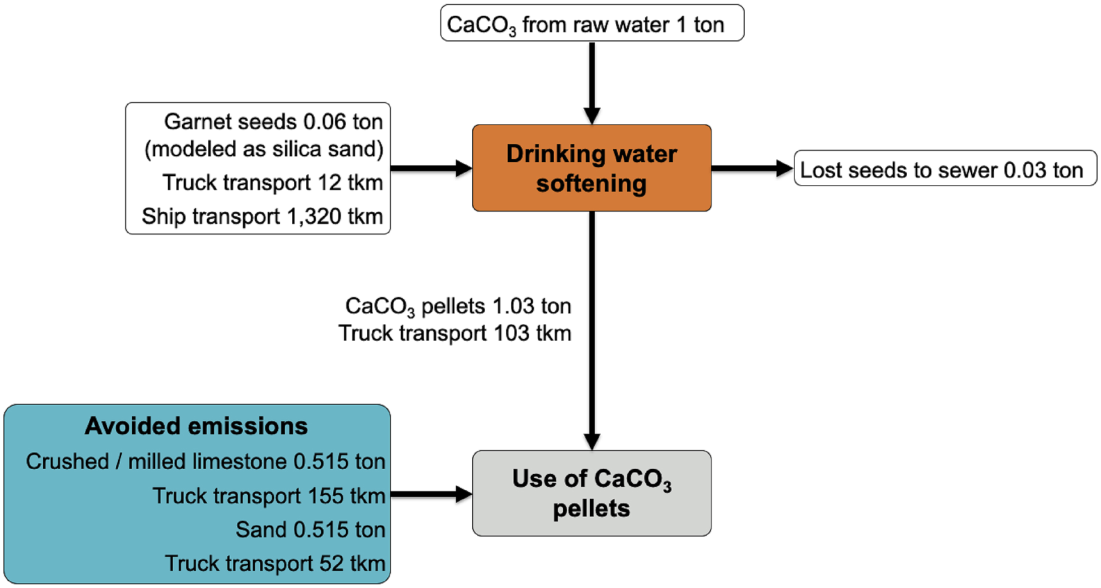

Figure 16.4 Data inventory for softening by the conventional scenario.

Table 16.3 Data inventory for all three scenarios.

Process	Conventional	Innovative Original	Innovative Revised
Inoculum	0.06 ton garnet seed 12 tkm truck transport 1.320 tkm ship transport	0.06 ton limestone residue 12 tkm truck transport	0.111 ton calcium carbonate 122 tkm truck transport 22.2 MJ energy
Lost to sewer	0.03 ton $CaCO_3$	0.03 ton $CaCO_3$	0.056 ton $CaCO_3$
External transport	103 tkm truck transport	103 tkm truck transport	106 tkm truck transport
Avoided emissions	0.515 ton $CaCO_3$ 0.515 ton sand 207 tkm truck transport	1.03 ton $CaCO_3$ 309 tkm truck transport	1.06 ton $CaCO_3$ 317 tkm truck transport

In short, this analysis employed SimaPro 8.0 software, the EcoInvent 3.0 database, and the ReCiPe Endpoint (E) 1.12 method. The functional unit is the removal of 1 ton of calcium carbonate from water, so that the comparison is based on the production of this recovered resource. A detailed description of the data inventory and assumptions is given in Palmen *et al.* (2015). However, new insights have been obtained after that first LCA study. More specific information became available about calcite, resulting in a revised inventory data set (Table 16.3). This third scenario is referred to as the revised innovative concept. The revision resulted from using a more precise method to model the calcite inoculum within the LCA. This illustrates that while performing LCA research, it is important to realize that the outcome is strongly dependent on the data inventory. As a result, new insights can drastically affect the environmental impact calculation, potentially leading to new conclusions. Accordingly, this analysis includes not only the comparison between the conventional and innovative scenario, but also illustrates more robust outcomes of LCA analyses (Figure 16.6).

To indicate the importance of iteratively improving a LCA study, Figure 16.6 shows that the revised assumptions further reduce the environmental impacts of the innovative scenario, improving from −2.8 to −5.3 ecopoints per ton of calcium carbonate removed from water. Note that a negative value signifies a positive contribution to the environment – in this case, avoided emissions. The changes in the data inventory are not only a result of new insights (more detailed information regarding calcite production), but also of improved information in the inventory database used (an update to the EcoInvent database) and impact assesment method (Huijbregts *et al.*, 2016). Given that these new assumptions lead to an environmental impact that improved almost twice, it is very important to occasionally revise an LCA study and reevaluate the assumptions used. Also, it should always be remembered that LCA results should not be the sole contributor to decision making, but they can be used as a tool to facilitate discussions.

Based on the revised assumptions, a comparison between the conventional and innovative scenarios (Figure 16.6) illustrates that the environmental impact of the innovative concept (using calcite as seeds/seeding material) has a substantially lower environmental impact (−5.3 Pt) than the conventional situation with garnet as seed (−3.8 Pt). A detailed evaluation of the innovative revised calcite scenario, based on the tree structure (Figure 16.5), specifies that the improved environmental impact is a direct result of the increase in avoided emissions for crushed/milled limestone (from 1.03 to 1.06 tons). This increase in avoided limestone is caused by the higher quality of the calcium carbonate recovered in this scenario. The tree structure shows which processes (transport, chemicals, etc.) are included in the LCA analyses. Furthermore, red arrows show a negative impact, while green arrows show the positive environmental impacts (avoided emissions). The size of each arrow shows the degree to which it contributes to the total environmental impact. Therefore, the tree structure is a useful tool to identify hotspots in a scenario, and it also provides guidance on which parameters to consider in sensitivity analyses.

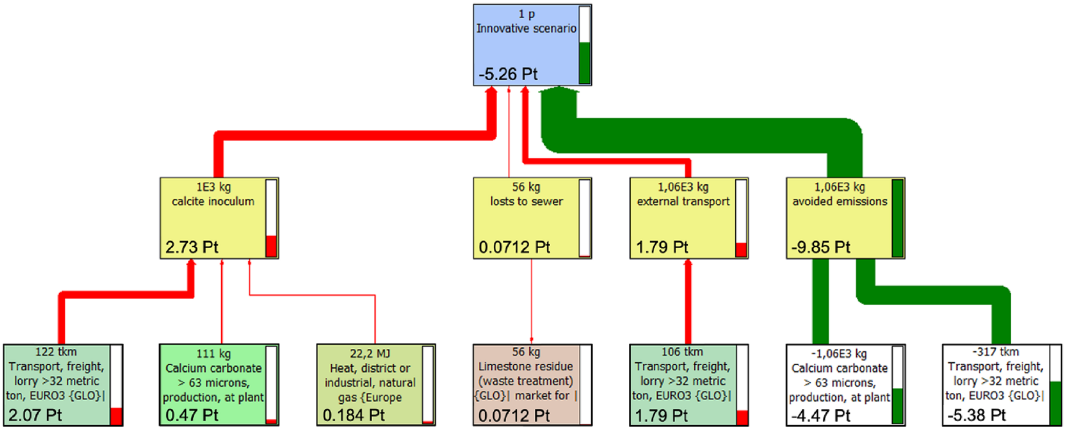

Figure 16.5 Tree structure of the innovative revised scenario (calcite as inoculum), based on ReCiPe Endpoint (E) V1.13.

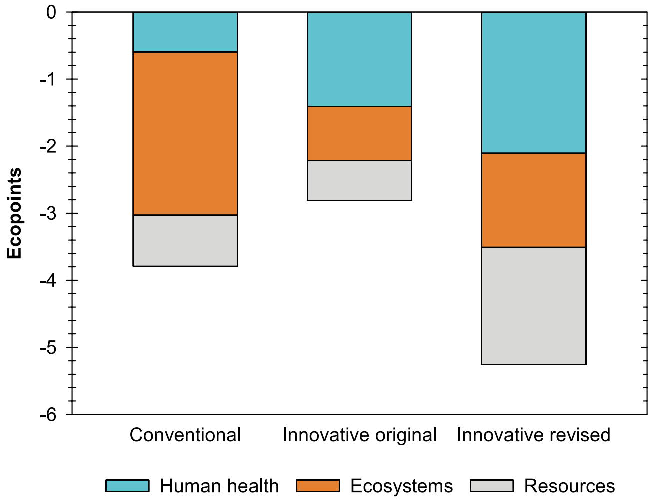

Figure 16.6 Comparison between the conventional (garnet) scenario and two versions of the innovative (calcite) scenario, based on original (center) and revised (right) assumptions. Method: ReCiPe Endpoint (E) V1.13/Europe ReCipE E/A/single score.

16.5 CHALLENGES MOVING FORWARD

The process of measuring, calculating, and discussing environmental impact faces several challenges. A common problem with LCA and other environmental impact studies is its use to determine whether one scenario is better than another. However, the results cannot be considered as a definitive indication of superiority/inferiority of a scenario. There are too many assumptions and issues related to data availability, time-framing, midpoint and endpoint metric selection, and other challenges and considerations (including economics, etc.), all of which must be considered. Several of the most crucial points and challenges related to calculating and measuring environmental impact are discussed below.

16.5.1 Environmental impact terms

An important issue within this discipline is the use of different definitions for environmental impact, sustainability, and circular economy. It is essential to be aware of the different definitions and assure that all parties understand these distinctions when collaborating. Sustainability is not the same as environmental impact. Sustainability goes beyond environmental impact, as it also includes effects on people and the economy. A sustainable scenario meets the needs of the present without compromising the ability of future generations to meet their needs (World Commission on Environment and Development (WCED), 1987), while an assessment of environmental impacts may only consider aggregated global impacts and the present. Sustainability is concerned with the 'three P's': people, profit, and planet. We should pursue favorable outcomes in all three categories to continue to move toward more sustainable systems. Environmental impact calculations, such as those in LCA, do not include any social or economic evaluations, but focus on elements like emissions (e.g., CO_2, CH_4, H_2S), use of resources (e.g., energy, metals, water), and the potential for human, environmental, and ecological consequences from these emissions and resource demands. The circular economy concept represents another way to talk about environmental impacts. The idea of the circular economy is to regenerate and reuse materials and resources (onsite, preferably), avoiding the use of virgin material and the production of waste. These efforts do not always result in a lower LCA environmental impact calculation; for example, the regeneration of a material may require large quantities of energy and chemicals. Ultimately, however, a circular economy would progress toward greater use of renewable energy and material sources, converging to environmental sustainability.

16.5.2 Data inventory

There are several issues related to the accuracy and precision of the data inventory. Examples of data inventories are given in Tables 16.2 and 16.3, and Figure 16.4. First, completing a data inventory often requires numerous assumptions. Examples of cases where assumptions may be required include: (1) when a future scenario is analyzed; (2) the actual consumption data are only known for pilot studies; or (3) when values (energy for instance) are known for the entire facility but not for one particular process. It is important to discuss and quantify the effect and importance of any assumptions. The best approach for evaluating assumptions is to perform uncertainty and sensitivity analyses, the latter of which will indicate whether a given assumption has drastic effects on the total calculated environmental impact. When the effect of your assumption is significant, additional research may be required to improve the data inventory. Ultimately, new insights can alter the data inventory considerably. It is therefore advisable to revise environmental impact studies frequently.

16.5.3 Completeness and representativeness of database information

Conducting an accurate environmental impact study is strongly dependent on the quality of the database. It is critical to use a database that is trustworthy – for example, one that goes through regular and independent review processes. The database should be transparent and well documented, and the origin of the data should be clear.

The data in commercially available databases may not always be representative for a given case. Examine the completeness of the process with regard to issues such as whether transport is included, whether the material is packaged, or whether the chemical production method aligns with the specifics of the application. For example, sodium hydroxide can be produced by different methods, resulting in different environmental impacts. Furthermore, sometimes processes in a database represent the mass of the bulk solution, but at other times the database corrects for the quantity of active substance contained within the solution. Always check if the processes behind the indicator apply to the case at hand, and if not, try to obtain data from the parties in the value chain.

Another issue relates to whether all the data required for the impact analysis are available in the database. For example, the ReCiPe method does not include characterization factors for some emissions (i.e., there is not a default value to normalize an emission to the constituent units, such as kg-CO_2 eq. for global warming potential). According to the ReCiPe method, chloride, sodium, and bromide emissions to water have no environmental impact (Huijbregts *et al.*, 2016), although impacts do exist in some cases. Be aware of the fact that some emissions are not included due to a lack of impact information. Even when they are included as components in the model, the model will assign them an impact value of zero. These instances should be documented and reported as part of the limitations of a study.

16.5.4 The representative case study

To learn from a certain case study or to draw conclusions from an evaluation of a resource recovery concept, a representative case study can be very helpful. However, the development of a representative case study is rather difficult and perhaps even impossible. Not only is the current conventional scenario different in each country (or region), but market issues also play a key role in the environmental impact. For instance, case studies related to energy supply can be severely affected by geographic differences and variances in markets (International Energy Agency, 2014). The environmental impact of the electricity market mix in the Netherlands is more than 10 times higher than in Norway, because Norway's electricity supply includes a greater fraction of renewable sources (EcoInvent 3.0 database information of market conform electricity database in 2019). As a result, for a resource recovery method that is highly reliant on electricity, its environmental impacts may vary significantly when estimated for different countries.

Another essential parameter that can differ among case studies is the quality of the resource that is recovered. If calcium carbonate is recovered within the drinking water treatment process, the quality of the lime may vary. This variation is a direct result of differences in influent water quality and composition. As a result, one should be conscious of these challenges and avoid drawing general conclusions from specific case studies.

16.5.5 Evaluating future improvements to resource recovery processes

Resource recovery often involves new technologies that have not been fully developed, resulting in relatively high energy or material requirements. As a result, an LCA assessing whether a new resource recovery process can reduce environmental impacts relative to the current situation may have a negative outcome. If improvements are feasible in the near future, one could also assess the scenario with those improvements to provide a realistic outlook on the future situation.

16.5.6 Market information

Recovered resources that are placed on the market have the potential to replace other (mainly primary) resources. When calculating the avoided emissions, the choice of the substituted material and the process in which the material is applied both matter. For example, $CaCO_3$ pellets from drinking water softening could be used directly in the glass industry without further processing to replace milled limestone. However, another quality (composition) or status (e.g., milled) may differ depending on the market the recovered resource is applied. The avoided emission should be corrected for this as much as possible. This leads to a substantial difference in the avoided impacts.

Challenges arise when there is no information available on the current market mix or when a new market is created. In the first case, for example, a small survey could provide the necessary information. In the latter case, the avoided product could be modeled by choosing a surrogate product that fulfills the same function.

16.5.7 Allocation and system expansion

In general, allocation plays a key role in LCA. Allocation is applied to divide a certain environmental impact across the processes involved. Especially in resource recovery allocation, questions arise. For example, which part of the impact of drinking water or wastewater treatment should be allocated to the recovered residuals? There is no perfect approach. Some common methods include the following:

(1) Allocation of the impacts based on economic value, mass, or energy. For instance, when a tree is used to build a shelter, suppose only half of the wood is useful in building the shelter. The other half could be used to make paper. In this case, when using mass allocation, only the consumption of half of the tree is included in the LCA of the shelter, as the other half is used for an end product (paper) that is outside the scope of the shelter study.
(2) The 'cut-off' or 'recycled content' method, in which a recovered or recycled material is assigned no environmental impact. In contrast, all impacts are allocated to primary materials. In the example in section 16.4.1, we used the cut-off method, meaning that the recycled acid used to produce the green coagulant was assigned zero environmental burden.
(3) 'System expansion' or 'substitution' (favored by the ISO 14040). In system expansion, co-products are considered alternatives to other products on the global market. For instance, we want to evaluate the impact of a wastewater treatment plant, taking into account the struvite that is recovered from the wastewater. The struvite replaces fertilizer on the market (avoided production), which allocates a negative contribution (less impact) to the environmental impact of the wastewater treatment plant.

16.5.8 Process design and its influence on resource recovery (and vice versa)

As described in Chapter 3, drinking water production sites are designed to achieve a certain goal, such as the production of hygienic, safe, colorless, and odor-free water. When new scenarios are proposed to maximize the recovery of certain resources, they should not diminish the efficacy of drinking water production. However, simple changes in process design can occasionally lead to better quality of the recovered resource – for instance, the use of calcite for the softening process in the Netherlands (Chapter 3).

When an environmental impact of an innovative process design is calculated, all effects on the total water cycle should be included. For example, when more water is lost during the last processing step in drinking water treatment, more water must be treated in the preceding steps, increasing the total environmental impact of the drinking water process. Other examples include a change in the type of chemical used (thereby changing required chemical transport), altered recovered resource quality, and modifications in the market where the resource is sold.

16.5.9 Comparisons with previous studies

During research, comparisons with previous studies are both desired and necessary. However, it is crucial to understand that new results cannot always be directly compared to previous studies. For example, differences in the functional unit require that each set of results be reframed using a consistent functional unit. Also, different databases or impact assessment methods may have been used. Furthermore, in the case of ecopoints, it is vital to know that the total annual impact of one person living in Western Europe is defined as 1000 ecopoints (Baayen, 2000). As per capita environmental impacts change, the values from different years cannot be directly compared.

16.6 CHAPTER SUMMARY

In this chapter we have discussed the crucial steps in performing a comprehensive environmental impact study. In particular, LCA represents an established methodology to transparently characterize the global environmental impacts across the life cycle of a product or process. Given that many assumptions must be made to execute an LCA, the use of well-studied and documented inventory data is critical. These data sets can change over time, which is why it is advisable to update previous LCA studies before leveraging them for decision-making.

When executing an LCA, quick scan analyses or intensive LCAs can offer complementary insight. Reasons to perform a quick scan analysis could be to investigate the potential of a resource recovery technology or concept, or to further direct and focus scientific research along a specific pathway to reduce environmental impacts.

16.7 EXERCISES

Exercise 16.1: Suppose a new vendor is found for the calcite-seed pellets (from the revised innovative scenario described in Figures 16.5 and 16.6), which would reduce transport requirements to the treatment plant by 50%. Calculate the overall environmental impact of revised innovative scenario before and after this transportation savings in units of Ecopoints (Pts).

Exercise 16.2: Suppose additional research showed that the innovative revised process described in section 16.4.2 eliminates losses to the sewer. Based on the data in Table 16.3 and Figure 16.5, what is the new single score resulting from the LCA of the 'innovative revised' scenario with no calcium carbonate loss to the sewer?

Exercise 16.3: A drinking water production site generates 150,000 m^3 of water and 680 tons of $CaCO_3$ per day. The calcium carbonate recovery offsets conventional calcium carbonate production. The environmental impacts of calcium carbonate production can be extracted from Figure 16.5. Determine the unit impacts of conventional calcium carbonate production (in units of Pts per ton $CaCO_3$) and the environmental benefits of its recovery (in units of Pts per year).

Exercise 16.4: You are performing a quick scan analysis of a process that requires the following materials and processes for construction and across its lifetime: 3.9 tons of reinforcing steel, 179 m^3 of concrete, and 16,600 Wh of electricity. Over the same lifetime, nutrient recovery and distribution to agriculture offset 139 tons of nitrogen fertilizer and 55 tons of phosphorus fertilizer. Given the unit impacts below: (a) determine the relative global warming impact of steel, concrete, and electricity (determine the total impacts of the three, and each's contribution to that total as a percentage); and (b) determine what percentage of impacts are offset by both nitrogen fertilizer offsets and phosphorus fertilizer offsets.

- Nitrogen fertilizer: 11.5 kg-CO_2 eq. per kg N
- Phosphorus fertilizer: 2.1 kg-CO_2 eq. per kg P
- Reinforcing steel: 2.5 kg-CO_2 eq. per kg steel
- Concrete: 398 kg-CO_2 eq. per m^3 concrete
- Electricity: 0.64 kg-CO_2 eq. per kWh

Exercise 16.5: A resource recovery and treatment process results in fugitive emissions of nitrous oxide (N_2O) and methane (CH_4). Ultimately, 0.5% of influent nitrogen is released as N_2O and 2 g of CH_4 is released per m^3 treated. If the characterization factors of N_2O and CH_4 are 298 g-CO_2 eq. per g N_2O and 28 g-CO_2 eq. per g CH_4, what is the total global warming potential resulting from fugitive emissions (in units of g-CO_2 per m^3 treated) for a wastewater with 35 mg-N·L^{-1} in the influent?

16.8 DISCUSSION QUESTIONS

Question 16.1: What is the value offered by conducting a LCA study, and what is the practical difference between a quick-scan and an intensive LCA study? When might you apply one vs. the other?

Question 16.2: Why should you be cautious about drawing generic conclusions from specific case studies?

Question 16.3: What are three examples in which a quick scan environmental impact assessment could provide added value to a resource recovery decision?

Question 16.4: What challenge in the interpretation phase of LCA do you think has the highest impact on results? Why?

Question 16.5: What is an alternative functional unit for the intensive LCA calcite study (instead of the removal of 1 ton of calcium carbonate from water)? Can you explain why this alternative functional unit may not have been chosen?

Question 16.6: A research group is deciding whether to focus on a particular treatment process and whether to modify a specific component, as it may reduce the environmental impact. Do you advise performing a quick scan analysis or an intensive LCA study? Why?

Question 16.7: After five years, the LCA concerning calcite (described in section 4.2) is repeated. How can we compare the results?

Question 16.8: Choose a correct functional unit for a LCA that compares a wastewater treatment system with and without anaerobic digestion of sludge (leading to biogas production). Discuss why the selected functional unit is appropriate.

Question 16.9: You are asked to perform an LCA of an entire drinking water production plant. List what you would include in your data inventory. Hypothesize which of these items may contribute the most to the plant's environmental impacts (representing a hotspot).

Question 16.10: A drinking water production plant improves its softening process, which is the sixth treatment step in its process sequence. This improvement decreases water loss. Previously, the environmental impact of the plant has been expressed relative to a functional unit representing the production of 1 m^3 of water. When revising the estimate of the plant's environmental impact, what items will be important to include in the data inventory?

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