Life Cycle Assessment based on the standards of ISO for the evaluation of complex systems

–

practices, issues and limits

Master Thesis

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Conceptual Formulation

Mr. **Markus MARX, BSc.** is assigned to elaborate a Master Thesis with the topic

"Life Cycle Assessment based on the Standards of ISO for the Evaluation of Complex Systems
–
Practices, Issues and Limits"

In a first step, the principles, the framework and guidelines of Life-Cycle Assessment(LCA), developed by the 'International Organization for Standardization' (ISO) and represented by the ISO 14040 ff. standards, have to be thoroughly illustrated, to provide a point of departure for elaborating relevant aspects, issues and recommendations related to the actual procedure of LCA, which will be done on basis of a selection of case studies.

The main focus of this thesis, on one hand, is, after a selection of a number of representative LCA case studies referring to the subject of complex system evaluation and compliant with the ISO 14040 ff. standards, the examination of LCA practices implemented in each of the selected studies. These systems have to address a topic incorporating future-oriented technologies and processes at an early stage of realization, thus representing the required complexity in the sense of insubstantial empirical system knowledge, highly diversified types of processes, and afflicted by shortcomings in data availability, to highlight how the procedure of the actual LCA method has been implemented within the examined studies. Subsequently a number of aspects, referring to the LCA procedure as described by the 'International Organization for Standardization', and interrelated with the selected case studies, including examined practices, noticed issues, limits as also recommendations related to LCA, have to be compiled.

On the other hand, it has to be confirmed that the aspects, priorly established, as well apply to other, not yet conducted, LCA studies of systems referring to similar complex topics. Therefore it has to be substantiated, on basis of another example of a complex system, if the current LCA tool acts adequately competent for evaluating such systems, and criteria for a point of departure on discussions should be delivered.

Leoben, October 2013 o.Univ.Prof. Dr. Hubert Biedermann

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AFFIDAVIT

I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume.

Leben 2.6.2014

Ort/Datum

Markus Mayr

Unterschrift

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Abstract

In a time of increasing awareness on environmental pollution and scarcity of natural resources, the term sustainability gained importance. This fact led to the evolution of methods and tools to account for consequences on the environment caused by products, services and new technologies developed, provided, and used by human being to, in succession, reduce the negative effects on our environmental system, now and in the future. Life cycle assessment (LCA) is one of a compilation of methods developed to investigate the environmental impacts, by taking into account comprehensive environmental information on the whole life cycle of product systems. This work, which is split into three parts, is focused on highlighting the best practices as also related issues that may emerge when conducting the life cycle assessment tool, in order to determine environmental burdens of complex systems. Complex in these terms is used to describe modeling of future related systems, including processes that are in an early stage of implementation, where system data is scarce, and where environmental impacts and mechanisms of certain processes are not yet entirely understood. It is feared that the validity of the current LCA procedure can be overrated, if applied beyond its limits. The first part of this thesis provides an insight into the characteristics, terms and procedures of the LCA tool, based on literature and the references of the International Organization for Standardization. Because of their international acceptance, the compilation of the 14040 series of ISO standards is employed as a basis for this work at hand. The second part comprises a research on selected case studies, related to the application of the LCA method in the area of complex system evaluation. An electricity generation system utilizing carbon capture and storage provides the addressed complexity to illustrate the requested practices as also the possible issues and limits of the LCA method. The third part constitutes an analysis on the examined LCA studies, emphasizing the basic practices but also the most relevant issues where the LCA method is seemingly stretched to its limit, which is presumably the circumstance if applied to complex systems. Additionally another example of a complex system, probably facing similar issues, is introduced, to confirm the relevance of emphasized aspects that might be subject for upcoming LCA improvement efforts. This example system then relates to the topic of energy storage, the utilization of the power-to-gas technology and underground hydrogen storage.

Kurzfassung

Das steigende Bewusstsein für die Belastung unserer Umwelt, durch Abfälle und Emissionen, sowie der voranschreitenden Rohstoffknappheit hat den Begriff Nachhaltigkeit zusehends in den Vordergrund gestellt. Aus diesem Grund wurden unter anderem Methoden und Instrumente entwickelt, die es uns ermöglichen die Auswirkungen auf die Umwelt, die sich durch die Bereitstellung sowie den Gebrauch von Produkten, Dienstleistungen und neuen Technologien ergeben, zu ermitteln, um in weiterer Folge der Umweltbelastung entgegenwirken zu können. Life Cycle Assessment (LCA) ermittelt in umfassender Hinsicht umweltrelevante Informationen eines Produktsystems, über dessen gesamten Lebenszyklus hinweg, um damit einhergehende mögliche Umweltwirkungen abschätzen zu können. Die vorliegende Arbeit ist in drei Teile gegliedert und befasst sich mit der Ermittlung von Vorgehensweisen und Problemen die sich bei der Durchführung einer LCA-Studie, welche die Umweltwirkungen eines komplexen Systems ermitteln soll, ergeben. Komplex dient in diesem Zusammenhang um zukunftsbezogene Systeme zu beschreiben, die Technologien beinhalten welche sich in einem frühen Stadium der Umsetzung befinden, und daher mit Datenmangel, sowie unvollständigem Verständnis der Auswirkungen und Umweltmechanismen einzelner Prozesse dieser Technologie zu rechnen ist. Es wird befürchtet, dass die Aussagekraft dieses Instruments fraglich ist wenn es über seine derzeitige Tauglichkeit hinweg angewendet wird, was bei einem derartigem System der Fall sein könnte. Im ersten Teil der Arbeit werden Eigenschaften, Begriffe und Vorgehensweisen des LCA auf Basis vorhandener Literatur sowie der ISO Normen erläutert. Aufgrund der internationalen Akzeptanz bilden die ISO 14040 ff. Normen den Ausgangspunkt für diese Arbeit. Im zweiten Teil der Arbeit erfolgen Fallstudien von Veröffentlichungen, welche das LCA zur Ermittlung der möglichen Umweltwirkungen von Systemen dieser Komplexität eingesetzt haben. Als komplexes System wird die Stromerzeugung mit CO_2 Abscheidung und Speicherung dienen, um später die Vorgehensweisen und mögliche Probleme des LCA bei dessen Anwendung zu verdeutlichen. Der dritte Teil der Arbeit besteht aus einer Analyse der Fallstudien, und hebt die angesprochenen Vorgehensweisen, Probleme und Grenzen der LCA-Methode hervor, die sich bei der Evaluierung von System dieser Art ergeben können. Ein weiteres gleichermaßen komplexes System, nämlich die Energiespeicherung mit Power-to-Gas Technologie und Untergrund Wasserstoffspeicherung, in dessen Zusammenhang vergleichbare Bedenken nahe liegend sind, wird vorgestellt um die Relevanz der im zweiten Teil ermittelten Aspekte zu bestätigen, die einen möglichen Überarbeitungsbedarf der LCA-Methode aufzeigen sollen.

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List of Abbreviations

AP	Acidification Potential
APME	The Association of Plastics Manufacturers in Europe
BUWAL	Bundesamt für Umwelt, Wald und Landschaft (Switzerland)
CAPEX	Capital Expenditures
CBA	Cost-Benefit Analysis
CCS	Carbon Capture and Sequestration
CED	Cumulative Energy Demand
Cf.	confer
CML	Institute of Environmental Sciences of the University in Leiden
CNG	Compressed Natural Gas
DALY	Disability Adjusted Life Years
DEAM	Data for Environmental Analysis and Management
DLR	German Aerospace Center
EA	Environmental Auditing
EAA	European Aluminium Association
ECBM	Enhanced Coal Bed Methane
EDIP	Environmental Design of Industrial Products (Denmark)
EDP	Ecosystem Damage Potential
EIA	Environmental Impact Assessment
EIO	Economic Input/Output
ELU	Environmental Load Unit
EN	European Standard
EOR	Enhanced Oil Recovery
EP	Eutrophication Potential
EPA	U.S. Environmental Protection Agency
EPS	Environmental Priority Strategies
ERA	Environmental Risk Assessment
ESU	Environmental Consultancy for Business and Authorities in Switzerland
et al.	et alteri or et alii
etc.	et cetera
ETH	Swiss Federal Institute of Technology
ETP	Ecotoxicity Potential
GEMIS	Global Emission Model for Integrated Systems
GWP	Global Warming Potential
HENG	Hydrogen Enriched Natural Gas
HF	Hydrogen Fluoride
HTP	Human Toxicity Potential
IEA	International Energy Agency
IFEU	Institut für Energie- und Umweltforschung in Heidelberg
Ifu	Institut für Unfallanalysen in Hamburg
IISI	International Iron and Steel Institute
ILCD	International Reference Life Cycle Data System

IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
ISO/TS	ISO/Technical Specification
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MEA	Mono-ethanolamine
MIPS	Material Intensity per Service Unit
MFA	Material Flow Analysis
n.a.	not available
NMVOC	Non-Methane Volatile Organic Compound
NO_x	Nitrogen Oxides
NREL	National Renewable Energy Laboratory
ODP	Ozone Depletion Potential
p.	Page
PDF	Potentially Disappeared Fraction
PEM	Poly-Electrolyte-Membrane
PMFP	Particulate Matter Formation Potential
POFP	Photochemical Oxidant Formation Potential
pp.	Pages
RA	Risk Assessment
REPA	Resource and Environmental Profile Analysis
RIVM	Dutch National Institute for Public Health and the Environment
SC	Subcommittee
SEA	Strategic Environmental Assessment
SETAC	Society of Environmental Toxicology and Chemistry
SI	Système International
SLCA	Sustainability Life Cycle Assessment
SNG	Synthetic Natural Gas
TC	Technical Committee
TEAM	Tool for Environmental Analysis and Management
TR	Technical Report
UBA	German Federal Environment Agency
UCTE	Union for the Coordination of Transmission of Electricity
UNEP	United Nations Environmental Programme
yr.	Year

1 Introduction

1.1 Initial Situation

At least since 1987 with the constitution of the Brundtland Report the term 'Sustainable Development' is kept in mind by the society. The raising sensibility to environmental problems such as the depletion of natural resources, the proceeding climatic change and environmental pollution to name but a few, but also the increasing demand for energy and products, coming along with the aspire of emerging markets and the steady growing world population, resulted in the development of methods and tools, addressing environmental impacts caused by the community.

Amongst others, governments, environmental organizations and companies developed environmental management systems, waste reduction models and other environmental analysis methods to get rid of the careless interaction with the environment, thus enabling future generations to meet their needs, as it was defined by the Brundtland Commission in 1987.

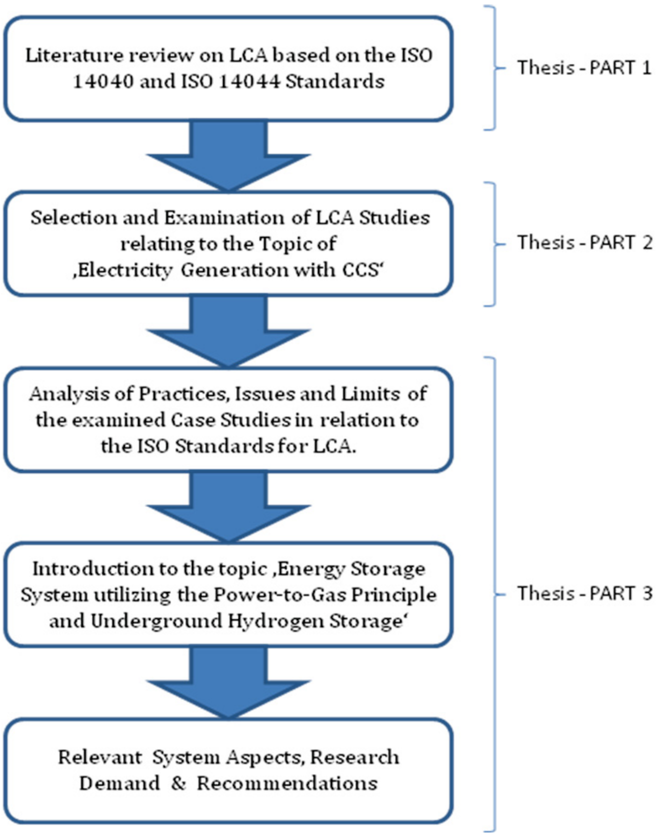
Life Cycle Assessment (LCA) is a tool to analyze the impacts on the environment caused by the provision of products and services with the unique feature of considering a product system from a life-cycle point of view therefore making it possible to include every vital aspect or activity associated with environmental burdens beginning with the extraction of raw materials and use of resources to removal of waste matter and waste treatment. Several attempts, including international workshops, have been performed by different organizations, such as the Society of Environmental Toxicology and Chemistry (SETAC), the United Nations Environmental Programme (UNEP), the Environmental Protection Agency of the U.S. (U.S. EPA), the Institute of Environmental Sciences in the Netherlands (CML) or the International Organization for Standardization (ISO), to provide a standardized approach. With growing comprehension, different applications of LCA are nowadays common in decision making processes of the industry, in order to obtain information on environmental loads accompanied by process and product development, manufacturing, use and reuse as also disposal.

On the other hand there are still some areas where the standards of LCA method application presumably do not necessarily result in a comprehensive determination of environmental loads because of the involved complexity, such as in case of electricity production systems with carbon capture and storage (CCS) technology, which is used as a reference scenario in this thesis to highlight common practices and issues. Complex in these terms is used to describe modeling of future related systems, including processes that are in an early stage of implementation, where system data is scarce, and where environmental impacts and mechanisms of certain processes are not yet entirely understood.

LCA studies recently performed, concerning the field of electricity production by fossil fuel fired power plants with carbon dioxide capture and sequestration, were faced with several complications. Expected problems include, for example, how to accurately model future related system component implementations without actual available data because of their novelty or how to include processes and substances into the assessment, which are not evaluated for the time being, in terms of their impacts on the environment. Issues especially concern complete parts of the system, such as the process of underground gas storage, where not only the availability of data is limited but also the lack of understanding environmental mechanisms may probably result in a restriction of the LCA method integrity.

1.2 Thesis Approach and Goals

Because of the international wide spread acceptance of the ISO standards in the area of environmental management, or more precisely of the assessment of potential environmental impacts of product systems, the ISO 14040 ff. standard series are chosen as the basis for this work at hand. The structure of the thesis follows the progression illustrated below.



Starting point for this master thesis, which is composed of three parts represented by the chapters 2 to 5, was a comprehensive research on literature referred to suggestions of the common life-cycle assessment procedure. After a short introduction to the history, the limitations and the benefits of the LCA tool as also other common terms, ISO's approach to LCA is described, including the definition of essential key elements.

Based on the findings of the research of available books and scientific publications from the academic library together with the recommendations of the ISO standards, the first part of this work explains the course of action to life-cycle assessment. This is done with the intention to obtain a basic understanding of ISO's current state of LCA characteristics, how the tool is supposed to be applicable, and in which way the general procedure is performed.

The second part of this master thesis deals with the selection and examination of representative case studies performed in relation to the assessment of environmental impacts of processes involved in complex systems. The intention is to appoint relevant LCA methods adopted in such studies, which resulted in comprehensive conclusions of the results and other aspects, possibly making the LCA approach questionable. The investigation of the second part, of the thesis at hand, is the point of departure for the third and last part of this work.

The last part comprises an analysis of the selected case studies, concludes the insights gained during the case study examination and further investigates if other upcoming LCA studies could be subject to the actual LCA procedure, thus probably facing similar issues. It is aimed to especially address those certain system elements, where already major concerns raised on the applicability of the LCA tool. This is done with respect to the proclaimed standards of ISO, and thus should support a practitioner of future studies when conducting a detailed life-cycle assessment with the aim of receiving a meaningful, transparent and comprehensive conclusion of potential environmental impacts.

The areas, subject to demand for improvement of the LCA tool, are accentuated by introducing another example of a complex system, in this case relating to energy storage, the utilization of power-to-gas technology and underground hydrogen storage. To repeat that, complex addresses the severity of modeling of future related energy storage systems within an LCA, the inherence of a high variety of different processes and substances, the lack of data availability because of the early stage of implementation of power-to-gas system technology and the incomplete comprehension of underground hydrogen storage.

After a description of the characteristics and possible layout of such an energy storage system, the relevance of current LCA shortcomings are emphasized.

Finally a wrap-up of the most relevant aspects of the case study examination is done, relevant recommendations are given for upcoming LCA studies, and a statement on the conclusions developed in this work is made, which is intended to highlight facets but also limits of the common LCA procedure for determining the potential environmental impacts of rather unconventional and complex systems.

Within this thesis the following questions are scientifically faithfully answered:

1. What are the general benefits and limitations of the Life-Cycle Assessment tool, which LCA types, approaches, levels of sophistications, software tools, databases and LCIA methods are common?
2. How is LCA generally conducted, what are the key elements, and what has to be considered when performing an LCA study, according to the standards of ISO?
3. Which case studies, performed until now, seem representative for the identification of LCA methods in relation to evaluation of complex systems, and what comprised their substance?
4. Which methods have been applied in this representative selection of case studies leading to a comprehensive conclusion of LCA results, which methods seem difficult to be implemented in a meaningful way, and where general drawbacks can be observed?
5. Which areas of an energy storage system utilizing the power-to-gas technology and underground hydrogen storage cannot be accurately assessed with the current LCA methodology, and thus require additional improvement of the LCA tool.
6. What are the major concerns to be kept in mind when evaluating the environmental impacts of complex systems by utilization of the LCA tool, on basis of the insights gained by the case study examination, and in relation to the example of an, above mentioned, energy storage system?

2 Life Cycle Assessment (LCA)

The rising importance of environmental protection has led to the development of tools making it possible to address potential impacts on the environment associated with the manufacturing and consumption of products. Considering the key issues to meet customer needs as well as to stay competitive on the market, companies desire to detect and understand the environmental impacts of their processes and products.[1]

Life cycle assessment is one method, among others, that enables the user to better understand and account for such environmental impacts.[2] It is used to analyze environmental aspects of product systems. The expression 'product system' involves the total system of unit processes in a product's life-cycle.[3]

Examples of other tools that have been developed for assessing environmental aspects of different systems include Environmental Impact Assessment (EIA), Environmental Auditing (EA), Environmental Performance Evaluation, Environmental Risk Assessment (ERA), Cost-Benefit Analysis (CBA), Strategic Environmental Assessment (SEA) or Material Flow Analysis (MFA). "The unique feature of LCA is the focus on products in a life-cycle perspective"[4].

For the continuous improvement of products along their whole life cycle, including raw material acquisition and extraction of resources, production and use phases of the product as also recycling and disposal, likewise denoted from cradle-to-grave, it is essential to get knowledge of the environmental performance and related impacts.[5] The life cycle framework ensures that unwanted shifts of environmental burdens, such as any kind of considered substances and harmful media, between parts of the regarded system depicted in terms of life-cycle stages, are prevented.[6]

Life cycle assessment facilitates a basis for decisions, which are of high concern for businesses that try to improve their products and services in terms of environmental performance on a comparative basis, to determine sources of weak points or to design new products. The comprehensive nature of LCA, by studying an entire system, allows the decision makers to get information about environmental impacts that are related to products and processes and finally to opt for the product or process with the least environmental effects that are of concern.[7]

In these days the standards ISO EN 14040 and 14044 define the LCA method as a tool to analyze the potential environmental impacts through all life-cycle stages of a product or process.

ISO[8] notes that the term "product", as well, includes services, and that potential environmental impacts are related to the functional unit of a product system, whereas neither the economic nor the social aspects of a product are typically addressed in an LCA, and that LCA might not be the most appropriate method to be used under all circumstances.

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[1] Cf. Curran 1996, p. 1.1.

[2] Cf. ISO 2006a, p.v.

[3] Cf. Guinée et al. 2002, p. 6.

[4] Finnveden et al. 2009, p. 1

[5] Cf. Guinée et al. 2002, p.vii.

[6] Cf. Curran 1996, p. 1.5.

[7] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 3.

[8] Cf. ISO 2006a, pp. v-vi.

2.1 LCA - A General Overview

History

A product is linked to the environment in all phases of its life-cycle, from raw material acquisition, manufacturing, use, reuse and recycling to deposition. The integration of environmental aspects into assessment procedures, product systems and product development was one step towards environmental protection.[9]

Beginning in the 1960's, where noticeably attention was paid to the raising energy use and the accompanied awareness of the finiteness of natural resources, interests predominantly aroused to account for cumulative energy requirements, as well as for future energy supply.[10] For the time being, the first studies, carried out by the U.S. Department of Energy, were focused on resource based energy input in terms of fuel cycles involved in the manufacturing process.[11]

During the first oil crisis, in the early seventies, the predictions of fast depleting fossil fuels, the prospective shortage of oil and the climate change, going along with raising resource use, led to a growing interest for the determination of energy requirements and releases of product systems.[12] The investigation to pollution prevention, at the time practiced in the U.S., was called Resource and Environmental Profile Analysis (REPA) and described a life-cycle inventory, whereas accordingly the first activities related to LCA in Europe were referred to as Product Ecobalance.[13]

The Society of Environmental Toxicology and Chemistry (SETAC) was the first international organisation that aimed for a standardized technical framework to make progress in the application and practice of LCA. The workshop called 'A Technical Framework for Life Cycle Assessment' was organised by SETAC in August 1990 in Smugglers Notch, Vermont where the aim was structuring the LCA, by including three interrelated components which are Inventory, Impact Analysis and Improvement Analysis.[14]

In 1993, SETAC held another workshop at Sesimbra, Portugal, called 'Life Cycle Assessment: A Code of Practice', which was the first internationally accepted LCA-framework, and substantially represents the basis for the Standards of ISO.[15]

The International Standard Organization (ISO) published the 14000 series of ISO standards, dealing with environmental management. Beginning in the late nineties the ISO 14040 series of standards (Environmental management – Life cycle assessment) were released to consolidate the approach to the LCA method. These series included:

- Environmental management – Life cycle assessment – Principles and framework (ISO 14040:1997)
- Environmental management – Life cycle assessment – Goal and scope definition and inventory analysis (ISO 14041:1999)
- Environmental management – Life cycle assessment – Life cycle impact assessment (ISO 14042:2000)

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[9] Cf. Curran 1996, p. 11.1.

[10] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 4.

[11] Cf. Curran 1996, p. 1.3.

[12] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 4.

[13] Cf. Guinée et al. 2002, p. 10.

[14] Cf. Klöpffer and Grahl 2009, p. 9.

[15] Cf. Guinée et al. 2002, p. 11.

- Environmental management – Life cycle assessment – Life cycle interpretation (ISO 14043:2000)

The structure developed by SETAC was basically adopted by ISO in the 14040 series, with exception of SETAC's 'Improvement Assessment' component, which in the ISO standards is called 'Interpretation', thus the assessment of opportunities to reduce environmental burdens of the product system was not taken over into the standards of ISO.[16]

In 2006, a revised ISO standard was published where the ISO 14041:1999, ISO 14042:2000 and ISO 14043:2000 standards were replaced by the actual valid standard called Environmental management – Life cycle assessment – Requirements and guidelines (ISO 14044:2006).

Benefits of LCA

As already mentioned, Life Cycle Assessment is a tool used to systematically determine potential environmental impacts and effects on human health by looking upon the entire life cycle of a system from cradle-to-grave.[17] LCA may be used for internal product or process specific improvements like strategic decisions, resource and energy input or product (re)design, but also for external information purposes to stakeholders (manufacturers, suppliers, customers, government, etc.).

The holistic view on a product or process, from raw material acquisition and energy input to recycling and final disposal, assesses the transfer of potential impacts, and therefore allows users of this tool to select a product or process with the least environmental loads. This ensures that sub-optimization, of shifting environmental burdens from one life cycle stage to another when only considering a single stage of a system, is avoided.[18]

Life Cycle Assessment assists in creating a quantitative basis of information on material and energy input and release, which can be used to realize the following benefits:

- To estimate the demand of energy and raw materials for the whole life-cycle of the product system or specific stages that are of concern. This information can be used in terms of cost containment to reduce energy consumption or material input.
- To estimate environmental consequences referring to emissions, solid waste, wastewater or other releases to air, water and land in order to choose between different product- or process-alternatives with the least environmental impacts, to better meet customer needs, to lower the disposal costs or to identify the capability of recycling procedures.[19]
- For strategic planning and marketing purposes like Ecolabbeling, to advance the company image and market share.[20]
- To provide information for public policy, improving the relationship with policy makers and regulators and as well to increase acceptance by stakeholders.[21]
- To point out data gaps and to give indications where the available data is poor in relation to particular processes.[22]

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[16] Cf. Klöpffer and Grahl 2009, p. 12.

[17] Cf. ISO 2006a, p. v.

[18] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 3.

[19] Cf. Curran 1996, p. 11.12.

[20] Cf. ISO 2006a, p. v.

[21] Cf. Curran 1996, p. 11.12.

[22] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 8.

- For product or process design and development of new products or processes in terms of decreasing environmental burdens associated with the production system.[23]
- To identify the environmental performance and considerable shifts of burdens between specific stages in the life cycle to estimate those parts of the system that are highly resource-, energy- or pollutant-intensive, in order to reveal opportunities for product- and process-improvement.[24]

Limitations of LCA

LCA not necessarily gives information on the life-cycles of certain substances that might quote a product system or risk related issues, and it is suggested to investigate those facets by using, for instance, Substance Flow Analysis (SFA) or Risk Assessment (RA) instead.[25]

The comprehensive nature of LCA, of course, is its strength but simultaneously this includes some limitation because the analysis of a system along its whole life cycle is very data intensive and time consuming. Therefore the execution of the assessment most often can only be accomplished by performing simplifications and assumptions, which in turn may lead to a reduction of quality and transparency.[26]

Attention should also be paid to the type of data and assumptions used for the analysis. Because of lacking availability of data concerning certain substances or processes, users of LCA are forced to apply average or generic data resulting in a heterogeneous mix of data sources. Some of these sources are often out of date, do not implicitly depict industry-wide practice or are of doubtful quality, making it difficult to compare the results of a life cycle stage determined from average data with the results of a stage where more process- or product-specific data was applied.[27]

The focus of LCA lies on the assessment of potential environmental impacts. Social and economic aspects are at the most omitted when performing the LCA.[28] To accent every of the three dimensions of sustainability other tools, like Life Cycle Costing (LCC) or Sustainability Life Cycle Assessment (SLCA), may be used supplementary to LCA.

Moreover the determined environmental burdens are weakly defined in time and space.[29] LCA is not intended to reveal a comprehensive statement on local impacts of a particular industry at a specific site or the actuality of the impacts. To address the limitation of space, the application of an Environmental Impact Assessment (EIA), in case of site-selection, or, an Environmental Audit (EA), for identification of local environmental impacts of a specific business, are suggested.[30]

LCA is an analytical tool that facilitates the user in the decision making process by information supply, but does not evaluate the best suiting product or process, for example, when considering technical performance.[31] The determinations made in LCA generally aim to be

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[23] Cf. Guinée et al. 2002, p. 7.

[24] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 3.

[25] Cf. Curran 1996, p. 17.4.

[26] Cf. Guinée et al. 2002, p. 8.

[27] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 10.

[28] Cf. ISO 2006a, p. vi.

[29] Cf. Klöpffer and Grahl 2009, p. 387.

[30] Cf. Curran 1996, p. 17.5.

[31] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 5.

based on natural science but also include subjective value choices that may lead to arbitrariness.[32]

As the data availability significantly impacts the results of the LCA, future developments in the area of resource supply and technology are difficult to substantiate, whereas linear modelling may be used to describe future related aspects, which however may come at the price of questionable data quality.[33]

2.2 LCA Types, Approaches and Levels of Sophistication

Some common expressions, frequently used in relation to LCA studies, are now briefly explained, whereas it has to be noted that the below mentioned definitions are often discussed by various authors. A detailed discussion of the following terms is out of the scope of this master thesis, thus for further information additional literature, especially addressing those LCA aspects, should be taken into consideration.

Process LCA

Underlying the recommendations of ISO's standards, this type of LCA is based on process specific quantification of environmental input and output flows, for example, in terms of mass and energy, but this approach is often faced with the problem of data gaps, as the development of detailed and specific inventory tables is very cost and time intensive.[34]

The main advantage of process-LCA is that it allows a detailed analysis of systems by incorporating time and site specific physical data, thus avoiding average system data and generic models.[35]

The disadvantage of the process-LCA is, as already indicated, the assessment of incomplete system models as the lack of data availability or the effort to gather the required unit process input and output data might result in omission of system elements and a general simplification of the system.[36]

EIO-LCA

The use of economic input/output data to model the product system processes in terms of material and energy requirements, as also releases to the environment, enables the practitioner to incorporate broader range of processes where unit process specific physical data is not available, thus resulting in a more complete system description.[37]

Rebitzer et al.[38] mentions that differences between the EIO-LCA and the process-LCA especially address the data sources, the flow units, the level of detail and the incorporated life-cycle stages.

Concerning the data sources and data units, the process-LCA uses, as already mentioned above, specific unit process data in physical units whereas the EIO-LCA applies statistical economic data tables based on economic values, which are, for example, developed by national authorities, to model the product system.[39]

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[32] Cf. ISO 2006a, p. 7.

[33] Cf. Guinée et al. 2002, p. 8.

[34] Cf. Lewandowska and Foltynowicz 2004, p. 464 and Rebitzer et al. 2004, pp. 711-712.

[35] Cf. Lewandowska and Foltynowicz 2004, p. 464.

[36] Cf. Lewandowska and Foltynowicz 2004, p. 464.

[37] Cf. Rebitzer et al. 2004, pp. 711-712.

[38] Cf. Rebitzer et al. 2004, p. 712.

[39] Cf. Rebitzer et al. 2004, p. 712.

These economic input/output tables provide information on the relationship of commodities and products in terms of transactions within the industry.[40] The tables depict the destination of products, for example, to be sold to consumers or manufacturers as part of other products.[41]

In relation to the level of detail and the included life-cycle stages, it has to be kept in mind that the EIO-LCA is a more rough estimation of environmental burdens and may not be useful when comparing systems on basis of rather equal products, for instance, when aiming to determine the choice of best suitable materials, as the EIO-LCA is limited in terms of specific physical unit process data.[42] Economic databases are rather focused on complete industry sectors than on specific processes, thus incorporating aggregated data.[43]

Rebitzer et al.[44] states three steps towards an EIO-LCA inventory, which are listed in the following:

1. Development of a matrix that depicts the input and output flows of a process in terms of commodities by using statistical economical data tables.
2. Connect environmental loads in terms of raw material requirements and emissions to the matrix, which was developed in step 1 above.
3. Develop the LCI on basis of the first two steps.

Hybrid-LCA

Hybrid-LCA refers to a combination of an EIO-LCA and process-LCA, where unit process specific data is gathered to develop the LCI for the important main system processes as also near upstream system elements, and economic input/output databases are used to compile the inventory for far upstream system components, which are considered not that relevant.[45]

The hybrid approach should combine the advantages of the process LCA and an economic input/output LCA approach in a way to avoid data gaps, or to be able to compare products, which are rather identical, where, for instance, the EIO-LCA might result in unrewarding conclusions.[46]

Thus the incompleteness of system models resulting from the process-LCA should be reduced by this combination of approaches.[47] Hybrid-LCA is considered to be one step towards the improvement of the future LCA procedure.[48]

Screening-LCA

A screening LCA may be conducted prior to a full LCA to determine significant system elements in terms of processes and elementary flows, on basis of easily accessible data, such as statistical data tables or generic assumptions, as the labor of performing such an screening LCA is not that extensive.[49]

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[40] Cf. http://captoolkit.wikispaces.com/EIO-LCA

[41] Cf. Lewandowska and Foltynowicz 2004, p. 464.

[42] Cf. Rebitzer et al. 2004, p. 712.

[43] Cf. Curran 2012, p. 222.

[44] Cf. Rebitzer et al. 2004, p. 712.

[45] Cf. Rebitzer et al. 2004, p. 712.

[46] Cf. Curran 2012, p. 220.

[47] Cf. Lewandowska and Foltynowicz 2004, p. 465.

[48] Cf. Lewandowska and Foltynowicz 2004, p. 465.

[49] Cf. http://www.eebguide.eu/?p=913

The screening LCA depicts a lower development level, compared to the simplified LCA, and should not be used for external purposes.[50] It can be used in an early design phase to estimate an overview of the environmental performance of a product system.[51]

Screening LCAs does not necessarily cover the whole life cycle in terms of unit processes of a system and is rather used to determine significant elements in predefined areas, such as identification of important system elements where certain substances are involved.[52]

A screening LCA should not be confused with the screening step of simplified LCAs, which supports the practitioner in determining certain system elements that can be omitted, after they have been identified not to be significant.[53]

Simplified LCA

This type of LCA, which is often referred to streamlined LCA, has evolved because the time and labor associated with the development of a detailed-LCA, which might also be denoted as full- or complete-LCA, where the environmental loads of a system are determined on a high level of system detail, may not turn to account the benefits associated with the insights gained after a detailed LCA.[54]

However it is mentioned[55] that in reality only a small number of actually detailed LCA studies have been conducted, although the standardization efforts have been made towards full LCA approaches.

Generally a simplified LCA should provide similar results as the full LCA while reducing the effort, or at least aims to determine non-significant system components.[56]

Different approaches developed in the past to save cost and time inhered in the development of an LCA, especially addressing the LCI phase, as this part of an LCA is considered to be one of the most time consuming steps, which is also adhered to high efforts.[57]

Examples of process-LCA simplification steps are the omission of up- and downstream components of the product system, the use of economic flow tables for development of the LCI or hybrid methods, where the process-LCA is combined with economic input/output modeling to develop the LCI.[58]

Rebitzer et al. mentions three steps towards a simplified LCA:[59]

1. Screening
2. Simplifying
3. Reliability check

During the screening step the relevance of certain system components is assessed, for instance, by calculating the cumulative energy demand of processes or the ‘material intensity per service unit’ (MIPS).[60] This step should address the whole life cycle of a product but can be conducted on a superficial level of detail, for example, by using qualitative or quan-

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[50] Cf. http://www.eebguide.eu/?p=913 and http://www.eebguide.eu/?p=922

[51] Cf. http://www.eebguide.eu/?p=913

[52] Cf. European Environment Agency 1997, p. 31.

[53] Cf. European Environment Agency 1997, p. 31.

[54] Cf. European Environment Agency 1997, p. 31.

[55] Cf. European Environment Agency 1997, p. 29.

[56] Cf. European Environment Agency 1997, p. 31.

[57] Cf. Rebitzer et al. 2004, p. 709.

[58] Cf. Rebitzer et al. 2004, pp. 709-713.

[59] Cf. Rebitzer et al. 2004, p. 710.

[60] Cf. European Environment Agency 1997, p. 31 and Rebitzer et al. 2004, p. 710.

titative generic data, to ensure that the identification of significant system parameters is possible.[61]

After the simplification step itself, the LCI can be developed according to the simplified system model.[62]

Simplification procedure examples include:[63]

- Simplification or omission of life-cycle stages in terms of neglecting up- and/or downstream unit processes.
- Using surrogate data from similar processes
- Neglection of unimportant LCI components according to the requirements of chosen impact categories.
- Incorporating qualitative data together with quantitative data.

The reliability check should ensure that the simplification step does not result in unrewarding or unreliable conclusions of the LCA.[64]

It is possible to use simplified LCA studies for external purposes if they were performed according to the standards of ISO.[65]

Dynamic LCA

The dynamic LCA approach is usually referred to an LCA that incorporates temporal and spatial alteration of system components or the environment, as changes during the lifetime of system components may have significant impacts on the final results.[66]

This especially addresses the improvement of products and processes like technical improvements, for example, resulting in better efficiencies, but also the time-dependency of emissions.[67]

The main characteristic of the dynamic LCA would be that the inventory data is a function of time instead of steady state model based assumptions, whereas also the LCIA procedure accounts for the spatial and temporal variations of the LCI data.[68]

Attributional vs. consequentional method approach

In the recent past two differing approaches to process-LCA have been mentioned by different authors[69] describing unlike modes of analysis, which are by name attributional and consequentional LCA also called descriptive or retrospective approach and change-oriented or prospective approach.[70]

The type of modeling approach is actually defined by the goal and scope of the study, but as it affects the kind of data and some methodologies utilized in the LCI, the procedure of the LCIA and ultimately the type of information provided by the LCA, some differences concerning the two approaches are clarified within this section of the thesis.

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[61] Cf. European Environment Agency 1997, p. 31.

[62] Cf. Rebitzer et al. 2004, p. 710.

[63] Cf. Curran 1996, p. 4.3.

[64] Cf. Rebitzer et al. 2004, p. 711.

[65] Cf. European Environment Agency 1997, p. 32.

[66] Cf. Collinge et al. 2013, p. 538.

[67] Cf. Pehnt 2006, pp. 62-63.

[68] Cf. Matsumoto et al. 2012, p. 616.

[69] Cf. Guinée et al. 2002, p. 31; Finnveden et al. 2009, p. 3; Lewandowska and Foltynowicz 2004, p. 464 and UNEP/SETAC Life Cycle Initiative 2011, p. 47.

[70] Cf. Lewandowska and Foltynowicz 2004, p. 464 and Rebitzer et al. 2004, p. 712.

The attributional LCA regards assessment of environmental aspects in terms of input and output flows immediately connected to the functional unit, thus depicting the environmental burdens associated with a product or process under consideration.[71] This modeling approach applies, for example, if the environmental burdens of a product or process are to be determined.[72]

The consequentional approach, as its name implies, is focused on determination of direct or indirect consequences of input and output flows caused by possible decisions, where the system under study includes those processes influenced by the decisions.[73] When assessing, for instance, the impacts on the environment as a result of certain decisions the consequentional procedure is appropriate.[74]

It is obvious to utilize the consequentional LCA method in case of decision-making but some situations request reflections of the implementation of this method. Generally both methods can be applied to evaluate past, present and future systems as also for the purpose of decision making, but it is suggested[75] to apply the attributional method if no decision exists, if the results of both methods are expectably quiet the same, or if the uncertainties of decisions inhered in the consequentional approach are intolerable.

The differences of both methods regard the following. In case of the attributional method average data, depicting the average environmental loads linked to unit processes of the product system, is applied, or else in the event of a consequentional LCA marginal data, illustrating environmental impacts due to a marginal alteration of outputs resulting from decisions, are utilized.[76] The problem adhered to marginal data is the uncertainty of expected effects, which can be considerably, for instance, when incorporating the elasticity of supply and demand.[77]

Another difference of these two approaches affects the way they handle allocation when defining the system boundary. As already mentioned, the consequentional method includes every element impacting the system under study by certain decisions, even if those elements are not regarded to be a direct part of the product or process life-cycle. This inevitably results in system expansion rather than allocation, which might of course be appropriate for the attributional LCA, but it is the actual motivation of the consequentional LCA to evaluate the impacts of decision dependent elements.[78]

2.3 Software tools

Numerous LCA software tools emerged in the past with the general purpose to support the practitioner in performing calculations, data management, system modelling as also determination and analysis of the final outcomes, when conducting an LCA study.[79]

In the following some commonly used software tools and their principal characteristic are briefly explained, as a detailed discussion on software tools is out of the scope of this thesis. Many authors examined the characteristics and suitability of different kinds of software

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[71] Cf. Rebitzer et al. 2004, p. 705 and UNEP/SETAC Life Cycle Initiative 2011, p. 47.

[72] Cf. Finnveden et al. 2009, p. 4.

[73] Cf. UNEP/SETAC Life Cycle Initiative 2011, p. 47.

[74] Cf. Finnveden et al. 2009, p. 4.

[75] Cf. Finnveden et al. 2009, p. 3.

[76] Cf. Finnveden et al. 2009, p. 3 and UNEP/SETAC Life Cycle Initiative 2011, p. 74.

[77] Cf. Finnveden et al. 2009, pp. 3-4.

[78] Cf. Finnveden et al. 2009, p. 6; Rebitzer et al. 2004, p. 705 and UNEP/SETAC Life Cycle Initiative 2011, p. 74.

[79] Cf. Unger et al., pp. 1-2.

tools for various purposes, thus for more detailed information, additional literature, publications, and vendors of such tools, should be taken into consideration.

Usually an LCA software tool incorporates a number of databases, providing a huge amount of data that can be used to develop the inventory of a system, and often these already included databases can be supplemented with own data of the operator.

Additionally various impact assessment methods and options are mostly at hand, enabling the practitioner of a study to determine the environmental loads of the modelled system, for instance, on basis of normalized and/or weighted LCIA methods.

Concerning the interpretation phase of an LCA, also various possibilities are often provided within the offered software packages like, for example, sensitivity analyses, measures of uncertainty of the final results, or accentuation of dominant system elements.

The following list of software is not all inclusive but already indicates the vast number of nowadays available LCA software tools:[80]

- Athena
- BEES
- DPL 1.0
- Ecoinvent
- Eco-Quantum
- EIME
- Environmental Impact Estimator V3.0.2
- EPD Tool suite 2007
- GaBi
- GEMIS
- KCL-ECO 4.0
- LCA-Evaluator 2.0
- Modular MSWI Model 1.0
- REGIS
- SALCA
- SimaPro
- TEAM
- The Boustead Model
- Umberto

Some tools are now shortly explained to highlight the differences of currently available LCA software, which not only differ in their price, but also in the features they offer like the included databases, the incorporated impact assessment methods and the possible area of applications.

Rebitzer et al.[81] distinguishes three types of LCA software, differing in their intended use and the type of incorporated data. Generic software types provide standard databases and are most of all suitable for specialist users of LCA, whereas specialized software types were designed to support decision makers in the areas of, for example, construction or waste

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[80] Cf. European Commission - Institute for Environment and Sustainability 2008, p. 1.

[81] Cf. Rebitzer et al. 2004, p. 708.

management.[82] Both of these two software types mostly include a collection of datasets from public and industrial databases, while tailored LCA software, the third type of software Rebitzer et al.[83] mentions, additionally includes company specific internal data to enable conducting an LCA study in relation to a certain business.

GaBi

This software tool was developed in Germany by the University of Stuttgart and the company 'PE International', provides a very comprehensive amount of datasets, and is in line with the ISO standards.[84] GaBi is a proper software to be used, for example, in the areas of chemistry, construction, energy, renewable, transportation, mining, electronics, metals and plastics.[85] The software allows definition of own impact assessment methods and weighting factors, which makes this tool very flexible.[86]

<u>Impact Assessment Methods:</u>[87]

- CML 2011
- CML 1996
- Eco-Indicator 95
- Eco-Indicator 99
- EDIP 1997
- EDIP 2003
- IMPACT 2002+
- Ecological Scarcity
- ReCiPe
- TRACI 2.0
- USEtox

<u>Databases:</u>[88]

- GaBi
- APME
- BUWAL 250
- EAA
- Ecoinvent
- GaBi database
- IISI
- U.S. LCI

SimaPro

SimaPro is capable to conduct hybrid LCA studies and it is possible that input as also output data can include uncertainties, depicted in terms of probability distributions, but does not allow assessment of site specific impacts or definition of non-linear relations.[89] The software was developed in the Netherland by the company 'Pré Consultants', is in line with the ISO standards and allows easy assessment of complex system models.[90] SimaPro is one of the mostly used software tools and depicts the inventory data that was not incorporated

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[82] Cf. Rebitzer et al. 2004, pp. 708-709.

[83] Cf. Rebitzer et al. 2004, pp. 708-709.

[84] Cf. Loijos 2012; European Commission - Institute for Environment and Sustainability 2008, p. 13 and Klöpffer and Grahl 2009, p. 138.

[85] Cf. Siegenthaler et al. 2005, p. 63 and Baitz et al. 2011, p. 4.

[86] Cf. European Commission - Institute for Environment and Sustainability 2008, p. 14 and http://www.gabi-software.com/austria/databases/

[87] http://database-documentation.gabi-software.com/austria/support/gabi/gabi-5-lcia-documentation/life-cycle-impact-assessment-lcia-methods/

[88] Cf. Siegenthaler et al. 2005, p. 63 and http://www.gabi-software.com/austria/databases/

[89] Cf. European Commission - Institute for Environment and Sustainability 2008, pp. 29-30 and Siegenthaler et al. 2005, p. 97.

[90] Cf. http://www.buildingecology.com/sustainability/life-cycle-assessment/life-cycle-assessment-software and Klöpffer and Grahl 2009, p. 138.

in the impact assessment, thus giving an indication of completeness.[91] The impact assessment methods can be adjusted to the needs of the practitioner, for example, in terms of weighting the results.[92]

Impact Assessment Methods:[93]

- CML IA
- USEtox
- IPCC 2007
- TRACI 2
- BEES
- EDIP 2003
- EPD
- Eco-Indicator 99 (not included in the new software version)
- Ecological Scarcity
- Greenhouse Gas Protocol
- Ecological Footprint
- ILCD 2011 Midpoint
- ReCiPe
- IMPACT 2002+
- EPS 2000
- Selected LCI results
- Ecosystem Damage Potential
- Cumulative Energy Demand
- Cumulative Exergy Demand

Databases:[94]

- Ecoinvent
- Franklin US LCI 98 library
- European Life Cycle Data
- US Input Output Library
- EU and Danish Input Output Library
- Swiss Input Output
- LCA Food
- Industry data v2
- BUWAL 250

TEAM (Tool for Environmental Analysis and Management)

The software is in line with the 14040 series of ISO standards and can be applied, for example, in the areas of buildings, chemistry, energy, raw materials and transports as suggested by Siegenthaler et al.[95].[96]

TEAM was developed in France by the company 'Ecobilan'.[97] Allocation procedures can be described for each flow of an unit process individually by entering formulas and additionally the construction of modules, where subsystems are included, decreasing the complexity of comprehensive systems.[98]

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[91] Cf. European Commission - Institute for Environment and Sustainability 2008, p. 30 and Klöpffer and Grahl 2009, p. 138.

[92] Cf. Siegenthaler et al. 2005, p. 97 and European Commission - Institute for Environment and Sustainability 2008, p. 29.

[93] Cf. http://www.pre-sustainability.com/databases and PRé 2013, pp. 4-38

[94] http://www.pre-sustainability.com/databases and Siegenthaler et al. 2005, p. 97.

[95] Cf. Siegenthaler et al. 2005, p. 109.

[96] Cf. http://ecobilan.pwc.fr/en/boite-a-outils/team.jhtml

[97] Cf. Klöpffer and Grahl 2009, p. 138.

[98] Cf. Menke et al. 1996, p. 16.

Impact Assessment Methods:[99]

- CML
- USEtox
- Eco-Indicator 95
- Eco-Indicator 99
- EPS
- Critical Volumes
- IPCC 2007

Databases:[100]

- DEAM
- APME
- BUWAL
- ETH-ESU 96
- Boustead
- Ecoinvent

Umberto

This LCA software is applicable to various industry sectors and areas such as automotives, metals, waste management, chemicals, mines, pharmaceuticals, semiconductors or food and allows linear, non-linear, as also dynamic input/output flows, in terms of process modeling.[101] Umberto is capable of assessing very complex systems while providing the possibility to examine the desired level of detail like, for example, looking at a complete product system or a certain process.[102]

The impacts of varying system parameters are depicted in a transparent way by providing a graphical model of the system and it is possible to individually aggregate LCI scores to final indicator values.[103] Additionally Umberto, which was developed in Germany by the 'Institut für Unfallanalysen' (Ifu) in Hamburg, together with the 'Institut für Energie- und Umweltforschung' (IFEU) in Heidelberg, can be linked to Enterprise-Resource-Planning software such as SAP, thus saving the time for double data entry.[104]

Impact Assessment Methods:[105]

- ReCiPe
- IMPACT 2002+
- Eco-Indicator 99
- CML
- TRACI
- IPCC
- German UBA Method
- Ecological Scarcity

Databases:[106]

- Umberto Library
- APME
- BUWAL
- GEMIS
- ETH-ESU 96
- Ecoinvent
- GaBi

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[99] Cf. Siegenthaler et al. 2005, p. 109 and http://ecobilan.pwc.fr/en/boite-a-outils/team.jhtml

[100] Cf. Siegenthaler et al. 2005, p. 109.

[101] Cf. Siegenthaler et al. 2005, p. 119; http://www.umberto.de/en/versions/umberto-nxt-lca/ and European Commission - Institute for Environment and Sustainability 2008, pp. 33-34.

[102] Cf. European Commission - Institute for Environment and Sustainability 2008, p. 34.

[103] Cf. European Commission - Institute for Environment and Sustainability 2008, pp. 33-34.

[104] Cf. European Commission - Institute for Environment and Sustainability 2008, p. 34 and Klöpffer and Grahl 2009, p. 138.

[105] Cf. Siegenthaler et al. 2005, p. 119 and http://www.umberto.de/en/versions/umberto-nxt-lca/

[106] Cf. Siegenthaler et al. 2005, p. 119 and http://www.umberto.de/en/versions/umberto-nxt-lca/

2.4 Databases

As a complete system comprises a considerable number of processes the effort of collecting data to assess the environmental loads of such a system can be considerable. Generally a mix of data is used to perform an LCA study including different types of data from different sources. The lists below should outline at least some aspects in relation to data types, sources, and categories, but are not considered to be all-inclusive.

Types:[107]

- Calculated data
- Measured data
- Estimated data
- Sampled data
- Vendor data
- Modelled data
- Surrogate data

Sources:[108]

- Meter readings from equipment
- Equipment operating logs/journals
- Industry data reports, databases, or consultants
- Laboratory test results
- Government documents, reports, databases, and clearinghouses
- Other publicly available databases or clearinghouses
- Journals, papers, books, and patents
- Reference books
- Trade associations
- Related/previous life cycle inventory studies
- Equipment and process specifications
- Best engineering judgment

Categories:[109]

- Specific data from distinct processes, operations or companies.
- Composite data consisting of similar subjects compiled from diverse origins.
- Aggregated data representing combined information of a plural of processes.
- Average data is based on statistics, which evolved from samples that are considered to be adequate for denotation of characteristics related to certain process or industry.
- Generic data describing particular practices or operations in a qualitative way without declaration of provided representativeness.

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[107] Cf. ISO 2006b, p. 9 and Scientific Applications International Corporation (SAIC) 2006, p. 23.

[108] Scientific Applications International Corporation (SAIC) 2006, p. 23.

[109] Cf. Scientific Applications International Corporation (SAIC) 2006, pp. 23-24.

Databases provide a huge amount of secondary data related to a different kind of processes, commodities and services, thus facilitating the development of the life cycle inventory for the practitioner of an LCA study.

Secondary data in these terms means that the data was not compiled for the specific purpose of an LCA study and stays in contrast to primary data, which, for example, is measured or calculated by the study practitioner himself to describe the main processes of interest. But this secondary data can be used to model the background processes of a system, therefore significantly reducing the time and labor of the data collection procedure.

Many external databases, which are not proprietary to specific LCA software packages and thus independently available, were prepared by different public and industry initiatives such as governments, clearinghouses, statistical offices and manufacturers. It is to mention that default software specific databases, included in the purchased software license, were often compiled with aid of such external databases.

In the next an abstract of available external and default software databases, which are nowadays available for the development of life cycle inventories, is given, including a brief explanation of the database origin and content.

APME

This free available database was developed by 'The Association of Plastics Manufacturers in Europe' and comprises aggregated data in relation to consumption and recovery of plastics gathered from companies in Europe.[110]

Athena

'Athena Life Cycle Inventory Databases' developed by the Canadian 'Athena Sustainable Materials Institute', is non-commercial, and includes data for building materials and products, transportation, construction and demolition processes, maintenance tasks and disposal.[111]

Boustead

This database is considered to be one of the most comprehensible collection of data and was compiled by the British 'Boustead Consulting Ltd.'.[112] Datasets address information on raw materials, fuels, materials processing, different kinds of manufacturing processes and related emissions to air and water, solid waste as also feedstocks.[113]

BUWAL

Based on industry statistics and developed by the 'Swiss Office of Environmental Protection', this database especially addresses information on material production and end-of-life treatment of packaging and materials such as metals, paper, plastics and glass.[114]

DEAM

'Data for Environmental Analysis and Management' (DEAM) is a database proprietary to the TEAM software package developed by the 'Ecobilan Group' and includes datasets related to energy carriers, transports and material production.[115]

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[110] Cf. http://www.epa.gov/nrmrl/std/lca/resources.html and Klöpffer and Grahl 2009, p. 136.

[111] Cf. http://www.athenasmi.org/our-software-data/lca-databases/

[112] Cf. Klöpffer and Grahl 2009, p. 138.

[113] Cf. http://www.boustead-consulting.co.uk/products.htm

[114] Cf. Klöpffer and Grahl 2009, p. 136.

[115] Cf. http://www.ghgprotocol.org/Third-Party-Databases and European Commission - Institute for Environment and Sustainability 2008, p. 40.

EAA

The 'European Aluminium Association' provides free available LCI data for aluminium related processes such as mining of Bauxite, production of alumina and semi-finished products, product manufacture, use and recycling.[116]

Ecoinvent

Developed by the 'Swiss Centre for Life Cycle Inventories' and including up-to-date information on several areas such as agriculture, energy supply and electricity mixes, power plants, basic chemicals, metals, electronics, construction and packaging materials, wood materials, transport services and waste management services to name but a few, this database is said to be one of the best databases internationally available.[117]

ETH-ESU 96

The database developed by the Swiss 'Environmental Consultancy for Business and Authorities' (ESU-services) provides information especially for western Europe, is free available and includes datasets for primary energy extraction, energy conversion, electricity supply and transmission, raw material and materials production, transport services, construction of infrastructure and waste treatment.[118]

GaBi

The database covers several areas such as electricity mix data, metals, minerals, coatings, electronics, construction materials, textiles, etc. and constitutes one of the largest database concepts worldwide.[119]

GEMIS

The 'Global Emission Model for Integrated Systems' developed by the German 'Institute for Applied Ecology' is free available and comprises important information on energy data with relation to the European Union region.[120] Within the database, efficiencies, operating time, lifetime, emissions, wastes, land use etc. are given for energy carriers, heat and electricity supply, base chemicals, metals, plastics, food, textiles, transport services as also recycling and waste treatment processes.[121]

IISI

This non-commercial database was developed by the 'International Iron and Steel Institute' and provides industry statistics based datasets related to resource use, extraction of raw materials, energy input, material processing for fourteen different metal and semimetal products.[122]

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[116] Cf. http://www.alueurope.eu/sustainability/life-cycle-assessment/

[117] Cf. http://www.ecoinvent.org/database/ and European Commission - Institute for Environment and Sustainability 2008, pp. 41-42.

[118] Cf. http://www.pre-sustainability.com/download/manuals/DatabaseManualETH-ESU96.pdf, pp. 2-3 and http://www.ghgprotocol.org/Third-Party-Databases

[119] Cf. http://www.openlca.org/gabi-databases and European Commission - Institute for Environment and Sustainability 2008, p. 44.

[120] Cf. Klöpffer and Grahl 2009, p. 137.

[121] Cf. http://www.ghgprotocol.org/Third-Party-Databases; http://www.iinas.org/gemis-database-en.html and European Commission - Institute for Environment and Sustainability 2008, p. 45.

[122] Cf. http://www.ghgprotocol.org/Third-Party-Databases

ProBas

The 'Prozessorientierte Basisdaten für Umweltmanagement-Instrumente' database developed by the German 'Federal Environment Agency' is free available and includes datasets for energy carriers, production of materials, transport and disposal.[123]

U.S. LCI

The 'U.S. Life Cycle Inventory' database was compiled by the 'National Renewable Energy Laboratory' (NREL), is free available, especially addresses the USA and Canada, and provides information on energy carriers, raw materials, food, agriculture, transports, production of materials and other common processes.[124]

2.5 LCIA Methods

Life-cycle impact assessment is one of the core steps to a complete LCA study, and different methods have been developed to determine the ensuing consequences, to the environment, of input and output flows of a system under study, which have been quantified and compiled prior to the impact assessment in the LCI.

A more detailed discussion on how the general impact assessment procedure is conducted is given in chapter 3, which follows the recommendations of the ISO 14040 and ISO 14044 standards for life-cycle assessment.

The following list of common LCIA methods is not considered to be all-inclusive but already reveals the broad range of offered methods:[125]

- BEES (Building for Environmental and Economic Sustainability)
- CML
- Critical Volumes
- Cumulative Energy Demand
- Cumulative Exergy Demand
- Eco-Indicator 95
- Eco-Indicator 99
- Ecological Footprint
- Ecological Scarcity
- EDP (Ecosystem Damage Potential)
- EDIP (Environmental Design of Industrial Products)
- EPD (Environmental Product Declarations)
- EPS 2000 (Environmental Priority Strategies in Product Development)
- Greenhouse Gas Protocol
- IMPACT 2002+
- ILCD
- IPCC (Climate Change)

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[123] Cf. http://www.ghgprotocol.org/Third-Party-Databases and European Commission - Institute for Environment and Sustainability 2008, p. 49.

[124] Cf. http://www.ghgprotocol.org/Third-Party-Databases and European Commission - Institute for Environment and Sustainability 2008, p. 53.

[125] Cf. Althaus et al. 2010, p. i.

- ReCiPe
- Selected LCI results
- TRACI
- UBA-Method
- USEtox

As nowadays available software tools often provide a number of various impact assessment methods, it is now the aim to highlight at least some principal characteristics of some common LCIA methods often used, to direct one's attention to the inhered fundamental differences, which presumably should be regarded when conduction an LCIA procedure.

In general, differences among several methods are mainly related to:

- the type of modelling approach, either assessing environmental impacts on a midpoint indicator level (problem-oriented approach) or determining impacts on basis of endpoint indicator results (damage-oriented approach).
- the provided impact categories as also the units of the impact category indicators that can be considered and evaluated by the practitioner of an LCA study. Examples of these varieties are given in Annex A for the CML, Eco-Indicator 99 EDIP and IMPACT 2002+ methods.
- the possibility to conduct normalization and weighting steps in the impact assessment procedure, and, in consequence of these steps also the temporal and spatial relationships, and the incorporated weighting factors.

A detailed discussion of certain impact assessment methods is out of the scope of this thesis, therefore additional literature should be taken into consideration for further information.

CML

The CML method was developed in the Netherlands by 'The University of Leiden', is a problem-oriented approach, and provides the possibility to conduct a normalization step with normalized values for the Netherlands (1997), western Europe (1995) and the world population (1990, 1995 and 2000).[126]

Impact Categories:[127]

- Climate change
- Acidification potential
- Depletion of abiotic resources
- Freshwater aquatic ecotoxicity
- Freshwater sedimental ecotoxicity
- Marine aquatic ecotoxicity
- Marine sedimental ecotoxicity
- Terrestrial ecotoxicity
- Eutrophication
- Human toxicity

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[126] Cf. Acero et al. 2014, p. 9 and Althaus et al. 2010, pp. 26-27.

[127] Cf. Acero et al. 2014, pp. 8-9.

- Ozone layer depletion
- Photochemical oxidation
- Ionising radiation
- Land use
- Odour

EDIP

This method was created in Denmark by the IPU (Institute for Product Development) at the 'Technical University of Lyngby', including normalization data for Europe (1990) and the world (1990).[128] The problem-oriented approach also enables the practitioner to conduct a weighting step with weighting values related to the year 1990.[129]

Impact Categories:[130]

- Global warming
- Acidification potential
- Ecotoxicity – in continental water
- Ecotoxicity – in marine water
- Ecotoxicity – in soil
- Aquatic eutrophication
- Terrestrial eutrophication
- Human toxicity – via air
- Human toxicity – via soil
- Human toxicity – via water
- Startospheric ozone depletion
- Photochemical ozone formation – human health
- Photochemical ozone formation – vegetation

Eco-Indicator 99

The method is a damage-oriented approach and aggregates intermediate endpoint scores to three endpoint indicators, which are resources, human health, and ecosystems.[131] Depletion of abiotic resources is notified in '[MJ] surplus energy', thus accounting for the additional energy needed to meet the future resource demand, and human health damage is indicated as DALY (Disability Adjusted Life Years), which is a measure of the number of year life lost.[132] Damage to ecosystems is evaluated in terms of lost species over a given temporal period and spatial area.[133]

Three different archetypes, namely Hierarchist (H), Individualist (I) and Egalitarian (E), are available to which western Europe specific normalization and weighting factors are attributed, thus expressing distinct cultural perspectives.[134] The Hierarchist type weights all

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[128] Cf. Acero et al. 2014, p. 11 and Althaus et al. 2010, pp. 89-100.

[129] Cf. Simões et al. 2011, p. 4.

[130] Cf. Acero et al. 2014, pp. 11-12.

[131] Cf. Acero et al. 2014, p. 10.

[132] Cf. PRé 2013, p. 63.

[133] Cf. PRé 2013, p. 63.

[134] Cf. Acero et al. 2014, p. 10.

endpoint categories equally, whereas in the Individualist perspective higher weight is put to human health and within the Egalitarian scenario ecosystem quality is prioritized.[135]

Figure 1 below shows the principle procedure, this method follows, to end up in a single result, which is then given in Pt (point) or mPt (millipoint).[136]

Intermediate Endpoint Categories:[137]

- Ecosystem Quality – Land conversion (PDF*m²)
- Ecosystem Quality – Land conversion (PDF*m²*year)
- Ecosystem Quality – Acidification and Eutrophication
- Ecosystem Quality – Ecotoxicity
- Human Health – Carcinogens
- Human Health – Climate change
- Human Health – Ionising radiation
- Human Health – Ozone layer depletion
- Human Health – Respiratory effects caused by inorganic substances
- Human Health – Respiratory effects caused by organic substances
- Resources – Fossil fuels
- Resources - Minerals

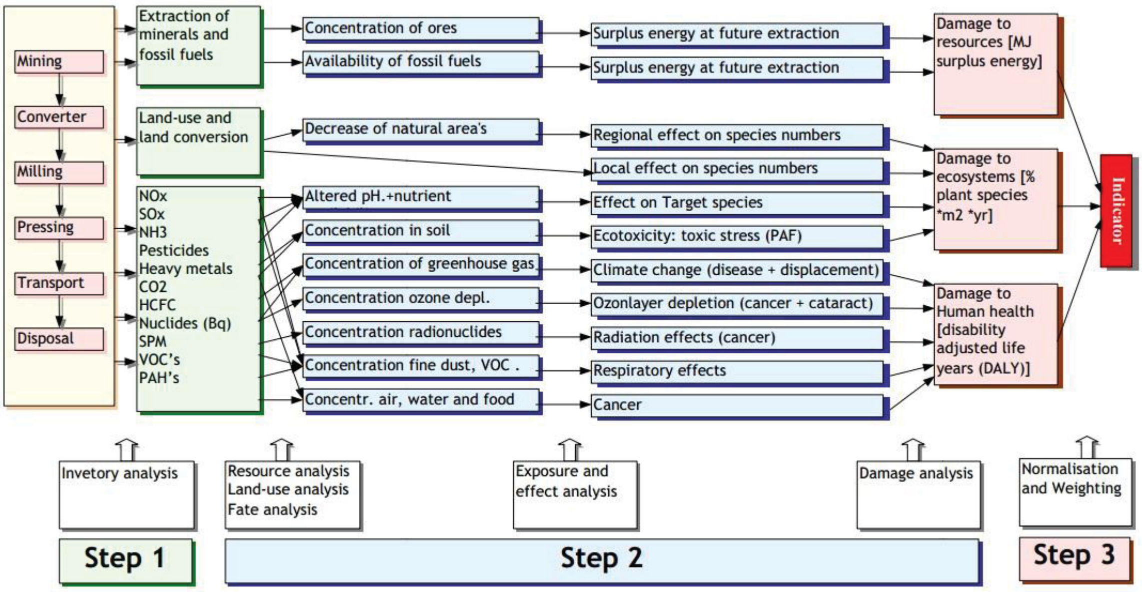

Figure 1: The Eco-Indicator 99 impact assessment model.[138]

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[135] Cf. Simões et al. 2011, p. 4.

[136] Cf. Acero et al. 2014, p. 10.

[137] Cf. Acero et al. 2014, pp. 11-12.

[138] PRé 2013, p. 63.

EPS 2000

The 'Environmental Priority Strategy in Product design' (EPS) method was developed by Ryding and Steen, and as well provides a damage-oriented impact assessment approach.[139]

The LCI results are multiplied by weighting factors, based on the willingness to pay for avoiding changes of the present environmental state, or, in other words, to restore impacts on the present state.[140]

'Environmental Load Units' (ELU) represent the characterized, normalized and weighted overall indicators, which state recreational and cultural values, as also the impacts on human health, ecosystem production capacity, biodiversity and abiotic resources, on a relative scale.[141]

Impact Categories:[142]

- Human Health – Life expectancy
- Human Health – Severe morbidity
- Human Health – Morbidity
- Human Health –Severe nuisance
- Human Health – Nuisance
- Ecosystem Production Capacity – Crop growth capacity
- Ecosystem Production Capacity – Wood growth capacity
- Ecosystem Production Capacity – Fish and meat production capacity
- Ecosystem Production Capacity – Soil acidification
- Ecosystem Production Capacity – Production capacity for irrigation water
- Ecosystem Production Capacity – Production capacity for drinking water
- Biodiversity – Species extinction

IMPACT 2002+

The method was developed by the 'Swiss Federal Institute of Technology' in Lausanne and is a combination of a midpoint- and endpoint-modeling approach.[143] Fourteen problem-oriented midpoint impact categories are linked to four damage-oriented end points, namely human health, ecosystem quality, climate change and resources.[144]

After normalization of the characterized midpoint category results, with factors given for Europe, the weighted final scores are displayed in 'DALY' for the endpoint category human health, in 'PDF*m²*year' for the endpoint category ecosystem quality, in 'kg_{eg}-CO_2 into air' for the endpoint category climate change, and in '[MJ]' for the endpoint category resources.[145]

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[139] Cf. Althaus et al. 2010, p. 102.

[140] Cf. PRé 2013, p. 18 and Simões et al. 2011, p. 4.

[141] Cf. Althaus et al. 2010, p. 103; PRé 2013, p. 18 and Simões et al. 2011, p. 4.

[142] Cf. Althaus et al. 2010, p. 103.

[143] Cf. Jolliet et al. 2003, p. 325.

[144] Cf. Jolliet et al. 2003, p. 325.

[145] Cf. Humbert et al. 2012, p. 17 and Jolliet et al. 2003, p. 325.

Impact Categories:[146]

- Human Health – Human toxicity (carcinogens and non-carcinogens)
- Human Health – Respiratory inorganics
- Human Health – Ionizing radiation
- Human Health – Ozone layer depletion
- Human Health/Ecosystem quality – Photochemical oxidation
- Ecosystem Quality – Aquatic ecotoxicity
- Ecosystem Quality – Terrestrial ecotoxicity
- Ecosystem Quality – Terrestrial acidification/nutrification
- Ecosystem Quality – Aquatic acidification
- Ecosystem Quality – Aquatic eutrophication
- Ecosystem Quality – Land occupation
- Climate Change – Global warming
- Resources – Non-renewable energy
- Resources – Mineral extraction

IPCC

This method was developed by the 'Intergovernmental Panel on Climate Change' to determine the effects of greenhouse gas emissions on the global warming potential, calculated in terms of CO_2-equivalents.[147] The characterization factors for different greenhouse gases are based on the publications of the IPCC for global warming potentials of air emissions, wheras three different timeframes, namely GWP 20a, GWP 100a and GWP 500a, are implemented to account for the varying lifetimes of distinct greenhouse gases.[148]

Normalization and weighting steps to this method are not provided.[149]

Impact Categories:[150]

- GWP 20a – Climate change
- GWP 100a – Climate change
- GWP 500a – Climate change

ReCiPe

ReCiPe was developed by 'Netherlands National Institute for Public Health and the Environment' (RIVM), the Dutch 'Institute of Environmental Sciences' at the University in Leiden (CML), the Dutch company 'PRé Consultants', and the 'Radboud University Nijmegen' in the Netherlands.[151]

This method depicts a combination of midpoint- as also endpoint-results and provides distinct types of cultural perspectives for the normalization and weighting steps, namely the

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[146] Cf. Jolliet et al. 2003, p. 325.

[147] Cf. Althaus et al. 2010, p. 126 and PRé 2013, p 33.

[148] Cf. Althaus et al. 2010, p. 126 and PRé 2013, p 33.

[149] Cf. PRé 2013, p 33.

[150] Cf. Althaus et al. 2010, p. 126.

[151] Cf. http://www.lcia-recipe.net/

Individualist, Egalitarian and the Hierarchist, with normalization factors given for Europe and the World relating to the year 2000.[152]

The Individualist perspective weights damage to human health the most, the Egalitarian and the Hierarchist prioritize ecosystem quality, whereas the latter equally weights damage to human health and resource availability.[153]

Eighteen midpoint impact categories are aggregated to three endpoint indicators, which are human health damage (DALY), ecosystem damage (species*year), and damage to resources (U.S. $).[154]

The damage to ecosystem quality is measured in species lost within a certain timeframe and region, and damage to resources, in terms of availability, is indicated as the additional cost to extract future resources.[155]

Figure 2 below shows the principle of the ReCiPe impact assessment model.

Impact Categories:[156]

- Human Health – Ozone depletion
- Human Health – Human toxicity
- Human Health – Particulate matter formation
- Human Health – Photochemical oxidant formation
- Human Health – Ionising radiation
- Human Health/Ecosystem Quality – Climate change
- Ecosystem Quality – Freshwater eutrophication
- Ecosystem Quality – Marine eutrophication
- Ecosystem Quality – Terrestrial acidification
- Ecosystem Quality – Terrestrial ecotoxicity
- Ecosystem Quality – Freshwater ecotoxicity
- Ecosystem Quality – Marine ecotoxicity
- Ecosystem Quality – Agricultural land occupation
- Ecosystem Quality – Urban land occupation
- Ecosystem Quality – Natural land transformation
- Ecosystem Quality – Water depletion
- Resources – Mineral resource depletion
- Resources – Fossil fuel depletion

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[152] Cf. Althaus et al. 2010, p. 144 and http://www.lcia-recipe.net/

[153] Cf. http://www.lcia-recipe.net/

[154] Cf. http://www.lcia-recipe.net/

[155] Cf. PRé 2013, p. 19.

[156] Cf. http://www.lcia-recipe.net/

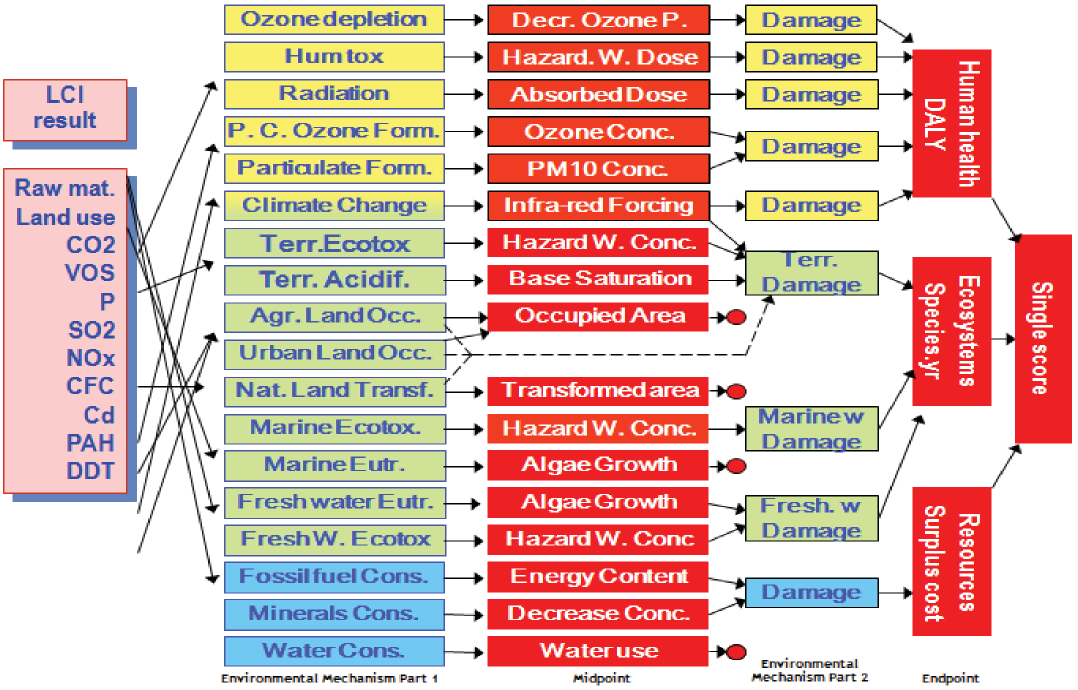

Figure 2: ReCiPe model and relationship between inventory results, midpoint categories and endpoint indicators.[157]

UBA-Method

Developed by the German 'Federal Environmental Agency' (UBA), this method provides ten problem-oriented impact categories and the LCIA steps of normalization and ranking with normalization factors related to Germany.[158]

Impact Categories:[159]

- Global warming potential
- Acidification
- Ozone depletion potential
- Photo oxidant formation
- Aquatic eutrophication
- Terrestrial eutrophication
- Human toxicity
- Ecotoxicity
- Land use
- Resources

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[157] http://www.lcia-recipe.net/

[158] Cf. Schmitz and Paulini 1999, pp. 13-19.

[159] Cf. Schmitz and Paulini 1999, p. 13.

3 LCA after the International Organization for Standardization (ISO)

ISO is a network of 160 national standard bodies, preparing worldwide standards for management tools, products and services to ensure safety, reliability, quality, comparability and conformity amongst others.[160]

These normative documents are developed for the market by technical committees, composed of ISO member bodies.[161]

The Technical Committee ISO/TC 207 was founded in 1993 to form environmental management standards, also known as the ISO 14000 family of standards that are internationally used to address sustainable development.

The Subcommittee SC 5 'Life cycle assessment' prepared the ISO 14040 (Principles and framework) and ISO 14044 (Requirements and guidelines), which are today's standards used for the application of LCA.[162]

Both standards address, in their specific intention, the below listed aspects to an LCA procedure:[163]

- the goal and scope definition of the LCA,
- the life cycle inventory analysis (LCI) phase,
- the life cycle impact assessment (LCIA) phase,
- the life cycle interpretation phase,
- reporting and critical review of the LCA,
- limitations of the LCA,
- relationship between the LCA phases, and
- conditions for use of value choices and optional elements.

Additionally two technical reports were released, which are by name ISO/TR 14047 (Illustrative examples on how to apply ISO 14044 to impact assessment situations) and ISO/TR 14049 (Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis). Furthermore one technical specification termed ISO/TS 14048 (Data documentation format) supplements the ISO 14040 series of standards.

3.1 General Description to ISO's LCA

Herein before mentioned, LCA identifies potential environmental impacts of a product system from cradle-to-grave. The approach, composed of four different stages, uses an arbitrarily predefined functional unit to determine the environmental effects related to this unit, thus making it a relative approach. Life cycle assessment can be applied with other analytical management methods as one part of a more comprehensive survey used for a decision process.[164]

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[160] Cf. http://www.iso.org/iso/home/about.htm

[161] Cf. ISO 2006a, p. iv.

[162] Cf. ISO 2006a, p. iv

[163] ISO 2006a, p. 1

[164] Cf. Guinée et al. 2002, p. 9

The International Standards comprises references and guidelines to ensure a transparent procedure, which is an important issue for comparison of the LCA results particularly needed for the decision process.

ISO[165] states that the ISO 14040 and the ISO 14044 standards cover two sorts of appraisals, called by name LCA studies and LCI studies, whereas the only difference is that a LCI study omits the Life Cycle Impact Assessment (LCIA) phase.

According to the ISO[166] standards the list below exhibits the four stages that are distinguished to an LCA approach. These steps are thoroughly explained in this chapter and their relation to each other is shown in figure 3.

1. **Goal and scope definition**
2. **Life cycle inventory (LCI)**
3. **Life cycle impact assessment (LCIA)**
4. **Life cycle interpretation**

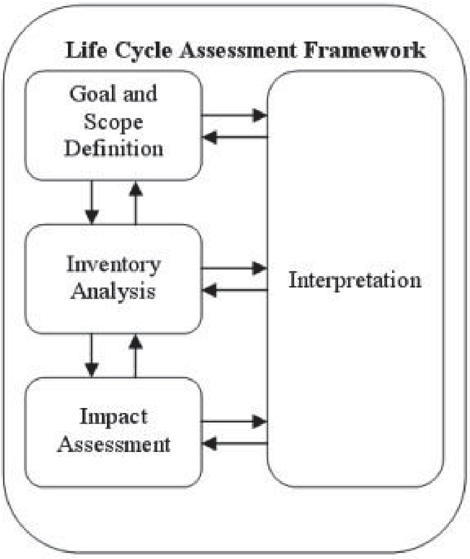

Figure 3: Life Cycle Assessment Framework[167]

Reporting as well is an essential part of an LCA study, because even if the study is intended to be used only for internal purposes it will be of limited benefit if the assumptions made and the methodologies applied are not transparent to the target audience.[168] Additionally a

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[165] Cf. ISO 2006a, p. vi

[166] Cf. ISO 2006a, p. 7.

[167] ISO 2006a, p. 8.

[168] Cf. Guinée et al. 2002, p. 27.

critical review should be conducted to ascertain the study's plausibility as also the specifications of methodology selection and application in each stage of the LCA process.[169]

3.2 Goal Definition and Scoping

The first step, when carrying out an LCA, is to clearly define the goal, including the principal choices like the purpose of the study, the questions to be addressed, the involved parties and the target group to which the achievements of the study are presented, the intent of public announcement or if there will be the aim for comparative statements of the results.[170]

When performing the goal definition, the limitations of the LCA should be kept in mind, not only to determine if LCA is the best suiting tool for the intended use but also if the LCA should be complemented with other tools to satisfy the aims.[171]

Scoping addresses the overall character of the study in terms of temporal and geographical extent, technical boundaries, system function, the level of detail necessary and a statement how the methodologies are appointed to meet the assignment of tasks.[172]

In the event of system comparison, the scope definitions should ensure the equivalence of the systems by choosing the same functional unit, an equivalent system boundary, consistent allocation procedures and other equal methodological choices concerning performance, cut-off criteria, data requirements or impact assessment.[173] The equivalence has to be assessed prior to evaluation of the results and deviations have to be reported for the purpose of validity.[174]

This step of LCA already incorporates information of considered impact categories, category indicators and characterization models that are part of the LCIA methodology.[175] This should be done because methodological choices related to impact assessment may influence the data acquisition and the results of the study and thus have to be declared.

The ISO 14044 standard notes that the scope should specify the following issues:[176]

- the product system to be studied;
- the functions of the product system or, in the case of comparative studies, the systems;
- the functional unit;
- the system boundary;
- allocation procedures;
- LCIA methodology and types of impacts;
- interpretation to be used;
- data requirements;
- assumptions;

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[169] Cf. ISO 2006a, p. 17.
[170] Cf. Klöpffer and Grahl 2009, p. 27.
[171] Cf. Guinée et al. 2002, p. 34.
[172] Cf. Klöpffer and Grahl 2009, pp. 28-59.
[173] Cf. ISO 2006b, p. 11.
[174] Cf. Klöpffer and Grahl 2009, p. 46.
[175] Cf. ISO 2006b, p. 9.
[176] ISO 2006b, p. 7.

- value choices and optional elements;
- limitations;
- data quality requirements;
- the type of critical review, if any;
- type and format of the report required for the study.

LCA is an iterative process, which includes that modifications in goal and scope can be done during the procedure. A sheer sequential advancement is not practicable because the priority is to stay consistent with the intentions of the study. It is suggested[177] to justify and report every refinement during the approach to maintain a transparent line of action.

The Product System

The life-cycle of a product is examined as a product system, including all main stages from raw material extraction and acquisition over transport, product manufacture and use to waste treatment and final disposal, allowing determination of environmental load shifts when changing certain parameters related to the functional unit.

Nevertheless the degree of the study's depth and transparency will depend on the availability of data, because this consequences the ability to further apportion the main life-cycle stages.[178]

The product system, an example is shown in figure 4 below, implies different functions and is split into several elements called unit processes. The interrelationships between unit processes are preferably described by the use of such a system flow chart.[179]

The break down assists the identification of material as also energy input and output of the product system, whereas the detail of breakdown is dictated by the goal and scope requirements, which also define the boundary of each unit process.[180]

Unit processes are connected to each other by intermediate flows, which might be basic materials, subassemblies, products, waste or a combination of several. The input and output flows of a unit process are represented by elementary flows and/or product flows.

Product flows link the unit processes to other product systems like, for instance, recycled materials, whereas elementary flows quantify resource requirements or releases of media to the environment.[181]

Problems may arise when cut-off criteria on basis of mass, energy and environmental significance are applied and whole unit processes are omitted, which is basically not forbidden, but comprises the risk of misinterpretation of the LCA results.

In case of product or process comparison, it is legitimate to express exact matching unit processes as a black-box to reduce the overall complexity of the product system.[182]

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[177] Cf. ISO 2006b, p. 7.

[178] Cf. Curran 1996, p. 15.4.

[179] Cf. Klöpffer and Grahl 2009, p. 28

[180] Cf. ISO 2006a, p. 9

[181] Cf. ISO 2006a, p. 9.

[182] Cf. Klöpffer and Grahl 2009, pp. 28-29.

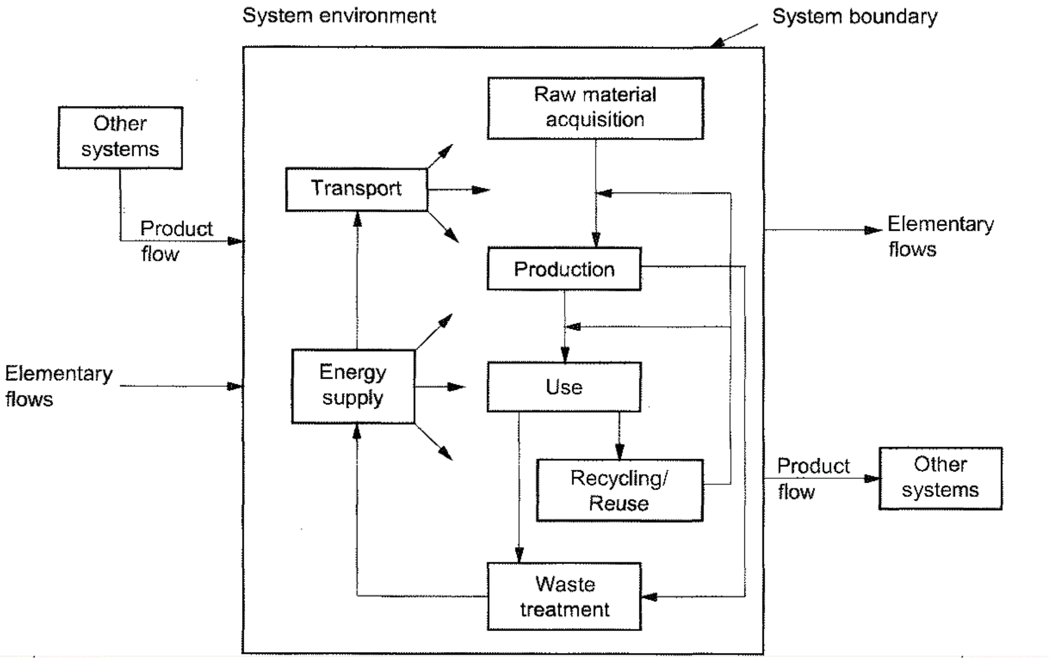

Figure 4: Example of a product system for LCA[183]

The Functional Unit

On basis of the goal definitions and scope of the study a functional unit has to be chosen, representing the quantification of performance characteristics of the regarded product system.[184]

The intention of defining a functional unit is to represent the primary relevant functions of interest and to establish a basis for comparison with other product systems.[185] Thus the functional unit also represents the premise to develop the reference flows for different systems, which are the quantified outputs delivered from a system, in terms of amount of product needed to achieve the functions of interest.[186]

The size of key parameters of the functional unit like, for example, the life span, mass or amount of energy to be provided, is more or less an arbitrary selection but it has to be kept in mind that all inputs and outputs of the system are then related to the functional unit, thus it is essential to unambiguously define the functional unit.[187]

It is approved[188] to use a representative size of the functional unit and as well to apply SI-based units, when defining the functional unit and reference flows, in order to retain clarity.

Four aspects are advised[189] to be considered for choosing the proper functional unit when comparing systems while factoring efficiency differences of products, which are the product's life-span and efficiency to satisfy the demands, the implementation of the default spe-

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[183] ISO 2006a, p. 10.
[184] Cf. ISO 2006a, p. 12 and ISO 2006b, p. 8.
[185] Cf. ISO 2000, p. 5 and ISO 2006a, p. 12.
[186] Cf. Guinée et al. 2002, p. 37.
[187] Cf. Guinée et al. 2002, p. 38 and Klöpffer and Grahl 2009, p. 38.
[188] Cf. Guinée et al. 2002, p. 38 and Klöpffer and Grahl 2009, p. 38.
[189] Cf. Curran 1996, pp. 14.28-14.29.

cifications to a defined standard, and the implementation of several features of the product, in terms of primary, secondary and tertiary functions.

In the technical report ISO/TR 14049:2000 three distinct steps, to the approach of determining the functional unit and the reference flows, are indicated. An example of the approach is given in Annex A.

The first step is the identification of functions, fulfilled by one or more products, needed to meet the final demand, whereas ISO[190] notes that it is irrelevant whether to start with the function or with the product.

The second step is the identification of relevant functions to achieve the functional unit and its key parameters because not all functions provided by a product or process are necessary.[191] It is suggested[192] to disregard irrelevant functions but to report it in this case.

The third step addresses the appointment of the reference flow, meaning in other words, to evaluate the amount and performance of one or more specific products needed to meet requirements of the functional unit.[193]

In case of comparative assertions the alternative systems have to provide the equivalent functions, in order to meet the demands of the functional unit.[194]

It might be the case that an alternative system has one or more additional functions that are not taken into account to make the systems comparable, or alternatively, in the event of diverging system functions, the reference system can be enlarged by an element that provides this additional function to ensure similarity between the reference system and its alternatives, which should be documented.[195]

The System Boundary

The system boundary separates the product system from the surrounding environment. The technosphere and the ecosphere are acting as a source and represent the surrounding physical environment of the examined system, interrelated with those two systems by input and output flows.[196]

Those inputs and outputs are ideally demonstrated by elementary and product flows.[197]

The technosphere illustrates the part of the environment that is under human influence and control, including raw materials and supplies on the input side or when considering output flows, examples include co-products, intermediate products and releases designated for waste treatment facilities.[198]

The ecosphere, on the other hand, is connected to the product system with inputs, such as natural resources and outputs to air, water, and land, describing those flows that aren't affected by human being, also known as elementary flows.[199]

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[190] Cf. ISO 2000, p. 4.
[191] Cf. ISO 2000, p. 5.
[192] Cf. Guinée et al. 2002, p. 37.
[193] Cf. ISO 2000, p. 5.
[194] Cf. ISO 2000, p. 6.
[195] Cf. ISO 2000, p. 6.
[196] Cf. Klöpffer and Grahl 2009, p. 30.
[197] Cf. ISO 2006b, p. 8.
[198] Cf. http://www.answers.com/topic/technosphere
[199] Cf. ISO 2006b, p. 3.

As already mentioned, the product system is a combination of unit processes, associated with the life cycle stages of a product or process, including raw material acquisition, fossil fuel processing, generation of electricity, material manufacture, product manufacture, transportation, product-use, -maintenance, -reuse and –disposal, recycling, waste treatment, recovery of secondary raw materials and energy, to cite only some examples.

This sample list of unit processes already shows that, when considering every single aspect of the product system, the entire LCA my get too complex to be executed within a certain frame of time, effort and costs.[200]

An example of one unit process, with the flows entering the unit process and those leaving it, is shown in figure 5.

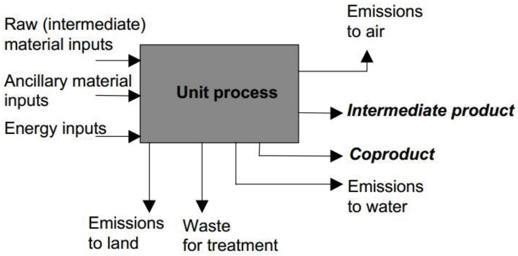

Figure 5: Example of a unit process[201]

The development of cradle-to-gate LCAs, representing complete life cycle assessments of product systems, from raw material acquisition to provision of products or processes, which subsequently can be used as subsystems in other LCAs, may contribute to a reduction of complexity and expenditure of time.[202]

Proper definition of the system's boundaries is an indispensable part to successfully execute the LCA approach and some[203] say it is one of the most important steps of LCA. The act of defining the system boundary has to be coherent with the goal definitions and leads to identification of the mandatory unit processes.[204]

The varieties of contained unit processes depend, among other things, on the intended level of detail and depth of the study, the target audience, the data availability and the applied cut-off criteria.[205]

Nevertheless to make an LCA study feasible some of the identified elements of the product system such as input and output flows or whole unit processes, where it was determined that they are not contributing to a significant change of the study's statement, might be omitted. Excluding elements related to the product system incorporates deep understanding of each system part and causes of omissions need to be reported precisely.[206]

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[200] Cf. ISO 2006a, p. 12 and Curran 1996, p. 2.5.

[201] ISO 2000, p. 12.

[202] Cf. Curran 1996, p.2.5.

[203] Cf. Klöpffer and Grahl 2009, p. 30

[204] Cf. ISO 2006b, p. 8

[205] Cf. ISO 2006a, p. 12 and ISO 2006b, p. 8.

[206] Cf. ISO 2006b, p. 8.

ISO[207] states three **cut-off criteria** dealing with the process of excluding inputs and outputs, based on the issues of mass, energy and environmental significance.

The mass and energy criterions are based on the exclusion of minor fractions of mass or energy flows that contribute less than a certain percentage to the cumulative mass or energy flows of the entire product system analyzed.

A predefined fraction of 1% of mass or energy, in relation to the cumulative amount of mass or energy of the product system, is often used as a cut-off criterion.[208] Simultaneously the commitment of excluding not more than an amount of 5% of input or output flows per unit process can be applied, if, for example, a large number of input or outputs are separately only contributing to a minor fraction of 1% but in sum are a yielding a remarkable fraction of the overall mass or energy flows of a specific unit process.[209]

If only the mass criterion is applied, revealing a minor fraction of a certain input or output, thus alleged in omission of this certain flow, it is not proven that this flow does not accompany high energy consumption and ISO[210] suggests performing a sensitivity analysis on input and output data and to use more than one single decision rule when defining the system boundaries.

The environmental significance criterion is intended to account for inputs and outputs smaller than a predefined amount, to avoid shortfall of environmental relevant data such as highly toxic substances that might be omitted when only applying the mass and energy criteria.[211]

Geographical boundaries as well play an essential role because of the diverse nature of available data that could be related to a certain region with different industrial characteristics or policy regulations, and occasionally, adoption of data from different regions is required for the integrity of the LCA study, which not necessarily results in wrong conclusions especially if the geographical reference is known.[212]

Problems with spatial boundaries may arise when commodities with high production volumes such as metals or chemicals are part of the product system, as it is often not clear where they have been produced.[213]

To set a reasonable time boundary is even tougher, because of the varying durability of product system elements, the technological progress or changing environmental regulations where the operator then has to decide if the available data still constitutes, or if more actual data is needed to ensure representative conclusions.[214]

ISO[215] suggests in the technical report ISO/TR 14049:2000 the following approach for developing an initial framework of the product system, including inputs and outputs, as well as the system boundaries:

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[207] Cf. ISO 2006b, p. 9.

[208] Cf. Klöpffer and Grahl 2009, p. 31.

[209] Cf. Klöpffer and Grahl 2009, p. 31.

[210] Cf. ISO 2006b, pp. 8-9.

[211] Cf. ISO 2006b, p. 9 and Klöpffer and Grahl 2009, p. 32.

[212] Cf. Curran 1996, p. 2.8.

[213] Cf. Klöpffer and Grahl 2009, p. 36.

[214] Cf. Curran 1996, p. 2.8.

[215] Cf. ISO 2000, pp. 11-15.

1. Identify the unit processes coherent with the goal and scope of the study and define unit process boundaries within the meaning of flows that are persuaded to other product systems, thus giving an indication for allocation procedures or system expansion.
2. First unit process data compilation with focus on information on the reference unit, the data content, the spatial relation of the data origin, the level of technology applied within the unit process, and information on additional products, co-products, or intermediate products, which might be subject to allocation.

   Input and output data aspects, such as the time frame and representativeness of the data collection, comprising, for instance, measuring and calculation methods, but also information on the origin and destination of flows, are to be disclosed.
3. Primary assessment of input and output flows for each unit process along the entire life cycle of the product system with information from the first data compilation to give a valuation on the embodied material and energy extent.
4. Implementation of cut-off criteria. Reasons for application of decision rules for mass, energy and environmental significance and accompanied exclusion of flows should be reported, as well as the assumptions made for implementation of decision rules and the involved effects on the results of the LCA.[216]

Data Requirements

The feasibility and the quality of the LCA approach, as also the level of detail, certainly depend on the availability, the type, and the quality of data.

It has to be evaluated for which unit processes site specific data has to be gathered by the researcher himself, also known as primary data, and for which processes already existing average or generic data, known as secondary data, suffice, because preparation of primary data can be difficult to be afforded within a particular frame of cost and time.[217]

However, it is cited[218] to rather head for time and process specific data when accounting the characteristics of particular operations in the area of production and manufacturing, as those processes often involve fast advancing technological progress.

Alternatively if the actuality and relevance of data gets questionable and issues concerning confidentiality are at hand, the practitioner of the study might conduct industry experts that approve the representativeness and correctness of available data without providing particular internal data.[219]

Thus the following data aspects should already be considered in the first stage of the LCA procedure:[220]

- Types of data
- Data sources
- Data categories
- Data quality requirements

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[216] Cf. ISO 2006b, p. 8.

[217] Cf. Klöpffer and Grahl 2009, p. 45.

[218] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 23.

[219] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 24.

[220] Cf. ISO 2006b, pp. 9-10.

To depict the characteristics of the utilized data, which in turn affect the correctness and consistency of the LCA conclusions, the data quality requirements listed below should be considered within the scoping phase, particularly in case of comparative assertions intended for public disclosure the data quality requirements are essential.[221]

The **time related coverage** specifies over which period of time the data should be gathered. Concerning the time span ISO[222] suggests a minimum of one year to eliminate seasonal variations or common fluctuations involved in processes and deviations from the time related data targets should be documented.

Geographical coverage objectives affect the spatial origin of adoptable data. In case of site specific data, the supply chain of a product or service of demand has to be examined within the certain company, which provides the product or service.[223]

The **technology coverage** inherent in processes, control devices and industrial practices enables to account for actuality of data and the derived LCA results. Some data may only be available for obsolete technologies and technological development should be taken into account if it is expected to occur within the time frame of the study's execution.[224]

Precision gives information on the degree of data variation for each unit process and is depicted in terms of mean, variance and standard deviation, thus providing the ability to appraise uncertainty and to facilitate a sensitivity analysis of the final outcomes.[225]

Completeness indicates the order to which extent, for example, a flow is measured or assessed, or for how many sites primary data can be gathered compared to the total number of sites under consideration, which is generally a predefined percentage goal for a certain process that allows comparison of different product systems on an equivalent basis.[226]

Representativeness qualitatively exhibits to which temporal, geographical and technological extent the utilized data represents the holistic realities, whereas fundamental deviations from the representativeness of the used data should be indicated and clarified.[227]

Consistency addresses the steady application of the methodology employed in the LCA. Requesting data from different companies from different locations accompanies the pitfall of errors in measurements of data or the way the data is collected.[228]

Reproducibility indicates the degree, an independent operator can recreate the study results based on the information on applied methodology and data.[229]

A statement which **data sources** are utilized with respect to the goal definitions, for example, if data is obtained from literature information on the source, the time of data collection or other relevant quality aspects, should be stated.[230]

To establish an understanding for the **uncertainty of information** in terms of used data, assumptions made and methodologies chosen, a sensitivity analysis should be performed.[231]

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[221] Cf. ISO 2006a, p. 13 and ISO 2006b, p. 10.
[222] Cf. ISO 2000, p. 37.
[223] Cf. ISO 2000, p. 37.
[224] Cf. ISO 2000, p. 37.
[225] Cf. ISO 2006b, p. 10; Guinée et al. 2002, p. 50 and ISO 2000, p. 37.
[226] Cf. ISO 2006b, p. 10; Guinée et al. 2002, p. 50 and ISO 2000, p. 37.
[227] Cf. ISO 2006b, p. 10; Guinée et al. 2002, p. 50 and ISO 2000, pp. 37-38.
[228] Cf. ISO 2000, p. 38 and Guinée et al. 2002, p. 50.
[229] Cf. ISO 2000, p. 38 and Guinée et al. 2002, p. 50.
[230] Cf. ISO 2006b, p. 10 and ISO 2000, p.35.
[231] Cf. ISO 2006b, p. 10 and ISO 2000, pp. 35-39.

Whenever data gaps or data anomalies are detected for a data category or reporting location they should be documented and substituted, by a data or a zero value that is well declared or by calculated alternatively directly adopted values derived from available data of unit processes with identical technology.[232]

ISO[233] suggests applying site specific and representative average data to those unit process flows with the highest share to mass and energy, or to input and output flows of unit processes, which are supposed to have environmental significance.

Sensitivity Analysis

Sensitivity analysis is a technique that determines the impact of an input variable on the final result. It helps to understand the influence of decisions and assumptions on a certain target variable.

Within the goal definition and scoping phase a sensitivity analysis may be performed, for instance, when choosing the functional unit or when considering quality aspects to determine the uncertainty of data values but also when judging other assumptions and methodological choices.[234]

The uncertainty of system boundaries as well can be evaluated by performing a sensitivity analysis on input and output flows resulting in inclusion or exclusion of life cycle stages, unit processes or certain flows where relevant impacts, or, in case of exclusion, no significant effects on the results, are indicated.[235]

ISO[236] notes that, in case of comparative assertions for public disclosure, the sensitivity analysis on inputs and outputs should as well address the cut-off criteria.

Other commitments within the goal and scoping phase

Within the scope, considerations should include if a critical review is necessary, which is the case if the results of the study are intended to be used for comparative assertions disclosed to the public, whereas the type of review should be appointed, how to perform it, who executes the review and their professional competence.[237]

ISO[238] notes that applied allocation procedures should already be defined in the goal definition and scoping phase, if allocation is not expendable by implementation of system expansion.

Optional elements such as normalization, grouping, weighting or data quality analysis are in fact part of the impact assessment but the intention of performing such methods should be documented in the goal and scope of the study as well as value choices, limitations and assumptions made.[239] Limitations include, for example, constraints in comparability due to a certain defined reference period.

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[232] Cf. ISO 2006b, p. 10 and ISO 2000, pp. 38-39.

[233] Cf. ISO 2006b, p. 10.

[234] Cf. ISO 2000, p. 40.

[235] Cf. ISO 2000, pp. 40-41.

[236] Cf. ISO 2006b, p. 9.

[237] Cf. ISO 2006b, p. 11.

[238] Cf. ISO 2006b, p. 7 and Klöpffer and Grahl 2009, p. 35.

[239] Cf. ISO 2006b, p. 7 and Klöpffer and Grahl 2009, p. 47.

3.3 Life Cycle Inventory (LCI)

The second step to the LCA approach is a quantitative analysis of energy and material requirements as also releases of the product system, represented in a list of data, called life-cycle inventory.[240]

This implies accurate definition of the system boundaries including allocation procedures, the development of a flow diagram showing the interactions of the unit processes as also the collection of input and output data of each unit process, in terms of raw material and energy inputs, releases to air, water and land, and other outputs to the environment.[241]

The result is the compilation of an inventory list of relevant data, composed of amounts of materials and energy, in sense of the regarded functional unit, which are necessary for the provision of products or processes, or else are released by the product system.

The LCI incorporates a huge amount of data, which can be gathered from public databases, from industry specific databases developed by consultants or companies in their own favor, as also from approximations based on natural science. Due to lacking of data, this part of the whole LCA procedure may be one of the most costly and time consuming.[242]

The vast majority of the methodologies applied in the life-cycle inventory analysis phase, concerning natural science, are based on rules such as the law of conservation of mass and energy, the laws of stoichiometry, describing chemical reaction equations, the second law of thermodynamics, affecting the entropy, and also Einstein's mass-energy equivalence.[243]

These rules can be applied if, for example, measured specific unit process data are not available to anyhow estimate relevant input and output data that are at least, or at the most, interconnected in terms of amounts with the provision of a product or process.[244] It is noted[245] that the conclusions based on these rules have to be regarded with caution.

Some outcomes of the LCI are however related to decisions based on subjective perceptions of importance, such as the definition of the system boundaries, and to which extent allocation or system expansion procedures are involved.[246]

ISO[247] notes that the analysis of life-cycle inventory is of iterative nature because within the procedure of data collection and definition of the system boundary issues on data aspects may arise, thus resulting in the need for modification of the LCI methods used.

The procedure to a complete inventory including all necessary steps suggested by ISO[248] is shown in figure 6.

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[240] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 19 and ISO 2006a, p. 13.

[241] Cf. Guinée et al. 2002, p. 41; Klöpffer and Grahl 2009, p. 63 and Curran 1996, p. 2.8.

[242] Cf. Finnveden et al. 2009, p. 6.

[243] Cf. Klöpffer and Grahl 2009, pp. 63-64.

[244] Cf. Klöpffer and Grahl 2009, p. 64.

[245] Cf. Klöpffer and Grahl 2009, p. 64.

[246] Cf. Curran 1996, pp. 2.8-2.9.

[247] Cf. ISO 2006a, p. 13.

[248] Cf. ISO 2006b, p. 12.

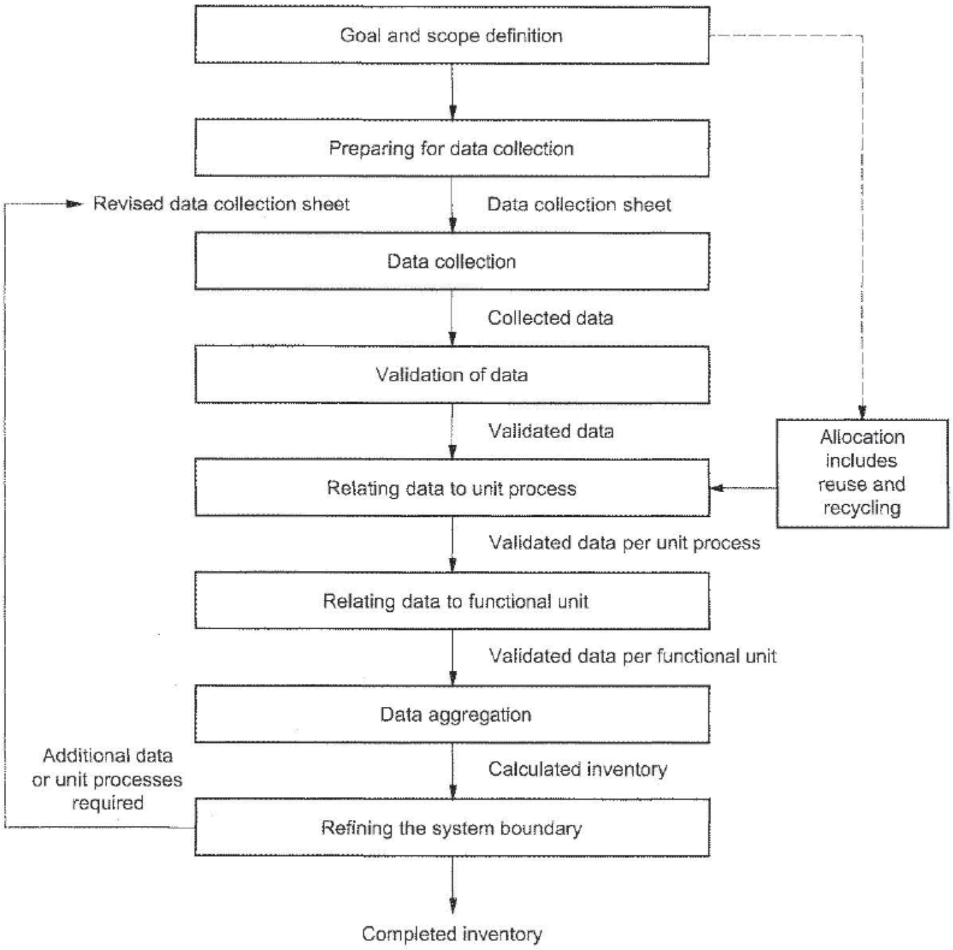

Figure 6: Simplified steps to the LCI[249]

The Flow Diagram

The purpose of a process flow chart is a graphic description of the examined product system with respect to the identified system boundaries. It is constituted of all relevant unit processes, linked to each other by quantitative input and output flows, represented as arrows, thus facilitating information on the interrelationship between the unit processes, the direction of flows and provision of an overview of the system structure as a whole.[250]

A flow diagram is also vital for the development of a data collection sheet as relations between unit processes and/or subsystems are declared by factors of proportionality, thus providing quantitative information on relative shares of processes to the overall system.[251] An example of a simplified flow diagram is given in Annex A.

Depending on the availability of specific process data, each unit process, illustrated as a box in the chart, at best represents an operation that cannot be further partitioned into a smaller stage like, for instance, a transportation process.[252]

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[249] ISO 2006b, p. 12.

[250] Cf. Curran 1996, p. 17.9.

[251] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 26.

[252] Cf. Klöpffer and Grahl 2009, p. 66.

De facto it is not always possible to implement the desired level of specificity as a result of data availability and the associated effort, thus depiction of aggregated operations or of whole manufacturing facilities as one box is often unavoidable.[253]

The flow diagram, at its best, constitutes several life-cycle stages from raw material acquisition and energy supply over transport, manufacture and product use to waste treatment, recycling loops and final disposal with every accompanied input and output flow as also belonging branches, while paying attention to the system boundaries.

For each unit process the inputs and outputs are determined including operating supplies and intermediate products or co-products, thus also characterizing the multifunctional nature of certain unit processes, which are then subject to allocation or system expansion.[254]

Again the iterative nature of LCA should to be kept in mind and it is suggested[255] to initially incorporate as much detail and level of specification into the flow diagram, as allowed by time, labor and the goal and scope of the study, to provide a broad view on the product system, even if in the first instance no specific data is available and approximations have to be made for certain elements.

With advancing progress of the LCA procedure, when data is collected, some processes may be combined to subsystems, other elements are probably marked as non-significant or else it may have turned out that a higher level of specification is needed for certain parts of the system, thus resulting in subdivision of aggregated unit processes.[256]

Allocation procedures

One issue that arises with almost every LCA study is the handling of multifunctional processes for the purpose of a life-cycle assessment, because in practice, almost every industrial process has multiple flows of inputs and outputs, shared with other product systems where often only one is in the focus of the analyst.[257]

This especially concerns the determination of amounts of elementary flows, in terms of energy, materials and releases to the environment, related to the input or output of interest, and defined by the functional unit.[258]

The precise definition of the system boundaries and the functional unit, first and foremost, appropriates the inputs and outputs to be accounted and the requirement for allocation procedures.[259]

In case a process incorporates multiple inputs including, for instance, intermediate or discarded products or delivers more than one product, thus comprising outputs of, for example, co-products or industrial scrap, the practitioner has to investigate to which extent the elementary flows and environmental burdens are partitioned and attributed to each of the multiples of inputs and outputs of a unit process.[260]

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[253] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 20 and Klöpffer and Grahl 2009, p 66.

[254] Cf. Klöpffer and Grahl 2009, pp. 69-73.

[255] Cf. Curran 1996, p. 17.10.

[256] Cf. Curran 1996, p. 17.10 and Klöpffer and Grahl 2009, p. 69.

[257] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 28; Guinée et al. 2002, p.57; ISO 2006a, p. 13 and Klöpffer and Grahl 2009, p. 94.

[258] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 28; Finnveden et al. 2009, p. 5; Guinée et al. 2002, p.57 and Klöpffer and Grahl 2009, p. 94.

[259] Cf. Guinée et al. 2002, p. 57.

[260] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 28 and Guinée et al. 2002, p.57.

Already the definition of an output, whether considered as a co-product or as waste, has a significant effect on the inventory, as environmental burdens are never allocated to wastes.[261]

Co-products are outputs of multifunctional unit processes that go along with the life-cycle of the main product, defined by the functional unit, but at some point leave the product system because they are not in demand of the product system any more.[262] They are also not considered as waste, to the contrary, they can be used as inputs in other systems and are only important for the analysis to an instant of time where they do not influence the main product or process any more.[263]

The intention behind this definition is that outputs of unit processes, referred to the system under study that can be used as inputs in other systems, should carry a proportional share of the environmental loads related to the product system under examination.[264]

An example of the impacts on the inventory going along with the definition, whether to be handled as waste or a co-product, relates to industrial scrap that emerges from a process, and, which is considered to be an unwanted process waste entailing a value.[265]

If it is treated as waste no inputs and outputs are allocated to the industrial scrap as the waste is made up in the recycling process that is part of the product system in the cradle-to-grave approach of an LCA.[266]

Opposed to this, the handling of industrial scrap as a co-product that can be used as a raw material in other processes, outside the system boundary, would result in allocation of environmental loads to the co-product, which is not in the scope of the analysis anymore.[267]

ISO[268] suggests three steps in relation to the allocation procedure after the determination of product system elements that are shared with other product systems, such as in case of co-products. Figure 7 shows a flow diagram where the approach to the selection of methodology referring to allocation is depicted.

In the first instance (ISO step 1), allocation is favorably avoided by firstly performing a more in-depth investigation on unit processes.[269] Processes, that are supposed to be subject to allocation because of their multifunctionality, are subdivided, thus resulting in sub-processes without multifunctionality.[270] In fact this means that more detailed information on input and output data of unit processes is needed, whether by making additional measurements, or by calling in additive database information.[271]

If this is not feasible because of lacking data availability, the multiple of process functions should be incorporated by system expansion, meaning that the environmental aspects of, for example, co-products are included in the study while paying attention to the definitions of the functional unit, the reference flow and the system boundaries.[272]

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[261] Cf. Klöpffer and Grahl 2009, p. 104.

[262] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 37 and Klöpffer and Grahl 2009, p. 95.

[263] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 37.

[264] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 41.

[265] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 40.

[266] Cf. Curran 1996, p. 2.20 and Scientific Applications International Corporation (SAIC) 2006, p. 40.

[267] Cf. Curran 1996, pp. 2.20-2.22 and Scientific Applications International Corporation (SAIC) 2006, pp. 40-41.

[268] Cf. ISO 2006b, p. 14.

[269] Cf. ISO 2006b, p. 14.

[270] Cf. Guinée et al. 2002, p. 58 and ISO 2006b, p. 14.

[271] Cf. Guinée et al. 2002, p. 58.

[272] Cf. Scientific Applications International Corporation (SAIC) 2006 p. 29; ISO 2006b, p. 14 and Klöpffer and Grahl 2009, p 100.

In case co-products fall within the system boundaries, as a result of system expansion, they have to be traced and analyzed all along their life-cycle, from cradle-to-grave, and incorporated in the inventory analysis as well.[273]

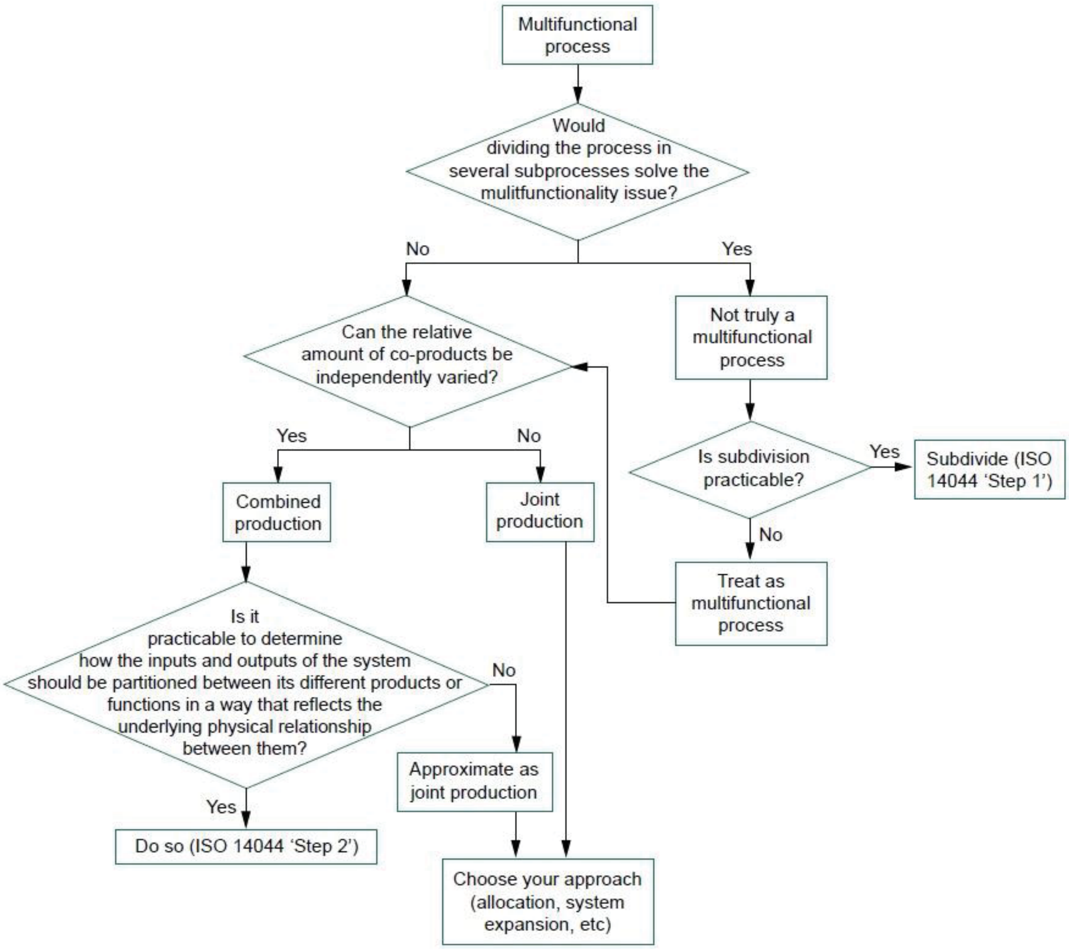

Figure 7: Allocation methodology approach[274]

If system expansion is considered, to compare two systems with different functions, both systems have to be expanded by supplementary processes in a way that the functions, the delivered products and quantities of the reference flow are equal, in terms of symmetry, to enable determination of elementary input and output flows.[275] An example of comparing two systems with different outcomes is given in Annex A.

Another option to develop symmetry is to subtract certain processes, causing dissimilarity from one system, to make the two systems comparable on basis of the same functional unit, which is then called the 'avoided burden approach'.[276]

If allocation procedures have to be executed, appointment of input and output flows to each of the multiple process functions, should be based on the physical relationships be-

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[273] Cf. Klöpffer and Grahl 2009, pp. 99-101.

[274] UNEP/SETAC Life Cycle Initiative 2011, p. 78.

[275] Cf. ISO 2000, p. 20.

[276] Cf. ISO 2000, p. 20.

tween flows and functions to allow illustration of the proportional alteration of inputs and outputs as the quantities of the functions are changed (ISO step 2).[277]

Allocation procedures, mentioned in different literature regarding the physical relationship between unit process flows and functions, are mostly based on either mass or volume, but allocation can also be based on other relationships such as stoichiometry, specific mass, viscosity, thermal conductivity or heat of reaction.[278]

In this instance, the inputs and outputs are quantitatively partitioned to the proportional amounts (mass or volume) of functions delivered by a unit process, beginning with the unit process that delivers the final product in terms of the functional unit.[279]

Another option for allocation of unit process flows, if partitioning of input and output flows based on physical relations is not possible, might be based on the economic value of products (ISO step 3).[280]

Although the allocation of flows on basis of gross sales implies the effort inhered in the life-cycle of products or services, in terms of, for instance, energy consumption and in further consequence the environmental loads, it comprises the issues of market volatility, geographical reference and price rigging.[281] It is suggested[282], to use average gross sale values looked upon longer time periods, to at least exclude some market volatility.

It is noted[283] that the allocation procedures have to be consistently applied along the unit processes of the product system as also on identical inputs and outputs. This means that if the allocation procedure for intermediate products as inputs is based on mass it should also be based on mass if the intermediate products are considered as outputs.[284]

ISO[285] analogously states, as a general allocation guideline, that the requirements and releases of a unit process have to be equal before allocation procedures and after they have been performed.

Allocation procedures constitute a deviation of the scientific approach, to which the LCA procedure intentionally underlies, because subjectivity and arbitrariness is always inhered to a certain degree when performing allocation.[286]

ISO[287] therefore suggests to report the allocation procedures applied, and to execute a sensitivity analysis to determine the consequences on the inventory results of different allocation procedures that can be conducted.

In case of **reuse and recycling** the above mentioned allocation procedures as well can be applied but some considerations have to be taken into account as the impacts in the inventory are different, depending on the definition of the system boundaries, the nature of the recycling system, as also the recycled material.[288]

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[277] Cf. Klöpffer and Grahl 2009, p. 108.

[278] Cf. Curran 1996, p. 2.19; Scientific Applications International Corporation (SAIC) 2006, p. 28; ISO 2000, pp. 21-24 and Klöpffer and Grahl 2009, pp. 97-104.

[279] Cf. Klöpffer and Grahl 2009, p. 97.

[280] Cf. Guinée et al. 2002, p. 58; ISO 2006b, p. 14 and Klöpffer and Grahl 2009, p. 104.

[281] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 28 and Klöpffer and Grahl 2009, p. 104.

[282] Cf. ISO 2000, p. 24 and Klöpffer and Grahl 2009, p. 104.

[283] Cf. ISO 2006b, p. 14 and Klöpffer and Grahl 2009, p. 97.

[284] Cf. ISO 2006b, p. 14.

[285] Cf. ISO 2006b, p. 14.

[286] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 28 and Klöpffer and Grahl 2009, p. 105.

[287] Cf. ISO 2006b, p. 14.

[288] Cf. Curran 1996, p. 2.23 and ISO 2006b, p. 14.

These considerations concern the alteration of material properties, as a result of reuse and recycling, and the definition of the system boundaries in relation to recovery processes where input and output flows of some product system processes, like raw material acquisition and final disposal, are partitioned to other product systems.[289]

Closed-loop recycling refers to the circumstance where a material is separated from the waste stream of the product system, and, after recycling, is reused as a part of the same product system again.[290] If the assumption is that the material can be recycled and reused unlimited times without alteration of material properties, disposal of the material is avoid, thus leading to a reduced demand of virgin raw materials.[291]

Only the additional requirements related to the recycling process, like energy consumption, inhered releases to the environment or transport operations, have to be added to the inventory of the production system, therefore allocation procedures are obsolete, as the recycling step as also the material remains within the system boundaries.[292]

A certain event is referred to **open-loop with closed-loop recycling** procedure, where the product system supplies an independent material pool with secondary raw materials, and, after recycling, receives secondary raw materials from that pool.[293]

Assuming that the amounts of secondary material delivered to and withdrawn from that pool are equal, it is possible to treat the system as in case of closed-loop recycling, but if consumption and supply in relation to the material pool are dissimilar allocation issues arise and ISO[294] suggests system expansion to sidestep allocation.

In the **open-loop recycling** model, the material is recycled in another product system and the material properties are altered, thus allocation procedures are necessary if system expansion is not possible.[295] In the open-loop system products, manufactured from materials that derived from virgin resources, are recycled into another product, which again might be recycled into a third product and so forth.[296]

The purpose of the allocation procedure, again, is to partition the environmental loads, related to the life-cycle of the first product system, to some extent to the second product system, as the demand of virgin resources and the associated burdens are reduced.[297]

Although system expansion would be preferably suggested by ISO[298], it is often not possible as the increased complexity of the product system under study would be too difficult to handle, if other product systems have to be incorporated because of shared unit processes related to reuse and recycling, and apart from the labor associated with data acquisition.[299] In the first instance allocation on basis of physical properties is preferred for reuse and recycling, but if not possible again the economic value, or, as a last consequence, allocation on basis of the number of uses of the recycled material, helps determining an allocation factor, describing the partitioning of environmental loads between different systems.[300]

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[289] Cf. ISO 2006b, p. 15 and Klöpffer and Grahl 2009, p. 109.
[290] Cf. ISO 2006b, p. 15.
[291] Cf. Curran 1996, p. 2.23; ISO 2006b, p. 15 and Klöpffer and Grahl 2009, p. 109.
[292] Cf. ISO 2000, p. 26; ISO 2006b, p. 15 and Klöpffer and Grahl 2009, p. 110.
[293] Cf. ISO 2000, p. 27.
[294] Cf. ISO 2000, p. 27.
[295] Cf. ISO 2006b, p. 15 and Klöpffer and Grahl 2009, p. 112.
[296] Cf. Klöpffer and Grahl 2009, pp. 112-113.
[297] Cf. Curran 1996, p. 2.23.
[298] Cf. ISO 2006b, p. 14.
[299] Cf. ISO 2006b, p. 15 and Klöpffer and Grahl 2009, p. 113.
[300] Cf. ISO 2006b, p. 15.

Data Aspects in LCI analysis

The most essential part of the LCI, after all necessary processes describing the product system have been identified and depicted in a flow diagram, is the preparation and gathering of data for each unit process located within the system boundary.[301]

Different types of data have to be collected for the inputs and outputs of the identified unit processes, thus requiring deep understanding of the product or process characteristics to ensure the required data quality.[302]

When developing unit process datasets, the practitioner has to keep in mind the data quality requirements defined by the goal and scope of the study.[303] ISO[304] suggests to reference the sources of data as well to document supportive information on the collection process, on quality aspects and deviations from the data quality requirements.

As stated above, the procedure towards the inventory table implies first of all the preparation of a flow diagram and a detailed description of the involved unit processes in terms of interrelationships, material and energy flows as also information on parameter influencing the flows.[305]

This is followed by the creation of a list of input and output flows and the collection of raw data from different sources. Since the utilization of LCA, databases evolved with increasing level of sophistication, thus providing a remarkable source of information for generic data that can be complemented with case-specific primary data from individual researches and measures.[306]

Subsequently the acts of applying calculation techniques that quantitatively refer the input and output flows of each unit process to the functional unit, the development of unit process dataset, and provision of supportive descriptions, are executed, to finally result in an inventory table composed of several interventions of the functional unit with the environment.[307]

The establishment of a **data collection plan** is suggested by the U.S. EPA[308] after having developed a system flow diagram. This plan reports data quality goals, as well as appointed data-sources, -types and –quality characteristics, to finally end up in a spreadsheet with listed input and output flows that supports the practitioner in achieving the defined data requirements.[309]

A computational spreadsheet also aids different types of calculations, concerning the input and output data of unit processes, such as unit conversions and sensitivity analyses, and helps to avoid double-counting or unintentional negligence of inventory components.[310] ISO[311] as well suggests the application of data collection sheets and examples are given in Annex A.

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[301] Cf. Klöpffer and Grahl 2009, p. 124.

[302] Cf. Klöpffer and Grahl 2009, p. 128.

[303] Cf. UNEP/SETAC Life Cycle Initiative 2011, p. 56.

[304] Cf. ISO 2006b, p. 11.

[305] Cf. ISO 2006b, p. 11.

[306] Cf. UNEP/SETAC Life Cycle Initiative 2011, p. 48.

[307] Cf. UNEP/SETAC Life Cycle Initiative 2011, p. 54 and ISO 2006b p. 11.

[308] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 22.

[309] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 22.

[310] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 26.

[311] Cf. ISO 2006b, pp. 11-12.

Specific data, as its name implies and in contrast to average data, is focused on the specificity of unit processes, thus providing a higher degree of relation to technological improvements involved as well as to temporal and spatial aspects of the data.[312]

Nevertheless an inventory is commonly a mixture of different categories of data, not only because the collection of primary data is costly and time consuming, but also because of the availability of specific unit process data, which is often constricted due to reasons of concealment.[313]

Generally, but also depending on the intention of the study whether to be published or for internal purposes, the availability of specific data decreases with decreasing integration of the study commissioner to processes where foreground data has to be collected.[314] This means that for internal purposes the provision of specific data affecting, for instance, material input, type of input energy, operating equipment, co-products and waste or transport processes, usually is not problematic, whereas determination of data on pollutants released to air, water, and land downstream of treatment facilities, is more delicate.[315]

Generic data is a good source of background data that enables the practitioner to avoid spending tremendous time and effort on developing data for certain components like, for example, concerning refineries or other raw material processing facilities.[316] Generic data describes certain elements of systems with a relation to certain regions and temporal evidence, thus a reference on the defined temporal and geographical boundaries is important when utilizing such data.[317]

The fact that a comprehensive LCA study often comprises a large number of involved materials unit processes and sub-systems, the availability of databases that provide generic data is inevitable for the development of a complete inventory.

Datasets are available for specific unit processes or whole sub-systems, testifying the results of so called cradle-to-gate life-cycle inventories, already implying aggregation of results.[318] A large number of chemicals, raw materials, commodities like metals and transport processes either by train, ship, airplane or pipeline are covered by databases providing generic data.[319]

Depending on the purpose of the study, generic data might even be more favorable, as specific data can be limited in that way that it is not representing the average of a whole industry.[320]

However the quality of such data, or more precisely the transparency and reliability, is somehow questionable, depending on the source, and the practitioner has to decide whether to utilize such data or not, as the data quality requirements play an important role in the LCI analysis.[321]

Aggregation of data is the procedure of summarizing the inputs and outputs of a number of unit processes to a single dataset.[322] The cause of aggregation might be, for instance, to

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[312] Cf. Finnveden et al. 2009, p. 7 and Klöpffer and Grahl 2009, p. 125.

[313] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 24.

[314] Cf. Klöpffer and Grahl 2009, p. 125.

[315] Cf. Klöpffer and Grahl 2009, p. 127.

[316] Cf. Finnveden et al. 2009, p. 7.

[317] Cf. Klöpffer and Grahl 2009, p. 133.

[318] Cf. Finnveden et al. 2009, p. 6 and Klöpffer and Grahl 2009, p. 134.

[319] Cf. Klöpffer and Grahl 2009, p. 135.

[320] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 41.

[321] Cf. Finnveden et al. 2009, p. 7 and ISO 2006a, p. 7.

[322] Cf. UNEP/SETAC Life Cycle Initiative 2011, p. 68.

protect confidential information of a company.[323] The aggregation of similar input and output flow types that are properly referred to the functional unit usually does not appear to be troublesome.[324]

In case of aggregating, important information, on how unit processes are linked to each other, in terms of intermediary flows, and to which extent transportation is included, might get lost, thus affecting transparency but also provokes double-counting or neglecting certain process parts.[325]

Examples of aggregated datasets include industry average process datasets and gate-to-gate or cradle-to-gate process datasets.[326]

Approximations are necessary whenever data gaps are at hand and omission of product system elements preferably is avoided.[327] As stated by ISO[328], and already mentioned in this thesis, missing data either because of confidentiality or simply not appointed yet, has to result in a decent clarified "zero" or "non-zero" value, or a value calculated from available data that refers to comparable unit processes.

Estimation of values can be based on access to data from different regions, obsolescent data or also on calculations based on scientific rules.[329] Care has to be taken in relation to approximations, in order to ensure unit process similarity, for instance, in terms of technology or materials, and, whenever data gaps are overcome, the way of handling should be properly documented.[330]

Data Collection

After the development of a data collection sheet, including data aspects according to the goal and scope of the study as well as all relevant inputs and outputs of the unit processes involved, the collection of data begins. The practitioner has to choose between different collection methods for the establishment of the inventory.[331]

Generally there are three methods, ranked by suggestion[332], in the following order. Preferably data is collected from measurements followed by calculations. Although is recommended[333] to avoid estimation of data, it might be useful in charge of data gaps that have to result in an explained "zero" or "non-zero" value, if calculation of such data is not possible.[334]

The construction of facilities, process equipment, and other **capital equipment** usually contributes only a minor fraction of the total inputs and outputs of the life-cycle, and therefore related data is often excluded from the inventory.[335]

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[323] Cf. UNEP/SETAC Life Cycle Initiative 2011, p. 70.

[324] Cf. Klöpffer and Grahl 2009, p. 141.

[325] Cf. UNEP/SETAC Life Cycle Initiative 2011, p. 71.

[326] Cf. UNEP/SETAC Life Cycle Initiative 2011, p. 70.

[327] Cf. Klöpffer and Grahl 2009, p. 139.

[328] Cf. ISO 2006b, p. 10.

[329] Cf. Klöpffer and Grahl 2009, pp. 64-139.

[330] Cf. ISO 2006b, p. 10 and Klöpffer and Grahl 2009, p. 139.

[331] Cf. ISO 2006b, p. 11.

[332] Cf. UNEP/SETAC Life Cycle Initiative 2011, p. 59.

[333] Cf. UNEP/SETAC Life Cycle Initiative 2011, p. 59.

[334] Cf. ISO 2006b, p. 10.

[335] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 42.

But especially in case of comparative studies it has to be evaluated if the symmetry of the systems is affected by the energy and material input as also the releases of capital equipment, which would result in faulty comparison of systems.[336]

Also some impact categories, particularly land use, are affected by capital equipment too and the operator has to decide, and justify the decision, if capital equipment has to be included for comprehensive results of the LCA.[337]

Data Validation

Validation of data, to prove that the defined data quality requirements, such as completeness, accuracy or uncertainty of data, are met, should already be a part of the data collection step, thus ensuring that the established process dataset is valid to represent the reality.[338]

In other words validation is a quality control procedure that applies different methods like mass- and energy-balances, completeness-, consistency-, sensitivity- and uncertainty-checks on input and output flows of the described unit processes, to identify and eliminate possible issues on inventory data quality.[339] Likewise experts and consultants may support the process of validation.[340]

A completeness and plausibility check on all material and energy flows, for example, by a comparative analysis with experiences on cut-off procedures based on contribution of mass and energy concerning similar unit processes, is helpful when ascertaining that all relevant flows are incorporated in the inventory.[341]

If technological, temporal or spatial deviations from the goal and scope definitions are detected, or data anomalies with respect to the nature of input-, transformation- and output-relationship are identified, further effort to a complete unit process dataset is inevitably.[342]

Besides the comparison of already developed data from other sources, where care has to be taken that these sources incorporate an adequate level of quality and completeness, utilization of scientific rules, such as the laws of conservation of mass and energy or stoichiometry, support the identification of errors.[343]

Data calculation

After having modeled the product system adequately, including mathematical relationships between unit processes depicted in the flow diagram as also allocation procedures used, and after the gathered data is transformed to a convenient form that as well reflects the quality requirements, in this step the inventory data is calculated.[344] The input and output flows of each unit process are appropriately scaled to the reference flow, thus representing the quantity of elementary flow that is necessary to deliver the functional unit.[345]

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[336] Cf. Klöpffer and Grahl 2009, pp. 85-86.

[337] Cf. Klöpffer and Grahl 2009, p. 86.

[338] Cf. ISO 2006b, p. 13 and UNEP/SETAC Life Cycle Initiative 2011, p. 61.

[339] Cf. ISO 2006b, p. 13; Guinée et al. 2002, p. 54 and UNEP/SETAC Life Cycle Initiative 2011, p. 61.

[340] Cf. UNEP/SETAC Life Cycle Initiative 2011, p. 62.

[341] Cf. UNEP/SETAC Life Cycle Initiative 2011, pp. 61-62.

[342] Cf. ISO 2006b, p. 13 and UNEP/SETAC Life Cycle Initiative 2011, p. 62.

[343] Cf. UNEP/SETAC Life Cycle Initiative 2011, p. 62.

[344] Cf. Curran 1996, p. 17.20; Klöpffer and Grahl 2009, p. 167 and UNEP/SETAC Life Cycle Initiative 2011, p. 80.

[345] Cf. Klöpffer and Grahl 2009, pp. 167-168 and Guinée et al. 2002, p. 60.

The result of the LCI is a quantification of all withdrawals and releases referred to the environment that have been considered in relation to the product system.[346]

ISO[347] suggests that aggregations, to be performed in the inventory analysis phase are declared in the goal and scope, but should only be made if the data corresponds to a similar environmental burden and identical substance. Anyhow, care has to be taken when aggregations are performed, because these might come at the price of loosing information on temporal and geographical dispersion of, for example, emissions.[348]

ISO[349] also notes, that the calculations performed and the assumptions made should be reported and that a sensitivity analysis should be applied on the inventory data, in this stage of the LCA, to evaluate the significance and accuracy of data, and if set, to make refinements on the system boundary. This is suggested because the effort in the succeeding phases of the LCA is reduced if it can already be shown in this stage that the accuracy of certain data does not suffice to a meaningful conclusion.[350]

3.4 Life Cycle Impact Assessment (LCIA)

The third step to an LCA study, namely the Life-Cycle Impact Assessment phase, processes the elementary input and output flows determined during the inventory analysis. The inventory table, outlining the environmental loads of a product system in terms of withdrawals and releases from and to the environment, represents the basis for assessment of potential environmental impacts.

The main task of an LCIA is to quantify effects on the environment, related to the life-cycle of a product or process, by developing a linkage between environmental loads, such as emissions, resource requirements, etc. and potential impacts on basis of a cause-effect chain.[351] Because the outcome of the inventory analysis comprises a confusing huge amount of data, the impact assessment emphasizes the environmental significance, referred to environmental themes, by classification and characterization of every impact parameter outlined in the inventory list of tables.[352] Thus the procedure of impact assessment establishes a starting point for interpretation of environmental impacts and comparison of product systems on basis of a readily comprehensible number of impact categories to which the inventory results are assigned.[353]

The selection of impact categories should already be made in the goal definition and scoping phase, as the collection of data in the inventory analysis is impact category orientated, and, because of the iterative nature of LCA, refinements may be necessary to meet the objectives of the goal and scope.[354] In reference to this it is reasonable to ensure that the system boundaries, the functional unit, the data quality requirements, as also other aspects associated with the LCI results agree with the goal and scope and to allow a meaningful realization of the LCIA.[355]

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[346] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 45.

[347] Cf. ISO 2006b, p. 13.

[348] Cf. UNEP/SETAC Life Cycle Initiative 2011, p. 81.

[349] Cf. ISO 2006b, p. 13.

[350] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 45.

[351] Cf. ISO 2006a, p. 14 and Klöpffer and Grahl 2009, pp. 195-196.

[352] Cf. Curran 1996, p. 17.25 and ISO 2006a, p. 14.

[353] Cf. Curran 1996, p. 13.6 and Scientific Applications International Corporation (SAIC) 2006, p. 46.

[354] Cf. ISO 2006a, p. 14 and Klöpffer and Grahl 2009, p. 203.

[355] Cf. ISO 2006b, p. 16.

The assumptions made in relation to impact categories, category indicators and characterization models should be clearly documented to ensure transparency, because some degree of subjectivity may be involved, although the LCA procedure attempts to be as objective and scientific as possible.[356]

This very subjectivity, running like a common thread through the definitions of the goal and scope as also the commitments of elements of the inventory analysis, leads to the fact that the impact assessment is not considered to be an all-inclusive assessment procedure for determination of ultimate environmental impacts.[357] Therefore it is also not taken for granted to determine a clear advantage or disadvantage of one product system over another when performing a system comparison.[358]

The circumstance that the whole procedure is based on LCI data, incorporating different spatial and temporal aspects, makes it impossible to indicate absolute risk or to determine an actual occurring damage, as the uncertainty of LCIA results is affected by the specific characteristics of the impact categories in terms of time and location.[359]

Another limitation of the impact assessment concerns the development status of impact categories, indicators, etc. as also of broadly accepted methodologies for relating inventory results to environmental effects.[360]

Figure 8 below depicts the sequence of components of the life-cycle impact assessment procedure according to the standards of ISO, which are precisely outlined in this chapter.

The segregation of the LCIA procedure facilitates transparency by describing and reporting the assumptions and value choices, separately made in each step, and enables quality determination of the selected methods in each component.[361]

The impact assessment step includes mandatory aspects that transform the LCI results to category indicator scores, whereas the optional elements should support in interpreting the final LCIA results.[362]

The impact assessment procedure of ISO is based on the valuation method developed by CML, following the sequence of figure 8, namely beginning with the selection of environmental impact categories, which refer to environmental themes and treating them separately.[363]

The category indicators, derived from a characterization model, are necessary to relate the inventory results to a specific category, depending on the nature of inventory scores, and to calculate the LCIA results.[364]

Other valuation methods include, for example, the Ecoscarcity methodology, developed by BUWAL, or the system of EPS (Environmental Priority Strategies) developed by Steen and Ryding.[365]

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[356] Cf. ISO 2006a, p. 14 and Klöpffer and Grahl 2009 p. 205.

[357] Cf. ISO 2006a, p. 15.

[358] Cf. ISO 2006a, p. 15.

[359] Cf. ISO 2006a, p. 16 and Scientific Applications International Corporation (SAIC) 2006, p. 46.

[360] Cf. Curran 1996, p. 13.5; ISO 2006a, p. 16 and Klöpffer and Grahl 2009, p. 205.

[361] Cf. ISO 2006a, p. 14.

[362] Cf. ISO 2003, p. 3.

[363] Cf. Curran 1996, p. 13.5.

[364] Cf. ISO 2006a, p. 5 and ISO 2006b, p. 20.

[365] Cf. Curran 1996, p. 13.4.

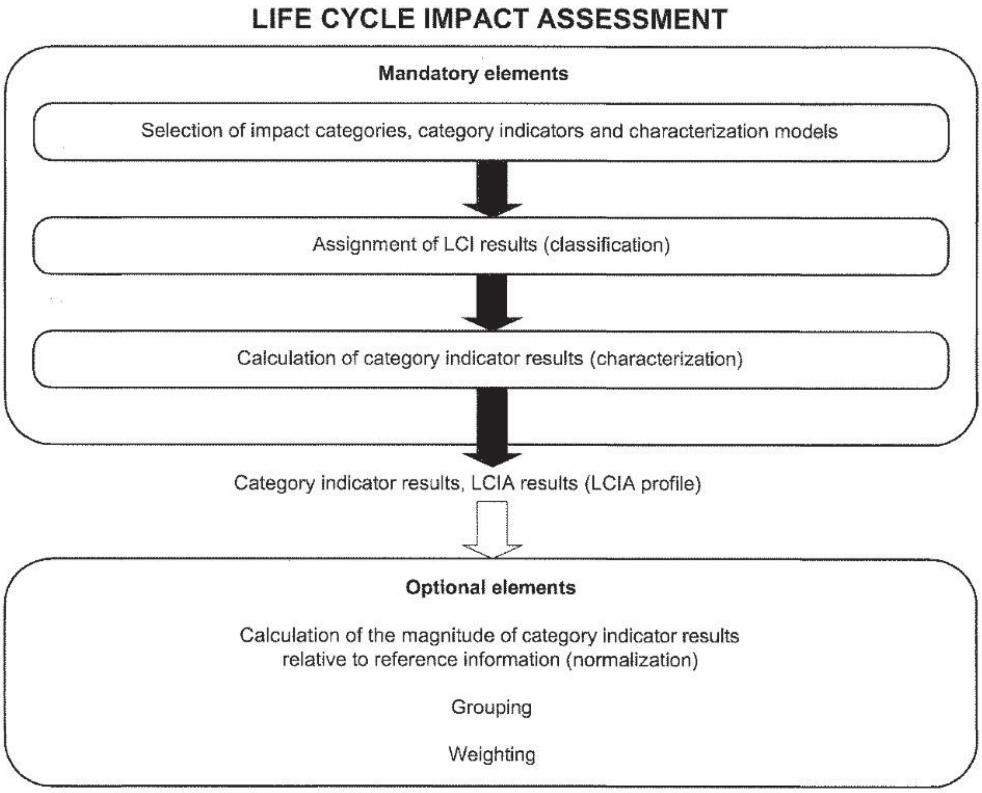

Figure 8: Life Cycle Impact Assessment sequence and components.[366]

Choice of impact categories, selection of category indicators and characterization models

The selection of impact categories, to be incorporated in an LCA, is left to the practitioner and should already be declared in the goal and scoping phase, as the collection of data has to be orientated according to the chosen categories.[367]

ISO[368] notes that the selection should be justified and enclose all categories that allow a thorough evaluation of the product system as described in goal and scope definition phase.

An explanation of the appropriateness and selection of environmental mechanisms, impact categories, category indicators, and characterization models should be described and documented, which seems overblown for already existing and well defined categories, indicators and models, but it might be necessary to define new ones in order to ensure a comprehensive assessment of the product system, thus the need for a clear description is obvious.[369]

The purpose of impact categories is to illustrate the confusing amount of mass and energy flows, represented in the LCI, in a clearer manner, therefore facilitating the determination of potential environmental impacts and their environmental relevance.[370]

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[366] ISO 2006a, p. 15.

[367] Cf. Klöpffer and Grahl 2009, p. 203.

[368] Cf. ISO 2006b, p. 17.

[369] Cf. ISO 2006b, p. 17 and Klöpffer and Grahl 2009, p. 204.

[370] Cf. Klöpffer and Grahl 2009, p. 196.

The selection of impact categories as well depends on the product system boundaries.[371] Some examples of developed impact categories are given in the following:

- Global warming potential
- Ozone depletion potential
- Human toxicity potential
- Aquatic acidification potential
- Terrestrial acidification potential
- Eutrophication potential
- Marine ecotoxicity potential
- Terrestrial ecotoxicity potential
- Freshwater ecotoxicity potential
- Abiotic resource depletion
- Biotic resource depletion
- Photochemical ozone formation potential
- Land use
- Water use
- Respiratory inorganics
- Respiratory organics
- Ionising radiation
- Noise
- Heat

The above listed impact categories, to which the inputs and outputs of the LCI are assigned, describe environmental problems on a so called mid-point or intermediate basis where category indicators are chosen anywhere along an environmental mechanism, thus the procedure is also denoted as problem-oriented approach, as opposed to the so called damage-oriented approach where the results are represented as end-point indicators, describing damage on areas of protection such as human health, natural resources and natural environment.[372] Results at an end-point level demands the pursuit of LCI results along the complete environmental mechanism to their impact on the areas of protection, which may incorporate in higher uncertainties, as the cause-effect chains of environmental mechanisms are not always absolutely understood.[373]

For calculation of the LCIA results for an impact category, the characterization models and category indicators, following certain environmental mechanisms and depending on the category, have to be selected.[374]

The category indicator should be representative for all impacts within a certain category, and it is chosen somewhere along an environmental mechanism, beginning at the outcomes of the LCI and ending at the category endpoints.[375]

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[371] Cf. ISO 2003, p. 13.

[372] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 47; Guinée et al. 2002, p. 67 and ISO 2003, p. 7.

[373] Cf. Simões et al. 2011, p. 2 and European Commission - Joint Research Centre - Institute for Environment and Sustainability 2010, p. 4.

[374] Cf. ISO 2006b, p. 17.

[375] Cf. ISO 2003, p. 11.

The indicators depend on the characterization model, described by the LCIA method, thus the EDIP method might use distinct definitions of characterization models, category indicators, indicator results and category endpoints than, for instance, the Eco-Indicator 99 method.[376] It is noted[377] that indicators chosen close to endpoints represent higher environmental relevance but at the same time may incorporate higher uncertainties, as environmental mechanisms are not always completely understood.

ISO's wording in relation to LCIA methods is rather hazily and does not adduce a strict directive on a certain method to be utilized in a specific situation but recommends that impact categories, category indicators and characterization models should be internationally accepted and incorporate an environmental relevant background, as little as possible be based on assumptions as also on subjective choices and that double counting of results should be avoided.[378]

After assignment of LCI results to an impact category, called classification, depending on the nature of results, the characterization model enables determination of the category indicators and category endpoints by applying characterization factors to the LCI results denoted as characterization.[379]

Classification and Characterization

Following the definition and selection, of scientifically and technically valid impact categories, characterization models and category indicators on basis of environmental mechanisms, the quantitative assignment of LCI results to each impact category is performed.[380]

Classification by itself is the procedure of assigning LCI scores to the selected impact categories as already mentioned. By derivation of scientifically based conversion factors and applying them to the LCI results, the elementary flows of the product system are then aggregated to final indicator results of a designated impact category.[381]

This procedure, called characterization, allows straight forward comparison of LCI results that contribute to a category. Usually the below mentioned equation is used to end up in the final category indicator result.[382]

$$\boxed{\text{LCI Score} \times \text{Characterization Factor} = \text{Category Indictor Result}}$$

In case the LCI results contribute to more than one impact category, it is distinguished between parallel and serial mechanisms.[383] Where the effects underlie serial mechanisms entirely all LCI scores are completely assigned to those categories to which they contribute, whereas if effects refer to parallel mechanisms the LCI results are partitioned between impact categories.[384]

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[376] Cf. ISO 2003, p. 12.

[377] Cf. ISO 2003, p. 12.

[378] Cf. ISO 2006b, p. 19.

[379] Cf. ISO 2006b, p. 17.

[380] Cf. ISO 2006b, p. 19 and Scientific Applications International Corporation (SAIC) 2006, p. 47.

[381] Cf. ISO 2006b, p. 20.

[382] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 50.

[383] Cf. ISO 2006b, p. 20.

[384] Cf. ISO 2006b, p. 20.

An example for a serial mechanism could be nitrogen dioxide, which is responsible for formation of ground level ozone as also acidification, thus the whole amount of nitrogen dioxide is attributed to both mid-point categories at the same time.[385]

The procedure of calculating category indicators and category endpoints is depicted in figure 9 below.

It is noted[386] that the quality of the indicator results, represented for a certain category, varies because of simplified complex environmental mechanisms, geographical and time related differences of substance characteristics and dose-response properties, therefore a clear report on the environmental relevance, applied characterization factors, assumptions made and value choices incorporated, should be made.

The LCIA indicator results are then represented for the selected impact categories and additionally the LCI results, not attributed to impact categories, for example, because of missing environmental relevance, are declared.[387]

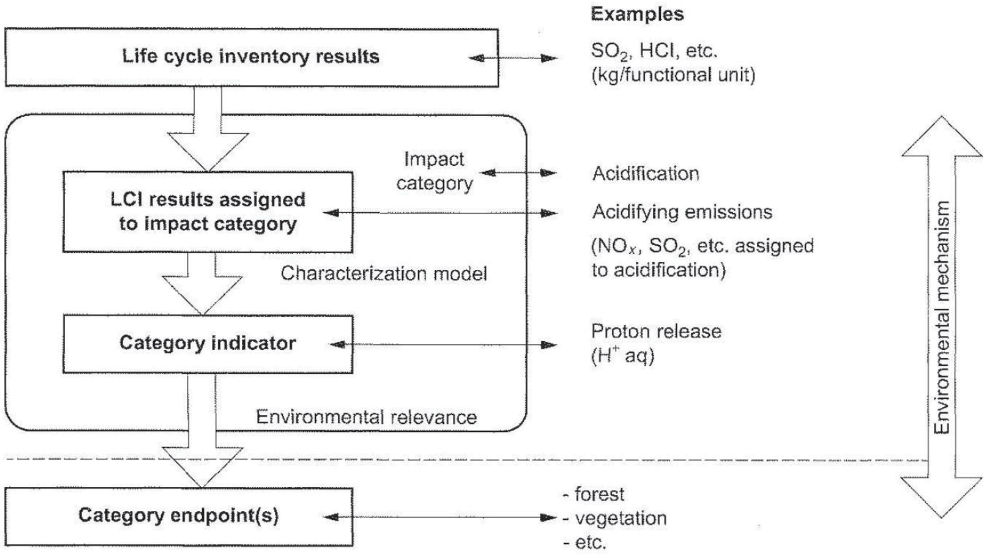

Figure 9: Example procedure assigning LCI results to category endpoints[388]

Normalization

Normalizing LCIA results highlights their relative significance by relating them to a certain reference value, which might, for instance, be based on a particular geographical area, a temporal period, per capita or also future related alternative systems.[389]

This supports identification of inconsistencies and can be used as an initialization step prior to grouping and weighting as noted by ISO.[390] The relative magnitude is calculated by dividing the category indicator results by the selected normalization factors.[391]

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[385] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 48.

[386] Cf. ISO 2006b, p. 20.

[387] Cf. ISO 2006b, p. 20.

[388] ISO 2006b, p. 18.

[389] Cf. Scientific Applications International Corporation (SAIC) 2006, pp. 51-52; ISO 2006b, p. 21; ISO 2003 p. 15 and Guinée et al. 2002, p. 90.

[390] Cf. ISO 2003, p. 15 and ISO 2006b, p. 21.

[391] Cf. Guinée et al. 2002, p. 90.

Grouping

This optional step allows aggregation of impact categories into one or more sorted or ranked sets, and in contrast to the below explained weighting step, ranking is also allowed for comparative studies intended to be disclosed to public, although it is mentioned[392] that normative grouping on basis of priority or level of certainty of impacts rests upon subjective choices and thus may lead to different rankings.

Category indicators may also be grouped by sorting, which is considered to be descriptive grouping, on basis of, for example, emissions, areas of protection or geographical scales.[393]

Weighting

Weighting of impact assessment results, also denoted as valuation, in contrast to grouping applies numerical values to the indicator results, based on value choices.[394] When multiplying the indicator results with weighting factors, the issue of losing information arises as the indicator results are often aggregated across impact categories to a single score without scientific background.[395]

Weighting factors underlie different methods of derivation such as monetary, distance-to-target or panel methods, and should, for instance, reflect values of stakeholders, which inevitably results in some kind of subjectivity.[396]

Monetization methods are based on the cost of goods and services like ,for example, their market price or the willingness of the society to pay for the retention of environmental safeguard subjects, then used to develop a weighting factor.[397]

Distance-to-target methods relate the weighting factor in terms of distance, which is mathematically characterized, to an environmental goal that might be set, for example, by governments, scientists or experts.[398]

Panel methods utilize the results of conducted questionnaires where, for instance, people, stakeholders, experts or scientists were asked how important specific impact categories seem to them.[399]

The purpose of weighting is to facilitate the decision making process by delivering aggregated results that are easy to handle, but according to ISO[400] is not allowed for comparative assertions intended for public disclosure as weighting is based on subjectivity.

ISO[401] mentions two practices related to the weighting step, which are to transform the indicator or normalized indicator scores by applying weighting factors, or else, to combine the already weighted results across several impact categories to an aggregated score.

If a weighting procedure is performed, ISO[402] suggests to represent the non-weighted indicator or normalized indicator results, in order to avoid loss of information and to ensure transparency.

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[392] Cf. Guinée et al. 2002, p. 92; ISO 2003, p. 16; ISO 2006b, p. 21 and Klöpffer and Grahl 2009, pp. 212-213.

[393] Cf. ISO 2003, p. 15 and ISO 2006b p. 21.

[394] Cf. ISO 2003, p. 16; ISO 2006a, p. 22 and Scientific Applications International Corporation (SAIC) 2006, p. 52.

[395] Cf. ISO 2003, p. 16; ISO 2006a, p. 22 and Klöpffer and Grahl 2009, p. 216.

[396] Cf. ISO 2003, p. 16 and Scientific Applications International Corporation (SAIC) 2006, p. 52.

[397] Cf. Johansson 1999, p. 9.

[398] Cf. Johansson 1999, p. 9.

[399] Cf. Johansson 1999, p. 9.

[400] Cf. ISO 2003, p. 16 and ISO 2006b, p.23.

[401] Cf. ISO 2006a, p. 22.

[402] Cf. ISO 2006a, p. 22.

Additional quality analysis of LCIA results

Especially for comparative assertions intended for public disclosure, ISO[403] suggests the application of additional analysis methods, namely gravity, uncertainty and sensitivity analysis, to identify the significance or uncertainty of impact assessment results that, in turn, may lead to additional effort for improving the inventory data.

3.5 Life Cycle Interpretation

The last phase of the LCA procedure the final results are evaluated and analyzed, in order to allow drawing conclusions, identifying limitations and making recommendations according to the goal and scope of the study.[404]

As the study incorporates several decisions, assumptions and methodological choices, the interpretation step also investigates if the study fulfills the essential requirements of the goal definition and scoping phase.[405]

The aim is to determine relevant parameters and to check the robustness, consistency and completeness of results to finally determine the advantages and disadvantages of the evaluated system in terms of potential environmental impacts.[406]

Identification of significant parameters

Relevant issues and contributions related to product system elements, LCI data, and impact assessment are to be identified to avoid misinterpretation of the results as uncertainties are introduced during the study approach, depending on the quality of modeling LCA aspects.[407]

Sources of relevant information include value choices, aspects and outcomes related to the LCI and LCIA, decisions on applied methodologies such as system boundary definitions, allocation and cut-off rules but also the influence of interested parties on the study.[408]

By reviewing the first three steps of the LCA, those aspects should be determined that contribute the most to the insights gained, which then is the basis for the evaluation of data completeness, sensitivity and consistency.[409]

For determination of significance, contribution, dominance or anomaly analyses might be utilized, supporting the identification.[410]

Evaluation

The purpose of evaluation is to provide and increase the confidence and reliability of the LCA results and significant parameters by comprehensibly representing the results of the completeness check, the sensitivity check and the consistency check, which are the suggested evaluation methods to be conducted while regarding the goal and scope as also the intended purpose of the study results.[411]

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[403] Cf. ISO 2006a, p. 22 and Klöpffer and Grahl 2009, p. 217.

[404] Cf. Guinée et al. 2002, p. 97.

[405] Cf. ISO 2006b, p. 24 and Klöpffer and Grahl 2009, pp. 355-357.

[406] Cf. ISO 2006a, p. 23 and Klöpffer and Grahl 2009, p. 357.

[407] Cf. ISO 2006a, p. 24 and Klöpffer and Grahl 2009, p. 359.

[408] Cf. ISO 2006a, p. 25 and Klöpffer and Grahl 2009, p. 359.

[409] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 55.

[410] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 56.

[411] Cf. ISO 2006b, p. 25; Scientific Applications International Corporation (SAIC) 2006, p. 56 and Klöpffer and Grahl 2009, p. 360.

The **completeness check** addresses the availability of mandatory elements that have been determined prior to evaluation, and the completeness of LCA elements required for the interpretation.[412] This might include development of a checklist, indicating representativity and integrity of LCI data, or an error check by consultation of experts that may identify wrong assumptions or methodological choices.[413]

If issues on completeness arise the first three steps of the LCA might have to be revised, in terms of filling data gaps or adjusting the goal and scope definitions.[414] Otherwise, if these issues are considered not to be important, a justification should be made and documented.[415]

The **sensitivity check** determines the uncertainty of the LCA results after different methods have been utilized and value choices or assumptions have been made. ISO[416] states, for example, to conduct a sensitivity analysis if more than a single allocation method can be applied to depict the effect of different allocation procedures on the inventory results.

The sensitivity check should address issues of the first three phases of the LCA to evaluate how assumptions, for instance, related to the system model, the data quality or the impact assessment methods affect the results.[417]

Common methods, to evaluate the reliability of the results, include contribution analyses, uncertainty analyses and sensitivity analyses and if these analyses have already been conducted in the preceding phase their results should be incorporated in the sensitivity check.[418]

The conclusion drawn from the sensitivity check may be a non relevant effect of evaluated parameters on the results, apparent effects on the results, probably demanding further sensitivity checks or the validity of results within a certain range of parameter variation.[419]

If shortcomings are detected the assumptions, the data quality or method selection should be reviewed if possible to increase robustness and reliability of the study, and, if this is not feasible, the deficiencies should be documented qualitatively or quantitatively.[420]

A **consistency check** may address the issues of utilized methods, assumptions, and the representativeness of data in relation to actuality, technology or location.[421] It should be secured that methodological choices, like the modeling approach, nomenclature, calculation procedures and extrapolations, the appointed data accuracy and precision or the definition of foreground processes, demanding primary data, to name but a few, satisfy the requirements of the goal and scope.[422]

This is the last method within the evaluation element, and the check for consistency of methods, incorporated data, assumptions and models in relation to the goal and scope

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[412] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 56; Guinée et al. 2002, p. 102 and ISO 2006b, p. 25.

[413] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 56 and Guinée et al. 2002, p. 102.

[414] Cf. ISO 2006b, p. 26 and Klöpffer and Grahl 2009, p. 360.

[415] Cf. ISO 2006b, p. 26.

[416] Cf. ISO 2006b, p. 14.

[417] Cf. ISO 2006b, p. 26.

[418] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 57 and ISO 2006b, p. 26.

[419] Cf. ISO 2006b, p. 26 and Klöpffer and Grahl 2009, p. 360.

[420] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 57.

[421] Cf. UNEP/SETAC Life Cycle Initiative 2011, pp. 63-64.

[422] Cf. ISO 2006b, p. 13 and UNEP/SETAC Life Cycle Initiative 2011, pp. 63-64.

definitions is, especially in case of comparative studies, vital for proper interpretation of the results.[423]

Drawing conclusions, making recommendations and identify limitations

After identification of significant parameter, the evaluation of completeness, sensitivity and consistency, conclusions can be drawn from the results, which should be done as unambiguously and transparent as possible.[424]

The conclusions drawn and recommendations made have to be based on facts, logical consequences, in accordance with the goal and scope of the study, as also the insights gained after the evaluation element.[425] Information about the limitations on which the conclusions and recommendations are based should be documented, to secure transparency and comprehensibility for decision-makers.[426]

3.6 Reporting and Critical Review

Already within the goal definition and scoping phase the type and format of the report has to be specified as noted by ISO[427]. It has to address all four phases of the LCA in terms of methodological choices, assumptions, expert judgements, results, quality trade-offs, conclusions and limitations and as well has to consider important aspects related to the intended audience such as comprehensibility, transparency etc. without incorporating manipulation as a result of audience interests.[428]

ISO[429] distinguishes in the 14044 standard different requirements for reports intended for third-parties and comparative studies intended for public disclosure, which are not further discussed in this work at hand. In summary, information, such as name and address of the operator that conducted the study, the date of the report as also name of reviewers, are to be documented within the report, besides the already mentioned characteristics of the four LCA phases.[430]

The purpose of the report is to transmit and communicate a comprehensively readable study where several value choices, aspects, insights, assumptions and justifications in relation to each phase of the LCA, including a critical review if necessary, are documented.

Because of the exceptional huge amount of information concerning the interrelationships of unit processes, the input and output data, the defined quality requirements as also the presentation of results has to be meaningful, without leaving crucial information.[431]

The content of the report addresses the methodologies applied and the assumptions made during the development of the LCA, such as the selection of the functional unit or the system boundaries set, to ensure transparency and reproducibility on how the results of the study have been developed.[432] The representation of results whether in a tabular or a graph-

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[423] Cf. ISO 2006b, pp. 26-27 and Klöpffer and Grahl 2009, p. 361.

[424] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 58; Guinée et al. 2002, p. 107 and ISO 2006b, p. 27.

[425] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 58; Guinée et al. 2002, p. 107 and ISO 2006b, p. 27.

[426] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 58 and Guinée et al. 2002, p. 107.

[427] Cf. ISO 2006b, p. 27.

[428] Cf. ISO 2006a, pp. 16-17 and ISO 2006b, p. 27.

[429] Cf. ISO 2006b, pp. 27-31.

[430] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 59.

[431] Cf. Curran 1996, p. 2.14.

[432] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 44 and Klöpffer and Grahl 2009, p. 143.

ical format might be supplemented with figures, charts, graphs and other explanations on inventory development handling.[433]

Klöpffer and Grahl[434] suggest to carefully read these requirements especially in case of comparative studies.

The critical review may be conducted by internal or external experts as also by a panel of interested parties and should address the proper accordance of applied methods, in relation to the standards of ISO, as well as the scientific and technical validity.[435] Furthermore the purpose of the critical review is to ensure the transparency and consistency of the report as also the correctness of utilized data and interpretations made, in relation to the goal and scope.[436]

The aim of the review is to enhance the reliability and quality of the study, and additionally to ensure sufficient transparency, whereas it is explicitly stated[437] that the goal definitions made by operator and the subsequent use of the results are not part of the critical review, because both underlie the operator's arbitration.

ISO[438] notes that a panel of interested parties should be comprised of at least three members, and furthermore that internal or external experts should be capable of the technical and scientific knowledge related to the LCA study.

In case of comparative assertions intended to be disclosed to the public the critical review has to be executed by a panel of interested parties, whereas the study commissioner has to select an external expert that acts as a chairperson within the panel.[439]

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[433] Cf. Scientific Applications International Corporation (SAIC) 2006, p. 44.

[434] Cf. Klöpffer and Grahl 2009, p. 366.

[435] Cf. ISO 2006b, p. 31.

[436] Cf. ISO 2006b, p. 31 and Klöpffer and Grahl 2009, p. 48.

[437] Cf. ISO 2006a, p. 17 and ISO 2006b, p. 31.

[438] Cf. ISO 2006b, p. 17.

[439] Cf. ISO 2006a, p. 17 and ISO 2006b, p. 31.

4 Case Study Research

Life cycle assessment, based on the standards of ISO, is supposed to be a valuable tool determining the potential environmental impacts of various kinds of products, including different processes, necessary for the provision of a product, whereas the results of LCA studies can play an important role within the decision making process.

The purpose of the ISO standards is somehow to provide a standardized assessment procedure that even might enable comparison of different LCA studies among each other, if the assumptions and objectives were the same.

After describing requirements and criteria for the case study selection, this chapter of the master thesis comprises a selection of LCA studies that have been performed in recent time, and an examination of the studies, with the primary goal to highlight favorable adopted methods, practices of execution and procedure characteristics related to Life Cycle Assessment on basis of the standards of ISO when aiming to assess the environmental burdens of processes, which are in a relative early stage of implementation.

4.1 Requirements and Criteria for Case Study Selection

Because of the vast number of life-cycle assessment studies, conducted in relation to a very large variety of products and process areas, the selection of representative case studies is chosen to be limited to a certain framework of conditions. These restraints, explained in the following, allow a more precise determination of practices and possible issues related to the LCA procedure.

As an imposing example for a complex system, which in fact is more complex than a milk carton, the system of electricity generation with carbon capture and sequestration (CCS) technology was chosen.

Complexity in these terms especially addresses the modeling of future related electricity production systems, the inherence of a high variety of different processes and substances, the lack of data availability because of the early stage of implementation of CCS system technology and the incomplete comprehension of underground carbon dioxide storage.

The determination of associated environmental burdens according to ISO's LCA procedure was increasingly in the focus of different power suppliers as this topic may play an important role for upcoming fossil fuel based energy production systems in terms of greenhouse gas control.

The number of yet conducted and actual LCA studies in this area is manageable and the experience, of conducting a comprehensive LCA procedure on electricity generation with carbon capture and storage technology, to allow the determination of related environmental loads, is relatively scarce.

Thus it might not possible to draw obvious conclusions from already performed studies in order to make further recommendations for improvement of future studies, but at least, it is attempted to underline the issues that are at hand and correlated to the general procedure of an LCA.

In this chapter, and in the first instance, it is aimed to find intersections between the selected studies, especially with focus on the issues that seemingly raised, as a possible basis for further development of an LCA procedure, complying to the standards of ISO.

Also characteristics and system parameters of the selected studies are appointed in this section of the work at hand that are considered to have a major impact on the results, and, thus have been regarded crucial by several authors.

To sum up, the search for representative case studies was based on the criteria listed below:

- LCA studies that deal with the determination of environmental loads of processes related to electricity generation systems including carbon capture and sequestration.
- LCA studies that satisfy and incorporate the recommendations of the ISO 14040 and ISO 14044 standards.
- Studies that have been carried out after the year 2007, to ensure that actual achievements and recommendations of ISO's LCA approach are considered.

4.2 The Electricity Generation with Carbon Capture and Sequestration System

A short introduction on the main system components of an electricity generation system with CCS technology that may be examined within an LCA study is now given to provide a general overview on the power plant system with carbon capture and sequestration. A detailed discussion of involved processes, state of the art power plant or carbon capture technologies is out of the scope of this work. It is only aimed to accent obvious aspects that might be considered when assessing such a system in terms of environmental loads. Figure 10 below depicts the main processes of a power plant system utilizing the CCS principle.

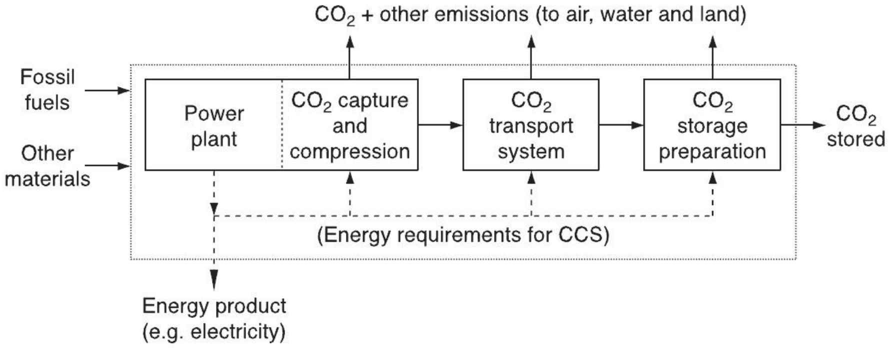

Figure 10: Main components of a power plant with CCS technology system.[440]

The intention of utilizing CCS technology to fossil fuel based power plants is to decrease the greenhouse gas emissions after combustion of fossil fuels such as coal.

Within the meaning of an LCA study, the complete electricity generation system should encompass all process steps from cradle-to-grave, namely beginning with the extraction of resources, the processing of raw materials, transport operations, construction of facilities such as power plants and infrastructural requirements, the main processes of electricity generation, the carbon capture process, the transport of CO_2 to the storage site, but also the maintenance and dismantling of facilities and infrastructure, the reuse and recycling of materials and the waste treatment.

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[440] Intergovernmental Panel on Climate Change 2005, p. 63.

As a matter of fact it is not possible to retrace every single unit process and the involved substances to its origin but the more comprehensively a system is considered, while keeping in mind the time and labor for gathering the data as also the quality of the data, the higher the meaningfulness of the LCA study will be.

Resources

The most obvious type of resources needed within this system are of course the fuels such as coal or natural gas for the generation of electricity within the power plant, which are produced by either mining or oil and gas production operations. But also the development of infrastructure and the construction of facilities require a variety of resources for the provision of, for example, steel, concrete, etc. As a result of each of these activities other types of resources are required, emissions occur and wastes emerge which could play an important role within an LCA study and the practitioner itself has to decide where to set the boundaries of the examined system.

Raw material processing

Also the processing of raw materials may result in a dominant fraction of environmental loads, if for example, the product system requires a huge amount of steel for the development of pipeline infrastructure to transport CO_2 from the capture facility to the storage site. Processing of iron ore to produce high quality steel is very resource consuming, highly energy intensive and thus causes negative impacts on the environment, therfore involving such processes within an LCA seems vital.

But it is not necessarily the process that is obviously the main reason for environmental burdens, such as the production of steel. Also the production of other substances such as solvents, which are in terms of production probably not as resource and energy consuming but after all are extremely harmful for the environment.

Transport

A fossil fuel fired power plant needs continuous supply of coal or gas that has to be transported somehow to the site of electricity production. It depends on several aspects such as the location of the power plant, the availability of fossil fuels, the type of fuel, etc. how significant the impact of transport operations on the environment will be. Coal transport by ship over large distances can have a considerable impact on the results of an LCA study and therefore incorporation of transport operations is inevitable for a comprehensive study.

Construction, maintenance and dismantling of facilities, infrastructure and equipment

These processes are possibly not the highest contributors to environmental impacts and the construction of equipment, facilities and infrastructure may be of secondary importance compared to other unit processes such as coal mining and electricity generation itself, but involving facility and infrastructure related construction and maintenance operations may highlight unexpected environmental loads, especially in terms of land use and resource requirements.

For example, construction and monitoring of many hundred kilometres of CO_2 transport pipeline in inaccessible areas can be resource and energy intensive as well, or when deciding to store CO_2 in geological formations also wells have to be drilled and monitored.

Electricity generation

The implementation of carbon capture technology is especially reasonable for fossil fuel fired electricity generation systems as this type of power plants produce significant amounts greenhouse gas emissions. Therefore coal and natural gas fired power plant systems were in the focus of various LCA studies, assessing the environmental impacts of such systems on basis of emissions caused during the plant operation as also the inputs needed to run the power plant.

When assessing the power plant model it necessary to consider the efficiency of the electricity generation system, as it directly affects the fuel requirements and releases to the environment to provide a certain amount of electricity.

Carbon capture

Different options have been developed in the past to capture CO_2 as also to isolate it, which are now briefly explained. As already mentioned, a detailed discussion of the carbon capture technology is not possible within this thesis, but the inhered energy demand and the involved substances that are to some extent highly detrimental to the environment, either in terms of releases to the environment, or in terms of process requirements, are at least indicated.

Pre-Combustion carbon capture is a process where the fuel is converted into a mixture of hydrogen and carbon monoxide by either reaction with oxygen or steam prior to combustion of the fossil fuel in the power plant. Carbon monoxide is then transformed into CO_2 and hydrogen with steam and in the presence of a catalyst. During both reactions hydrogen is generated, which then acts as the fuel for electricity generation in the power plant. CO_2 can be separated with different options similar to the post-combustion carbon capture process.

Post-Combustion capture of CO_2 occurs, as the name implies, after the combustion of fossil fuels in the power plant. Processes such as chemical absorption, membrane separation or adsorption, to name but a few, are used to separate the CO_2 from the flue gas stream of the power plant. In absorption and adsorption processes, solvents such as monoethanolamine (MEA) and solid sorbents such as calcium-oxide are used to bond the CO_2. After regeneration of the solvents or sorbents, they can be reused again.

Oxyfuel is a process where the fossil fuel is burnt together with nearly pure oxygen, some flue gas is needed to control the combustion temperature, to produce a CO_2 rich flue gas stream. CO_2 then can be separated from steam and transported to the storage site. The inherent amount of energy needed to produce pure oxygen is certainly obvious.

Depending on the type of carbon capture technology and the separation efficiency different types and amounts of environmental burdens develop, such as production and use of toxic solvents needed for chemical absorption or high energy requirements for producing oxygen. Also other substances such as sulfur, SO_2, HCl, H_2S, ammonia, NO_x, dust, hazardous waste like heavy metals, ash, etc. arise during the capture process and have to be handled, thus a detailed examination of this process would be meaningful.

CO_2 transport and storage

The type of transport system either pipeline, ship, rail or truck depends somehow on the type of storage. Different alternatives can be considered for the storage of CO_2. These options include storage in geological formations such as depleted oil and gas fields, salt formations or other natural underground trapping formations. But also ocean and mineral storage or industrial use of CO_2 are possible to isolate the greenhouse gas from the atmosphere. The options mainly differ in the involved effort of the storage process, the achievable amount of stored CO_2, and the environmental risks related to the storage. Large scale CO_2 storage seems mainly feasible by ocean storage and storage in geological formations but involves high environmental risks such as leakage, impacts on surface and subsurface living organisms, contamination of soil and water, etc.

Transport via pipeline and storage of CO_2 in geological formations seems viable as experience with natural gas transport and storage gathered over the last decades provides a basis for this combination of CO_2 transport and storage alternatives to be executed.

Considering this combination of alternatives a practitioner of an LCA study may incorporate several aspects, for example, the transport distance, affecting the need for recompression of CO_2 along the pipeline length, but also the depth of the storage site, the transport and storage conditions in terms of temperature, pressure, CO_2-density and -purity, and all other parameters, in turn affecting the energy and resource requirements, and consequently the releases to the environment.

This energy requirements, depending on the type of supply, can result in considerable impacts on the environment as well. Energy supply for transport and storage processes may be provided, for example, by electricity from the local power transmission system or by onsite diesel generators. When energy is delivered by a local power transmission system, the national electricity mix may as well play an important role as different types and amounts of energy carriers are involved that again have impacts on the environment.

Recycling and waste treatment

During the operation of the plant and the carbon capture unit, obviously different kinds of substances, detrimental to the environment, arise, like heavy metals, hazardous wastes, degraded solvents, waste water, etc., which are subject to waste management procedures and thus should also be included in a comprehensive LCA study.

Dismantling of facilities and infrastructure after their life time is exceeded provides a good source of secondary raw materials, such as metals, which might be incorporated into the system analysis to reduce the environmental loads inhered in the extraction and processing of virgin raw materials. The ISO standards described in chapter 3 of the thesis provide a good basis on how to handle and incorporate recycling steps into an LCA study.

4.3 Examination of Case Studies

The following studies have been selected because of the information content that allows drawing some conclusions needed to establish a number of suggestions, or at least highlight issues that may be kept in mind and considered helpful if operators of future LCA studies heading for performing such a procedure, thus probably facing similar challenges.

The information read out of these studies is described in the following for each study separately already aiming to accent their apparent commonalities in terms of goals and scope, system boundaries, selected functional unit, inventory data and data sources, LCA methods and relevant impacts on the results.

4.3.1 Life cycle assessment of selected technologies for CO_2 transport and sequestration (Caroline Wildbolz, 2007)[441]

Wildbolz conducted an LCA study with the intention to determine the environmental loads of different CO_2 capture, transport and storage options, relating the inventory analysis to European conditions, with the main focus on a comparative analysis of transport and storage options.

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[441] Cf. Wildbolz 2007, pp. 19-58.

The **goals** stated were to assess the energy and material requirements, the potential environmental impacts, the most viable transport and storage option from an ecological point of view and the processes with the highest contribution to the environmental loads in relation to CO_2 transport and storage.

Furthermore the questions of how far a 'near-zero-emission' concept could be attained by the considered CCS chain, including electricity production in a hard-coal fired power plant, and, which elements of this electricity generation system with CCS contributed the most to the environmental burdens, should be answered.

As the whole the study was mainly focused on transport and storage of CO_2, a functional unit of 'kg CO_2 stored' was chosen and complemented with a functional unit of 1 kWh net electricity generated in a pulverized hard coal power plant with capture technology, to compare the complete process chains of electricity generation systems with various CCS technologies.

In a first step, the system boundary included the transport and storage related elements without the electricity generation and capture related processes. Wildbolz assumed transport of pure CO_2 in supercritical state via an onshore pipeline of 200km, respectively 400km in length, and onshore storage in a deep saline aquifer located at 800m of depth, and as a second option storage in a depleted gas field in a depth of 2500m, while leakage of CO_2 from the storage sites was not regarded.

In relation to CO_2 transport Wildbolz identified important system model parameters, to dimension the system elements included in the study, which were:

- the mass flow rate of CO_2
- the average transport temperature
- the pressure and pressure drop in the pipeline
- the density of CO_2
- the transport distance pipeline dimensions and material characteristics
- the pipeline insulation
- the burial depth of the pipeline
- the transport velocity of CO_2
- the lifetime of the infrastructure
- leakage rate during the transport
- the energy requirements for recompression

Assumptions on the values for these parameters were based on a literature review and calculations performed by Wildbolz.

In case of the two geological storage options, storage depth, reservoir temperature and pressure, storage capacity, establishment of injection and monitoring wells, lifetime of the storage infrastructure, injection pressure and rate, number of wells required for storage, and energy requirements for injection, were considered in this study for dimensioning of the system components. As in case of the transport parameters the assumed values for the storage parameters were based on literature review and calculations.

Wildbolz indicated a qualitative statement on the uncertainty related to above mentioned parameters for transport and storage, which was considered to be higher if several assumptions were necessary to end up in a parameter value.

The **inventory**, developed with the SimaPro software, accounted resource requirements, energy demands and releases to the environment in relation to transport and storage elements, including construction as also dismantling and disposal of 200km, respectively 400km, of buried rock wool coated pipeline, two injection wells and one monitoring well for each storage alternative, the monitoring of infrastructure per helicopter, and recompression of CO_2 with a gas turbine, necessary for the 400km pipeline.

The inventory data, gathered from the Ecoinvent database related to the electricity supply for the transport and storage operations, was based on the Western Europe mix UCTE.

Wildbolz created a Sankey-diagram for the transport process with recompression and determined that the steel requirements as also the labour for construction of the pipeline played an essential role within this process.

The **impact assessment** was performed using two different methods, namely the Eco-Indicator 99 method on basis of the Hierarchist scenario, and the IPCC 2001 (GWP 100) method, which indicated the global warming potential over a period of 100 years, in terms of CO_2-equivalents by applied weighting factors to different kinds of substances.

The midpoint impact categories considered within the Eco-Indicator 99 method were:

- Fossil fuels
- Minerals
- Land use
- Acidification/Eutrophication
- Ecotoxicity
- Ozone layer
- Radiation
- Climate change
- Respiratory organics
- Respiratory inorganics
- Carcinogens

The impact assessment was performed for the two geological storage options with two different transport lengths, namely 200km and 400km of pipeline length, for each storage option. The results showed that the highest values were located in the categories of fossil fuels, respiratory inorganics and climate change.

Wildbolz concluded that both, the transport distance and injection depth, had the highest influence on the environmental impacts and that the infrastructure lifetime significantly affected the construction labour of the CO_2 transport and storage infrastructure. The considerable effect of the injection depth on the environmental impacts was related to the energy needed for injection, where the most important parameters identified were the injection pressure and the volume flow, both affected by the average CO_2 density. Wildbolz noted that the supplementary material demand for the 400km pipeline compared to the 200km pipeline length had a minor effect on the results.

Concerning the relation between the energy requirements and the effect on the results she also mentioned that the electricity mix, used in her study for the assessment, was dominated by the share of conventional thermal power and that the Eco-Indicator 99 method gave high weight to fossil energy sources, which substantiated the noticeable magnitude of results related to fossil fuels, respiratory inorganics and climate change.

Unfortunately she did not depict the contribution of processes to each Eco-Indicator impact category on a higher level of detail, making it impossible to determine the processes that mostly affected a certain impact category.

In relation to the results determined with the IPCC 2001 method, referring to the greenhouse gas emissions, Wildbolz made similar conclusions, which were increased environmental burdens with increased transport length and storage depth, due to higher energy demands for injection and material requirements for pipeline construction.

In a next step the author compared four alternatives on basis of 1 kWh as the functional unit. Electricity generation in a hard-coal fired power plant without CCS, the same plant with utilized capture technology, and to two combinations of the power plant with CCS where the transport and storage in a saline aquifer, with 200km pipeline distance, and a gas field, with 400km transport distance, were opposed against each other.

As in case of the transport and storage analysis she conducted the Eco-Indicator 99 method, on basis of the Hierarchist scenario, and the IPCC 2001 method.

Because of utilization of the Eco-Indicator, which highly focuses on consumption of fossil fuels, the results for the capture technologies of course depicted a decrease in the category climate change, but the additional material and energy demands related to the capture technology that especially affected the fossil fuels and respiratory inorganics categories, almost compensated this benefit.

In case of the power plant with carbon capture and storage in a gas field with 400km pipeline length that depicted the worst case scenario, in terms of transport and storage, the environmental burdens assessed with the Eco-Indicator were even slightly higher in comparison to the power plant without CCS.

In general, it seemed that the transport and storage related environmental burdens were only of a minor extent, compared to the fuel supply and electricity generation in the power plant with carbon capture, as the difference, between the two analyzed transport and storage options in combination with the power plant operation, was of a very low magnitude.

The IPCC 2001 method showed a more distinct difference in the results, between the electricity generation chain with and without CCS technology. But, as stated by Wildbolz, the environmental burdens related to the transport and storage processes were marginal.

A **contribution analysis** was performed in relation to the Eco-Indicator and the CO_2-equivalents methods for various electricity generation systems with and without CCS, to compare the different power plant system alternatives in relation to the processes of plant operation, plant construction, dismantling of the plant, hard coal supply, and CCS.

Wildbolz noted that the environmental loads within the climate change impact category clearly varied, depending on the particular transport and storage option, but as a whole the CO_2 capture, transport and storage processes depicted only a minor share compared the complete electricity generation chain.

In a **sensitivity analysis** the effect of the pressure difference, needed for the CO_2 injection, was examined, as high uncertainties were associated to the actual reservoir pressure and the overpressure needed for injection, which were both related to the pressure difference that in turn affected the injection rate.

The impact on the results of Eco-Indicator assessment method was high, especially on the fossil fuels, climate change and respiratory inorganics categories, which was attributed to the different energy demands caused by varying injection pressures, and again the electricity mix as also the Hierarchist-scenario, used for the assessment, played their role.

The results of the sensitivity analysis received with the IPCC 2001 method, led to a similar conclusion, namely a high influence of the pressure difference on the environmental impacts.

Wildbolz identified the life-time and the steel demand for the transport infrastructure as also the CO_2 density, which highly depended on temperature and pressure, as important system parameters to be further analyzed.

In the conclusion other impact assessment methods were suggested for future LCA studies and uncertainties related to assumptions, because of missing accurate data for the CO_2 density, the lifetime of system elements, and the storage site, such as reservoir characteristics, were underlined by Wildbolz.

4.3.2 Life cycle evaluation of CO_2 recovery and sequestration systems (Khoo Hsien Hui, 2007)[442]

In his work, Khoo performed a comparative LCA and analyzed the environmental burdens of coal-fired power plants with various carbon capture and storage technologies on basis of a functional unit of 1 MWh electricity generated. In the first instance, the system was separated in three stages where each stage represented a ‘stand alone’ subsystem, which then were individually analyzed.

The first stage included fuel production and electricity generation in the power plant.

The second stage refered to the process of CO_2 capture where four different capture technologies were examined.

The third stage comprised the CO_2 sequestration process where Khoo analyzed different alternatives, namely five ocean storage, two geological storage and five mineral storage options.

Finally the impact assessment was performed for the complete system where all stages were treated as a process-chain.

The stated **goals** were to develop an inventory for each stage separately, then to calculate the potential impacts of the individual stages and finally to evaluate the impacts of the complete process-chain.

The **inventory** data of the first stage was focused on determination of resources, wastes and emissions to air and water, related the processes of coal mining, transport and electricity generation. Site-specific data was used to develop the inventory for the power plant that produced 1 MWh of electricity.

Primary data, for the second stage that concerned the CO_2 recovery, was not available and Khoo assessed the data for energy demand and recovery efficiencies by consultation of experts and with help of literature reports.

The effectiveness of the storage process, in terms of percent CO_2 stored, were determined with literature findings, but again no primary data was available for the processes, such as recompression and injection of CO_2, which were related to the transport of CO_2 via pipeline and the sequestration, thus reports and expert interviews were used to estimate the energy values for those processes.

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[442] Cf. Khoo 2007, pp. 56-147.

The geological storage options considered by Khoo included the sequestration of CO_2 into a geological formation, for the purpose of enhanced oil recovery (EOR), and the injection of CO_2 into underground media, for the recovery of natural gas (ECBM).

Inventory data related to capital equipment such as materials needed for the manufacturing of equipment was not recorded in Khoo's study.

The **impact assessment** was executed by using the problem oriented EDIP (Environmental Design of Industrial Products) 97 method, implemented in the SimaPro 2005 software, and providing results on a mid-point basis. Eight impact categories were considered by Khoo on basis of available inventory data:

- Global warming potential
- Acidification
- Human toxicity to air
- Human toxicity to water
- Eutrophication
- Ecotoxicity
- Wastes
- Resources

In the following, the characterized results for each impact category were qualitatively analyzed for the two geological storage options to provide a basis for comparison, within the work at hand, to other studies that especially considered geological storage alternatives.

It seemed that the impact assessment scores were only depicted for the third stage of the complete electricity generation system, as the processes of fuel supply for the power plant, the electricity generation in the power plant, and the carbon capture processes were not indicated by the available impact category results.

In case of the global warming potential, the results for the processes related to the third stage, namely the CO_2 storage including pipeline transport, compression, injection and enhanced hydrocarbon recovery, were juxtaposed in opposition to the sequestered amount of CO_2.

Also an amount of potential CO_2 leakage was quoted for the two options, but no indication was given on which parameters this calculated amount was based, nor the way it was treated in the LCIA step.

Generally the processes of transport via pipeline, the compression, and the injection of CO_2, which were summarized to a single result, contributed the most to this category, followed by the amount of potentially leaked CO_2 when considering the sequestration process separately.

The environmental burdens, related to the enhanced recovery process of oil and natural gas, were very small compared to the others.

Concerning the categories acidification, human toxicity to air, human toxicity to water, eutrophication, and ecotoxicity, the trend, where the hydrocarbon recovery related processes contributions to each of the impact categories were very small, compared to the transport, compression and injection processes, clearly continued.

In terms of resources, the demands of the transport, compression, injection, and hydrocarbon recovery processes were as well aggregated into one total result, and displayed for each individual sequestration alternative separately. Additionally the potential amount of recovered oil and natural gas was opposed to the resource demands within this impact category in an impressing way, which exhibited the huge amount of energy that could be recovered, in terms of hydrocarbons, compared to the amount of energy needed to store the CO_2.

In the next step Khoo applied **normalization and weighting** methods to the impact indicator results of the impact assessment, which was performed for every stage of the complete system separately, in order to obtain a single final score for each combination of electricity generation, capture and storage alternatives, then treated as a chain of processes. He justified the application of normalization and weighting as a clear decision, of which combination of alternatives seemed most viable, could not be made only on the results of the impact assessment, determined for each stage separately and differently diversified over the eight impact categories.

On basis of the normalized and weighted final scores the author determined the most promising combination of alternatives and performed a hypothesis test to ascertain the relevance of his propositions, which were among others that the two geological sequestration options with enhanced hydrocarbon recovery were the best alternatives in terms of least environmental burdens, mainly because of the additional amount of resources produced and the CO_2 stored, which significantly reduced the global warming potential.

In an **error analysis** the effects of initial data errors on the results were determined with an estimated choice of ten percent error for all inventory data, as actual error values were not available. Khoo noted that the impact assessment results changed likewise according to the ten percent.

As a next step a **sensitivity analysis** was performed to compare the effects on the total study results of different CO_2 recovery efficiencies, elevated power plant emissions and different weighting factors of the EDIP method.

Generally the impacts were proportional to the varying values that were subject to the sensitivity analysis without considerable outliers, thus the trend in the final results was maintained.

Also the results of the problem oriented EDIP method, giving high weight to toxic effects, compared to the results of the damage oriented Eco-Indicator 99 method, with varying recovery efficiencies, were subject to a sensitivity analysis.

The impact categories taken into account by Khoo within the Eco-Indicator 99 method included:

- Climate change
- Respiratory organics
- Respiratory inorganics
- Carcinogens
- Acidification
- Ecotoxicity
- Fossil fuels

These categories were aggregated to three end-point indicators by normalization and weighting factors, which referred to the Hierarchist-Average version implemented in the SimaPro software.

The damage categories included human health, which is measured in disability adjusted life years, ecosystem quality, denoted in potentially disappeared fraction of plant species, respectively potentially affected fraction, and resources, measured in [MJ] surplus and indicating the extra energy needed for future resource production.

Again the trend in the results was almost equal, independent of the assessment method. The magnitudes of the final category indicator values, of course, were diverging but this fact could be attributed to the different nature of mid-point and end-point approaches.

Furthermore, Khoo calculated the sequestration effectiveness, which indicated the percentage of CO_2 that was stored in relation to the overall CO_2 generated within the system boundaries. The calculation was performed for different recovery efficiencies, based on the CO_2 to be stored after generation in the power plant, and the additional CO_2 formation related to the energy penalty due to the capture and storage related processes. The result of this calculation fairly coincided with the final results of the impact assessment.

Concludingly Khoo noted that drawbacks of the applied LCA method were related to the data quality, the weighting step and a missing impact category that considered consequences of CO_2 on the marine environment, if stored in the ocean.

Weighting, as noted by the author, is debatable, as the weights, differently applied to various impact categories, depicted values that could not be justified scientifically.

He underlined that the goal of the LCA study was not to encourage a certain combination of CCS alternatives, but to make a comparison of CCS alternatives and to determine potential environmental impacts. Khoo also remarked concerns about possible pipeline leaks, which were not incorporated in his study because of missing data.

As a whole, the weighted and normalized final results of the study and the calculation of the sequestration effectiveness led to a combination of CCS alternatives that seemed the most promising, compared to the others, as a similar trend among the utilized methods was approved by the results.

4.3.3 Comparison of carbon capture and storage with renewable energy technologies regarding structural, economic, and ecological aspects in Germany (Peter Viebahn et al., 2007)[443]

This future oriented comparative LCA study, denoted as a prospective LCA, was not referred to a detailed LCA, because of unavailable future related data, but a screening LCA where certain process steps were cut-off. The analysis was focused on various alternatives of electricity generation, including carbon capture and storage as also hydrogen production.

The stated **goals** of the LCA study were, first, to assess potential environmental impacts of different electricity generation types and CCS technologies separately, and then to compare them to each other, for determination of advantages and disadvantages of the certain option.

As a functional unit 1 kWh of electricity produced was chosen for the electricity generation, by either fossil fuel based power plants or else regenerative electricity production systems that were assumed to be available and commercially operated until the year 2020.

The fossil fuel power plants were located in Germany and the CO_2 captured was transported via a new built pipeline over a distance of 300km to a depleted onshore gas reservoir that acted as the CO_2 storage site.

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[443] Cf. Viebahn et al. 2007, pp. 2-13 and Viebahn et al. 2007b, pp. 105-143.

The regenerative electricity production systems included solar thermal power plants, located in Algeria, and wind power stations in the North Sea with electricity transport via high voltage direct current transmission systems to provide electricity at the hydrogen production facility, which as well was located in Germany. Thus secured the same spatial reference, namely Germany, as in case of the fossil fuel power plant systems.

As the author performed a prospective LCA, where not yet implemented technology systems were assessed, the temporal reference was related to the year 2020, which was factored, for example, in terms of modified power plant efficiencies. The electricity mix and the process related conditions of material production, like improved recycling rates, were related to the year 2010.

The system boundaries included exploration, production, processing and transport of fossil fuels to the power plant, development of infrastructure requirements such as pipelines, material demands for construction and dismantling of facilities, energy and resource inputs as also emissions related to system operation and recycling.

The recycling procedure was modelled according to ISO's closed-loop recycling definition, which accounted a mixture of primary and secondary materials on the input side for steel, aluminium and copper.

Other assumptions were CO_2 storage without leakage and a non existing pipeline infrastructure for the onshore transport of CO_2 to the storage site, which therefore had to be constructed.

The **inventory** was compiled with the Umberto software tool and data, for the fossil fuel fired power plants, the gas pipelines, and the fuel related processes, was taken from the Ecoinvent 2006 and the Umberto databases.

Data related to carbon capture systems, the high voltage direct current transmission system, and the regenerative electricity production systems, was gathered from literature, already existing LCA studies, the DLR database provided by the German Aerospace Center, and to some extent from the Ecoinvent database.

The fossil fuel supply chain was modelled according to the Umberto database modules with spatial relation to the plant location in Germany respecting different import shares of fossil fuels from various countries.

Data concerning the material requirements, land use, monitoring and dismantling of onshore pipeline infrastructure for CO_2 transport of 300km, was adopted from the Ecoinvent database for natural gas pipelines, which incorporated recompression of natural gas at distances of 150km and a lifetime of 50 years.

As primary or secondary data for CO_2 storage were unavailable, the related emissions and energy requirements were assumed to account to 50% of the transport related inputs and outputs, justified by the fact, found in literature, that the transport costs added up to about double of the storage costs.

The **impact assessment** was performed with a method, implemented in the Umberto software, namely the "UBA-Verfahren" developed by the German Federal Environment Agency. The impact categories included in the study were:

- Resources/Cumulative energy demand
- Global warming potential
- Acidification
- Eutrophication

- Human toxicity (PM10-equivalents)
- Photo-oxidant formation (Photosmog)

In a first step, deputizing for all fossil fuel fired plants, the hard coal-fired power plants with and without CCS were compared to each other to determine the individual impacts of fuel supply, electricity generation, CO_2-capture, CO_2-transport and CO_2-storage on the category results of CO_2-emissions, CO_2-equivalents and cumulative energy demand.

Furthermore the effects of CCS technology application on the final results were examined, which showed a clear reduction of CO_2-emissions and CO_2-equivalents by application of the CCS technology, whereas the reduction of CO_2-equivalents was not as extensive, because of methane emissions related to the fuel supply chain.

The higher energy demand of the hard coal fired power plant with CCS technology was mainly attributed to the CO_2-capture process.

The impacts of the transport and storage processes on the CO_2-emission and CO_2-equivalent results were obviously of a minor severity compared to the high burdens related to fuel supply and the electricity generation processes.

In terms of the cumulative energy demand, the fuel supply chain clearly dominated this category, whereas the transport and storage processes were almost equal but again contributed marginally to the whole system.

The regenerative electricity production systems, represented as wind and solar power plants, were also compared to each other on basis of CO_2-emissions, greenhouse gas emissions and cumulative energy demand. As the processes of fuel supply, carbon capture, CO_2 transport and storage were not necessary, only the impacts of the power plant operation and the electricity transport via high voltage direct current transmission systems were evaluated.

Among those two system components the main contribution to the environmental loads was clearly attributed to the power plant itself for each of the regenerative power plant system cases.

In the next step, all electricity generation systems were taken into consideration. Fossil fuel fired power plants with and without CCS technology, as also regenerative energy based power plants were compared to each other on basis of CO_2-emissions, greenhouse gas emissions and cumulative energy demand, and showed a similar trend in the results, as in case of the individual evaluation of environmental loads, done in the first step. The impacts of regenerative power plant systems, within the assessed environmental parameters, were infinitesimal in comparison to the fossil fuel based power plants.

The impact assessment was completed by comparison of the considered power plant systems within the impact categories of photo-oxidant formation, eutrophication, acidification and PM-10-equivalents.

The impacts of fossil fuel fired power plants on the above stated categories, even though with different shares, were again mainly attributed to the processes of fuel supply, power plant operation and the capture process. CO_2 transport and storage caused only minor environmental loads compared to the other processes.

Power plants that utilized CCS technology generally showed higher environmental burdens in the categories photo-oxidant formation and eutrophication, which was primarily assigned to the capture process, particularly because of the involved chemicals, but also to some extent to the CO_2 transport and storage processes.

The results of the acidification category depicted a decrease, related to the environmental impacts of power plants that used CCS, because of reduced SO_2-emissions during the power plant operation.

The highest impacts of the CO_2 transport and storage processes, even though they were small compared to the other processes, were revealed in the photo-oxidant formation, eutrophication and acidification categories.

Finally the regenerative power plant systems were opposed to the fuel fired power plant systems, within the categories photo-oxidant formation, eutrophication as also acidification, and showed a clear environmental load reduction of regenerative power plant systems compared to the fossil fuel based systems.

The environmental impacts of the regenerative power plant systems were mainly referred to the construction process of the power plants.

Within the LCA study, a **sensitivity analysis** was performed to determine the impacts of crucial parameters on the study results. The investigated parameters included leakage rates of CO_2 from the storage site, the CO_2 recovery rate and the methane emissions related to the hard-coal production.

In terms of leakage rates the values were varied between 0.1 and 0.0001 percent leakage of CO_2 per year from the reservoir. It was assumed that the full leakage rate occurs 30 years after the first injection of CO_2, representing the point of time when the reservoir was completely filled. As determined, the leakage rates indeed had an impact on the time until the whole CO_2 will be released from the storage, but, as today's LCA methodologies do not distinguish between emissions occurring at present and future times, the whole CO_2 will be released in any scenario, independent of the leakage rate.

The impacts of different CO_2 recovery rates were determined on basis of two scenarios, which were increased CO_2 recovery with nowadays capture technology including elevated energy requirements, as also increased CO_2 recovery with constant energy requirements and assumed technological improvements.

Both case scenarios showed a similar trend, namely decreased total environmental impacts in terms of CO_2-emissions and CO_2-equivalents with increased recovery rates, although it was stated that the increased energy demand, of the capture, transport and storage processes, caused higher emissions compared to the reference scenario.

The last analysis of parameter uncertainty was performed in relation to the impacts on the total results of methane emissions that resulted from the hard coal production process. It was assumed that the methane emissions of the hard coal mix, incorporated in the LCA study and related to the year 2000, provided by the Umberto software, were reduced until the year 2020. The decrease of greenhouse gas emissions was clearly apparent.

In a statement on additional environmental assessment parameters, Viebahn mentioned the land use, which was not accounted in the study, as also risks related to the transport, such as impacts on the environment due to sudden pipeline leakages that could result in release of huge amounts of CO_2.

Concerning the storage sites, where the long term CO_2 storage efficiency of depleted gas reservoirs was questionable, Viebahn noted that CO_2 leakage and subsequent impacts on underground as also on surface living organisms contained not assessed risks.

4.3.4 Life-cycle assessment of carbon dioxide capture for enhanced oil recovery (Edgar G. Hertwich et al., 2008)[444]

The authors utilized a hybrid LCA method to assess the environmental impacts of three distinct oil production systems, one without enhanced oil recovery and two production systems that used CO_2 injection to increase oil production, where carbon dioxide was delivered from a natural gas fired power plant that utilized chemical absorption as a carbon capture technology.

Within this hybrid LCA approach the foreground processes were modelled on basis of physical principles, whereas the background processes were estimated through economic input-output analysis based on purchases from an economic system.

The **goals** were to determine the environmental loads of each production system option and to compare them in order to determine the most promising oil production alternative, on basis of a functional unit of $1m^3$ produced oil.

The considered foreground system included the elements of fuel supply to the power plant, the electricity generation system with the carbon capture facility, CO_2 transport and injection for EOR purposes, and the oil production system, represented by an offshore platform located in the Norwegian Sea.

Three oil production alternatives were evaluated. In the first system option that represented the base case, oil was produced at the offshore platform without EOR, where power for the platform operation was supplied by on site produced natural gas and diesel from the refinery, which included diesel transport to the platform.

The second and third alternatives were not supplied with natural gas, produced on site, as the breakthrough of CO_2 made the gas useless for power supply, therefore the following system options were distinguished by their type of power supply.

The second alternative represented included EOR for oil production at the same platform, with power supply for the platform operation based only on diesel fuel. The CO_2 for injection was compressed and delivered from the gas fired power plant 'Tjeldbergodden', with amine-based capture technology, via a chromium steel pipeline over a distance of 150km to the offshore oil field.

The third option considered was oil production with EOR, as explained in the previous case with the difference that the platform was completely operated with electricity delivered from the gas fired power plant via a sea cable after breakthrough of CO_2.

The fuel supply chain of the power plant, for the two oil production alternatives that used EOR, included production of natural gas from the 'Heidrun field', compression of gas and transport, through the 'Halten pipeline' to the power plant, as also diesel fuel supply for the natural gas production platform.

The **inventory** was generated with site specific data in relation to the fuel supply chain of the power plant operation, and literature data was used to compile the inventory for the construction of the power plant, which had an assumed life-time of 30 years.

The inventory related to the CO_2 transport via pipeline, the electricity supply requirements of the third oil production alternative as also environmental loads of the power plant with carbon capture technology, were primarily based on capital and operational expenditure data.

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[444] Cf. Hertwich et al. 2008, pp. 343-352.

Input and output data of the offshore oil production operation with and without EOR were based on models developed with a software tool called HYSYS for each system alternative separately, as the system component requirements were entirely different.

Despite the differences of equipment and infrastructural requirements, the energy consumption of the oil production systems with EOR and the system without EOR were within the same range, but as the amount of produced oil was considerably higher for the EOR systems, the energy consumption per functional unit was half as much, compared to the system without EOR.

Allocation of LCI data, between the oil delivery system and the electricity generation system, was performed as various system products were identified by the authors, such as oil and electricity.

On basis of the oil production platform's power demand, a share of data concerning electricity supply via sea cable in case of the third alternative, was allocated to the offshore platform.

Environmental loads referred to the power plant and the CO_2 capture facility were allocated to the product electricity, and the CO_2 transport as also the CO_2 injection related data were assigned to the extra amount of oil that could be produced with EOR.

The impact categories included in the **impact assessment** were:

- Global warming potential
- Acidification potential

On basis of 1 MWh electricity produced, at the power plant system using CCS, the authors identified a significant reduction of the global warming potential, whereas the electricity production in the power plant dominated this category, compared to other processes.

Furthermore a small increase, of the acidification potential that resulted from emissions of the amine based capture process, and an increased fuel demand, of the power plant that underlay the efficiency penalty due to CCS compared to the same power plant without CCS, were identified.

On basis of $1m^3$ oil produced and related to the global warming potential, the oil production system with EOR and electrical power supply via sea cable performed significantly better than the EOR system with diesel fuel power supply. However the diesel powered platform showed lower environmental impacts within this category compared to the system without EOR, which was related to the additional amount of oil that can be produced with EOR.

The primary part of the emissions were attributed to the combustion of diesel fuel used to operate the offshore production platform in case of the first and second oil production alternatives, which also highly affected the acidification potential category, whereas for the EOR system slightly lower impacts were assessed for this category, among the two alternatives. Thus the third oil production alternative, with EOR and electrical power supply by the power plant with carbon capture, performed by far the best in each impact category.

In a next step a structural path analysis was conducted for the second oil production alternative that depicted the contribution of foreground and background processes to the global warming potential result, thus facilitated the identification of important system elements.

The main contributor to this category was determined to be the diesel combustion for power supply of the platform operation, followed by the processes of diesel fuel production and transport.

The impacts of additional requirements for CO_2 compression and injection in relation to this oil production system with EOR were very low.

Finally the authors mentioned that data uncertainties primarily concerned the power plant with carbon capture technology, the reservoir properties and the CO_2 injection process, as also data estimates based on the economic input-output analysis.

4.3.5 Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO_2 (Joris Koorneef et al., 2008)[445]

The authors performed a comparative LCA study on three different electricity production alternatives of coal fired power plants located in the Netherlands, whereas one alternative utilized CCS technology.

The **goals** were to assess the potential environmental impacts of each alternative, to determine significant process contributions and to evaluate possible environmental impact related benefits as also trade-offs of the power plant system that used CCS.

The first option refered to an already existing coal fired power plant, the second alternative was related to a coal fired power plant that utilized available state-of-the-art technology with increased power plant and flue gas treatment efficiencies, and the last case assessed applied CCS to the same type of power plant as described in case two, but included MEA absorption to capture CO_2 as also pipeline transport and storage of CO_2 in a geological aquifer formation onshore.

The environmental impacts of the electricity generation system options were ascertained on basis of 1kWh electricity produced at the power plant with data spatially and temporally referenced to the Netherlands in the year 1997, and if regional data were not obtainable data was referenced to Europe or worldwide quotation.

The systems analyzed included the processes of extraction, transport and processing of resources and raw materials, development and dismantling of required infrastructure, electricity generation, construction and dismantling of power plant facilities, waste treatment as also capture, compression, transport and injection of CO_2.

The CO_2 storage process incorporated injection facilities, re-compression prior to injection, and six newly drilled wells each 3000m in length, which were abandoned after operation. It was assumed that no leakage of CO_2 from the storage site occurred.

The lifetimes of the power plant, the CO_2 capture facility as well as the transport infrastructure and the injection facility accounted to 30 years.

The **inventory** for the first power plant alternative was compiled with the Ecoinvent v1.3 database and the LCI for the other two options was developed by a mix of data sources that included calculations, estimations, literature findings, consultation of manufacturers, as also the Ecoinvent database.

Input and output data of the fuel supply chain incorporated the coal supply mix of the Netherlands, found in literature, and also comprised infrastructural and equipment demands besides mining, transport and processing operations.

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[445] Cf. Koorneef et al. 2008, pp. 2-18.

Data for the first power plant option included the processes of operation, construction, dismantling as well as accompanied infrastructural and facility requirements, which were compiled with the Ecoinvent database referenced to the Netherlands.

The data referring to the second and third electricity generation system options were based on those of case one but were modified on basis of literature findings towards expected technological improvements.

As a result of the flue gas treatment, a system part only included in the second and third power plant alternatives, gypsum was produced, which was considered to be a by-product, thus reduced the environmental burdens of mining virgin gypsum.

Data concerning emissions, efficiencies, material and infrastructural requirements of the CO_2 capture system were developed after consultation of manufacturers and with equations, but excluded material and energy demands for construction, maintenance, dismantling and waste processing as well as recycling of facilities and infrastructure.

Input and output data concerning MEA, such as emissions to air and water, were compiled with the help of the Ecoinvent database and mass balance relationships, but involvement of high data uncertainty was noted by the authors. Waste generated during the capture process due to MEA degradation was assumed to be transported by truck over a distance of 100km to a hazardous waste incinerator, and environmental loads related to waste composition, transport and treatment were estimated with the help of literature or else were calculated.

Data related to compression of CO_2, like energy and material demands as also CO_2 emissions during operation, were estimated on basis of an adequate equivalence, which was a gas turbine, but data for disposal and recycling of the compressor was not included.

In relation to transport of CO_2 over a distance of 50km via an onshore pipeline located in the Netherlands, the LCI incorporated data for construction, dismantling and maintenance of the transport infrastructure, derived from literature findings and estimations.

CO_2 injection facility related data was gathered with literature findings referring to underground gas storage, whereas electricity supply for recompression was based on the Dutch electricity mix for the year 2000. Energy demands for construction and dismantling as also related material recycling and waste disposal were not incorporated in the inventory, as data was not available.

Results of the inventory indicated that the power plant with CCS had the highest fuel requirements as also the highest amounts of waste but the lowest CO_2 emissions. For the second electricity system alternative the lowest amounts of consumed fuel, generated waste and emissions to water and air were identified.

The **impact assessment** of the study was based on the “CML 2 baseline V2.03” method and included the below listed impact categories:

- Global warming potential
- Abiotic resource depletion potential
- Ozone layer depletion potential
- Human toxicity potential
- Fresh water aquatic ecotoxicity potential
- Marine aquatic ecotoxicity potential
- Terrestrial ecotoxicity potential
- Photochemical oxidation potential

- Acidification potential
- Eutrophication potential

As characterization factors for MEA related emissions were not implemented in the CML method, factor values for relevant categories were based on estimations found in literature.

Concerning the global warming potential the third power plant alternative considerably reduced the environmental impacts, compared to the other power plant options, due to the carbon capture process, whereas the most significant contribution of impacts in this case, besides the power plant operation itself, were related to the coal supply chain especially mining operations and transport by ship.

In case of the first two power plant alternatives without carbon capture technology, the process of electricity generation within the power plant and the accompanied direct emissions dominated the global warming category.

The processes of MEA production and MEA related waste treatment as also CO_2 transport and storage were marginal contributors to this category when regarding the power plant with CCS technology.

As the LCI results already indicated, the environmental loads of the power plant with CCS were the highest within the abiotic resource depletion category due to the application of CCS, which induced a plant efficiency reduction as well as other additional material and energy requirements. This category was however dominated by the fuel supply processes in all examined electricity generation systems.

Concerning the ozone layer depletion category, primarily constituted by impacts of the coal supply process, the worst result was assessed for the third electricity generation system due to several additional processes as also equipment and infrastructural requirements that affected the crude oil and natural gas supply chain, because of elevated fuel demand for transport of coal by ship.

Within the human toxicity category the third power plant alternative performed by far worst because of emissions related to MEA production and application, which constituted the highest share of impacts in this category, followed by fuel supply and plant operation processes. The human toxicity potential of the first two power plant options was prevailed by direct emissions from the power plant and the coal supply process.

Referring to the fresh water ecotoxicity potential, again the power plant with CCS showed higher environmental impacts compared to the other alternatives, due to emissions released during transport and combustion of coal. Production of steel, required for the CO_2 transport infrastructure, as well played an important role in this category because of induced metal emissions.

In terms of marine aquatic ecotoxicity the second and third power plant options performed almost equal and much better than the first alternative, because of improved flue gas treatment technology and MEA absorption.

The highest contributions, in relation to the marine aquatic ecotoxicity and the terrestrial ecotoxicity potentials of the power plants without CCS, were depicted by the processes of the power plant operation and the coal supply.

In the remaining impact categories the second and third power plant scenarios performed better than the first option, which was assigned to the advanced technology employment, whereas the power plant with CCS showed higher environmental burdens in all remaining categories, compared to the second power plant alternative, because of the following reasons.

The impacts of the power plant with carbon capture were higher within the terrestrial ecotoxicity category as a result of the lower plant efficiency, additional infrastructural requirements and due to MEA production induced emissions.

The photochemical oxidation, acidification and eutrophication categories for all power plant alternatives were dominated by the coal supply and power plant operation processes, whereas the higher category scores, determined for the third alternative, underlay increased emissions from the coal supply chain, or more precisely the ship transport, as a result of an increased coal demand.

The degradation of MEA, in case of the power plant with carbon capture, was especially relevant for the acidification and eutrophication categories because of NH_3 emissions.

The authors conducted a normalization step that indicated the relevance of a certain impact category after the reference of characterized impact assessment results to a specific year and region, in this case the Netherlands in 1997. Normalization showed that the ozone depletion potential had the least, and the marine ecotoxicity potential the highest significance in relation to environmental interventions of the certain time and region.

The main limitations of the study identified by the authors concerned the lack and uncertainty of data, especially in relation to the carbon capture process and the accompanied emissions.

Thus a **sensitivity analysis** was executed to evaluate the effects on the impact assessment results when certain parameters were altered.

The increased flue gas treatment efficiency reduced the SO_2 emissions, thus resulted in lowered environmental burdens in all impact categories, but especially in the human toxicity category, as the MEA consumption that was affected by SO_2 emissions, was reduced, thus had effects on the production process of MEA, which showed high impacts on this category.

The altered net efficiency of the power plant system without CCS depicted a non-linear change of results, equal for all categories, and also indicted that the utilization of CCS, which reduced the overall system efficiency, had a negative impact on all categories.

Varying the CO_2 capture efficiency had a considerable impact on the global warming potential, and a slight increase in the other impact categories was observed with increased efficiency.

The elevated amount of removed HF by MEA absorption substantially decreased the results of the marine aquatic ecotoxicity potential, as this category was determined to be very sensitive to HF emissions, whereas the results of the other categories remained almost constant.

The consequences of varying MEA consumption were considerable in case of the human toxicity potential, but also the results of the eutrophication potential and the acidification potential were sensitive to different amounts of consumed MEA, even though to a lower extent.

If the thermal energy requirement of the capture process was changed, all categories behaved almost equal and showed linearly higher impacts as the energy requirement was raised.

The authors concluded that the benefit of the CCS system was a clear reduction of the global warming potential, but this came at the price of increased energy penalty, additional MEA related emissions and formation of other wastes.

4.3.6 Environmental assessment of German electricity generation from coal fired power plants with amine-based carbon capture (Andrea Schreiber et al., 2009)[446]

The comparative LCA performed by Schreiber evaluated the potential environmental impacts of different coal based electricity generation systems with and without the use of mono-ethanolamine washing, as a carbon capture technology, while distinct years of plant construction as also related different power plant and capture efficiencies were taken into account.

The stated **goals** included, a comparison of environmental impacts on basis of 1 kWh of a total of five different electricity generation systems with and without CCS, the identification of most the significant processes in relation to environmental burdens, as also a determination of effects on the total outcomes resulting from up- and downstream processes.

The analysis was performed for three pulverized coal fired power plants without carbon capture, related to the different years of operation, namely 2005, 2010 and 2020, one pulverized coal fired power plant, built in 2010 and retrofitted with capture technology in the year 2020, and one pulverized coal fired power plant with integrated MEA-wash built in 2020.

As a spatial reference, of the involved processes, the power plants were located in Germany.

The assessed system included the main processes of coal conditioning, power plant operation, flue gas treatment related processes such as desulfurization, decarbonization for MEA conditioning, compression and liquefaction of CO_2,as also NO_x and dust removal.

Fuel and raw material supply, land fill processes due to solid waste management, and manufacture of operating supplies referred to up- and downstream processes. Transport and storage related processes were not included in the analysis but subjected to a sensitivity analysis, to determine their impacts on the results.

Although the study indicated that electricity generation with carbon capture was a multifunctional process, no allocation procedures were performed.

For development of the **inventory** with the GaBi 4.2 software, and representative for Germany, site specific data for the power plant built in 2005, average data from literature for the plants constructed in 2010, and expert estimations for the plants established in 2020, were used. Fuel supply related data and other inventory components were generated with help of the Ecoinvent 1.3 database.

An analysis of the LCI results showed that the electricity generation efficiency, which increased until 2020, affected the fuel consumption, which was generally lower for the power plants without carbon capture technology due to an energy penalty caused by MEA-washing.

Simultaneously the outputs of the systems increased with decreasing efficiency, and the plants utilizing capture technology additionally produced hazardous waste, because of MEA conditioning.

The **impact assessment** was performed considering the following categories with the characterization step based on the CML 2001 method:

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[446] Cf. Schreiber et al. 2009, pp. 547-558; Markewitz et al. 2009, pp. 3763-3770 and Schreiber et al. 2010, pp. 7873-7883.

- Primary energy demand
- Global warming
- Human toxicity
- Acidification
- Photo-oxidant formation
- Eutrophication

It was observed that in case of the power plants without carbon capture, the environmental impacts decreased with increased combustion efficiency in every considered environmental impact category.

The main processes especially dominated the global warming, the acidification and the eutrophication categories, as also the primary energy demand.

The power plants with carbon capture, on one hand, significantly reduced the greenhouse gas potential but underlay a higher primary energy demand, compared to the plants without capture technology, because of the energy penalty that resulted from the capture related processes.

Although the environmental impacts within the global warming category were much lower for power plant systems with MEA-washing, compared to the conventional plants, the contributions of up- and downstream processes to the greenhouse gas potential was significant due to the increased fuel consumption of plants with CCS.

In the category acidification, the MEA-equipped plants performed poorly, opposed to the conventional plants, built in the same reference year, which was related to an elevated ammonia output.

Considering the eutrophication category, the power plants with carbon capture caused substantially increased burdens with high impact shares of up- and downstream processes, because their lower plant efficiencies led to a release of higher amounts of methane, ammonia and NO_x.

The highest influences of up- and downstream processes were detected in the categories photo-oxidant formation and human toxicity, resulting from emissions, such as methane from fuel supply and heavy metals generated by carbon capture related processes.

Additionally a **normalization** procedure was executed, to relate the results of each certain category to the according total quantity of Germany, in order to compare the results of the different impact categories, and it was shown that the same trend in the findings continued.

Finally a **sensitivity analysis** was conducted to determine the effects of coal origin, CO_2 transport and storage as also absorbability of MEA on the final results.

Long transport distances of coal via ship highly affected the acidification, photo-oxidant formation and eutrophication impact categories but also the human toxicity potential, because of diesel fuel requirements.

The CO_2 transport related system elements were modeled with data for natural gas transport, implemented in the Ecoinvent 1.3 database, with assumed 300km transport distance in Germany. The CO_2 storage related data accounted to 50% of those of the transport as an assumption. Leakage from the storage site was neglected.

It was stated that the overall impacts on the categories of those two processes were generally small but at the most affected the greenhouse gas and acidification potential and to a minor extent the eutrophication and photo-oxidant formation categories, as a result of increased energy requirements and methane emissions.

The variation of MEA solution absorbability to slightly higher efficiencies did not depict any benefit in the results.

4.3.7 Life cycle assessment of carbon dioxide capture and storage from lignite power plants (Martin Pehnt and Johannes Henkel, 2009)[447]

Pehnt and Henkel performed a comparative LCA study on the complete life cycles of different electricity generation systems with, and without, CCS technology, and took technical improvements, until the year 2020, into account by extrapolation of existed data.

The **goal** was to compare the potential environmental impacts of five lignite fired power plants, two plants without CCS technology and three plants that used diverse CCS technologies, on basis of 1 kWh electricity as the only product delivered, with temporal and spatial references related to the year 2020 and Germany.

The processes analyzed within the system boundary included, fuel supply, power plant operation, the carbon capture process, pipeline transport over a distance of 325 km, storage of CO_2 in a depleted gas field with existed infrastructure, solvent production as also dismantling of the power plant.

It was assumed that lignite production and the electricity mix were referred to Germany with a composition that corresponded to this region. Most of the system's performance data, such as emission factors, solvent loss and energy consumption of the capture process, CO_2 separation and power plant efficiencies related to the year 2020, was gathered from a literature review.

Another assumption made concerned the compression of CO_2 that was directly done after the capture process with two compressors, thus CO_2 compression was allocated to the power plant, which in turn reduced the net efficiency of the power plant.

The **inventory** was developed with data from literature and involved infrastructure, as also construction requirements of power plants and lignite mining, infrastructure and energy requirements for CO_2 transport, carbon capture process related requirements, such as MEA solvent consumption and manufacture. Fuel supply data in terms of lignite production was compiled with the help of Ecoinvent 2005.

Data that concerned the leakage of CO_2 from the storage site, the production of Selexol and capture process related losses of Selexol, which acted as a solvent in the CO_2 capture process, as also emissions of power plants to water and soil, was not available, and therefore was not included in the study.

The **impact assessment** comprised the below listed categories:

- Energy resources
- Global warming
- Photochemical ozone creation potential (Summer smog)
- Acidification
- Eutrophication
- Human toxicity

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[447] Cf. Pehnt and Henkel 2009, pp. 50-61.

The energy resources were assessed in terms of cumulative energy demand, and took the consumed fossil primary energy resources as well as the consumption of uranium into account. In all cases of electricity generation systems that applied CCS, the cumulative energy demand increased, caused by different components of the capture process.

The global warming potential was evaluated in relation to a period of 100 years, and the results of the summer smog as also the acidification categories were determined according to the definition of CML. The greenhouse gases decreased significantly due to the applied CCS technology.

The use of mono-ethanolamine (MEA) solvents resulted in a noticeable share of impacts in the categories eutrophication and acidification, for the power plant system that utilized this technology, because of the MEA production process. No MEA solvent characterization factor existed, thus the average NMVOC factor was used to determine the effects of MEA on the impact category summer smog.

Concerning the eutrophication category only emissions to air were regarded, which was justified by the dominance of airborne emissions in the system, and results showed that power plant with CCS caused higher environmental impacts, due to decreased plant efficiency and induced higher NO_x emissions. The electricity generation system that incorporated MEA solvents recorded high impacts within this category, because of degradation and production of the solvent.

The human toxicity category was characterized in terms of “Years of Life Lost”, according to literature definition, and impacts of power plants with CCS were higher compared to the same type of plant without CCS.

The effects of fuel supply and electricity generation in the power plant, read out of the performed contribution analysis, were dominating in every considered impact category, whereas the power plant operation had higher impacts on the global warming, eutrophication and acidification categories compared to the fuel supply process. The impacts of CO_2 transport and storage as also the construction and dismantling of the electricity generation system were of minor relevance, as noted by the authors.

Effects referring to the uncertainty of future oriented parameters, on each category, were determined by a **sensitivity analysis,** on different plant efficiencies and varying NO_x emissions for all power plants, on distinct CO_2 capture energy requirements in case of the plant using MEA, as also on different amounts of MEA consumption and NH_3 emissions generated due to degraded MEA.

In general the trends in the results kept the same with exception of the power plant with MEA, which showed considerable higher impacts in the acidification and eutrophication categories if the above mentioned parameters were altered to values that simulated the worst case.

4.3.8 Environmental evaluation of carbon capture and storage technology and large scale deployment scenarios (Bhawna Singh, 2010)[448]

The LCA study carried out by Bhawna Singh in 2010 utilized the methodology of hybrid life-cycle assessment, referring to a combination of economic input-output analyses, applied to infrastructural requirements, and conventional life-cycle inventories based on physical data for all processes considered.

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[448] Cf. Singh 2010, pp. 17-48; Singh et al. 2011, p. 20 and Singh et al. 2012, pp. 2-14.

The **goals** were to perform a comparative LCA of hard coal and natural gas fired power plants with different carbon capture and storage (CCS) technologies and without CCS as also a scenario assessment of large scale CCS applications. The different systems assessed were generic without a specific spatial reference, thus were hypothetical. As a functional unit 1 kWh of electricity produced at the plant was chosen.

Singh applied the method of curve fitting, until the year 2050, to certain system parameters like plant efficiency, which were identified to have an impact on the system's environmental performance, in order to incorporate effects of technical evolution of the CCS systems.

He as well regarded changes in the energy efficiency, the electricity generation and the energy mix until 2050, according to three different scenarios provided by the International Energy Agency (IEA), and analyzed the environmental effects of large scale CCS technology applications but neglected other developments, for example, in relation to material production such as fuel production processes.

Leakage of CO_2 from the storage site as also monitoring of the transport infrastructure and the storage site were also not factored in this study.

The LCA included the system components of fuel production, electricity generation in power plants with different CCS technologies and without CCS, the transport of CO_2 via 500 km of pipeline to the storage site, the storage of CO_2 in a geological formation via an injection well located offshore, and the capture related waste treatment as also disposal.

The infrastructure for the power plant and the carbon capture facility was incorporated as capital investment.

The study's **inventory** data was based on different data sources for data compilation of the fuel supply, other material requirements and releases to the environment. Singh used the Ecoinvent v2 database for data gathering, related to the pipeline for the transport process and the injection well for the storage of CO_2, and literature as also process modeling based information to quantify inputs and outputs related to the capture process.

The **impact assessment** was performed by using the ReCiPe 2008 method that provides eighteen midpoint impact categories, which are then aggregated to three damage oriented endpoint indicators. Singh considered ten below listed midpoint categories in his study:

- Global warming potential
- Terrestrial acidification potential
- Fresh water eutrophication potential
- Marine eutrophication potential
- Photochemical oxidant formation potential
- Particulate matter formation potential
- Human toxicity potential
- Terrestrial ecotoxicity potential
- Fresh water ecotoxicity potential
- Marine ecotoxicity potential

A **contribution analysis** was performed to determine the relative shares of the involved unit processes to each impact category for the different power plant system models. In the following the contribution analysis diagrams were examined qualitatively, for the purpose of the work at hand in order to determine processes that had a major impact on each category and processes which only constituted a minor share.

Main contributors to the global warming potential of course were the processes of fuel production, and electricity generation by the power plant. The significant contribution of fuel production to the global warming potential stemmed from the production and transport of fossil fuels.

Compared to the outstanding shares of fuel production and electricity generation in this impact category, the infrastructural contribution was very small, and mostly referred to the fuel production infrastructure.

Terrestrial acidification potential, as well and above all, was constituted, by the direct emissions of the power plant and the fuel production process.

Fresh water eutrophication was most notably caused by the power plant waste treatment, the transport and storage infrastructure of CO_2 and the fuel production infrastructure, because of furnace waste that originated from steel manufacturing.

The marine eutrophication potential, the photochemical oxidant formation potential and the particulate matter formation potential were dominated by the processes of fuel production, electricity generation and, to a minor extent, due to CO_2 transport and storage infrastructure as also the fuel production infrastructure.

The environmental load contributions of unit processes were unevenly distributed to the human toxicity potential, depending on the power plant model, but were mainly caused by the fuel production infrastructure, the transport and storage infrastructure, the waste treatment, and the direct emissions from the power plant due to electricity generation. The power plant infrastructure as well played a role but only to a minor degree.

Terrestrial ecotoxicity potential clearly existed because of the power plant infrastructure and the fuel production infrastructure, whereas the transport and storage infrastructure constituted only a small portion within this impact category.

The contributions to fresh water ecotoxicity and marine ecotoxicity potential were primarily composed of the transport and storage infrastructure and the fuel production infrastructure.

Power plant waste treatment showed a significant impact on those categories, surpassing the above two mentioned processes, depending on the power plant model, and in fact always had a higher influence on the fresh water ecotoxicity potential category.

It could be concluded that, tendentially, processes related to infrastructure, such as well drilling, electricity generation by the power plant, because of the direct emissions, and material production, due of heavy metal emissions and solid waste disposal, contributed the most to toxicity related impact categories.

The CO_2 transport and storage infrastructure had its highest influence on the marine ecotoxicity potential, the fresh water ecotoxicity potential, the human toxicity potential and the fresh water eutrophication potential.

The environmental loads related to CO_2 transport and storage in the other impact categories seemed very small, but this circumstance could be assigned to the predominant fraction of processes and requirements related to coal mining, gas production and electricity generation.

To assess the overall damage to the environment the endpoint indicators, namely human health, ecosystem damage and resource depletion, were utilized. Singh noted that the aggregated results of the endpoint indicators were more decent for decision making, although the uncertainty related to environmental mechanisms was higher for the endpoint approach.

Human health damage is measured in disability adjusted life years (DALY) and the study compared the different power plant models on the basis of processes, and to which extent they contributed to this endpoint indicator. Fuel production, power production, transport and storage were separately indicated, while the other system elements were summarized to a single parameter.

Additionally the plant models were compared on the basis of the contribution of impacts related to human health. This means, for the endpoint indicator human health, the contribution of selected impacts, namely climate change, human toxicity, particulate matter formation, ozone depletion, photochemical oxidation, and ionizing radiation were used for comparing the various electricity generation system models.

The measure for ecosystem damage is the loss of species during a year (species.yr) and, as in case of human health damage, the plant models were compared in relation to this endpoint indicator on basis of processes, and additionally in relation to impacts.

For the ecosystem damage the same four parameters were utilized, as it was done for the human health damage indicator, which were fuel production, power production, transport and storage and a summarized parameter called 'others'.

The impacts considered for ecosystem damage were differing from the human health damage indicator and included climate change, agricultural land occupation, urban land occupation, natural land transformation, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity and fresh water ecotoxicity.

The third endpoint indicator, called resource depletion, is measured in monetary units and indicates the elevated resource provision costs that can be expected in the future because of resource depletion.

The comparison on basis of processes again included the same four system components as in case of the previous endpoint indicators. The impacts related to the resource depletion indicator, which were chosen for comparison of the plant models, included metal depletion and fossil depletion.

From the damage assessment Singh concluded that the main contributing processes to human health damage were the fuel production and the power production, while transport and storage of CO_2 depicted only a share of about one percent. This coincided with the comparison on basis of impacts where the main contributions were constituted by the impacts of climate change and particulate matter formation due to power plant emissions.

Additionally Singh performed a structural path analysis on human health damage, for 1 kWh of generated electricity for each plant system, and showed details of the impacts of processes, which resulted in similar conclusions.

The trend of the human health damage indicator also applied to the ecosystem damage. Besides this fact, the impacts of agricultural land occupation, urban land occupation and natural land transformation, regarded within this endpoint indicator, were attributed to fuel production and power plant infrastructure.

In case of the resource depletion the results showed that metal depletion was primarily caused by the demand related to the infrastructure needed for CO_2 transport. Nevertheless the fossil depletion accounted to nearly 100% and made the metal depletion impact almost negligible.

A **sensitivity analysis** was conducted to depict effects on the selected impact categories of varying transport distance of CO_2 via a pipeline, the increased energy demand, because of the CO_2 capture technology, and the consequences on human toxicity of the applied characterization factor for the solvent mono-ethanolamine, which was developed by literature as no characterization factor was implemented in the ReCiPe software tool.

In terms of transport distance the analysis was performed for three different distances with two distinct CO_2 mass transport rates, expected to be delivered by given power plant dimension.

The results showed that the environmental burdens, which were increasing with increased transport distance and rate, could be related to pipeline development and energy demand for recompression of CO_2. The consequences of transport length on the impact categories were determined to be non-linear.

It was mentioned in the study that MEA might have toxic effects on humans but that a characterization factor was missing within the software tool.

Singh identified that the most relevant uncertainties were related to the efficiencies of the CCS technology and the background processes, such as possible technological improvements for fuel production.

4.3.9 Life cycle modeling and comparative assessment of the environmental impacts of oxy-fuel and post combustion CO_2 capture, transport and injection processes (Zhenggang Nie et al., 2011)[449]

This comparative study used a dynamic LCA model, developed at the Imperial College London. A conventional fossil fuel based electricity production system was opposed to two alternative fossil fuel fired power plant systems with carbon capture technology.

As commended by the authors, this LCA model allowed quantification of environmental loads at an upmost detailed level, regarding technological, temporal as also geographical varieties of the power plant systems.

In contrast to other methodologies, the system was modeled on basis of subsystems at an unit process level instead of applying gate-to-gate data, implicated in conventional databases, which depict whole system elements as a black-box, based on constants and linear coefficients, thus preventing alteration and identification of relevant system parameters.

The dynamic LCA model therefore provided a higher level of resolution and a flexible structure, when different system component alternatives were chosen, by breakdown of the complete system into subsystems, denoted as modularization by the authors.

The **goal** was to assess and compare the environmental burdens of a conventional coal fired power plant without CCS, a coal fired power plant with chemical absorption that used MEA washing, and a coal fired power plant with oxy-fuel combustion technology.

The comparison was based on a functional unit of 1 MWh electricity produced and incorporated the system components of fuel and raw material production and supply, electricity production at the power plant, CO_2 capture and compression, CO_2 transport over a distance of 300km via pipeline, storage of CO_2 in a geological formation and waste disposal.

The **inventory** data related to the power plant system with CCS included the processes of coal combustion, air separation, CO_2 capture and compression, particulate matter removal, flue gas desulfurization, NO_x removal as also solid waste disposal and were compiled from different sources that included site specific data, scientific calculations based on physical and chemical principles, as also empirical relationships.

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[449] Cf. Nie et al. 2011, pp. 2510-2516 and Korre et al. 2009, pp. 3771-3777.

With the help of literature and calculations performed within the GaBi v.4 software, LCI data was generated for background processes that included production and transport of underground coal, limestone, MEA and ammonia, as also for requirements related to the infrastructure and construction of the power plant, the air separation unit, the CO_2 capture facility and compression unit, as well as the CO_2 transport system.

The coal type used in the study referred to US Appalachian bituminous coal and was transported to the power plant by railway. Limestone, MEA and ammonia were transported by truck. The CO_2 was assumed to be stored at a depth of 1000m in a saline aquifer.

The **impact assessment** was based on the CML 2001 method, a damage oriented approach aggregating the LCI results to mid-point categories, and included the following impact categories:

- Global warming potential
- Ozone layer depletion potential
- Acidification potential
- Eutrophication potential
- Photo-oxidant formation potential
- Human toxicity potential
- Abiotic resources depletion potential
- Terrestrial ecotoxicity potential
- Marine aquatic ecotoxicity potential
- Fresh water aquatic ecotoxicity potential

In a first step the outcomes of the impact assessment were individually analyzed for each of the two electricity generation systems that used CCS technology.

The results for the global warming potential revealed the high impacts of greenhouse gas emissions that resulted from fuel production and the combustion of coal for electricity generation in the power plant. Those two processes dominated, even though at different shares, all impact categories with some exceptions.

In case of the MEA-equipped power plants, the process of MEA production constituted almost all environmental loads within the category of human toxicity.

Concerning the ozone layer depletion potential, the combustion of coal did not show any impacts, instead the main contributing system element within this impact category was the fuel supply process chain, and, to a very low extent, the power plant construction and infrastructural requirements for capture facilities and CO_2 transport.

It was mentioned that the acidification potential, eutrophication potential, global warming potential, human toxicity potential, the marine aquatic ecotoxicity potential and the photo-oxidant formation potential were affected because of emissions to air, whereas the terrestrial ecotoxicity potential and the freshwater aquatic ecotoxicity potential underlay emissions of trace metals released to soil and air.

Generally it was concluded that the coal transport, the production and transport of limestone, MEA and ammonia, the infrastructural requirements of the power plant as also the CO_2 capture and transport system had a negligible impact on the examined categories.

In the next step both power plants with carbon capture technologies were compared with the conventional coal fired power plant without CCS.

The global warming potential was significantly reduced by utilization of CCS, but an increase of impacts was observed in the abiotic resource depletion potential category, as a result of lower efficiencies of power plants with CCS technology, as well as of CO_2 transport and injection, which adversely influenced the coal demand.

Also the impacts, of electricity generation systems with carbon capture, on the ozone layer depletion category were higher, compared to the conventional power plant system, due to increased coal consumption, which increased the emissions of coal mining.

Regarding the freshwater aquatic ecotoxicity again the effects of CCS were unfavorable, which was to a marginal extent referred to an increased coal demand, or more specifically trace metals that were released to the environment during fuel production, and in case of the oxy-fuel system higher environmental impacts underlay hydrogen fluoride emissions into freshwater that resulted from the capture process.

Compared to the conventional plant, the power plant system that utilized MEA exhibited higher impacts in the categories acidification, human toxicity and eutrophication, because of higher NO_x emissions that resulted from coal consumption, MEA production and NH_3 generation due to the capture process. Opposed to this, the photo-oxidant formation potential and the marine ecotoxicity potential were reduced by MEA-wash, compared to the conventional power plant, because of reduced hydrogen fluoride and NO emissions.

A **sensitivity analysis** was performed to determine the consequences of a varying energy efficiency of the oxy-fuel electricity generation system on the results, and indicated a non-linear effect on the impact categories. Also different values for the O_2-purity were simulated, which resulted in an optimal oxygen purity of 98%.

Higher purities caused elevated energy demands adversely affecting the impact categories and lower values of purity decreased the benefit of global warming potential reduction.

Finally the authors compared the impact category scores to the results of other studies, in relation to coal fired power plants without CCS and coal fired power plants with the same capture technologies, and concluded that almost the same trends in the results could be observed.

Another study was performed by the same authors in 2009, based on the same LCA methodology with nearly identical system component assumptions, where a coal fired power plant without CCS and one power plant that used chemical absorption as the carbon capture technology, were compared to each other.

The study from 2009 showed that the type of coal had a high impact on the global warming potential, the human toxicity potential as also the ecotoxicity categories.

One big difference, to the study of 2011, was the application of the 1% cut-off rule to the MEA solvent production related LCI data, as the consumption of solvent was considered to be small.

The trend in the results was pretty similar in all impact categories with two exceptions, which were significant differences in relation to the category results of human toxicity and photo-oxidant formation.

One exception could be explained with the application of the 1% cut off rule and concerns the human toxicity potential, where the production of MEA significantly increased the impacts within this category, as shown in the study from 2011, thus resulted in higher environmental burdens of the power plant using MEA compared to the conventional power plant without CCS.

The other exception that concerned the considerably differed LCA results in relation to the photo-oxidant formation category could not be explained, as the information content of the published articles was very limited.

4.3.10 Weighting of environmental trade-offs in CCS - an LCA case study of electricity from a fossil gas power plant with post-combustion CO_2 capture, transport and storage (Ingunn Saur Modahl et al., 2012)[450]

In the LCA study of Modahl et al., electricity generation in a natural gas fired power plant without CCS was compared to a natural gas fired power plant with CCS that used different options of MEA absorption as the carbon capture technology. Three distinct weighting procedures were applied, in order to show the robustness of evaluation of environmental impacts that resulted from different weighting methods.

The **goals** were to assess and compare the potential environmental impacts of four gas fired electricity generation systems located in Norway, where three power plant systems used MEA absorption as a CCS technology.

The carbon capture equipped power plants differed in the amine regeneration alternatives only.

The second goal was to show the importance of the weighting step in relation to an LCA study performed on electricity generation and CCS technology.

On basis of 1 TWh electricity generated at the power plant, the systems that included fuel production and transport from a natural gas field in Norway, electricity generation in the power plant, the capture process, waste treatment, CO_2 compression and pipeline transport over a distance of 150km, as also geological storage of CO_2 at the Heidrun license area without leakage of CO_2 from the storage site, were compared to each other.

The **inventory** for the above mentioned processes was compiled with the help of the Ecoinvent 2.0 database, as also site specific and literature data. Process equipment, construction and dismantling of transport and storage infrastructure were as well incorporated.

The **impact assessment** was performed with the SimaPro software and included five impact categories, listed below:

- Global warming potential
- Acidification potential
- Eutrophication potential
- Photochemical ozone creation potential
- Cumulative energy demand

The global warming potential was significantly reduced in each electricity generation system case that applied CCS, whereas the combustion of gas contributed the most to this impact category followed by the fuel supply processes, independent of the application of carbon capture technology. Effects in relation to CO_2 transport and storage, waste treatment, and infrastructural requirements were marginal, as stated by the authors.

The environmental impacts in terms of eutrophication primarily underlay the processes of fuel supply. The carbon capture process as well caused obvious environmental loads within this category. The power plants that used capture technology generally performed worse

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[450] Cf. Modahl et al. 2009, pp. 3-9; Modahl et al. 2011, pp. 2470-2476 and Modahl et al. 2012, pp. 932-942.

compared to the power plant without CCS, not only because of the energy penalty related to the CO_2 capture, transport and storage processes, which increased the fuel demand, but also because of different emissions related to MEA.

The authors noted that the power plant systems equipped with CCS technology also performed poorer in the other impact categories, as a result of the CCS related processes, which decreased the plant efficiency, and because of the same reasons above mentioned that referred to eutrophication.

The effects of infrastructural requirements as well as transport and storage of CO_2 were determined to be very small.

In a next step the electricity generation system results were **normalized**, in reference to national emissions data of greenhouse and acidifying gases of Norway, for determination of the most significant impacts that resulted from different emissions.

As the impact categories had shown contrary results, the weighting of inventory data was performed to facilitate decision making, in relation to the different power plant alternatives.

Three different impact assessment methods, which apply weighing, namely ReCiPe, EPS 2000 and IMPACT 2002+, were used to study the robustness of the weighted results.

ReCiPe, where the 'Hierarchist-Average' scenario for Europe was chosen, is based on damage costs and focuses on climate change. The EPS 2000 model is based on willingness to pay to avoid environmental damage, and brings human health, and, especially, reserve depletion into focus, due to high damage factors.

IMPACT 2002+ which is based on damage costs, as well brings climate change and human health into focus, but also includes ecosystem quality and resources, thus representing the results in a total of four endpoint categories.

It was noted that although categories related to toxicity were omitted, because of data uncertainty and gaps that resulted, for instance, from lack of data concerning the MEA absorption process, weighting was useful for comparison, as data gaps and uncertainties were almost similar in every case of system alternatives.

The weighting showed that the power plant without CCS technology performed worst in the ReCiPe model, whereas the other models showed the highest results for one of the power plant alternatives equipped with CCS. But all three weighting methods determined the same power plant system option with CCS as the best alternative, therefore stayed in contrast to the results without the normalization step performed.

Overall the conclusion was made that the use of fossil fuel was a significant factor for all electricity generation systems and that other dominant environmental issues, related to the systems with CCS, concerned the energy penalty due to CCS, and the environmental loads referred to MEA absorption.

5 Practices, Issues and Limits

Within this chapter, the practices performed on the life-cycle evaluation of ten authors are examined in order to highlight if, and where, shortcomings of the actual LCA procedure can be expected when assessing the environmental loads of a complex product system.

A summary of the case studies in tabular form coarsely depicts the tenor of applied methodological choices related to the LCA method, such as the functional unit to which the LCI was related, temporal and spatial boundaries, implied data sources and data types, the LCIA method and considered impact categories, as also additional methods used to round out a particular LCA study.

Analysis of the case studies and their outcomes should emphasize accordances and unconformities, the authors have experienced, to indicate those practices that seemingly resulted in meaningful findings, or else rather led to questionable conclusions.

In a next step the applicability of ISO's LCA procedure is brought into focus, for the purpose of illustrating how the recommendations of ISO can be implemented in the life-cycle evaluation of complex systems. To repeat that, complex in these terms is used to characterize product systems using a novel technology procedure, thus facing difficulties like, for instance, data gaps, incorporation of future system models or unknown environmental mechanisms.

After having addressed the practices, issues and limits of LCA studies related to electricity generation with CCS, another complex product system relating to the topic of energy storage will be introduced. The ulterior motive is that, as no LCA studies have been published until now, aiming to assess the environmental burdens of an energy storage system utilizing the power-to-gas principle and underground hydrogen storage, this product system implicates comparable complexity to the electricity generation system with CCS technology, thus probably facing similar issues.

The characteristics of renewable energy storage, as well as the principle of the power-to-gas technology are explained, and it is gone into detail of a certain alternative for chemical energy storage, namely the underground storage of hydrogen in geological formations, with the intention to indicate those environmental aspects that might be subject to additional research requirement, in terms of capability of the current LCA procedure.

Based on the fact that the examination of case studies, relating to the LCAs of electricity generation systems with CCS, has yield the question of meaningfulness of the actual LCA tool, the emphasis of expected shortcomings of presumably upcoming energy storage LCA studies should highlight areas where urgent demand for improvement of the LCA method exists in order to avoid ending up with similar issues, like incompleteness and missing comprehensiveness as in case of the examined studies.

This chapter provides a foundation for a list of problems and recommendations not only addressed to practitioners of future LCA studies but also to experts, involved in the improvement process of the LCA tool.

Because of the uniqueness of this tool, which is without equal, by all means should be worth the effort to optimize the character of the LCA method, in order to be all set for upcoming challenges.

5.1 Case Study Analysis

After having described the characteristics and applied methods of case studies in the previous chapter it is now the aim to point out procedure similarities, which have been considered important across the already performed LCAs, the consensus of the different authors on significant study parameters, but also possible issues and problems that are seemingly present. This especially affects LCA methods and how they have been utilized by different authors, as well as emphasis of relevant system parts and their effects on the results, in order to allow drawing some conclusions on the meaningfulness of current LCA method utilization in the area of complex system evaluation.

As already mentioned, all of the ten LCA studies examined above are based on the procedure suggested by the standards of ISO, thus the following perceptions are listed with respect to the chronology of the standards of ISO, beginning with aspects related to the goal and scoping phase. In the next, a short summary of the above described case studies is given in tables 1 to 10, to depict those fundamental characteristics that could be read out from the examined case studies.

Table 1: Summary of the case study “Life cycle assessment of selected technologies for CO_2 transport and sequestration”

Author (Year)	Wildbolz (2007)	
Type of LCA denoted by author	n.a.	
LCA Software	SimaPro	
Functional unit	• 1 kg CO_2 stored • 1 kWh electricity produced	
Spatial reference	Europe	
Temporal reference	n.a.	
Data sources & types	Calculations, estimations, Ecoinvent	
LCIA Method	• Eco-Indicator 99 (Hierarchist scenario)	• IPCC 2001
Impact Categories	• Fossil fuels • Minerals • Land use • Acidification potential • Ecotoxicity potential • Ozone layer depletion potential • Radiation • Climate change • Respiratory inorganics • Respiratory organics • Carcinogens	• Global warming potential (GWP 100)
Data Aggregation Type	Weighting	
Additional Methods	• Sensitivity Analysis • Sankey diagram of the transport process • Contribution analysis	

Table 2: Summary of the case study “Life cycle evaluation of CO_2 recovery and sequestration systems”

Author (Year)	Khoo (2007)	
Type of LCA denoted by author	n.a.	
LCA Software	n.a.	
Functional unit	1 MWh electricity produced	
Spatial reference	n.a.	
Temporal reference	n.a.	
Data sources & types	Site-specific data, assumptions, estimations, expert interviews, literature	
LCIA Method	• EDIP 97	• Eco-Indicator 99 (Hierarchist-Average)
Impact Categories	• Global warming potential • Acidification potential • Human toxicity to air • Human toxicity to water • Eutrophication potential • Ecotoxicity potential • Wastes • Resources	• Climate change • Respiratory inorganics • Respiratory organics • Carcinogens • Acidification potential • Ecotoxicity potential • Fossil fuels
Data Aggregation Type	Normalization and Weighting	
Additional Methods	• Sensitivity Analysis • Error Analysis	

Table 3: Summary of the case study “Comparison of carbon capture and storage with renewable energy technologies regarding structural, economic, and ecological aspects in Germany”

Author (Year)	Viebahn et al. (2007)
Type of LCA denoted by author	Prospective screening LCA
LCA Software	Umberto
Functional unit	1 kWh electricity produced
Spatial reference	Germany
Temporal reference	• 2020 for power plant systems • 2010 for enegy mix and raw material supply
Data sources & types	Umberto, Ecoinvent, literature
LCIA Method	UBA-Verfahren
Impact Categories	• Resources / Cumulative energy demand • Global warming potential • Acidification potential • Eutrophication potential • Human toxicity potential • Photo-oxidant formation potential
Data Aggregation Type	none
Additional Methods	• Allocation • Sensitivity Analysis

Table 4: Summary of the case study "Life-cycle assessment of carbon dioxide capture for enhanced oil recovery"

Author (Year)	Hertwich et al. (2008)
Type of LCA denoted by author	Hybrid LCA
LCA Software	n.a.
Functional unit	• 1m^3 oil produced • 1 MWh electricity produced
Spatial reference	Norway
Temporal reference	n.a.
Data sources & types	Site-specific data, literature, estimations, EIO-analysis
LCIA Method	n.a.
Impact Categories	• Global warming potential • Acidification potential
Data Aggregation Type	none
Additional Methods	•Allocation •Structural path analysis

Table 5: Summary of the case study "Life-cycle assessment of a pulverized coal power plant with post combustion capture, transport and storage of CO_2"

Author (Year)	Koorneef et al. (2008)
Type of LCA denoted by author	n.a.
LCA Software	n.a.
Functional unit	1 kWh electricity produced
Spatial reference	Netherland, Europe, worldwide
Temporal reference	n.a.
Data sources & types	Calculations, estimates, literature, manufacturer interviews, Ecoinvent
LCIA Method	CML
Impact Categories	• Global warming potential • Abiotic resource depletion potential • Ozone layer depletion potential • Human toxicity potential • Fresh water aquatic ecotoxicity potential • Marine aquatic ecotoxicity potential • Terrestrial ecotoxicity potential • Photochemical oxidation potential • Acidification potential • Eutrophication potential
Data Aggregation Type	Normalization (Netherlands 1997)
Additional Methods	•Allocation •Sensitivity Analysis

Table 6: Summary of the case study “Environmental assessment of German electricity generation from coal fired power plants with amine-based carbon capture”

Author (Year)	Schreiber et al. (2009)
Type of LCA denoted by author	n.a.
LCA Software	GaBi
Functional unit	1 kWh electricity produced
Spatial reference	Germany
Temporal reference	2005, 2010 and 2020 for varying power plant and CO_2 capture efficiencies
Data sources & types	Site-specific data, literature, consultation of experts, Ecoinvent
LCIA Method	CML
Impact Categories	• Primary energy demand • Global warming potential • Human toxicity potential • Acidification • Photo-oxidant formation potential • Eutrophication potential
Data Aggregation Type	Normalization (Germany)
Additional Methods	Sensitivity Analysis

Table 7: Summary of the case study “Life cycle assessment carbon dioxide capture and storage from lignite power plants”

Author (Year)	Pehnt and Henkel (2009)
Type of LCA denoted by author	n.a.
LCA Software	n.a.
Functional unit	1 kWh electricity produced
Spatial reference	Germany
Temporal reference	2020
Data sources & types	Literature, extrapolations, Ecoinvent
LCIA Method	n.a.
Impact Categories	• Energy resources / Cumulative energy demand • Global warming potential • Photochemical ozone creation potential • Acidification potential • Eutrophication potential • Human toxicity potential
Data Aggregation Type	none
Additional Methods	• Allocation • Contribution Analysis • Sensitivity Analysis

Table 8: Summary of the case study “Environmental evaluation of carbon capture and storage technology and large scale deployment scenarios”

Author (Year)	Singh (2010)
Type of LCA denoted by author	Hybrid LCA
LCA Software	n.a.
Functional unit	1 kWh electricity produced
Spatial reference	n.a.
Temporal reference	2050
Data sources & types	EIO-analysis, curve fitting, process modelling, literature, Ecoinvent
LCIA Method	ReCiPe
Impact Categories	• Global warming potential • Terrestrial acidification potential • Fresh water eutrophication potential • Marine eutrophication potential • Photochemical oxidant formation potential • Particulate matter formation potential • Human toxicity potential • Terrestrial ecotoxicity potential • Fresh water ecotoxicity potential • Marine ecotoxicity potential
Data Aggregation Type	Weighting
Additional Methods	• Sensitivity Analysis • Structural path analysis

Table 9: Summary of the case study “Life cycle modeling and comparative assessment of the environmental impacts of oxy-fuel and post combustion CO_2 capture, transport and injection processes”

Author (Year)	Nie et al. (2011)
Type of LCA denoted by author	Dynamic LCA model
LCA Software	GaBi
Functional unit	1 MWh electricity produced
Spatial reference	US Appalachian bituminous coal
Temporal reference	n.a.
Data sources & types	Site-specific data, calculations, literature, GaBi
LCIA Method	CML
Impact Categories	• Global warming potential • Ozone layer depletion potential • Acidification potential • Eutrophication potential • Photo-oxidant formation potential • Human toxicity potential • Abiotic resource depletion potential • Terrestrial ecotoxicity potential • Marine aquatic ecotoxicity potential • Fresh water aquatic ecotoxicity potential
Data Aggregation Type	none
Additional Methods	• 1% cut-off rule • Sensitivity Analysis

Table 10: Summary of the case study “Weighting of environmental trade-offs in CCS – an LCA case study of electricity from a fossil fuel gas power plant with post-combustion CO_2 capture, transport and storage”

Author (Year)	Modahl et al. (2012)
Type of LCA denoted by author	n.a.
LCA Software	SimaPro
Functional unit	1 TWh electricity produced
Spatial reference	Norway, Europe
Temporal reference	n.a.
Data sources & types	Site-specific data, literature, Ecoinvent
LCIA Method	ReCiPe (Hierarchist), EPS 2000 and IMPACT 2002+
Impact Categories	• Global warming potential • Acidification potential • Eutrophication potential • Photochemical ozone creation potential • Cumulative energy demand
Data Aggregation Type	Normalization (Norway) and Weighting
Additional Methods	none

A straightforward comparison of the ten case studies, particularly their results, would have been valuable to highlight the best practices that ended up in a comprehensive assessment of complex product systems but seems not possible as they significantly differed in their assumptions on system boundaries, data references, analyzed technologies and assessment methods, to name but a few fundamental differences, already indicated to some extent in tables 1 to 10 above.

An evaluation of expedient method selection would be encouraged if a detailed breakdown of utilized input and output data was at hand, but due to the fact that a detailed description of LCI data was not depicted in the studies, a comparison of method and assumption impacts on the study results, and therefore a conclusion, of how methods were related to the quality of the performed LCA studies, was somehow difficult.

However, some practices applied by the authors and insights gained are now summarized according to their LCA methodology driven differentiation. Additionally the methods suggested by ISO and obeyed by all authors, as also those methods not incorporated, or where the applicability seemed difficult, are as well highlighted in the following.

With respect to the ISO standards almost all studies, analyzed in the work at hand, defined the goals, the system boundaries, the functional unit, the temporal and spatial relation, the technological coverage, as also assumptions, interpretations and the impact categories, intended to be evaluated, in the first part of their analysis.

A statement if the studies were made for comparative assertions intended to be disclosed to the public was not made by any of the authors, which would have had resulted in additional requirements suggested by ISO, such as the need for a critical review.

Despite the fact that the goals among the ten studies were not similar, all studies performed comparative LCAs on basis of a predefined functional unit, which is necessary for comparison of different systems within a study on an equal basis. Also the system boundaries were drawn in a way that facilitated the comparison of different product systems within the same study.

A description of the complete product systems by utilization of a system flow diagram, including all processes and their relationship to each other, in terms of quantitative input and output flows, was not illustrated by any study, at least in the publications that were available, although it would have increased the transparency significantly. Only simplified flow diagrams, to declare the overall assessed system components, were coarsely depicted by some authors.

As all LCAs are were related to electricity production systems, a functional unit was chosen to be a certain amount of Watt electricity produced by the system, with exception of the studies performed by Hertwich et al.[451] in 2008 who chose an additional functional unit of 1m^3 oil produced, to compare systems with and without EOR, and Wildbolz[452] who chose 1kg stored CO_2 as a second functional unit to compare CO_2 storage system alternatives.

Nevertheless Hertwich[453] defined 1 MWh electricity produced as a functional unit for comparison of different power plant technologies, which depicted the primary part of the complete system.

The LCA study of Hertwich et al.[454] was one of the few that not only identified a co-product but also incorporated more than one product delivered by the system, namely oil and electricity produced, whereas the other studies, even though other authors recognized that a multifunctional system was to be assessed, performed the LCA on basis of only one product, which was the electricity produced by the power plant systems.

Assessing multifunctional systems may lead to allocation problems, and allocation of environmental loads to other saleable co-products with an economic value, such as elemental sulfur, CO_2 in some countries, or nitrogen, which were generated by different capture processes of power plant systems with CCS technology, or recycled materials after dismantling of infrastructure and facilities, was not conducted by almost all authors.

In the study of Hertwich et al.[455], parts of the input and output data were shared between the oil production and the electricity generation system. Viebahn et al.[456] included a mixture of primary and secondary materials on the input side, according to ISO's closed-loop recycling definition.

Pehnt and Henkel[457] allocated the process step of CO_2 compression to the power plant operation, which in turn led to a reduced net efficiency of the power plant. Koorneef et al.[458] treated gypsum that resulted from the flue gas treatment, as a co-product, thus reduced the environmental burdens related to mining of virgin gypsum.

As the intention of a comprehensive LCA study is to incorporate all process steps, from cradle-to-grave, the authors incorporated almost all aspects of a full LCA process chain, even though at a very different level of detail, from raw material extraction and fuel supply, over construction, operation and dismantling of the main electricity generation and CCS system elements, as also infrastructural requirements.

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[451] Cf. Hertwich et al. 2008, pp. 343-352.

[452] Cf. Wildbolz 2007, pp. 19-58.

[453] Cf. Hertwich et al. 2008, pp. 343-352.

[454] Cf. Hertwich et al. 2008, pp. 343-352.

[455] Cf. Hertwich et al. 2008, pp. 343-352.

[456] Cf. Viebahn et al. 2007, pp. 2-13 and Viebahn et al. 2007b, pp. 105-143.

[457] Cf. Pehnt and Henkel 2009, pp. 50-61.

[458] Cf. Koorneef et al. 2008, pp. 2-18.

The incorporation of waste treatment, final disposal or recycling processes was however often not replicable.

All studies incorporated the processes of CO_2 transport via pipeline and the storage mostly in geological formations with exception of the study performed by Schreiber et al.[459], which only executed a sensitivity analysis on those processes, to determine the impacts of transport and storage on the final results.

Generally it seems that the processes of CO_2 transport and storage were related to background processes, rather than foreground system processes, as those processes were modeled on a relatively low level of detail. Only Wildbolz[460] tried to model the transport and storage processes more precisely by identification of relevant system parameters and conduction of several calculations in relation to those parameters.

The expected lifetime of facilities and system elements was as well regarded differently by the authors, whereas some did not indicate if their LCA incorporated a certain lifetime expectation of system components. Also the impacts of the lifetime on the final results could not be evaluated due to the limited information content of the published studies.

Only Wildbolz[461] determined the lifetime of the infrastructure to have a significant impact on the construction labor and stated that further investigations should be made in relation to that fact.

One of the basic reasons that seemingly led to differing results in some impact categories, among the examined LCA studies, relied on the shortcoming of data quality. As all studies aimed to assess more or less future technology systems, the availability of accurate primary data was scarce. The authors handled this shortcoming very distinctly.

Generally it was tried to develop primary or modeled data for foreground processes and consultation of experts to assess data on technological improved system components.

Besides consultations of experts, assumptions or calculations based on literature data, modifications including extrapolations and projections of system parameters towards technological improvements, based on available data from similar processes, were also performed to model the system's inventory with respect to the selected temporal reference, thus related to future technologies.

A degree of process unit data precision in terms of mean, variance and standard deviation, as suggested by ISO, was not indicated in any of the examined studies.

If high uncertainties to specific parameters were identified, usually a sensitivity analysis was performed to determine the impacts of uncertain parameters on the final results.

Information from databases, like the Ecoinvent database, or economic input output tables, was gathered for compiling the inventory of background processes, such as raw material and resource supply, energy mix and transport infrastructure related data.

Referring to background processes, such as energy mix and fuel supply, which as well were often identified to have an important effect on the final results especially in relation to their spatial reference, modifications and future improvements were rarely incorporated. Vie-

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[459] Cf. Schreiber et al. 2009, pp. 547-558; Markewitz et al. 2009, pp. 3763-3770 and Schreiber et al. 2010, pp. 7873-7883.

[460] Cf. Wildbolz 2007, pp. 19-58.

[461] Cf. Wildbolz 2007, pp. 19-58.

bahn et al.[462], for example, incorporated future developments of some background processes, such as the electricity mix and improved metal recycling rates.

Estimations based on literature findings were performed to fill data gaps, but also simple omission of process aspects, where data gaps were identified, was quiet usual, although when done so a justification was reported.

This especially concerned the leakage of CO_2 from the storage site, which was almost always completely neglected in the studies, whereas only Viebahn et al.[463] performed a sensitivity analysis on different leakage rates, to determine the according impacts on the LCA results, but he concluded that handling long-term emissions with today's LCA methods was unrewarding.

This relies on the fact that when assuming a specific leakage rate of CO_2 from the geological storage, it is not a question of how much substance leaks to the environment but rather how long it takes until the whole CO_2 is released from the storage, thus, if incorporated in the LCA, it would have had resulted in a general futile expenditure of CCS technology, because why store CO_2 if it is released anyway, only questioning a certain frame of time.

Among the different studies the system boundaries were, as in case of the data sources, drawn very distinctly, making the comparison of different studies nearly impossible, but as a comprehensive LCA study should encompass several processes from cradle-to-grave, the authors seemingly tried to incorporate all processes necessary, on a more or less higher level of detail, beginning with energy and raw material inputs over the foreground processes to waste treatment and releases to the environment.

Particularly the up- and downstream processes were modeled and incorporated very differently, according to the assumptions made by the authors. Some tried to model the background processes on the same level of detail, in terms of temporal and spatial reference, as done in case of the foreground processes, whereas others simply used existing database sets for complete subsystems.

Wildbolz[464], for instance, additionally conducted a Sankey-Diagram, which enhanced the determination of the most contributing process of the subsystem "transport with recompression".

Only Nie et al.[465] reported in their study of 2009 the application of the 1% cut-off rule on LCI data referred to mono-ethanolamine (MEA) solvent production, which ended up in different conclusions concerning the human toxicity potential, if compared to the study of 2011. As mentioned in the 14040 series of ISO standards, these cut-off rules have to be used with caution, as simple cut-off of complete processes can have a considerable impact on the final interpretation.

Viebahn et al.[466] denoted their study as screening LCA and cut-off complete process steps, due to missing data related to future developments of the incorporated technologies, and because a documentation and justification was made on doing so the study is still in line with the standards of ISO.

As the impact assessment procedure basically depends on the available inventory data, the impact categories were seemingly chosen according to the existence of data, which some-

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[462] Cf. Viebahn et al. 2007, pp. 2-13 and Viebahn et al. 2007b, pp. 105-143.

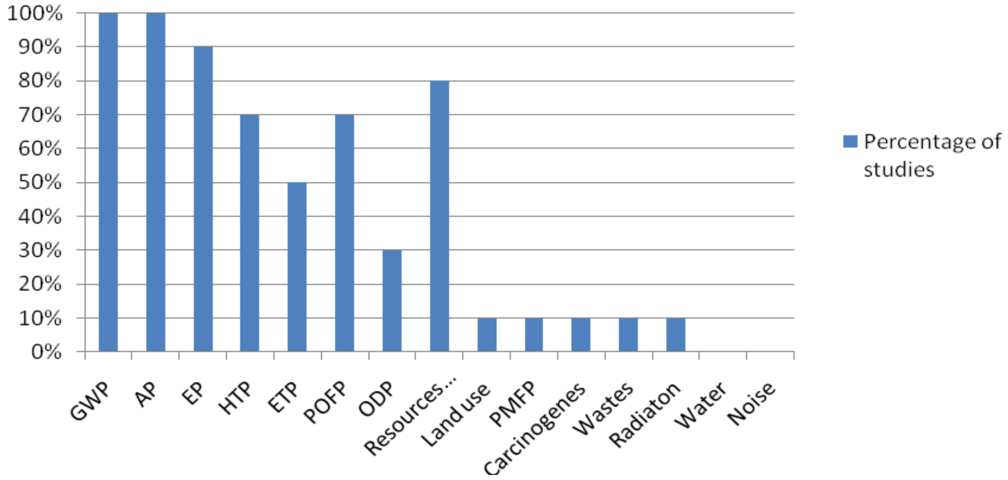
[463] Cf. Viebahn et al. 2007, pp. 2-13 and Viebahn et al. 2007b, pp. 105-143.

[464] Cf. Wildbolz 2007, pp. 19-58.

[465] Cf. Korre et al. 2009, pp. 3771-3777.

[466] Cf. Viebahn et al. 2007, pp. 2-13 and Viebahn et al. 2007b, pp. 105-143.

how depends on one's own choice. The impact categories considered by different authors in the examined studies are depicted, in terms of percentage of studies, in figure 11 below.



GWP…Global Warming Potential, AP…Acidification Potential, EP…Eutrophication Potential, HTP…Human Toxicity Potential, ETP…Ecotoxicity Potential, POFP…Photochemical Oxidant Formation Potential, ODP…Ozone Depletion Potential, PMFP…Particulate Matter Formation Potential.

Figure 11: Impact categories considered in the examined studies

The CCS technology was developed to decrease the emissions of CO_2 to the atmosphere so the consensus to incorporate the global warming potential category was at hand, and thus was found in all studies. Also the resource, eutrophication and toxicity related categories were almost always incorporated in the assessment. Generally, and in relation to other categories, the authors performed rather distinctly, like, for instance, in the study of Hertwich et al.[467], where only the acidification potential was assessed additionally to the global warming potential category, whereas Wildbolz[468] considered a overall of eleven different impact categories.

Concerning the global warming potential impact category, the time relation was not always clearly stated, but as a relation to 100 years is relatively common it was presumably used in every study, as other time relations were not mentioned.

The dominance of some processes, such as fuel supply and electricity production, on most of the impact categories can't be denied, but as shown by Nie et al.[469] the aim of modeling background processes on a higher level of detail revealed the dominance of monoethanolamine (MEA) production on the human toxicity category. Pehnt and Henkel[470] identified a considerable increase of impacts on the summer smog and acidification categories, as a result of used MEA solvents.

But the missing characterization factor for a certain impact category, to convert a substance into category indicator equivalents, was indicated by Pehnt and Henkel[471] in relation to

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[467] Cf. Hertwich et al. 2008, pp. 343-352.

[468] Cf. Wildbolz 2007, pp. 19-58.

[469] Cf. Nie et al. 2011, pp. 2510-2516 and Korre et al. 2009, pp. 3771-3777.

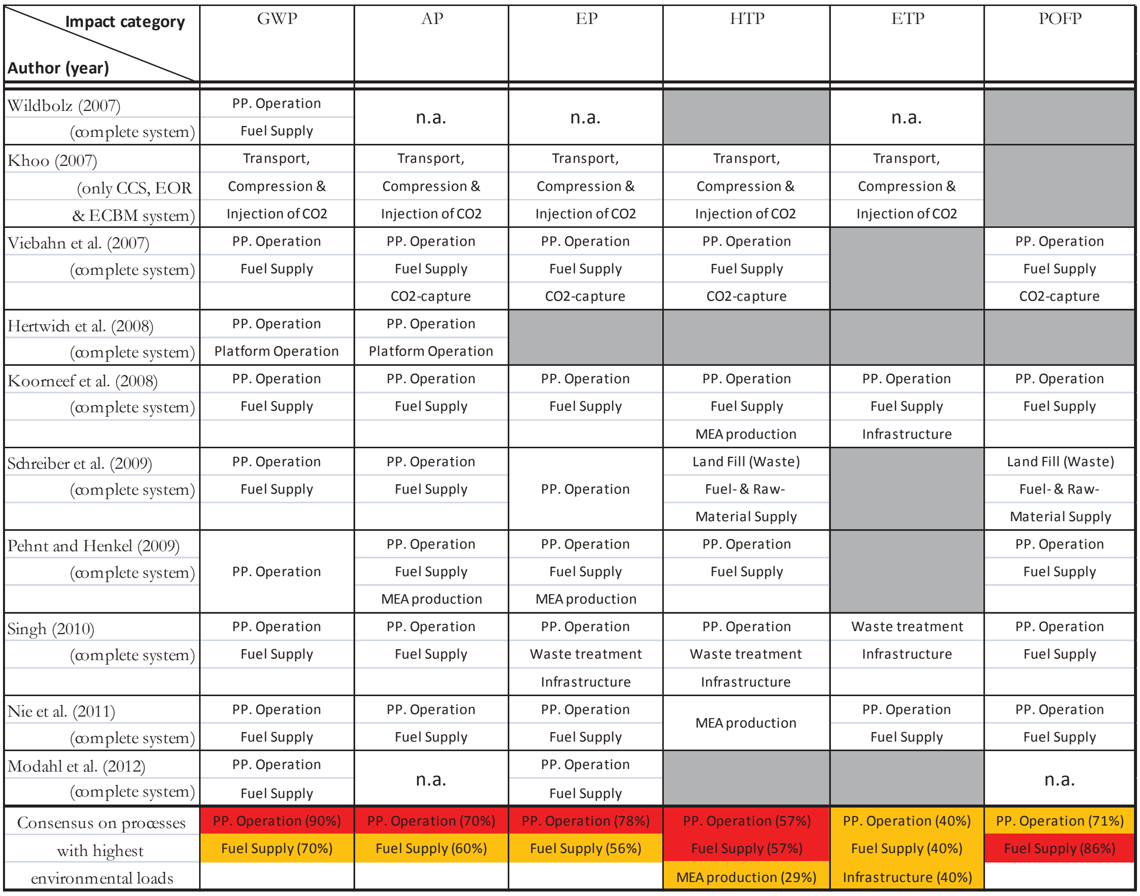
[470] Cf. Pehnt and Henkel 2009, pp. 50-61.

[471] Cf. Pehnt and Henkel 2009, pp. 50-61.

mono-ethanolamine. As the environmental mechanisms of this substance are not completely understood yet, the impacts of mono-ethanolamine (MEA) on the final category results were affected by additional uncertainty.

Pehnt and Henkel[472] treated MEA emissions within the category summer smog as non-methane volatile organic compounds (NMVOC) emissions and applied the average conversion factor of NMVOC to mono-ethanolamine.

Figures 12 and 13 show the main contributing processes according to the statements of the authors and the results of the examined studies.



Impact category / **Author (year)**	GWP	AP	EP	HTP	ETP	POFP
Wildbolz (2007) (complete system)	PP. Operation Fuel Supply	n.a.	n.a.		n.a.	
Khoo (2007) (only CCS, EOR & ECBM system)	Transport, Compression & Injection of CO2	Transport, Compression & Injection of CO2	Transport, Compression & Injection of CO2	Transport, Compression & Injection of CO2	Transport, Compression & Injection of CO2	
Viebahn et al. (2007) (complete system)	PP. Operation Fuel Supply	PP. Operation Fuel Supply CO2-capture	PP. Operation Fuel Supply CO2-capture	PP. Operation Fuel Supply CO2-capture		PP. Operation Fuel Supply CO2-capture
Hertwich et al. (2008) (complete system)	PP. Operation Platform Operation	PP. Operation Platform Operation				
Koorneef et al. (2008) (complete system)	PP. Operation Fuel Supply	PP. Operation Fuel Supply	PP. Operation Fuel Supply	PP. Operation Fuel Supply MEA production	PP. Operation Fuel Supply Infrastructure	PP. Operation Fuel Supply
Schreiber et al. (2009) (complete system)	PP. Operation Fuel Supply	PP. Operation Fuel Supply	PP. Operation	Land Fill (Waste) Fuel- & Raw-Material Supply		Land Fill (Waste) Fuel- & Raw-Material Supply
Pehnt and Henkel (2009) (complete system)	PP. Operation	PP. Operation Fuel Supply MEA production	PP. Operation Fuel Supply MEA production	PP. Operation Fuel Supply		PP. Operation Fuel Supply
Singh (2010) (complete system)	PP. Operation Fuel Supply	PP. Operation Fuel Supply	PP. Operation Waste treatment Infrastructure	PP. Operation Waste treatment Infrastructure	Waste treatment Infrastructure	PP. Operation Fuel Supply
Nie et al. (2011) (complete system)	PP. Operation Fuel Supply	PP. Operation Fuel Supply	PP. Operation Fuel Supply	MEA production	PP. Operation Fuel Supply	PP. Operation Fuel Supply
Modahl et al. (2012) (complete system)	PP. Operation Fuel Supply	n.a.	PP. Operation Fuel Supply			n.a.
Consensus on processes with highest environmental loads	PP. Operation (90%) Fuel Supply (70%)	PP. Operation (70%) Fuel Supply (60%)	PP. Operation (78%) Fuel Supply (56%)	PP. Operation (57%) Fuel Supply (57%) MEA production (29%)	PP. Operation (40%) Fuel Supply (40%) Infrastructure (40%)	PP. Operation (71%) Fuel Supply (86%)

GWP…Global Warming Potential, AP…Acidification Potential, EP…Eutrophication Potential, HTP…Human Toxicity Potential, ETP…Ecotoxicity Potential, POFP…Photochemical Oxidant Formation Potential, PP. Operation…Power Plant Operation.

Figure 12: Processes with highest contribution to impact categories

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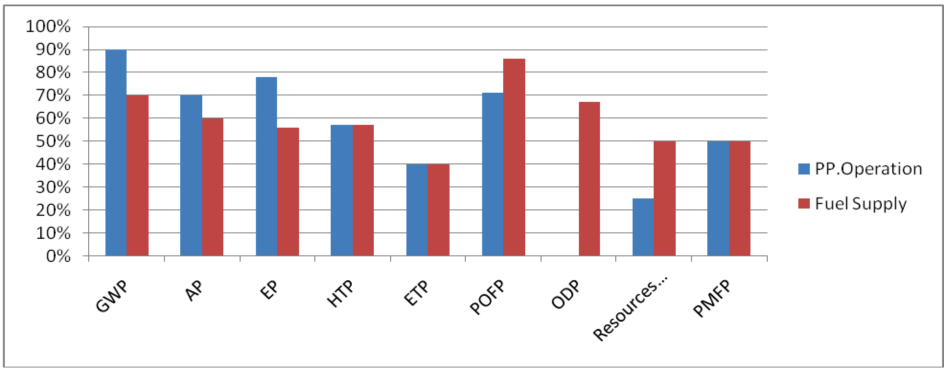
[472] Cf. Pehnt and Henkel 2009, pp. 50-61.

Impact category / **Author (year)**	ODP	Resources / Energy Demand	Land use	Respiratory Organics	Respiratory Inorganics	Carcinogenes	Wastes	Radiaton
				PMFP				
Wildbolz (2007) (complete system)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.		n.a.
Khoo (2007) (only CCS, EOR & ECBM system)		Transport, Compression & Injection of CO2					n.a.	
Viebahn et al. (2007) (complete system)		PP. Operation Fuel Supply CO2-capture						
Hertwich et al. (2008) (complete system)								
Koorneef et al. (2008) (complete system)	Fuel Supply	Fuel Supply						
Schreiber et al. (2009) (complete system)		PP. Operation CO2-capture						
Pehnt and Henkel (2009) (complete system)		Fuel Supply						
Singh (2010) (complete system)				PP. Operation Fuel Supply				
Nie et al. (2011) (complete system)	Fuel Supply	Fuel Supply						
Modahl et al. (2012) (complete system)		n.a.						
Consensus on processes with highest environmental loads	Fuel Supply (67%)	PP. Operation (25%) Fuel Supply (50%) CO2-capture (25%)	n.a.	PP. Operation (50%) Fuel Supply (50%)		n.a.		

ODP…Ozone Depletion Potential, PMFP…Particulate Matter Formation Potential, PP. Operation…Power Plant Operation

Figure 13: Processes with highest contribution to impact categories

Besides the main electricity production chain, the fuel production and transport processes were also identified to have a major influence on the impact categories global warming potential, acidification potential, eutrophication potential, human toxicity potential, photochemical ozone creation potential and ozone depletion potential, as evident in figure 14.



GWP…Global Warming Potential, AP…Acidification Potential, EP…Eutrophication Potential, HTP…Human Toxicity Potential, ETP…Ecotoxicity Potential, POFP…Photochemical Oxidant Formation Potential, ODP…Ozone Depletion Potential, PMFP…Particulate Matter Formation Potential, PP. Operation…Power Plant Operation

Figure 14: Author consensus of power plant operation and fuel supply processes given in percentage in relation to certain impact categories.

Especially emissions from mining, the transport distance, which was also dependent on the incorporated coal supply mix, as well as the heating value of coal, strongly affected the environmental loads. Thus again a comparison of results from various studies was complex, as the authors assumed different types of coal as also distinct coal origins.

The impact of the coal supply chain was also reflected in terms of energy mix, where the alteration of energy supply mixes showed a noticeable effect on the final results, particularly if endpoint indicator methods were applied that gave high weight on fossil resource depletion, such as the Hierarchist scenario of the Eco-Indicator 99 method.

Another important consensus, made by all authors, was that the contributions of transport and storage processes, although not always separately specified, as also the construction and dismantling of infrastructure and system facilities were of minor importance, compared to the fuel supply and electricity generation processes including CCS technology. It was determined that the coal supply chain infrastructure was the highest contributor to environmental loads among the other infrastructural requirements.

Although it seems obvious to be able to compare the results of different authors, on basis of the same category, it could lead to misinterpretation as the impact assessment methods often use different characterization models and therefore also varying category indicators.

Besides this fact, normalization and weighting of the inventory results, which was as well differently incorporated among the assessment methods or additionally applied by the authors, makes the comparison of different studies on basis of LCA results unrewarding.

Normalization was performed rather seldom, for instance, Koorneef et al.[473] referenced the results of the impact assessment to the Netherlands, Modahl et al.[474] to Norway and Schreiber et al.[475] translated the impact category scores by normalization to the regional reference of Germany.

Weighting of environmental impact was performed only by Wildbolz[476], Modahl et al.[477], Khoo[478] and Singh[479], which was often justified towards promotion of decision making. Different methods such as the EDIP, the Eco-Indicator 99, EPS 2000 and the IMPACT 2002+ were used to aggregate the results.

Within the certain studies, although with some differences in magnitude because of varying weighting factors, the trend in the results kept almost the same, even with application of more than one weighting method. All authors who applied weighting methods however identified slightly different indicator results, which were related the different focus of the various methods, like the high weight on non-renewable resources of the EPS 2000 and the Eco-Indicator methods, or the main focus of the EDIP method on toxic effects.

Some authors applied more than a single impact assessment method to examine the robustness of their results, which seems to be valuable, especially when representing the final results on an endpoint result basis, because damage-oriented methods emphasize the environmental evaluation with a diverse focus. Particularly valuation methods can significantly

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[473] Cf. Koorneef et al. 2008, pp. 2-18.

[474] Cf. Modahl et al. 2009, pp. 3-9; Modahl et al. 2011, pp. 2470-2476 and Modahl et al. 2012, pp. 932-942.

[475] Cf. Schreiber et al. 2009, pp. 547-558; Markewitz et al. 2009, pp. 3763-3770 and Schreiber et al. 2010, pp. 7873-7883.

[476] Cf. Wildbolz 2007, pp. 19-58.

[477] Cf. Modahl et al. 2009, pp. 3-9; Modahl et al. 2011, pp. 2470-2476 and Modahl et al. 2012, pp. 932-942.

[478] Cf. Khoo 2007, pp. 56-147.

[479] Cf. Singh 2010, pp. 17-48; Singh et al. 2011, p. 20 and Singh et al. 2012, pp. 2-14.

differ in their fundamental assumptions, as in case of methods based on monetary values compared to distance-to-target methods.

Representation of weighted outcomes within the endpoint indicator results, however, made the identification of main contributing processes impossible, and it appears useful to at least display the individual system processes, and their contributions within the impact assessment results, on a midpoint score basis, increasing the transparency of the whole study significantly.

In addition to the impact assessment, Hertwich et al.[480] and Singh[481] performed a structural path analysis, which facilitated the identification of significant process steps of the electricity generation system in relation to the global warming potential impacts.

Concerning the interpretation of results, the authors almost always concluded that additional research on certain parameters would be necessary, which therefore had consequences related to the data quality, and that the effects of future technologies were not completely understood, thus complicated the evaluation of potential environmental impacts within an LCA procedure.

LCA might not be the proper tool to explicitly suggest one system alternative among different options, but at least to give an indication in which area of the process chain additional effort is necessary for development of accurate data, because of incorporated uncertainties, and in which system parts the highest environmental loads, on basis of the reported assumptions made, are to be expected.

On which basis the assumptions were made, for example, in relation to the technological improvements, like future power plant system efficiencies or the type of releases such as CO_2 purities, in turn affecting the compression work for transport and storage, was not always clear, thus in any case a transparent procedure was not at hand, at least with the information that could be read out from the available publications.

Anyhow, the increased power plant and CO_2 capture efficiencies positively affected all impact categories, but because of the differences in time related coverage, the efficiency improvements were assumed very distinctly among the various studies.

One consensus of all authors concerned the reduction of environmental loads in the global warming impact category, and an energy penalty of the electricity production system, due to the application of CCS technology.

Conduction of a sensitivity analysis, on assumed system parameter values with high uncertainty has shown to be very useful, as it indicated the possible need for more accurate data if the effects of analyzed system parameters on certain impact categories were identified to be significant.

5.2 Issues related to the examined Studies

Generally, and besides the different systems examined, the diverse selection of the system boundaries, the data sources and quality as also the temporal and spatial relation were the main reasons making a comparison of different LCA studies almost impossible, even if transparent procedures were aspired.

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[480] Cf. Hertwich et al. 2008, pp. 343-352.

[481] Cf. Singh 2010, pp. 17-48; Singh et al. 2011, p. 20 and Singh et al. 2012, pp. 2-14.

The standards of ISO might indeed be useful when requiring a fundamental framework of performing an LCA procedure, but it can be misleading if someone expects a certain level of quality, reliability or a basis of comparison among different studies, simply because they are based on the standards of ISO.

In other words, although ISO cautions and tried to exclude as much arbitrariness and subjectivity as possible from the LCA tool, the broad interpretation, which is possible within the overall procedure, almost completely annihilates the effort of ISO's standards aiming for reliability, transparency, objectivity and comparability.

Although the consensus of different authors on potential impacts of some processes exists, other processes were however rather differently validated in terms of their significance, as indicated by the case study research. This especially concerned the impacts of processes related to certain impact categories, where the highest degree of consensus could be observed in relation to the impact categories of the global warming potential, the acidification potential, the photo oxidant formation potential and the resource depletion.

Apparently a trend of controversial interpretations mainly occurred in relation to toxicity categories.

The question may arise that the various kinds of available impact assessment methods were the reason of differing results between the studies, but those authors who incorporated more than a single impact assessment method came up with rather similar trends in their results, thus the integrity of the impact assessment methods was more or less approved, at least for those processes where the environmental mechanisms are well understood and accepted.

The variation of magnitude of the final impact assessment scores could be assigned to different characterization and weighting factors, whereas the highest variation of result trends, of course, was observed after weighting, as the focus of different weighting methods varies, as already stated above.

In terms of allocation or system expansion, which would be preferred by ISO, the authors acted with reserve, because it seemed they rather avoided conduction of allocation procedures and omitted processes instead of application of system expansion. The avoidance of system expansion might be justified in terms of ending up in too complex product systems to be evaluated.

Why allocation was avoided that consistently, although an apparent multifunctional system was at hand, was somehow elusive but might be attributed to the additional uncertainty of how to apportion input and output data between certain processes in an accurate way, thus making the procedure of allocation itself rather delicate. A sensitivity analysis would have had at least shown how allocation procedures affect the final results.

On fact that emerges, after examining the studies above, is that all processes were modeled on a relatively high level of detail, even if several assumptions were necessary to describe the system elements, up to a certain point in the system.

At this point within the product system one process was treated more or less as a 'black box', namely the process of CO_2 storage and to some extent the transport process of CO_2. Only within the study conducted by Wildbolz[482] it was tried to model the CO_2 transport and storage processes on a higher level of detail, but the high uncertainty of parameter values was explicitly noted.

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[482] Cf. Wildbolz 2007, pp. 19-58.

The transport and storage processes were not modeled in high detail and site specific data was rarely used as it was not available. But also assumptions were sparsely incorporated, which would at least have appeared to endeavor describing those processes in order to reveal the potential environmental impacts of the CO_2 storage.

This particularly concerned the leakage of CO_2 from the storage site where not only the problem of lacking data existed but also the issue of how to treat emissions to the environment within an LCA that occur in times faraway from now. Some authors already mentioned the problem of discounting future emissions with nowadays available LCA procedures.

This makes an LCA procedure referring to electricity generation with CCS technology somehow questionable, as the CO_2 transport and storage processes depict an indispensable element of the carbon capture and sequestration technology.

According to the low contribution of transport and storage to the overall impact results, which were overwhelmingly dominated by fuel supply, electricity generation and CO_2 capture related environmental burdens, the low resolution of modeling the transport and storage processes was seemingly tried to be justified based on the fact of the low contribution of resource and energy demand related environmental burdens.

But again, and as a fact, neglecting system components that in the first instance seem irrelevant can result in mistaken conclusions of the complete assessment, as in case of the study performed by Nie et al.[483] in 2009 where the 1% cut-off rule was applied to MEA production.

As already mentioned in Chapter 3 of the thesis at hand, the application of cut-off rules to highly toxic substances can result in errors in the final conclusions, which can also be true for the processes of CO_2 transport and storage. Because even if only contributing marginally to the overall system LCI data quantities, the environmental mechanisms are not very well understood, for instance, referring to impacts of CO_2 on the wildlife, the surface ecosystem or the underground environment, the potential impacts can be immense.

Again issues arise on the meaningfulness of the LCA procedure when, for example, processes are incorporated where environmental mechanisms are not well understood as in case of underground CO_2 storage. Even if authors would have tried to comprehensively evaluate this process, it would not have been possible for now, as the effects of media injected into the subsurface are not conceived and implied in the current LCA impact assessment models, thus making the determination of potential environmental impacts anyhow impossible.

Another concern rises with the lacking capability of incorporating temporal and spatial aspects such as ecosystem dynamics with a regional reference, which would be somehow vital for evaluating future related product systems with a highly site specific reference, or the discounting of future related emissions.

This prohibits, for example, the assessment of potential environmental impacts of sudden CO_2 pipeline or storage leakages on the surrounding surface environment such as wildlife or forests, which are presumably not the same for every region.

The IPCC special report on Carbon dioxide Capture and Storage as also Pehnt and Henkel addressed some potential risks on health safety and environment of geological storage of CO_2.

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[483] Cf. Korre et al. 2009, pp. 3771-3777.

These include for example:[484]

- The leakage of CO_2 due to degraded well completion infrastructure and bore hole equipment, but also leakage pathways in geological formations such as cracks, faults or fractures that may lead to a release of stored CO_2.
- Acidification and contamination of drinking water and shallower formations due to dissolution of CO_2 in formation fluids, causing acidic solutions and leakage through different pathways by water or brine movement, which may also mobilize trace metals from the surrounding rock.
- As it is not guaranteed that CO_2 will be stored at a 100% degree of purity, release of trace gases such as H_2S or SO_2 may result in increased health risks and include a higher possibility of trace metal dissolution from the surrounding formation, as these gases create stronger acidic solutions than CO_2 does.
- Geo-mechanical stress alteration, due to impacts on the geological structure as also thermodynamic variances, may lead to formation instability and seismic activity.
- The knowledge of geochemical impacts, due to reactions of substances and microbial activity, cannot be characterized sufficiently by now.

It is further mentioned that development of simulation models, to be able to predict the behavior of CO_2 in the underground storage, would be vital but that until now no risk assessment procedure exists, which allows the quantification of human health and local environmental risks caused by subsurface geological storage of CO_2.[485]

Existing risk assessment procedures common in the oil and gas industry and long-term risk assessment procedures referring to nuclear waste storage constitute a basis for systematic quantification models of potential CO_2 storage risks including, for instance, incidents related to pipelines, well equipment, etc.[486]

FEP methodology is considered to be a promising point of departure for well-established models, in order to reduce the assumptions on, for example, leakage, which are thus far afflicted by a high degree of subjectivity.[487] With this methodology, features, events and processes (FEP) such as reservoir characteristics, chemical reactions, seismic activity or other possible state changes are considered, to generate different scenarios, which might allow a statement on risk and environmental impact probabilities.[488]

Pehnt and Henkel stated in their study from 2009 that LCA is presumably not capable of assessing all of the aforementioned environmental impacts but at least may be useful to identify hot spots of the regarded system.[489]

If an LCA is performed, the impression of high significance of processes that are well understood, compared to those processes where data lacks, especially with relation to future environmental aspects, is at hand, and predictive modeling of environmental impacts is not within the scope of current LCA approaches. This would probably be possible if an ecosystem model is simulated or a risk assessment is performed, but the effort for providing the

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[484] Cf. Intergovernmental Panel on Climate Change 2005, pp. 250-264 and Pehnt and Henkel 2009, p. 50.

[485] Cf. Intergovernmental Panel on Climate Change 2005, p. 250.

[486] Cf. Intergovernmental Panel on Climate Change 2005, p. 250.

[487] Cf. Intergovernmental Panel on Climate Change 2005, pp. 250-251.

[488] Cf. Intergovernmental Panel on Climate Change 2005, p. 250.

[489] Cf. Pehnt and Henkel 2009, p. 50.

huge amount of data for such a model would presumably exceed the labor, which is already inhered in conducting an LCA.

The direct juxtaposition of stored CO_2, thus not being in the atmosphere anymore, to the additional amount of energy that can be produced with EOR and ECBM is somehow a pitfall in case of CCS systems, as with the additional supply of produced hydrocarbons simultaneously CO_2 is released to the atmosphere after combustion of hydrocarbon based fuels, thus altering the CO_2-balance.

Although it is often stated that LCA might not be the proper tool in any case, LCA might be preferred compared to the risk assessment of a certain substance or process, as risk assessment not only can incorporate even higher efforts but it also does not provide the cradle-to-grave examination, which is the one big feature LCA offers.

The insights gained after the examination of different case studies leads to one supposition, namely that conducting an LCA procedure on complex systems, including high process related data uncertainties, quickly can get very doubtful.

It appears that a detailed LCA, incorporating all aspects of ISO's standards, was not conducted by any of the authors. They rather ended up in streamlined or screening LCA studies, which might be attributed to the fact that the ISO 14040 and ISO 14044 standards are not completely adaptable for such complex systems.

Particularly where important system components cannot be modeled in sufficient detail because of lacking data, or where simply ecosystem dynamics and environmental mechanisms are not completely understood, the impact assessment procedure gets troublesome or deceptive, and the LCA tool is stretched to its limit.

5.3 An Upcoming System Evaluation facing similar Issues

Having examined the practices, issues and problems of the LCA method application, when assessing the potential environmental impacts of electricity generation systems using carbon capture and storage technology, it is now aimed to bring up a subject, namely that an LCA conducted to evaluate the environmental loads of other, but similar complex systems, will probably face identical shortages, in terms of comprehensiveness and meaningfulness of an LCA study.

After additional inquiries, another example of a complex product system was encountered, which, in relation to some aspects, is rather equal to the electricity generation with CCS technology system and that might be subject to upcoming life-cycle assessment studies.

This system refers to chemical energy storage, by utilization of the 'Power-to-Gas' technology and the implementation of underground hydrogen storage, which is briefly described within this chapter to accentuate that the LCA tool, at its current state, should be used with caution to avoid overrating of the LCA procedure, when assessing the environmental burdens of such an energy storage system.

Based on the examination of electricity generation with CCS, it seems that environmental effects of surface related processed are easier to determine, and evaluation of environmental loads within an LCA study is possible, not only because impacts can be observed and measured, or at least be estimated, but also due to the fact that environmental mechanisms are better understood.

The primary intention of this chapter is to hint that, in relation to most of the system components, data is presumably available, and thus the evaluation of environmental burdens within an LCA study is feasible.

But as in case of the electricity generation system with CCS technology especially one essential system element with potentially high environmental loads is included, namely the storage of hydrogen in underground geological formations, where an LCA study will presumably suffer from incompleteness again, as certain environmental impact aspects cannot be assessed accurately with this method, thus raising the question of meaningfulness and capability of the LCA method.

Highlighting those issues, which, for now, cannot be accurately evaluated with the LCA tool, should emphasize the areas where need for improvement exists, for example, in relation to more comprehensive impact assessment models, making it possible to assess environmental impacts of subsurface related processes that are not only limited to CO_2 and hydrogen.

Different projects all over the world, all following more or less the same system layout, and underlying the topics of power-to-gas and underground hydrogen storage, such as 'HyUnder', 'H2STORE' or 'HyChico', to name but a few, indicate the relevance of this technology for future energy carrier storage and supply models because of the demand for long-term energy storage.

As the systems are based on a technology, representing one step towards sustainability of future energy supply scenarios, it seems natural that these system alternatives will be subject to imminent LCA studies, and some relevant system aspects that might be considered, when performing an LCA study, are indicated in the following.

It has shown that the technological improvements of processes, in terms of efficiency increase, can have a considerable impact on the final LCA results, and due to the fact that an energy storage system and the power-to-gas technology are in an early stage of implementation, the incorporation of improvements may noticeably decrease the environmental impacts assessed by an LCA study, thus, for instance, increased metal recycling rates and future related electricity mix scenarios can be included.

It depends on the practitioner himself where to set the boundaries of an energy supply system, using the power-to-gas technology and underground hydrogen storage, but as in case of the electricity generation system with CCS technology several kinds of resources, such as fossil fuels, metal ores or minerals, are needed. Even if the dominance of coal supply will cease to apply for the main processes in this case, the resource requirements, for instance, to manufacture photovoltaic cells and the related mining of silica, might show a considerable impact on the final LCA scores.

Presumably the process of steel manufacturing may play an essential role as, for instance, the development of pipeline infrastructure, if the existing natural gas infrastructure cannot be used, requires a large amount of high quality steel, which has to be capable of containing hydrogen. Different concerns of the effects of hydrogen on metals, such as hydrogen embrittlement, are known, and provision of proper materials for transport and storage of hydrogen are vital for a safe system layout.

As already mentioned, the type of electricity mix incorporated in the LCA study can have a noticeable impact on the resource requirements as well, and although renewable energy sources show increasing shares, the currently provided electricity mix is still primarily based on fossil fuels.[490]

Also the consideration of toxic materials such as Cadmium compounds, emerging along the production chain of photovoltaic cells, may have a significant impact on human health

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[490] Cf. U.S. Energy Information Administration, p. 5.

as in case of MEA production, an essential solvent for the chemical absorption carbon capture process.

The construction of facilities and equipment, such as wind and photovoltaic power stations, electrolyzer stations, liquefaction facilities, compressor stations, storage facilities and infrastructure, etc., may not only play a significant role in terms of CAPEX, but presumably, are also of high importance in terms of environmental loads of the complete system, because the electricity generation process itself is not very resource intensive.

It has to be kept in mind that especially in case of comparative studies the system symmetry has to be ensured, and the environmental impacts of facilities, for example, in terms of land use, should be of interest as well. Also the life-time, of wind and photovoltaic power stations, has a direct impact on the emissions and energy requirements of such electricity generation systems.[491]

Monitoring and maintenance of equipment, facilities and infrastructure is an important aspect, as hydrogen possesses several safety relevant properties such as, flammability within a 4-75% range of concentration in air, high diffusivity characteristics because of the extremely small molecule size, not only affecting the possible rate of hydrogen leakage but also the negative effects on materials such as metals, and other properties, which highly address safety considerations, are the low ignition energy and the high explosion limits of 18-59% hydrogen in air.[492]

As the energy for the power-to-gas process is likely to be solely provided by the excess energy of renewable power generation systems, especially wind and solar photovoltaic systems, which do not require a constant feed of resources and raw materials, the electricity generation part of the complete energy supply and storage system should not result in significant environmental impacts. In case of wind power stations, the amount of full-load hours, which are usually averaged over several years, has a direct impact on the final results of an LCA, as well as the efficiency of the electricity generation system to which also transmission and rectifier losses belong, thus probably constituting the most dominant effects of the electricity generation process.[493]

The process of hydrogen production via water electrolysis, representing a core element of such an energy storage system, requires significant amounts of water for cooling as also production, which should be considered within an LCA study.

As in case of electricity generation with CCS, energy storage systems utilizing the power-to-gas technology are in an early stage of implementation and some effects of the underground hydrogen storage system component included, are not completely understood yet in terms of their impacts on the environment.

The startling similarities of an energy storage system using underground hydrogen storage and the power plant with CCS system, both representing complex product systems, which have been, and presumably will be, in the focus of LCA studies, but also the despite value and uniqueness of the LCA method itself, require further research and development of this tool, thus it is coarsely broached which environmental aspects especially in terms of underground energy storage cannot be accurately evaluated with LCA by now.

Taking into account the insights gained after the examination of electricity generation with carbon capture and storage case studies, performed in chapter 4 of this thesis, and the

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[491] Cf. Viebahn et al. 2008, p. 101.

[492] Cf. SBC Energy Institute 2014, pp. 242-243.

[493] Cf. Viebahn et al. 2008, pp. 100-103.

analogy to the power-to-gas energy supply scenarios, it might be possible to increase the transparency, comprehensibility and meaningfulness of future LCA study results.

5.3.1 Overview

A short introduction, to the power-to-gas technology and the options for hydrogen storage, is given to understand the main processes of such an energy storage system model.

Although fossil fuels and nuclear power will play the major role in future energy supply, the environmental awareness to reduce greenhouse gas emissions leads to an increasing share of renewable energy.[494] Besides bioenergy, hydropower and other renewable energy sources, the contribution of wind and solar photovoltaic power to the electricity mix will be significantly extended by 2035.[495]

The fluctuating nature of wind and photovoltaic power provision, which is also hardly to predict, has led to different options of energy storage to cover the demand for peak load electricity supply, as depicted in figure 15.

The problem of storing enormous amounts of electricity, especially for long time periods, is considered to be in the focus of future research, as the increased share of fluctuating wind and solar photovoltaic energy simultaneously requires additional accurate energy storage options.[496]

Energy storage options include, for instance, pumped-hydro power where the potential energy of water is used to store the fluctuating energy of renewable power generation systems, whereas this option is not only related to limited regional geographic opportunities but also to considerable impacts on landscape and environment.[497]

Other energy storage options, like compressed air energy storage, electrochemical energy storage systems, etc., are very costly, limited in storage capacity and often do not provide the possibility of long-term energy storage.[498]

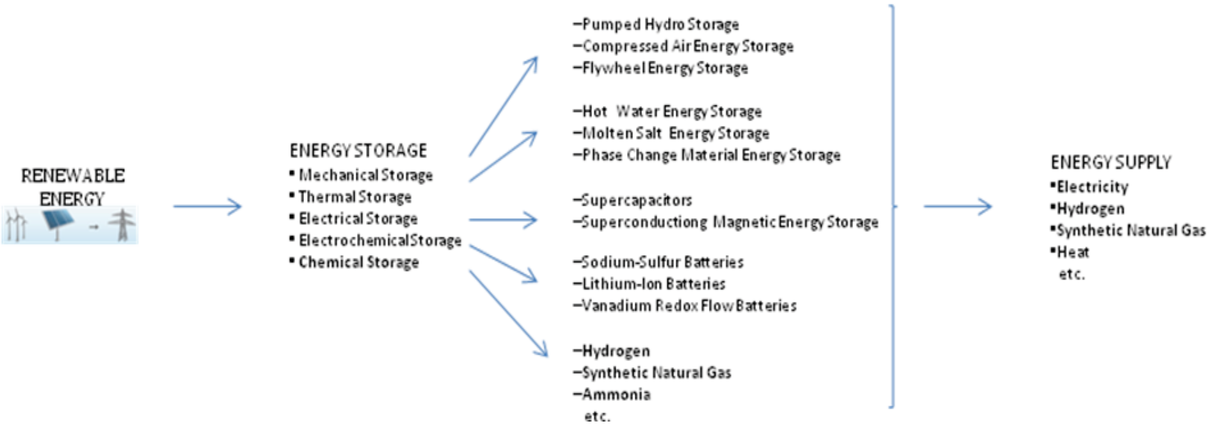

Figure 15: Energy storage alternatives[499]

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[494] Cf. International Energy Agency 2012, p. 179.

[495] Cf. International Energy Agency 2012, pp. 182-184.

[496] Cf. Bajohr et al. 2011, p. 208.

[497] Cf. Bajohr et al. 2011, p. 202.

[498] Cf. Bajohr et al. 2011, p. 202.

[499] Cf. SBC Energy Institute 2014, p. 29.

Power-to-Gas Principle

Power-to-gas is considered to be one option with a high potential to avoid the wastage of excess renewable energy, by utilizing wind and photovoltaic power in times it is generated, converting it via electrolysis, and storing it in terms of an chemical energy carrier.[500]

The significance of this principle, as a promising option for long-term storage of energy, is already illustrated by the number of performed and ongoing projects. A sample list of pilot projects utilizing the power-to-gas technology is given in Annex A.

Hydrogen seems to be a valuable and versatile option for an energy carrier, to store the surplus energy, for example, as it is not limited to be used in terms of a raw material for industrial processes such, as ammonia production, or converted into electricity within fuel cells and combustion turbines, but also plays an essential role after conversion into methane, which then can be directed into the existing natural gas grid.[501]

Another option is the direct addition of a percentage amount of hydrogen into the natural gas grid creating hydrogen enriched natural gas (HENG), whereas the tolerance of hydrogen in gas pipeline infrastructure and facilities has to be evaluated by additional research.[502]

The clear advantage of the power-to-gas principle, or more precisely of hydrogen and methane, is the long-term and high capacity storage of energy with an adequate demand based supply of energy.

Power-to-gas technology is a general description for a chain of processes to convert electricity into hydrogen, which can be further processed to synthetic natural gas, whereas different kinds of system configurations are possible, depending on the type of hydrogen use and the intention to produce SNG.

An example of the power-to-gas principle, as depicted in figure 16, shows the utilization of excess renewable energy to produce hydrogen by water electrolysis, which then, together with CO_2, can be converted into synthetic natural gas (SNG).

Hydrogen can be produced by different processes such as steam methane reforming, crude oil cracking, coal gasification or electrolysis, whereas the latter one today constitutes only a small percent share of the overall hydrogen production capacity, as this process is costly and highly energy consuming.[503]

But as most of the hydrogen production processes are based on production from fossil fuels, the combined use of excess renewable energy and electrolysis provides a promising alternative towards sustainability.[504]

Different options for water electrolysis are available, such as alkaline electrolysis, polymer electrolyte membrane (PEM) electrolysis and high-temperature electrolysis, which highly differ in their type of electrolyte and operational mode, the efficiency, and the production capacity.[505] Alkaline electrolysis is the most commonly used type as it is cheaper than, for example, PEM electrolysis, which has a lower operating equipment life-time.[506]

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[500] Cf. SBC Energy Institute 2014, p. 3.

[501] Cf. SBC Energy Institute 2014, pp. 85-103.

[502] Cf. Vogel et al. 2012, p. 661.

[503] Cf. SBC Energy Institute 2014, p. 66.

[504] Cf. Gahleitner 2013, p. 2043.

[505] Cf. Müller-Syring et al. 2013, pp. 108-109.

[506] Cf. Bajohr et al. 2011, p. 205.

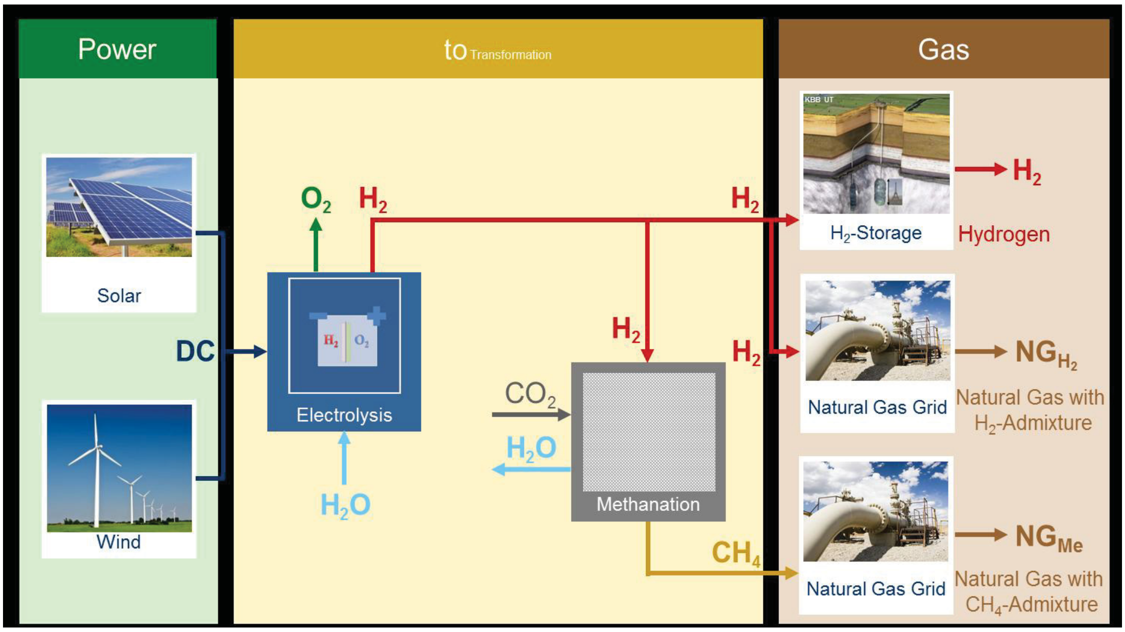

Figure 16: Principle of power-to-gas.[507]

Thermochemical methanation, according to the Sabatier process, is the preferred option for synthetic natural gas production and requires, besides CO_2, several components, such as catalysators, make-up facilities, etc., which can result in energy losses above 23%.[508] Methanation is a highly exothermic process where synthetic natural gas is produced from hydrogen and CO_2 according to the reaction depicted below:[509]

$$CO(g) + 3\,H_2(g) \rightarrow CH_4(g) + H_2O(g) \qquad \Delta_R H^0 = -206\ kJ/mol$$

$$CO_2(g) + 4\,H_2(g) \rightarrow CH_4(g) + 2\,H_2O(g) \qquad \Delta_R H^0 = -165\ kJ/mol$$

SNG provides a higher energy density, compared to hydrogen, and a full compatibility with the existing natural gas infrastructure, but additional components and process steps are required for methanation, such as catalysators, the supply and make-up of CO_2 prior to methanation, in order to eliminate impurities such as SO_x, COS, O_2, etc., and the make-up of SNG after methanation, for example, to reduce the water content.[510] Therefore additional energy is required, affecting the overall efficiency of a power-to-gas plant.

Depending on the system layout, either hydrogen or SNG are to be stored for further use. While SNG can be easily distributed and stored, using the existing natural gas infrastructure, the storage and distribution of hydrogen represents a more complex situation.

The allowable hydrogen amount to be directed through the existing natural gas infrastructure in terms of HENG currently accounts to a maximum of 2-5 Vol.%, as hydrogen induces several effects, such as altered heating value and density, which affect gas burners

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[507] Specht and Zuberbühler 2012 and Stolten and Scherer 2013, pp. 813-849.

[508] Cf. SBC Energy Institute 2014, p. 102.

[509] Cf. Bajohr et al. 2011, p. 205.

[510] Cf. Müller-Syring et al. 2013, pp. 108-109.

and turbines.[511] This leads to the circumstance that large volumes of hydrogen can only be distributed where high volumetric flow rates of natural gas exist.

Hydrogen storage

As the production of hydrogen, by utilization of the power-to-gas concept, varies with the alternating availability of renewable energy, the demand for accurate storage options is at hand.

Although decentralized production of hydrogen would overcome the claim of storage to some extent, different kinds of storage alternatives have been considered to provide a constant supply of hydrogen. An accurate storage depends on several parameters, such as the amount of hydrogen to be stored, space constraints, the cycling rate, the transport distance, infrastructural requirements and safety aspects.[512]

Figure 17 shows the main contributing processes from production to the provision of hydrogen at the end user, including distinct options for storage, whereas it is mentioned[513] that these processes may contribute a significant amount to cost and effort of an energy storage system underlying the power-to-gas principle.

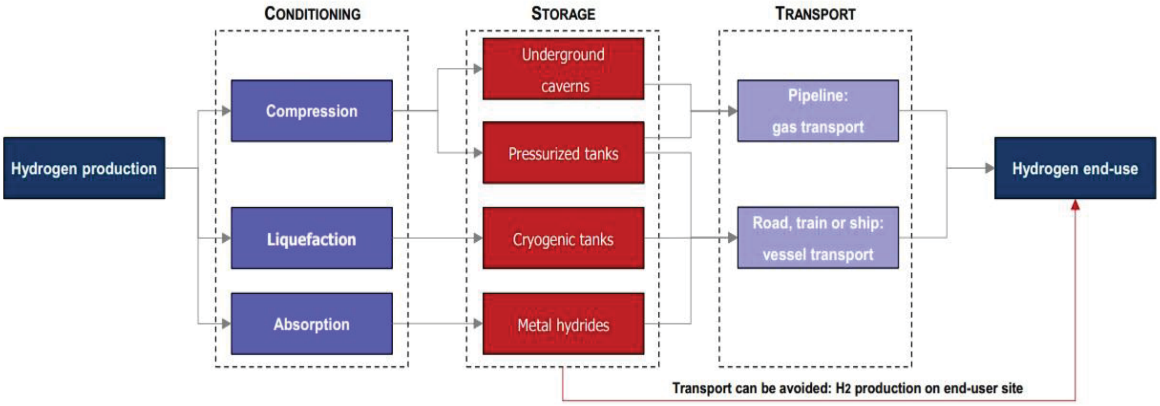

Figure 17: Process chain from hydrogen production to end-use.[514]

Pressurized tanks ensure the possibility of high cycling rates and long-term storage of hydrogen, as the rate of leakage from these tanks is considered to be low, but high the energy demand for compression, prior to storage, and the relatively low storage capacity per tank makes this option preferable for high operational cycling rates, small throughputs and short transport distances.[515]

Cryogenic tanks provide a storage option for high dense hydrogen in the liquid phase, but besides the liquefaction process, which is highly energy consuming as well, the effort of cooling, to keep the hydrogen liquid, is considerable and this type of storage is not the best alternative for long-term storage as the leakage rate accounts to about 0.1-0.5% per day.[516] High investment costs in liquefaction facilities, high boil-off rates and the unsuitability for

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[511] Cf. Gahleitner 2013, p. 2054 and Bajohr et al. 2011, p. 203.

[512] Cf. SBC Energy Institute 2014, p. 65.

[513] Cf. SBC Energy Institute 2014, p. 82.

[514] SBC Energy Institute 2014, p. 67.

[515] Cf. SBC Energy Institute 2014, pp. 68-79.

[516] Cf. SBC Energy Institute 2014, pp. 125-132.

long-term storage prevents the applicability to a stationary storage option, thus it might be most suitable for long distance transport uses.[517]

Utilization of metal hydrides, where hydrogen atoms are absorbed by metals, not only saves the trouble of liquefaction and compression efforts but also issues related to leakage are bypassed.[518] This storage option is, however, in a relatively young stage of implementation, and the long time of charging and discharging the metals as also the low cycling rates make this option rather suitable for long-term stationary hydrogen storage.[519]

Underground hydrogen storage in salt caverns, depleted oil and gas fields or aquifers, provides an efficient option for hydrogen storage as the energy required for injection, compared to other storage options, is low and the high capacity as also the suitability for long-term storage result in a promising option for hydrogen storage.[520] The disadvantages may, however, include the limited availability of accurate geological formations, low operational cycling rates and the demand of cushion gas, which cannot be used.[521]

5.3.2 Underground Hydrogen Storage

After having described the principle of energy storage projects, the importance of hydrogen storage in underground geological formations is at hand, as it represents one of few alternatives of large scale energy storage. Besides metal hydrides, pressurized and cryogenic tanks, which are especially limited in capacity, the storage in underground geological formations seems to be a promising option for long-term storage of large amounts of hydrogen.

Many projects such as ‘HyUnder’, ‘HyChico’, ‘H2STORE’, ‘Underground Sun Storage’ or the ‘NOW-Studie’ make use of the underground hydrogen storage option.

Some say that future hydrogen based energy supply models will be structurally the same as nowadays natural gas systems, which also addresses the type of underground geological storage options, including solution mined salt caverns, depleted oil and gas fields, aquifers, rock caverns and mines, whereas the last two options are not considered to contribute to a significant amount to hydrogen storage capacity.[522]

In the following, different geological types are explained to understand environmental aspects of energy storage systems where underground hydrogen storage plays a major role.

Aquifers and depleted oil and gas fields, refer to porous media storage, using the small interconnected void space between grains of sandstones, or cracks of carbonates, to contain the gas, which stays in contrast to salt caverns, where large open spaces for gas storage are artificially generated by solution mining.

The main characteristics of an adequate underground porous media storage are defined by its capacity, a proper geological formation, the ability to safely contain hydrogen without leakage by providing an accurate caprock seal, and high permeability, affecting injection and extraction rates.

Another vital aspect in relation to underground geological formations is the requirement for cushion gas that stabilizes the formation and maintains the permeability. This cushion

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[517] Cf. SBC Energy Institute 2014, pp. 72-75.

[518] Cf. SBC Energy Institute 2014, pp. 69-76.

[519] Cf. SBC Energy Institute 2014, p. 74.

[520] Cf. SBC Energy Institute 2014, pp. 68-72.

[521] Cf. SBC Energy Institute 2014, p. 72.

[522] Cf. Sherif et al. 2003, p. 50 and Kruck et al. 2013, p. 9.

gas is not available for further use and has to be left in the underground during the use of the storage formation, which can have a high impact on the cost.[523]

Salt domes can be operated with lower volumetric cushion gas requirements, or even zero cushion gas if brine is used to displace the extracted hydrogen, whereas in this case a surface brine pond of adequate size is required.[524]

All of the three types of geological formations differ in their capacity, cycling rate, development and operational cost, environmental risk, and amount of cushion gas. A qualitative comparison of those three alternatives is given in figure 18 below.

	Capacity	Cycling rate	Costs	Risk	Reactions with H_2	Cushion gas
Salt caverns	Medium	High	High	Low	Low	Low
Depleted O&G fields	High	Medium	Low	Medium	High	High
Aquifers	High	Low	Medium	High	High	High

Figure 18: Comparison of geological hydrogen storage alternatives.[525]

A detailed discussion on the spatial occurrence of geological storage options over different countries and their volumetric potential is out of the scope of this work, but it has to be mentioned that, until now, pure hydrogen has only been successfully stored in salt domes, by Praxair in the Clemens Dome (USA), by Air Liquide at Spindletop (USA), by Conoco Philips at Moss Bluff (USA) and by Sabic Petrochemicals at Teesside (UK).[526]

A short introduction on the three above quoted underground hydrogen storage alternatives is given in the following to be able to understand the possible risks and impacts on the environment, which are to be addressed later within this chapter.

Salt caverns

Salt caverns are artificially made in thick salt beds, salt domes or salt diapirs by dissolving salt with injected water, which can take a vast amount of time, to be exact one year or longer.[527] The process of constructing a cavern is achieved by drilling a well into the salt formation, providing a save gas tight access to the cavern by completion of the well with a cemented casing string, and injection of water into the salt formation to create a cavern.

During the time of construction considerable quantities of brine arise from leaching that have to be properly disposed. Figure 19 below shows the principle of this process.

The blanket is a medium, less dense than the water and brine, such as oil or an inert gas.[528] It controls the development of the cavern geometry and prohibits dissolving of salt around the cemented casing string.

The advantages of salt caverns are their extremely gas tight nature, the non-reactivity with hydrogen, higher cycling rates compared to porous media storage options, with about ten times of cycles a year ,and low cushion gas requirements.[529]

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[523] Cf. SBC Energy Institute 2014, p. 72.

[524] Cf. http://www.globalccsinstitute.com/publications/operating-flexibility-power-plants-ccs/online/104951 and SBC Energy Institute 2014, p. 73.

[525] SBC Energy Institute 2014, p. 77.

[526] Cf. SBC Energy Institute 2014, p. 73.

[527] Cf. SBC Energy Institute 2014, p. 77.

[528] Cf. Kruck et al. 2013, p. 14.

[529] Cf. Kruck et al. 2013, p. 24.

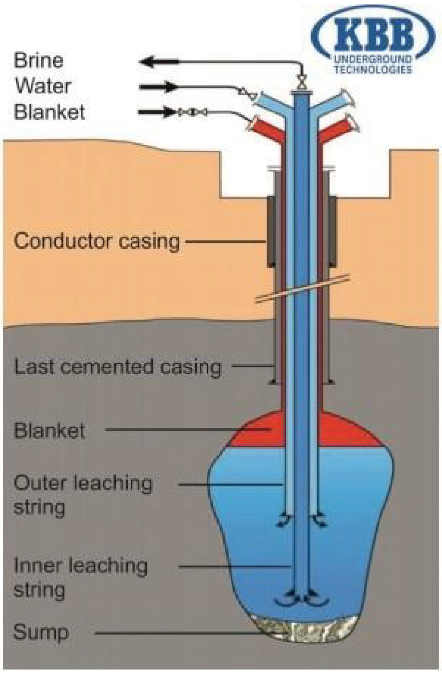

Figure 19: Salt cavern creation process.[530]

Aquifers

Aquifers are underground water bodies contained in permeable rock formations and possibly provide the largest volumetric capacity for hydrogen storage.[531] After drilling and completion of wells for injection and monitoring, hydrogen may be stored within the porespace of permeable rocks, with an accurate geological trap geometry such as anticlines, while displacing the contained water or brine.

A general layout of a possible porous media storage formation, which is in principal the same for aquifers as also depleted oil and gas fields, is depicted in figure 20 below, showing an anticline formation, capable of trapping gas.

A large share of up to two third of the injected hydrogen is required as cushion gas to prevent formation instability, and cycling rates are limited to about one turnover per year, depending on the number of wells, the permeability of the rock, and the occurrence of an active water drive.[532]

Several unknowns are related to the aquifer type of storage, such as the lack of information on proven hydrogen tightness, since gas was not in place prior to hydrogen injection, but also mineral and chemical reactions, maximum allowable injection pressure, displaced water movement, or effects of hydrogen biodegradation are unknown.[533]

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[530] Kruck et al. 2013, p. 14.

[531] Cf. SBC Energy Institute 2014, p. 77.

[532] Cf. http://www.globalccsinstitute.com/publications/operating-flexibility-power-plants-ccs/online/104951 and Kruck et al. 2013, p. 28.

[533] Cf. Kruck et al. 2013, pp. 32-37.

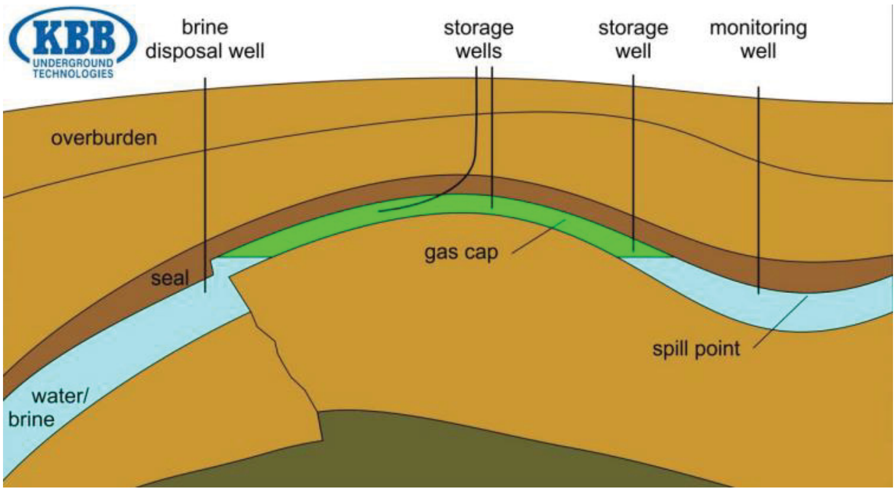

Figure 20: Porous media formation storage.[534]

Depleted oil and gas fields

Principally similar to aquifer storage, in terms of porous media storage, this alternative provides several advantages compared to aquifers, such as an existing well infrastructure, proven tightness, since hydrocarbons were in place, and existing information on reservoir characteristics such as formation pressure, permeability, etc.

Disadvantages address the same aspects as in case of aquifers, like low cycling rates, a high volumetric requirement of cushion gas, and unknown effects of hydrogen on, and with, the surrounding environment.[535]

Experiences with a town gas mixture of hydrogen, CO_2 and methane have shown that the reaction of CO_2 and hydrogen resulted in an increase of methane concentration and decreasing amounts of CO_2 and hydrogen, whereas a concurrent reduction of the overall gas volume was observed, which has been related micro bacterial activity.[536]

Reduction of volume goes along with a pressure drop, and, if the formation pressure drops below the a certain value formation, instability can provoke leakages of stored hydrogen through the caprock.

5.3.3 Environmental Issues of Underground Hydrogen Storage

After having described frequently discussed underground hydrogen storage options, it is aimed to indicate analogies to underground CO_2 storage. As already mentioned, the storage of hydrogen in underground geological formations may play a vital role in upcoming energy storage systems utilizing the power-to-gas concept, and presumably will be part of LCA studies as well, but expectably this part of the system will be treated as a black box again, as in case of the examined electricity generation systems with CCS technology.

In the following a bulleted list of potential environmental impacts related to effects of hydrogen on the subsurface environment is given on basis of past experiences and presumptions of experts.

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[534] Kruck et al. 2013, p. 25.

[535] Cf. SBC Energy Institute 2014, p. 77.

[536] Cf. http://www.ika.rwth-aachen.de/r2h/index.php/Large_Hydrogen_Underground_Storage#Underground_Hydrogen_Storage

The aim is to indicate a number of issues related to such underground storage scenarios and the demand for additional research towards an improved comprehensive LCA tool, to at least be able addressing some environmental concerns of manmade underground interventions.

Improving the LCA tool seems important, due to its uniqueness of providing a holistic life cycle view, the readily adaption in decision making, and its principal applicability to every product and chain of processes. For now, it appears that the holistic view of the method is quickly stretched to its limit if subsurface related system components are to be evaluated.

Hydrogen possesses several characteristics that can lead to complications, either in relation to equipment safety aspects, or leakage from the storage site because of its high diffusivity. Also degradation of hydrogen, because of microbacterial activity or reactions with CO_2, thus forming methane and leading to a loss of hydrogen, are only some issues that might be of concern for decision makers of upcoming energy storage projects that include underground hydrogen storage.

Of course these are sore points, which are important to be determined as these issues will especially affect the life-time of equipment, infrastructure and facilities as also the net energy efficiency and environmental load of the complete system. The point of matter is that after laboratory test, simulations and measurements most of these impacts can be quantified and incorporated in an actual LCA study, at least within a given range of certainty.

For example, the generation of H_2S, as a result of hydrogen storage, is known from past experience with town gas storage in geological formations.[537] The case study examination has shown that, in practice, some system components are subjectively ignored rather than estimated.

Ignoring potential leakages of CO_2 from the storage site, as it was the case for almost all examined case studies, may, in the slightest meaning, be justified as it especially affects the net CO_2 storage efficiency, if not accidentally released in high concentrations, but ignoring the release of even small amounts of H_2S in case of an underground hydrogen storage system seems reckless.

It is out of the scope of this thesis to explicitly ascertain all known risk related aspects of hydrogen that result in additional material requirements, energy losses or releases to the environment, having a highly site specific character and at least may be quantified by simulation methods, even though if several assumptions or estimations are needed. At this point it is suggested to perform numerical simulations and uncertainty analyses, to prove the accuracy of assumptions and estimations.

The focus of this chapter lies on highlighting some of those environmental impacts, which are pretty sure known, but, for now, cannot be evaluated within an LCA study, as the impacts of environmental mechanisms are not understood and accurate impact assessment models or characterization factors simply do not exist for the subsurface environment.

Temperature changes

It is proven that during the creation of salt caverns the temperature of subsurface salt formations is significantly altered, whereas it is mentioned that achieving the original temperature condition takes multiple times the duration of creating the cavern, which itself may take a timeframe of several years.[538] After the construction process of the cavern, the injec-

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[537] Cf. Müller-Syring et al. 2013, pp. 54-55.

[538] Cf. Kadner 2002, p. 10.

tion and extraction of gas as well affects the subsurface temperature of the surrounding formation, as can be seen in Figure 21 below for the case of natural gas extraction.

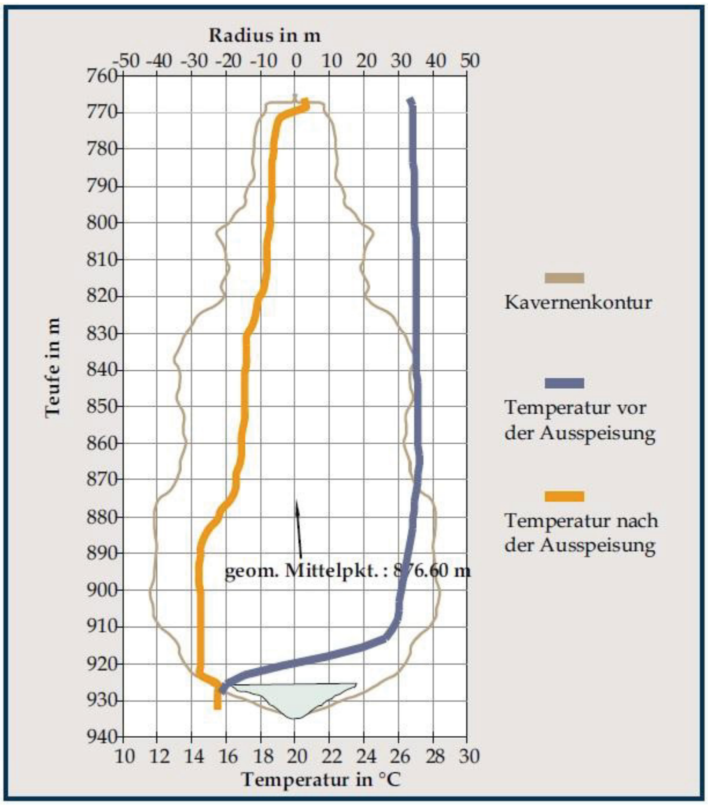

Figure 21: Temperature alteration prior and after extraction of natural gas[539]

Temperature alterations may also be a result of subsurface organism induced reactions.[540]

Changing the subsurface temperature can cause fluid density and viscosity dependent alterations in fluid movement, thus provoking, for instance, chemical and bacterial effects as also changes in mechanical behavior.[541]

Chemical and microbial induced reactions

Subsurface living microorganisms and chemical reactions of injected or dissolved substances can cause several unwanted reactions, which are not comprehensively addressed within this work as the primary aim is not to determine project specific aspects but to hint the demand for improvement of the current LCA method.

A number of experts and researchers currently determine the possible causes and paths of reactions as also induced effects of underground hydrogen storage, such as bacterial growth, formation damage related effects, characteristics of accurate rock formation, etc., thus the following aspects only provide an excerpt of potential environmental impacts related to this topic.

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[539] Kadner 2002, p. 11.

[540] Cf. Wagner 2013, p. 61.

[541] Cf. Bauer et al. 2013, pp. 3936-3940.

Besides the loss of hydrogen due to chemical reactions or precipitation products, which can plug the flow paths of underground porous media storage sites and well infrastructure, the generation of acidic media probably may occur, particularly depicting a relevant issue in relation to LCA.[542]

As many kinds of minerals and microbial organisms are present, providing a good source for a vast number of processes, the below listed reactions represent only an abstract of possible chemical or organism induced biochemical effects, but the relevance of unwanted reaction products and their environmental significance is already at hand:[543]

- Calcite dissolution: $CaCO_3(s) + H_2O + CO_2 \leftrightarrow Ca^{2+} + 2HCO_3^-$
- Anhydrite dissolution $CaSO_4(s) \leftrightarrow Ca^{2+} + SO_4^{2-}$
- Acetogenesis: $2CO_2 + 4H_2 \rightarrow CH_3COOH + 2H_2O$
- Acetate-methanogenesis:[544] $CH_3COOH \rightarrow CH_4 + CO_2$
- Sulfate-reduction: $4H_2 + SO_4^{2-} + 2H^+ \rightarrow H_2S + 4H_2O$

Acidification of underground environment due to generation of, for example, acetic acid, hydrogen sulfide or carbonic acid is an aspect, which may be difficult to quantify in terms of an LCI study, but with certainty cannot be evaluated with nowadays impact assessment methods, as environmental mechanisms and characterization factors do not exist for the subsurface.

But besides the highly toxic nature of some reaction products, especially the effect of acidification on, for instance, drinking water reservoirs, due to unwanted fluid movement, depicts a considerable issue, which favorably is to be assessed by an improved LCA procedure.

Pressure change

Injection of hydrogen into aquifers results in displacement of in-situ fluids such as brine. Invasion of brine into water bodies, used for agricultural irrigation, depicts only one effect that may have a considerable impact on the ecosystem quality and human health.

Pressure alterations due to multiple turnover cycles of the hydrogen storage, at worst, may also lead to land subsidence, upheaval of overburden rock formations or seismic effects.[545]

But also chemical reactions, induced by either microbial activity or direct reactions of injected fluids with the surrounding rock, can cause volume alteration, thus resulting in pressure changes probably provoking mechanical stresses, resulting in leakage pathways. Different kinds of substances dissolved in formation fluids may escape into areas where they can cause great harm to the environment.

An example of an accident, not directly related to underground hydrogen storage, but resulting from manmade intervention in the subsurface concerns the wildcat wells, drilled for the purpose of geothermal energy exploitation, at Staufen (Germany) where the invasion of fluids into an anhydrite formation caused serious damage.

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[542] Cf. Wagner 2013, pp. 24-35.

[543] Cf. Wagner 2013, p. 25.

[544] https://www.boundless.com/microbiology/microbial-metabolism/anaerobic-respiration/methanogenesis/

[545] Cf. Kruck et al. 2013, p. 33 and Bauer et al. 2013, p. 3940.

An Anhydrite formation, if invaded by water, results in extensive volume increase and possible upheaval at the surface, as it was the case at Staufen. Unwanted pressure induced fluid movement into other geological formations therefore can have considerable impacts on the environment and human health.

5.3.4 Demand for Additional Research

Based on the fact that the process of underground CO_2 storage was modeled on a rather low level of detail, not to say it was completely omitted from the system evaluation, it was investigated if a need exists, for upcoming LCA studies, in order to evaluate potential environmental impacts of other complex product systems, including subsurface related processes.

With increasing share of renewable energy production, the demand for accurate storage options will presumably be subject to future energy supply scenarios, including system elements that are hardly to characterize.

Concerns mainly address how to incorporate issues within the LCA, such as impacts of substances on the underground environment, as it seems that, besides missing data, the lack of understanding underground environmental mechanisms, which in turn results in the absence of accurate impact categories or impact assessment models, prohibits assessing environmental impacts of, for example, underground energy storage processes.

Figure 22 indicates only some of the interventions related to possible subsurface operations, but the demand for additional research, and the advantage to be able to consider possible environmental impacts on the subsurface within an LCA, is at hand.

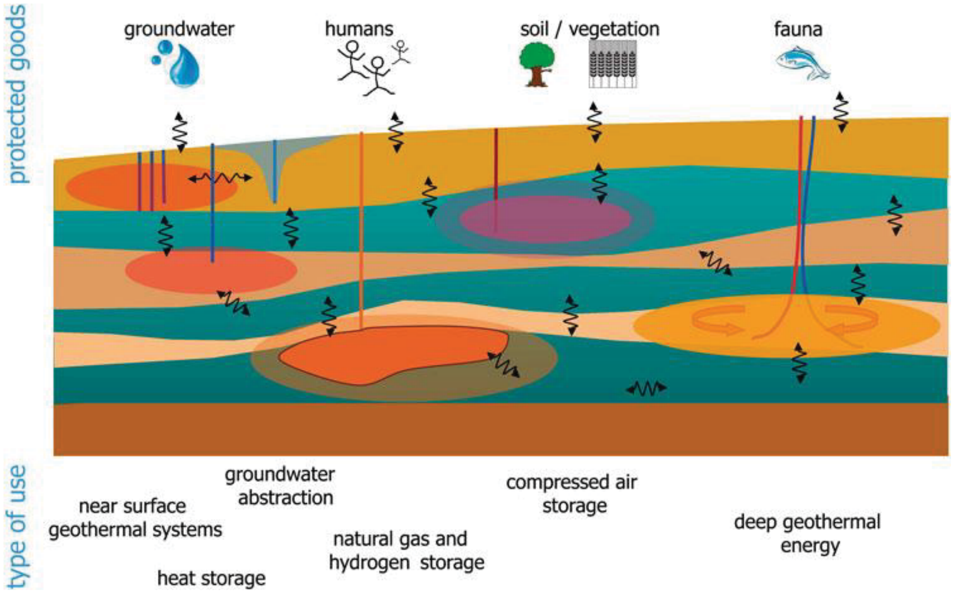

Figure 22: Protected goods affected by subsurface use alternatives[546]

Further research was undertaken if LCA studies have been conducted in the past that account for environmental burdens of underground related processes, such as nuclear power generation systems, in order to reveal if the current LCA tool can be used to comprehensi-

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[546] Bauer et al. 2013, p. 3937.

bly evaluate product systems, incorporating processes referring to unknown ecosystem dynamics and data uncertainty.

As expected the number of conducted LCA studies, in the field of nuclear waste disposal resulting from nuclear power generation, is actually sparser, as in case of electricity generation systems with carbon capture and sequestration, and in fact a published LCA including nuclear waste disposal was not found, which would have provided information on how the LCA was performed or which parameters were included.

Underlying the fact that environmental impacts of underground processes, whether storage of nuclear waste or storage of CO_2 to name but a few examples, highly depend on detailed site specific characteristics, such as reservoir properties in case of CO_2 or hydrogen storage, which, for example, influence the effects of possible leakages, brine movement, temperature alteration, etc., and as mentioned by ISO[547], LCA is not the proper tool to prognosticate strict or evident environmental impacts related to a certain time and region.

This results because LCA usually provides a broad view on the system model with lower level of detail compared to RA and considers longer periods of time with a combination of global and regional environmental impact categories, such as the global warming potential, which is an indicator for greenhouse gas emissions with a global relation and a time frame of, for instance, fifty or hundred years. The acidification potential, on the other hand, rates acidification impacts on a regional scale with distinct temporal restrictions, compared to the global warming impact category.

Again, the clear advantage of LCA is its ability to comprehensively examine a product system, including globally distributed processes and system components, with a broad view on potential environmental impacts, in terms of inputs and outputs of a system under investigation, generated along the complete life-cycle, and in relation to a large variety of environmental aspects, represented as environmental impact categories.

This special characteristic of the LCA tool enables the practitioner to identify system hot spots, namely those processes or elements of a product system having a considerable impact on the final results of the system evaluation, for example, in terms of resource requirements, energy input, emissions or other releases to the environment.

Not all of these determined hot spots are implicitly adhered to a specific temporal or spatial environmental risk. After identification of dominant effects, they can also be used as points of departure for further discussion, for example, in terms of process optimization and system efficiency improvement, or to provide information on areas where additional research demands, such as data gaps, data uncertainties or system model shortcomings, were ascertained. These areas, subject to additional research requirements, may result in refinements of the system model, thus also refers to the iterative nature of LCA.

The so called hot spots, however, may also incorporate highly site specific temporal and spatial threshold concerns, such as local substance concentrations or emissions. For this purpose Risk Assessment is the suitable tool, designed to determine ultimate environmental impacts on basis of dose-response assessment, in order to quantify risk.

In this case, only the combination of LCA and RA provides the essential level of detail necessary to come up with a measure, or to allow a prediction, on actual and site specific environmental impacts, including background concentrations to quantify the risk.

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[547] Cf. ISO 2006a, p. 9.

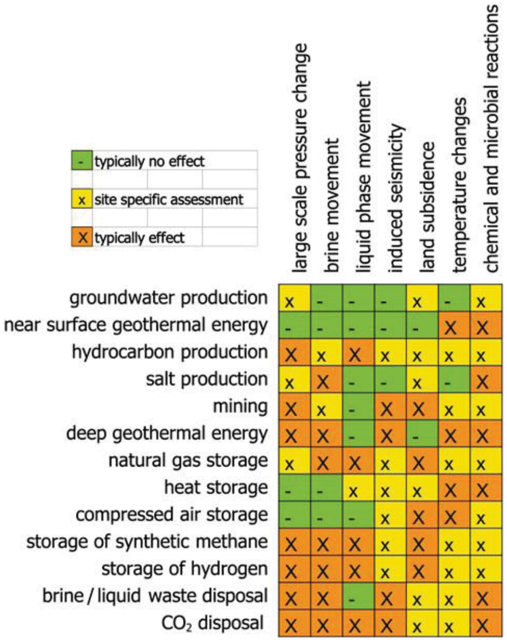
A detailed discussion on the differences of LCA and RA is beyond the scope of this work but it has to be mentioned that LCA, if conducted prior to RA, is able to highlight potential environmental hot spots, which then should be subject to RA, because LCA provides the consideration of a broad range of environmental impacts, as can be seen by the number of available impact categories.

Additional research, in terms of more comprehensive impact assessment models, to properly account for environmental loads of, for example, underground storage related processes, would presumably not only enhance the reliability of LCA studies, including product system elements adhered to lack of understanding and missing data, but also provides a higher possibility identifying those system components that, in further succession, should be subject to subsequent RA.

Since its development, LCA stays in a continuing process of improvement towards an increased comprehensive, transparent and reliable procedure to determine and evaluate environmental burdens, and furthermore to provide a basis for following discussions of potential environmental aspects of products and services.

Figure 23 shows some subsurface related interactions and a qualitative estimation of possible effects adhered to those certain processes. Determination of new environmental mechanisms and definition of potential effects on the ecosystem, human health and resources, to be able to account for effects, such as seismic activity, brine movement, etc., within an LCA study would embody a big step forward within the continuous improvement process of the LCA tool.

The proclamation towards the improvement of LCA, to be able to evaluate potential environmental impacts with focus on subsurface interventions, in order to avoid misinterpretation and short coming of LCA results by studies, trying to assess underground related processes such as CCS, hydrogen storage, geothermal use, etc., is only one aspect, among a number of upcoming upgrade efforts as, for instance, covering all three dimensions of sustainability, but the importance has been shown.



- typically no effect
x site specific assessment
X typically effect

	large scale pressure change	brine movement	liquid phase movement	induced seismicity	land subsidence	temperature changes	chemical and microbial reactions
groundwater production	x	-	-	-	x	-	x
near surface geothermal energy	-	-	-	-	-	X	X
hydrocarbon production	X	x	X	x	x	x	x
salt production	x	X	-	-	x	-	X
mining	X	x	-	X	X	x	x
deep geothermal energy	X	X	-	X	-	X	X
natural gas storage	x	X	X	x	X	x	x
heat storage	-	-	x	x	x	X	X
compressed air storage	-	-	-	x	X	X	x
storage of synthetic methane	X	X	X	x	X	x	x
storage of hydrogen	X	X	X	x	X	x	x
brine / liquid waste disposal	X	X	-	X	x	x	X
CO_2 disposal	X	X	X	X	x	x	X

Figure 23: Environmental impacts of subsurface use alternatives[548]

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[548] Bauer et al. 2013, p. 3940.

At the moment it seems vital for the comprehensiveness of actual LCA studies, including processes where ultimate impacts on the environment can be expected, to additionally complement the evaluation of potential environmental impacts with numerical simulation methods and ecosystem models, in order to allow depicture of worst case scenarios.

Especially if storage processes like, for instance, underground hydrogen storage, are not fully understood, including impacts on the environment, such as acidification due to acetate generation, effects of hydrogen and reaction products on underground organisms, temperature alterations due to subsurface related operations or effects of pressure changes, to name but a few potential impacts, LCA is currently not meant to be used as a capable tool comprehensively evaluating environmental effects of such product systems.

This is also true for nuclear power generation systems, where the storage process of nuclear waste environmental aspects seemingly cannot be assessed accurately in terms of LCA, as the leakage of radioactive material or waste is highly site specific, thus resulting in ultimate impacts on the environment of a certain region, which, for now, is completely out of the scope of the current LCA method.

Efforts towards the improvement of the LCA tool can be watched with interest as the uniqueness of this method, in terms of providing a comprehensive view on the environmental loads of a unlimited range of various product systems and its adaptability by different backgrounds of practitioners, is without equal.

6 Summary and Recommendations

A brief recap of all insights gained during the examination and analysis of case studies is given in the following. Although it appears that some points are self-evident, the examination of LCA studies, performed to evaluate the environmental loads of electricity generation with CCS, has spawned a number of issues and limits.

If special attention is paid to those aspects future LCA studies probably might not suffer from similar shortcomings again, thus increasing comprehensiveness, transparency and meaningfulness. The aspects listed below not only addresses the results of practices of authors but also concerns of the applicability of ISO's LCA procedure.

It has to be mentioned that the examination of case studies, as also the list below, is based on the information gathered from available publications of the authors. This comprises the probability of incomplete information, because of the nature of publications, such as limited space within articles, scientific papers and journals, meaning that the authors may have addressed the mentioned practices, issues and limits but have not, or were not able to publish them after all.

- Although all systems used 1kWh electricity produced as the functional unit, no straight forward comparison of case studies was possible, due to subjective selection of distinct system boundaries, spatial and temporal variations, different LCIA methods, etc.
- Shortcomings of transparency, such as missing quantitative system flow diagrams, not replicable derivation of assumptions related to LCI data, or bases for allocation procedures, as also exclusion of system components.
- No precision of input and output data. Numerical modelling methods, such as Monte Carlo Simulation and quantitative information of data uncertainty, was never depicted, which would have been interesting, especially for incorporated technological improvements.
- Technological improvements were mostly considered for foreground processes, not for background processes, such as resource supply, raw material processing, recycling, etc.
- Allocation procedures were seldomly performed. Allocations of LCI data were conducted subjectively without any indication for significance on doing so. Sensitivity analyses were seemingly never performed on executed allocation procedures.
- Omission of complete system components was seemingly often practiced rather than system expansion or allocation. The cradle-to-grave nature of the LCA method was apparently often not utilized, especially in terms of missing recycling, waste treatment and final disposal processes.
- Very low level of model detail of the CO_2 storage site characteristics. With the actual existing impact assessment models the contribution of CO_2 transport, via pipeline and the storage, to the overall environmental loads was determined to be nearly negligible.
- Neglection of CO_2 leakage rates from the storage site was almost always indicated, thus leakage rates of the storage were never incorporated in the final results. The missing ability to discount future emissions was sometimes mentioned.

- Selective choice of impact categories. Noise, land use, radiation, PMFP, etc., were seldomly considered within the assessment.
- The highest trend of discrepancies of authors in the category results was observed in relation to toxicity related impact categories.
- Missing characterization factor for mono-ethanolamine in the utilized LCA software was mentioned by some authors. As a result, incorporation of MEA related background processes were not always indicated, thus presumably were omitted.
- Indication for a conducted critical review was not ever given, thus a critical review was never published.

Due to basic shortcomings of the LCA procedure, such as the impossible incorporation of local and temporal environmental aspects (e.g. local impacts on the environment of sudden pipeline leaks, discounting of future relate CO_2 leakage rates, etc.), or missing impact categories, due to lack of understanding environmental mechanisms in order to evaluate environmental impacts of subsurface related interventions, but also seemingly difficult to implement LCA methods such as system expansion and allocation, requires additional improvement, to provide a well suited LCA tool, capable of upcoming demands.

It might not be possible to convert LCA into a predictive assessment method, able of evaluating highly site-specific ultimate impacts of processes, but efforts should be made towards the increase of practicability in order to ensure transparency, reliability, objectivity and comparability, as it seems that, on basis of the insights gained after the examination of case studies, the practitioners had serious problems to address those parameters.

Some statements of the authors on the refinements made during their LCA study, as it is iterative in nature it can be expected that some adjustments were necessary, would presumably have had encouraged other practitioners, aiming for an LCA study with the same topic, to concentrate on the difficulties former authors experienced. Thus reporting of iterative refinements might be vital to avoid similar restrictions.

On basis of the insights gained, from the examined electricity generation system with CCS case studies as also the possible similarities to the energy storage system utilizing the power-to-gas principle and underground hydrogen storage, a list of suggestions is given in the following.

These recommendations especially address LCA related methodological choices as well as criteria, which have had, or, could have an impact on reliability, transparency and meaningfulness of future LCA studies.

LCA-Methods/Criteria/System Aspects	**Practiced in examined power plant with CCS system LCA studies**	**Suggestions for upcoming energy storage with power-to-gas and underground hydrogen storage LCA studies**
Technological Improvements	Improvements in efficiency were usually considered only for foreground processes.	Improvements in electricity mix, process efficiencies, increased metal recycling rates, etc. can significantly affect the final results.
System Boundaries	System boundaries were drawn very distinctly, sometimes not reproducible and the system was seldomly, not to say never, modeled in the sense of a detailed process-LCA as proposed by the ISO standards.	To exploit the full potential of the LCA method, including all processes from cradle-to-grave would be meaningful. At least incorporation of resource supply, raw material processing, reuse, recycling and waste treatment of the main system elements is suggested.

Allocation and System Expansion	Allocation procedures were rarely conducted, and if, were very selective in nature. System expansion procedures were not indicated.	System expansion should preferred but may result in unrewarding high effort. But prior to exclusion of complete system parts, allocation procedures should be considered, and if done so, conducting a sensitivity analysis on the performed allocation step is suggested.
%-Cut-Off Rule	Among the examined studies a %-Cut-Off rule was only once applied for MEA production with considerable effects on the human toxicity potential category.	This rule should under no circumstances be applied to process where highly toxic substances are involved. A hint is here given, for example, to the production of solar photovoltaic cells.
Co-Products	Multifunctional systems were at hand, and sometime were indicated, but co-products were not incorporated in any of the examined LCA studies.	Co-products of foreground processes, which might be considered in the energy storage system are, for example, heat and oxygen from water electrolysis or salt from solution mining, if not treated as waste.
Data Precision	Measurements of data uncertainty, such as probability functions, were never indicated.	If assumptions and estimations are necessary, it is highly suggested to indicate the range of certainty of the included data, in order to prove the reliability of the final results.
Numerical Simulations	Not conducted	Numerical simulations, for example, with Monte Carlo Simulation, will presumably significantly increase the reliability of assumptions related to technological improvements, leakage rates, etc.
System Flow Diagram	A flow chart was rarely depicted, and if, very simplified without quantification of input and output flows.	A detailed flow diagram provides a straightforward identification of main contributing flows and processes for all readers of an LCA study.
Storage Site Leakage Rate	CO_2 leakage rate was always neglected.	Neglection of H_2 leakage might be justifiable according to some authors[549], but H_2 contributes to climate change as well. Neglection of H_2S leakage from the storage site seems reckless.
Impact Category Selection	The available impact categories were incorporated very distinctly.	Much effort was included to end up in a number of various impact categories, and although some categories probably seem unimportant, compared to others, as many impact categories as possible should be considered to be able to identify hot spots of a product system. Especially in case of renewable energy generation with wind and solar photovoltaic power plants the category of land use might play a considerable role within the final results.
Iterative Steps	Not indicated	Reporting difficulties that lead to iterative refinements may support following practitioners to focus on these aspects in order to improve their LCA study.

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[549] Cf. SBC Energy Institute 2014, p. 232.

7 Conclusions

The aim of the work at hand was not to unjustifiably criticise the LCA tool, as the limits are well stated, thus LCA, as a tool, should not be stretched beyond its limit by expecting the assessment of ultimate impacts of every product system.

Especially product systems including certain processes, which are not yet completely understood in terms of potential accidents, or environmental mechanisms, risk assessment might be conducted additionally for an overall image of complex systems. Otherwise there might be the pitfall of overrating the LCA tool as a standalone procedure to be able to consider every single aspect fraught with risk.

Limits of LCA are seemingly quickly exceeded when product systems are to be evaluated, including relatively unknown unit processes where data is missing and assumptions are related to high uncertainty, but also where environmental impacts are highly site specific.

ISO's efforts towards a standardized LCA approach are highly remarkable, but may include the need for improvement towards applicability as it seems that the authors had troubles with documenting a transparent procedure, but also with utilization of certain LCA procedures such as allocation, which was seldomly applied.

This, as well, concerns the iterative nature of LCA, because it was not achievable within the given information, of the examined studies above, where iterative modifications or improvements have been realized to end up in the final illustrated results. It would be helpful, for other authors or interested parties, to indicate where practitioners of certain studies were faced with difficulties, when evaluating the product system within the LCA, and how they have been overcome.

As LCA, since its development, gained in popularity, and evaluation of increasingly complex systems is noticeably in the focus of companies, the possibility of discounting future related emissions could possibly enhance the integrity of LCA, and might be one step towards the improvement of LCA. This could in turn facilitate addressing, for instance, storage site leaks.

It seems that, with the actual approach, LCA is particularly useful when assessing different kinds of product systems within one study, to allow comparison of potential environmental impacts within the same study, as the authors of one study would presumably try to model the various product systems on a comparable basis. A comparison of product systems of different studies has shown to be tricky, as it is very difficult for third parties to comprehend every assumption a certain author made during his specific study approach.

As the lack of understanding environmental mechanisms increases from mid-point to end-point impact assessment approach, it would probably increase the reliability, and, of course, the transparency of an LCA study, to concentrate on determination of mid-point indicator results, and illustrate them, in terms of contribution analyses, for every impact category separately, as midpoint indicator scores are considered to be more reliable than end point category results.

Also weighting of impact assessment scores almost completely comes at the price of transparency, thus making any comparison among different studies and the comprehensibility for third parties nearly impossible.

Other suggestions for future developments of the LCA tool would, for example, include aspiring one single database concept, which is peer-reviewed and internationally accepted. This could probably enhance the comparability of different LCA studies, as the varying data sources, besides the assumptions that might be incorporated in an LCA study, makes the comparison of distinct study results almost impossible.

Generally the practitioner of an LCA study is faced with the complexity of investigation depth and the applicability of the method. ISO's suggestions towards transparency, reliability and precision are somehow difficult to incorporate, as the effort to include several suggestions of ISO in an LCA study is considerable and the selective application of ISO's suggestions was apparent in the examined studies above.

The modelling of future processes, or those processes in an early stage of implementation, is accompanied with high uncertainty, and, approximations on future developments as performed by the authors, of the studies examined above, have not been substantiated with probabilistic modelling.

Uncertainty in LCA has been discussed by different authors and addresses several aspects, such as the data quality in terms of measurement accuracy and representativeness, system modelling related uncertainty, data assumptions to overcome data gaps, LCA method selection related uncertainty, effects of scale changes of the functional unit, etc.[550]

Simulation methods, such as the Monte Carlo Method, would at least have indicated a certain range of probability related to assumptions, which in turn could be used to evaluate a definite range of certainty of the final results, thus increasing the reliability of the study. It seems that most of the authors constrained their results to a single outcome, which might be based on the fact that LCA is supposed to be quantitative in nature, but at the same time it seems that some system elements incorporated rather qualitative assumptions.

Supporting the final results with probability simulation methods, for example, in case of occurrence of CO_2 leakage, if a storage site leaks, thus simulating a worst case scenario, could have been incorporated within a comprehensive LCA approach.

The LCA of complex systems is afflicted by high uncertainties, whether in relation to data quality aspects or the occurrence of certain future related situations, but also limited in terms of evaluating unknown environmental mechanism of certain unfamiliar or novel processes.

Even a detailed process-LCA, as proposed by ISO, is actually not capable of handling those issues, and the assessment of such product systems might preferably be complemented with ecosystem models, numerical simulations, or an evaluation of additional environmental loads accompanied by certain worst case situational conditions.

An all inclusive suggestion on how to perform an LCA study in order to evaluate the potential impacts of complex systems on the environment is out of the scope of the work at hand, but is was attempted to highlight practices and issues of the current LCA method, which might be considered useful for operators of future studies facing similar objectives.

Particularly where important system elements cannot be modeled in sufficient detail because of lacking data, or where simply ecosystem dynamics and environmental mechanisms are not completely understood, as in case of subsurface related interventions, the overall assessment procedure get troublesome or deceptive, and the LCA tool is stretched to its limit.

Efforts towards the improvement of the LCA tool can be watched with interest as the uniqueness of this method, in terms of providing a comprehensive view on the environmental

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[550] Cf. Reap et al. 2008, p. 383 and Weidema 2000, p. 63.

loads of a unlimited range of various product systems and the adaptability for different backgrounds of practitioners, is without equal.

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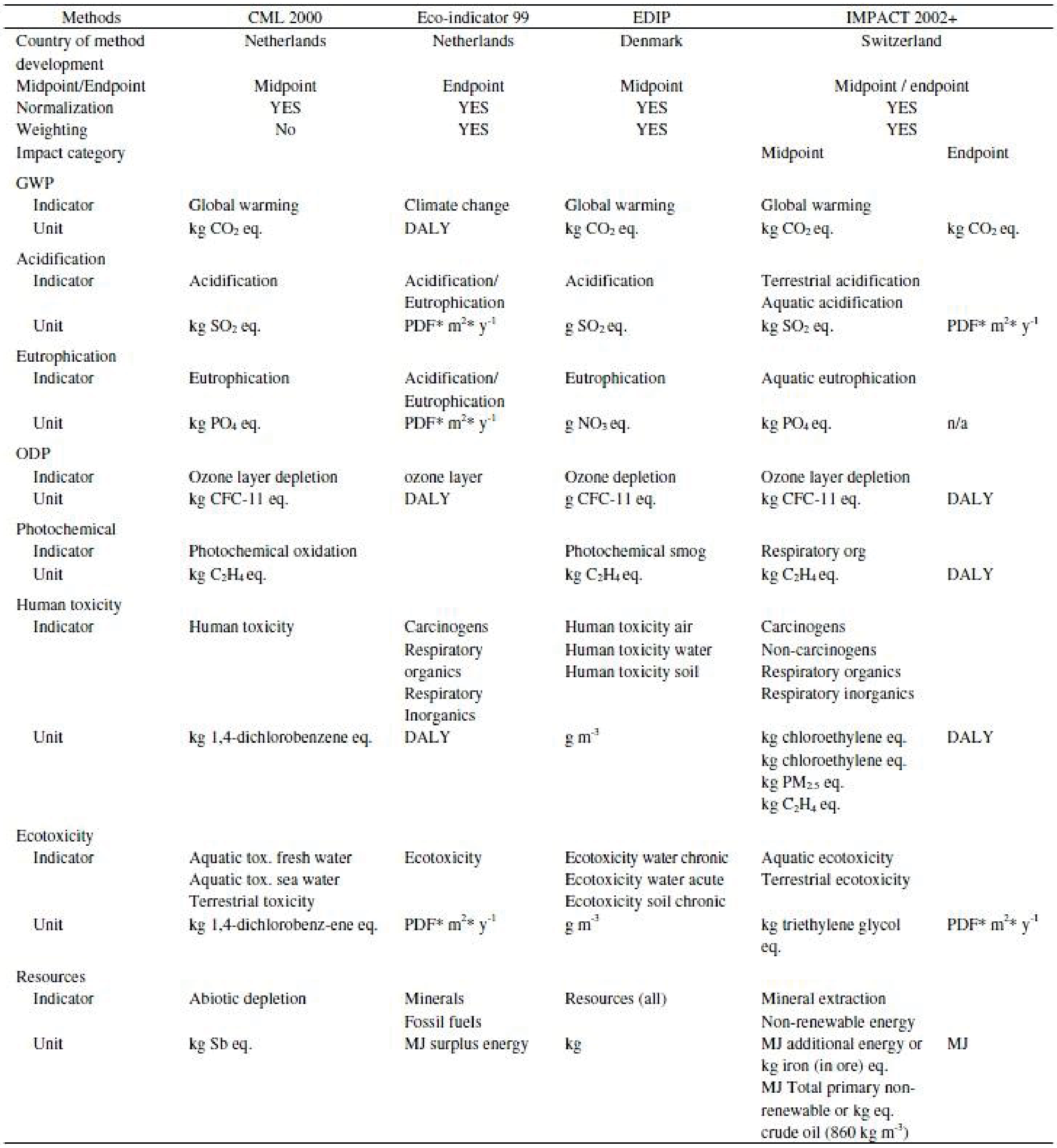
Annex A

A.1. Examples of different indicator units incorporated in distinct LCIA methods.[551]



Methods	CML 2000	Eco-indicator 99	EDIP	IMPACT 2002+	
Country of method development	Netherlands	Netherlands	Denmark	Switzerland	
Midpoint/Endpoint	Midpoint	Endpoint	Midpoint	Midpoint / endpoint	
Normalization	YES	YES	YES	YES	
Weighting	No	YES	YES	YES	
Impact category				Midpoint	Endpoint
GWP					
Indicator	Global warming	Climate change	Global warming	Global warming	
Unit	kg CO_2 eq.	DALY	kg CO_2 eq.	kg CO_2 eq.	kg CO_2 eq.
Acidification					
Indicator	Acidification	Acidification/ Eutrophication	Acidification	Terrestrial acidification Aquatic acidification	
Unit	kg SO_2 eq.	PDF* m^2* y^{-1}	g SO_2 eq.	kg SO_2 eq.	PDF* m^2* y^{-1}
Eutrophication					
Indicator	Eutrophication	Acidification/ Eutrophication	Eutrophication	Aquatic eutrophication	
Unit	kg PO_4 eq.	PDF* m^2* y^{-1}	g NO_3 eq.	kg PO_4 eq.	n/a
ODP					
Indicator	Ozone layer depletion	ozone layer	Ozone depletion	Ozone layer depletion	
Unit	kg CFC-11 eq.	DALY	g CFC-11 eq.	kg CFC-11 eq.	DALY
Photochemical					
Indicator	Photochemical oxidation		Photochemical smog	Respiratory org	
Unit	kg C_2H_4 eq.		kg C_2H_4 eq.	kg C_2H_4 eq.	DALY
Human toxicity					
Indicator	Human toxicity	Carcinogens Respiratory organics Respiratory Inorganics	Human toxicity air Human toxicity water Human toxicity soil	Carcinogens Non-carcinogens Respiratory organics Respiratory inorganics	
Unit	kg 1,4-dichlorobenzene eq.	DALY	g m^{-3}	kg chloroethylene eq. kg chloroethylene eq. kg $PM_{2.5}$ eq. kg C_2H_4 eq.	DALY
Ecotoxicity					
Indicator	Aquatic tox. fresh water Aquatic tox. sea water Terrestrial toxicity	Ecotoxicity	Ecotoxicity water chronic Ecotoxicity water acute Ecotoxicity soil chronic	Aquatic ecotoxicity Terrestrial ecotoxicity	
Unit	kg 1,4-dichlorobenz-ene eq.	PDF* m^2* y^{-1}	g m^{-3}	kg triethylene glycol eq.	PDF* m^2* y^{-1}
Resources					
Indicator	Abiotic depletion	Minerals Fossil fuels	Resources (all)	Mineral extraction Non-renewable energy	
Unit	kg Sb eq.	MJ surplus energy	kg	MJ additional energy or kg iron (in ore) eq. MJ Total primary non-renewable or kg eq. crude oil (860 kg m^{-3})	MJ

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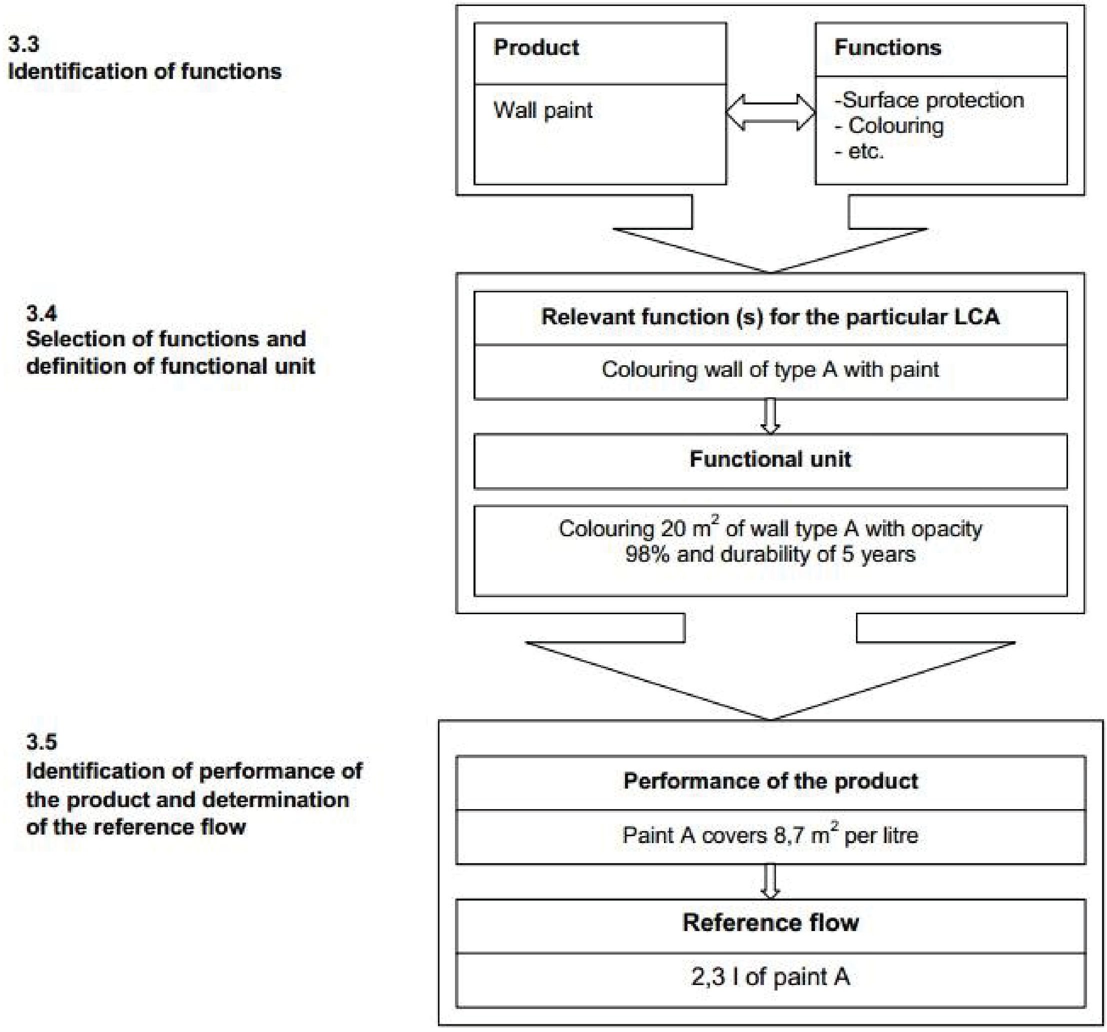
[551] Ming-Lung Hung et al. 2009, p. 157.

A.2. Example of developing functions, functional unit and reference flow.[552]



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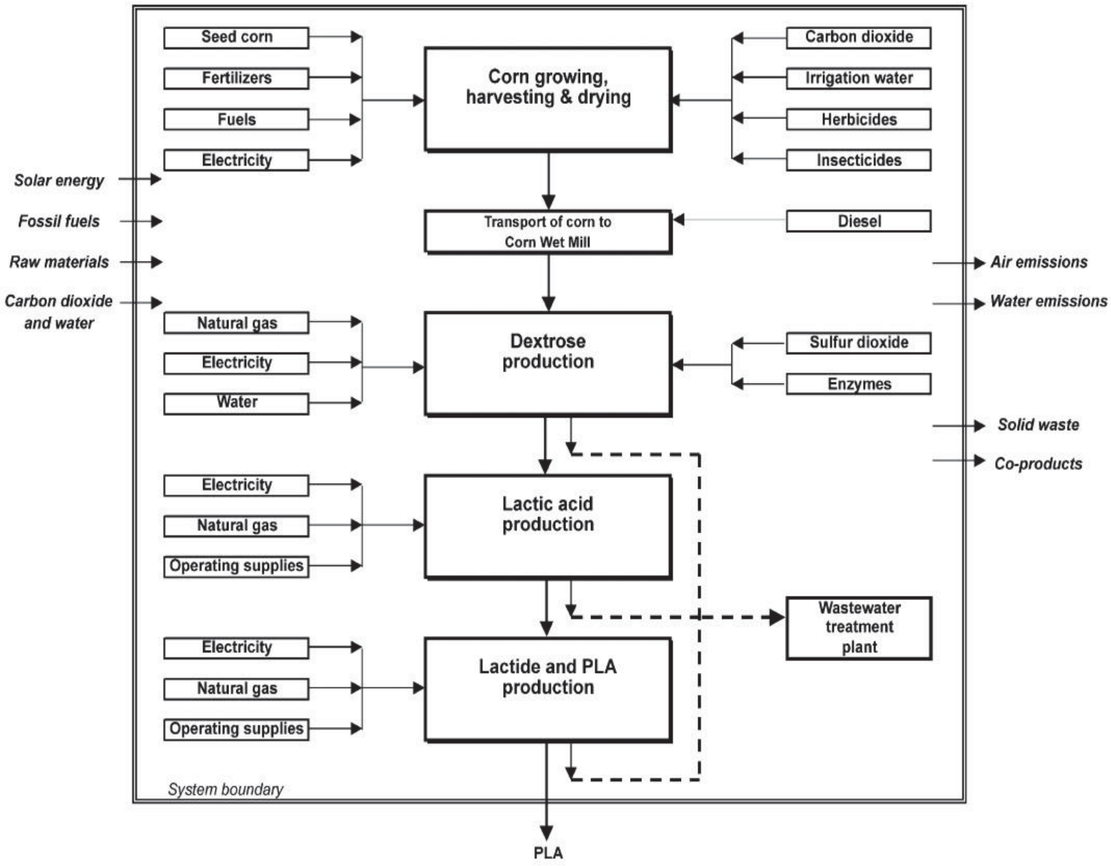
[552] ISO 2000, p. 4.

A.3. Example of a flow diagram for polylactide (PLA) production.[553]



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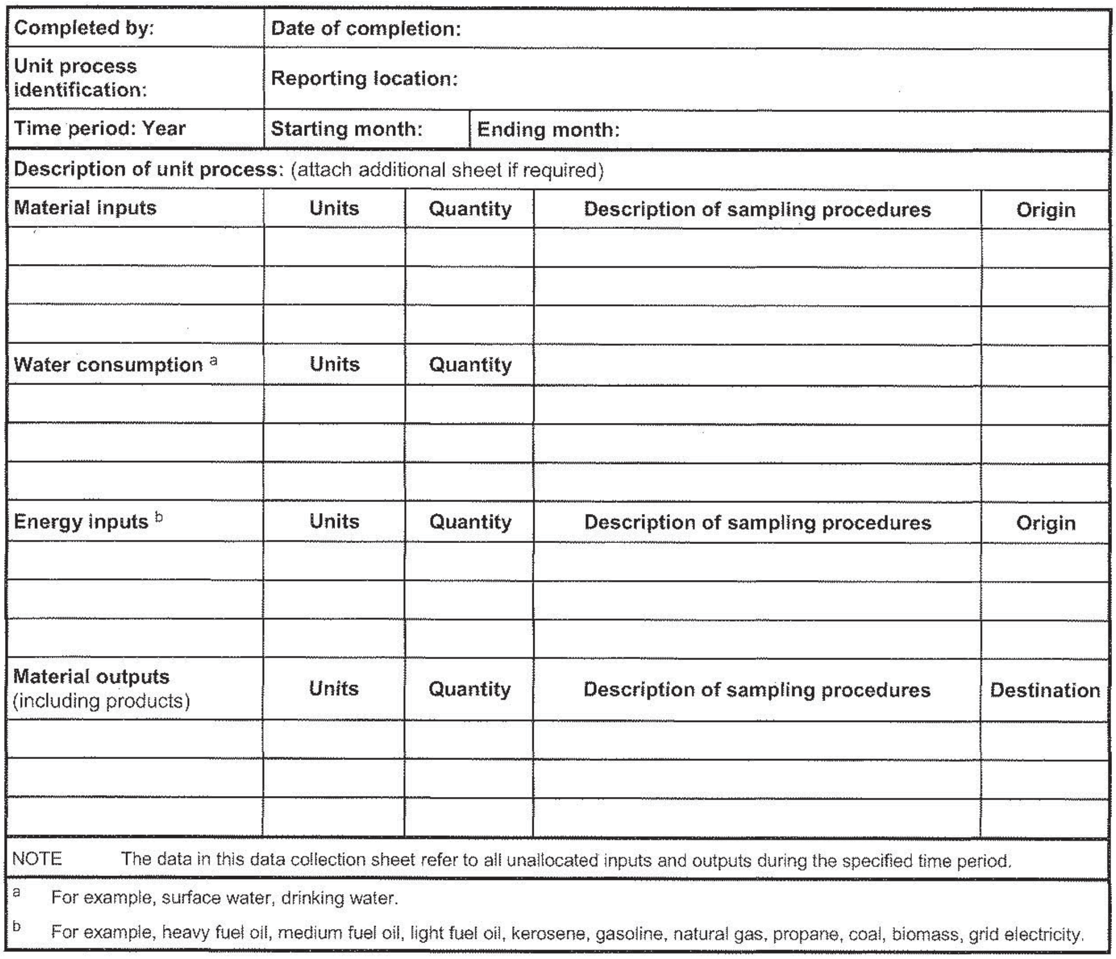
[553] Vink et al. 2003, p. 409.

A.4. Example of a data collection sheet for a unit process.[554]



Completed by:	**Date of completion:**			
Unit process identification:	**Reporting location:**			
Time period: Year	**Starting month:**	**Ending month:**		
Description of unit process: (attach additional sheet if required)				
Material inputs	**Units**	**Quantity**	**Description of sampling procedures**	**Origin**
Water consumption [a]	**Units**	**Quantity**		
Energy inputs [b]	**Units**	**Quantity**	**Description of sampling procedures**	**Origin**
Material outputs (including products)	**Units**	**Quantity**	**Description of sampling procedures**	**Destination**

NOTE The data in this data collection sheet refer to all unallocated inputs and outputs during the specified time period.

[a] For example, surface water, drinking water.

[b] For example, heavy fuel oil, medium fuel oil, light fuel oil, kerosene, gasoline, natural gas, propane, coal, biomass, grid electricity.

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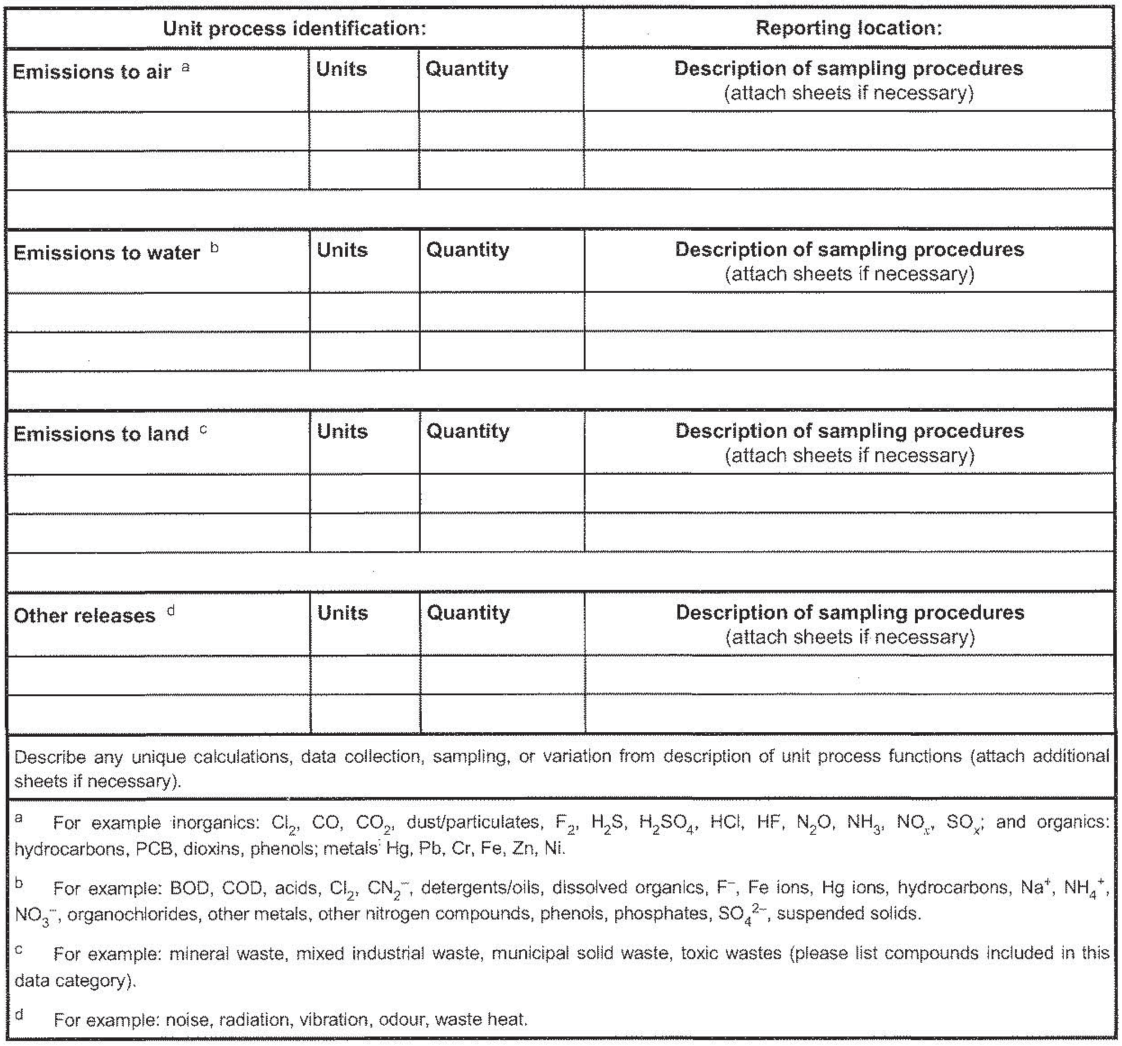
[554] ISO 2006b, p. 34.

A.5. Example of a LCI analysis data collection sheet.[555]



Unit process identification:			Reporting location:
Emissions to air [a]	**Units**	**Quantity**	**Description of sampling procedures** (attach sheets if necessary)
Emissions to water [b]	**Units**	**Quantity**	**Description of sampling procedures** (attach sheets if necessary)
Emissions to land [c]	**Units**	**Quantity**	**Description of sampling procedures** (attach sheets if necessary)
Other releases [d]	**Units**	**Quantity**	**Description of sampling procedures** (attach sheets if necessary)
Describe any unique calculations, data collection, sampling, or variation from description of unit process functions (attach additional sheets if necessary).			
[a] For example inorganics: Cl_2, CO, CO_2, dust/particulates, F_2, H_2S, H_2SO_4, HCl, HF, N_2O, NH_3, NO_x, SO_x; and organics: hydrocarbons, PCB, dioxins, phenols; metals: Hg, Pb, Cr, Fe, Zn, Ni. [b] For example: BOD, COD, acids, Cl_2, CN_2^-, detergents/oils, dissolved organics, F^-, Fe ions, Hg ions, hydrocarbons, Na^+, NH_4^+, NO_3^-, organochlorides, other metals, other nitrogen compounds, phenols, phosphates, SO_4^{2-}, suspended solids. [c] For example: mineral waste, mixed industrial waste, municipal solid waste, toxic wastes (please list compounds included in this data category). [d] For example: noise, radiation, vibration, odour, waste heat.			

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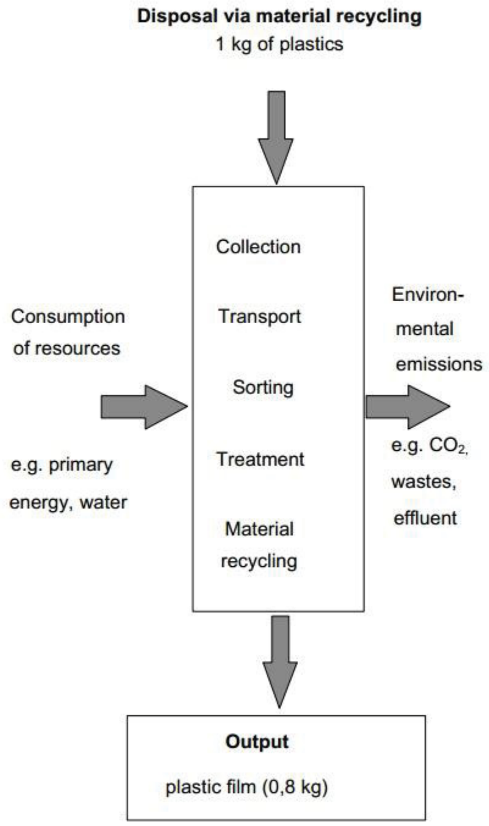
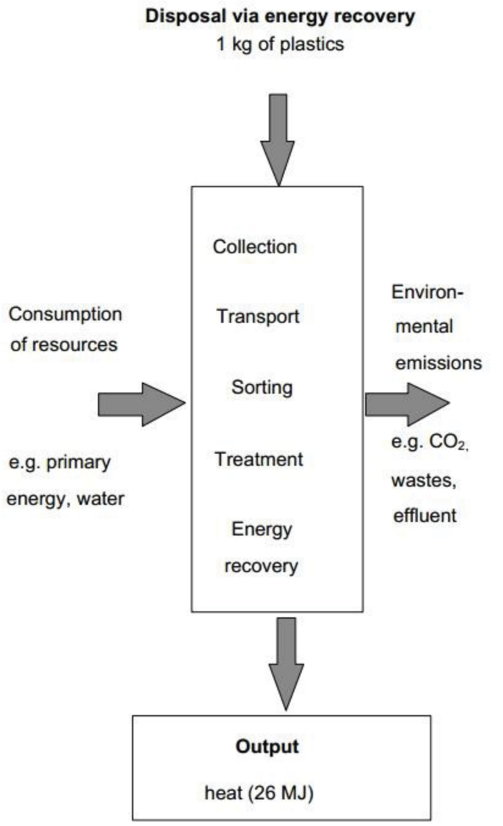
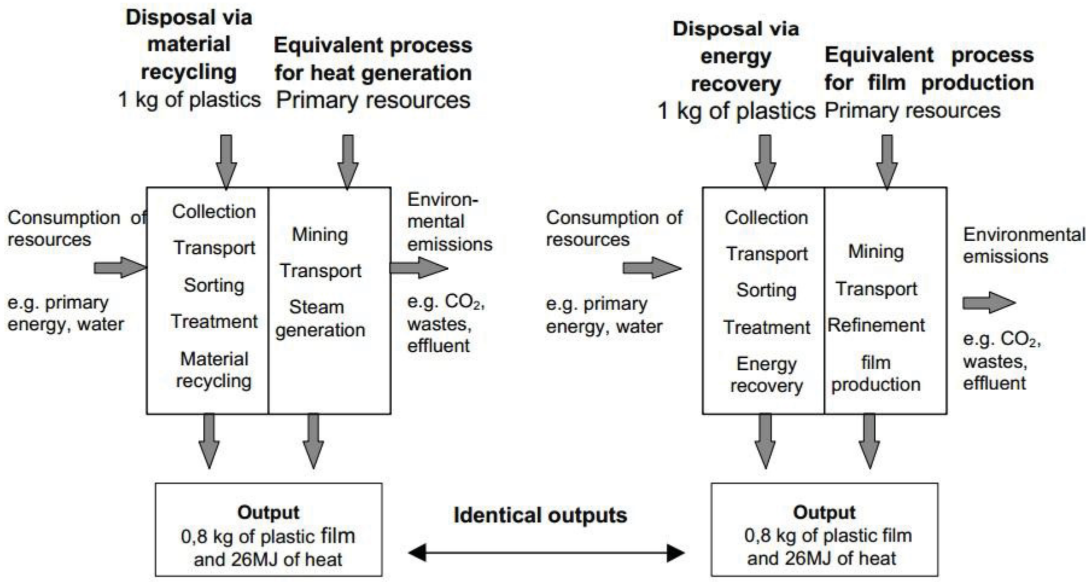
[555] ISO 2006b, p. 35.

A.6. Example of systems comparison different functions by system expansion.[556]







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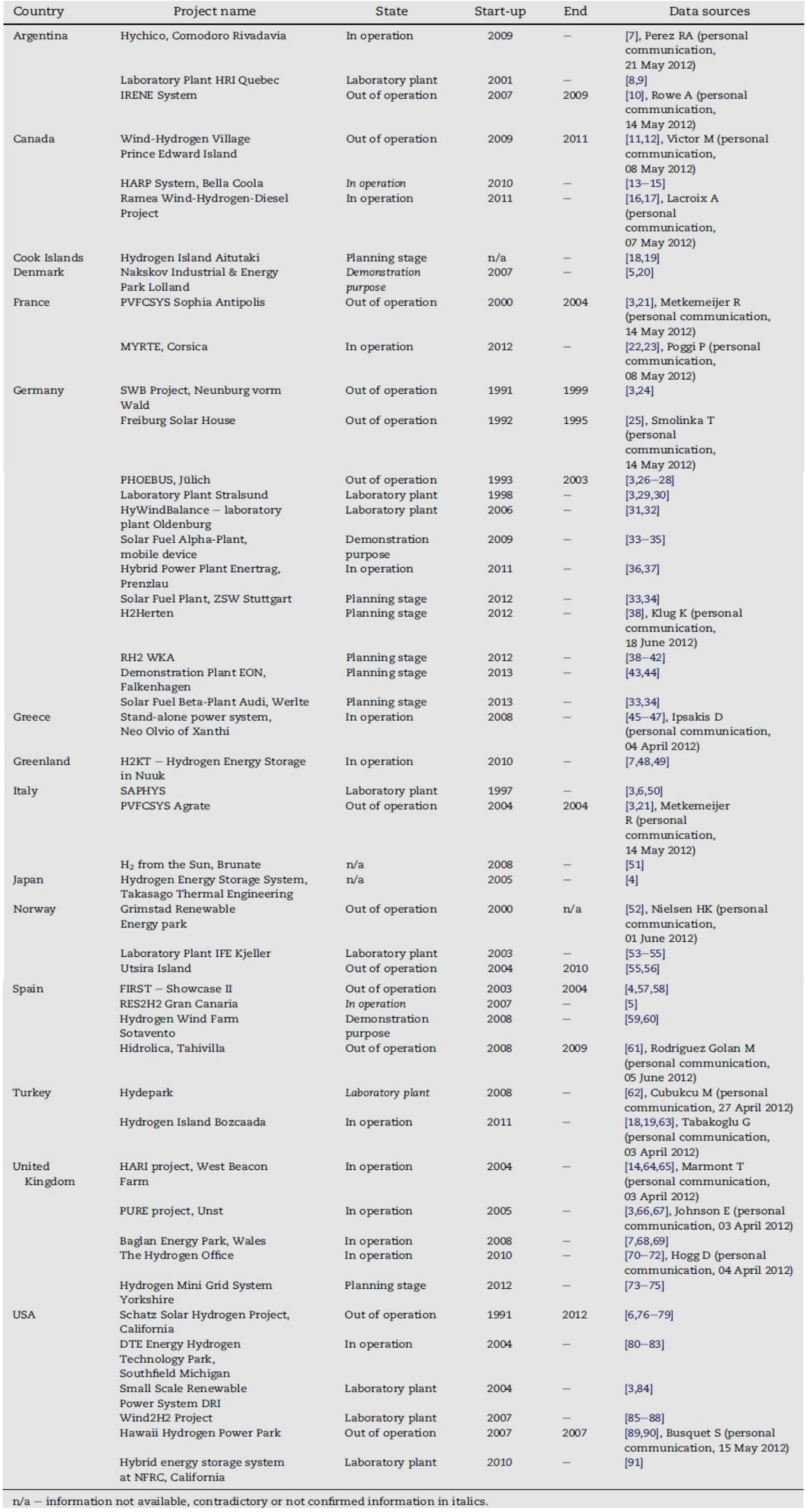
[556] ISO 2000, pp. 19-20.

A.7. Sample list of power-to-gas pilot plants.[557]



Country	Project name	State	Start-up	End	Data sources
Argentina	Hychico, Comodoro Rivadavia	In operation	2009	–	[7], Perez RA (personal communication, 21 May 2012)
	Laboratory Plant HRI Quebec	Laboratory plant	2001	–	[8,9]
	IRENE System	Out of operation	2007	2009	[10], Rowe A (personal communication, 14 May 2012)
Canada	Wind-Hydrogen Village Prince Edward Island	Out of operation	2009	2011	[11,12], Victor M (personal communication, 08 May 2012)
	HARP System, Bella Coola	*In operation*	2010	–	[13–15]
	Ramea Wind-Hydrogen-Diesel Project	In operation	2011	–	[16,17], Lacroix A (personal communication, 07 May 2012)
Cook Islands	Hydrogen Island Aitutaki	Planning stage	n/a	–	[18,19]
Denmark	Nakskov Industrial & Energy Park Lolland	*Demonstration purpose*	2007	–	[5,20]
France	PVFCSYS Sophia Antipolis	Out of operation	2000	2004	[3,21], Metkemeijer R (personal communication, 14 May 2012)
	MYRTE, Corsica	In operation	2012	–	[22,23], Poggi P (personal communication, 08 May 2012)
Germany	SWB Project, Neunburg vorm Wald	Out of operation	1991	1999	[3,24]
	Freiburg Solar House	Out of operation	1992	1995	[25], Smolinka T (personal communication, 14 May 2012)
	PHOEBUS, Jülich	Out of operation	1993	2003	[3,26–28]
	Laboratory Plant Stralsund	Laboratory plant	1998	–	[3,29,30]
	HyWindBalance – laboratory plant Oldenburg	Laboratory plant	2006	–	[31,32]
	Solar Fuel Alpha-Plant, mobile device	Demonstration purpose	2009	–	[33–35]
	Hybrid Power Plant Enertrag, Prenzlau	In operation	2011	–	[36,37]
	Solar Fuel Plant, ZSW Stuttgart	Planning stage	2012	–	[33,34]
	H2Herten	Planning stage	2012	–	[38], Klug K (personal communication, 18 June 2012)
	RH2 WKA	Planning stage	2012	–	[38–42]
	Demonstration Plant EON, Falkenhagen	Planning stage	2013	–	[43,44]
	Solar Fuel Beta-Plant Audi, Werlte	Planning stage	2013	–	[33,34]
Greece	Stand-alone power system, Neo Olvio of Xanthi	In operation	2008	–	[45–47], Ipsakis D (personal communication, 04 April 2012)
Greenland	H2KT – Hydrogen Energy Storage in Nuuk	In operation	2010	–	[7,48,49]
Italy	SAPHYS	Laboratory plant	1997	–	[3,6,50]
	PVFCSYS Agrate	Out of operation	2004	2004	[3,21], Metkemeijer R (personal communication, 14 May 2012)
	H_2 from the Sun, Brunate	n/a	2008	–	[51]
Japan	Hydrogen Energy Storage System, Takasago Thermal Engineering	n/a	2005	–	[4]
Norway	Grimstad Renewable Energy park	Out of operation	2000	n/a	[52], Nielsen HK (personal communication, 01 June 2012)
	Laboratory Plant IFE Kjeller	Laboratory plant	2003	–	[53–55]
	Utsira Island	Out of operation	2004	2010	[55,56]
Spain	FIRST – Showcase II	Out of operation	2003	2004	[4,57,58]
	RES2H2 Gran Canaria	*In operation*	2007	–	[5]
	Hydrogen Wind Farm Sotavento	Demonstration purpose	2008	–	[59,60]
	Hidrolica, Tahivilla	Out of operation	2008	2009	[61], Rodriguez Golan M (personal communication, 05 June 2012)
Turkey	Hydepark	*Laboratory plant*	2008	–	[62], Cubukcu M (personal communication, 27 April 2012)
	Hydrogen Island Bozcaada	In operation	2011	–	[18,19,63], Tabakoglu G (personal communication, 03 April 2012)
United Kingdom	HARI project, West Beacon Farm	In operation	2004	–	[14,64,65], Marmont T (personal communication, 03 April 2012)
	PURE project, Unst	In operation	2005	–	[3,66,67], Johnson E (personal communication, 03 April 2012)
	Baglan Energy Park, Wales	In operation	2008	–	[7,68,69]
	The Hydrogen Office	In operation	2010	–	[70–72], Hogg D (personal communication, 04 April 2012)
	Hydrogen Mini Grid System Yorkshire	Planning stage	2012	–	[73–75]
USA	Schatz Solar Hydrogen Project, California	Out of operation	1991	2012	[6,76–79]
	DTE Energy Hydrogen Technology Park, Southfield Michigan	In operation	2004	–	[80–83]
	Small Scale Renewable Power System DRI	Laboratory plant	2004	–	[3,84]
	Wind2H2 Project	Laboratory plant	2007	–	[85–88]
	Hawaii Hydrogen Power Park	Out of operation	2007	2007	[89,90], Busquet S (personal communication, 15 May 2012)
	Hybrid energy storage system at NFRC, California	Laboratory plant	2010	–	[91]

n/a – information not available, contradictory or not confirmed information in italics.

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[557] Gahleitner 2013, pp. 2042-2043.