New technologies and strategies for fuel cells and Hydrogen Technologies in the phase of recycling and dismantling

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WP4 LCA for FCH technologies considering new strategies & technologies in the phase of recycling and dismantling

D4.1 LCA approach in the end of life cycle of FCH technologies

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Document Change Control

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V03	29.06.2017	Mori M, Stropnik R., Lotrič A.., Drobnič B., Sekavčnik M.	Final

How to read this document

The document is structured as "ANNEX I - LCA Study Reporting Template on Fuel Cells" from Masoni and Zamagni (2011, p. 81 - 95) is suggesting, [1]. If identical information is addressed in more than one section, the corresponding information is provided only once and a cross-reference is made in the later sections.

Executive Summary

Fuel Cell and Hydrogen (FCH) technologies are expected to add to decarbonisation of energy and transport sector. One thing among others that prevents FCH commercialization is **recycling and dismantling stage**. Within the HyTechCycling project the LCA study will try to give the answer of currently used processes in end of life of considered technologies.

This document is defining basic concepts and LCA approach in the technology manufacturing, operational and end of life phase of considered FCH technologies. The LCA follows the FC related guidance document from HyGuide project, [1] that needs to be respected by any LCA conducted in the project funded by FCH JU. The LCA methodology builds on ISO 14040/44 standards, [2], [3].

In the study considered technologies are only those FCH technologies included in the project: PEMFCs, SOFCs, alkaline - AWE and PEM water electrolysers – PEMWE.

The ***functional unit*** is defined as 1 kWh of exergy in the form of electricity, heat and hydrogen (regarding the technology considered).

The **scope** of the study is from cradle to grave with distinct separation between LCA phases:

(a) In the ***manufacturing of the technologies*** the main focus is given to the core technology with some general model for considered technology. For BoP components manufacturing process LCI (Life Cycle Inventory) will be provided by consulting body from industry included in the project;

(b) In the ***operational phase hydrogen*** will be produced mainly with electrolysis (technology involved: PEMWE, AWE) and gas reforming for additional results evaluation. If some scenario will be added, it will be defined in LCI deliverable D4.2.

(c) In ***End of Life Assessment*** (EoLA) reuse of parts and components will be considered as priority, the second possibility will be recycling with known technologies, recycling with new technological processes and the worst possibility (recommendation for HyGuide, [1]) is landfill that is used as worst case scenario or/end in the case of non-existing technological processes..

The Life Cycle Impact Assessment (LCIA) methodology is described with al local, regional and global criteria described in the document, [4], [5]. The midpoint LCIA methodology will be used, since the endpoint methodology is more often used for general public and policy makers and rarely for research and industry sector as it is involved also in the HyTechCycling project.

The software used will be Gabi Thinkstep [6]–[8], since the software environment, knowledge and databases are available from other FCH JU funded projects in which HyTechCycling partners are involved [9]. In Gabi TS software databases (DB-ses) as Ecoinvent and Gabi Professional database with extension DB-ses are already available.

The step beyond this deliverable is to combine D2.1 (Assessment of critical materials and components in FCH technologies), D2.2 (Existing end-of-life technologies applicable to FCH products) and D4.1 (this report) to make appropriate Life Cycle Inventory Analysis (LCIA) for materials used in the considered technologies and processes used in EoLA phase. This will be the scope of the next deliverable D4.2.

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Abbreviations

AWE	Alkaline Water Electrolyser
BoP	Balance of Plant
EL	Electrolyser
ELCD	European reference Life Cycle Database
EoL	End of Life
EoLA	End of Life Assessment (Analysis)
EPLCA	European Platform on Life Cycle Assessment
FC	Fuel Cell
FCH	Fuel Cell and Hydrogen
FCH-JU	Fuel Cell and Hydrogen Joint Undertaking
ILCD	International Reference Life Cycle Data System
LCA	Life Cycle Analysis
LCC	Life Cycle Costs
LCDN	Life Cycle Data Network
LCI	Life Cycle Inventory
MEA	Membrane Electrode Assembly
PEM	Polymer Electrolyte Membrane
PEMEC	Polymer Electrolyte Membrane Electrolyser Cell
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PEMWE	Polymer Electrolyte Membrane Water Electrolyser
SOFC	Solid Oxide Fuel Cell

1. Introduction

High deployment of fuel cells and hydrogen technologies is expected in the near term in the EU to decarbonize energy and transport sectors. The idea is to generate vast amounts of green hydrogen from the expected surplus of renewable energy sources (implemented policies are going towards 65% of electricity from renewable energy sources by 2050) to be used in transport, energy and industries. However, the expected commercial FCH technologies (mainly PEM and alkaline electrolysers as well as PEM and Solid Oxide fuel cells) are not prepared for full deployment in what **regards to recycling and dismantling stage**. To cover the gap in legislation, guidelines, codes and standards in the area of recycling and dismantling of FCH technologies **HyTechCycling** project has been launched and founded by Fuel Cell and Hydrogen Joint Undertaking (FCH-JU). As part of the project, a Life Cycle Assessment (LCA) study has to be carried out for all life cycle phases for considered technologies.

To carry out the LCA study in the first step proper methodology, software environment, impact criteria, boundary conditions, functional unit and all relevant data required for LCA study has to be defined. That has to be done on the basis of current relevant literature, guidelines, and projects results and with the help of HYTECHCYCLING advisory board of manufacturers[1].

1.1 Aim of the study

The main aim of current study was to **analyse currently used LCA approach in dismantling and recycling** of FCH technologies according to standards, guidelines and processes in end of life stage of FCH technologies. The work will be based on outcome of WP2 and WP3 and will be entirely devoted to the life cycle assessment and environmental and health impacts of FCH technologies. On the basis of current LCA studies, guidelines and standards the review of end of life cycle stage will be done to identify:

- currently used methods and processes,
- proposed, but still not used methods and processes,
- future trends and obligations in end of life cycle stage.

Proper LCA methodology will be chosen with impact indicators to identify environmental and human health impacts. Basic research in this stage will be on basis of results, proposals and identified requirements of past EU projects as FCHyGuide, [1], European Platform on Life Cycle Assessment (EPLCA), [10], European reference Life Cycle Database (ELCD), [11], the International Reference Life Cycle Data System (ILCD) Handbook and the Life Cycle Data Network (LCDN), [12], [13]. Valid guidelines are used as a reference and starting point, [14], [15] of the study.

As main outcome of this task is the definition of the proper **LCIA methodology**, **software environment**, **impact criteria**, **boundary conditions** of the system, **LCA phases** considered (the scope of the study), **functional unit**, **cut off criteria** and all other relevant data relevant for LCA study. All definitions, materials, approaches and processes are considered just for technologies evaluated in the study.

[1] Advisory Board is constituted from industrial partners.

1.2 Considered LCA guidelines and standards

The work carried out in this task follows the ISO standards, [2], [3]. Moreover, provisions and suggestions given in the guidance document for performing LCAs on FCH technologies by Masoni and Zamagni (2011) are considered, [1], [16]. This guidance includes a number of provisions on what shall (requirement) and what should (guidance) be included in an LCA of FCH technologies.

2. GOAL OF THE STUDY

In this chapter, the goal of the LCA of the considered technology within HyTechCycling is defined. After the goal definition (chapter 2.1), the intended application(s) of the study is described (chapter 2.2), the used method, assumptions made and impact limitations (chapter 2.3), the reasons for carrying out the study (chapter 2.4) and its target audience (chapter **Error! Reference source not found.**).

2.1 Goal of the study

Since there is ***no adequate legislation*** in the EoL phase of FCH technologies, there is also ***no or limited knowledge regarding the environmental and health impacts*** of materials and processes in EoL of FCH technologies.

The goal of the current study is to define all relevant information regarding the LCA approach used in considered FCH technologies end of life phase. Technologies considered are PEMFCs, SOFCs, alkaline and PEM electrolysers. Definition of the proper LCIA methodology, software environment, impact criteria, boundary conditions of the system, LCA phases considered (the scope of the study), functional unit, cut off criteria, target audience and all other relevant data relevant for LCA study is the goal of this task and study.

2.2 Intended application

LCA approach defined in the scope of this study will be used internally and externally. The internal use is to inform the FCH JU, partners and linked industry in recycling and dismantling area. Based on the study outcome, the proposal for unifying the processes and guidelines can be proposed. According to the dissemination level of the related deliverable (i.e. D4.1 is classified as "PU" in the DOoA), the report will be available externally.

2.3 Method, assumptions and impact limitations

2.3.1 Method

The method used is chain based, cradle to grave LCA approach, modelled with software Thinkstep Gabi version [6]–[8]. The data used will be defined in LCIA that is the topic of next task 4.2 of HyTechCycling. Databases used are Ecoinvent version 3.1[2] and Thinkstep Gabi professional databases[3]. The ILCD characterisation factors of ILCD 1.0.8 2016 midpoint are used, [10], [12]. Water consumption is assessed according to AWARE method, [17].

2.3.2 Assumptions

2.3.2.1 Primary and secondary data

On the basis of advisory board recommendations a reference life cycle inventory data for manufacturing phase of considered technologies is defined to set up reference LCA model for all considered technologies. Where specific primary LCA data such as energy used during production or inventories of the different FC parts (e.g., steel or platinum used in the manufacturing of the reformer or the stack) are not

[2] Ecoinvent 3.1,

[3] GaBi databases Thinkstep AG; LBP-GaBi, University of Stuttgart: GaBi Software System, Leinfelden-Echterdingen / Germany

available, secondary data from the literature or generic databases is used. Secondary data were used from Ecoinvent data base 3.1 and Gabi Thinkstep professional database, [4].

2.4 Reasons to carry out the study

However, the expected commercial FCH technologies (mainly PEM and alkaline electrolysers as well as PEM and Solid Oxide fuel cells) are not prepared for full deployment in what regards to recycling and dismantling stage. To cover the gap in legislation, guidelines, codes and standards in the area of recycling and dismantling of FCH technologies HyTechCycling project has been launched and founded by Fuel Cell and Hydrogen Joint Undertaking (FCH-JU).

2.5 Limitations of the study

The main focus of the study is limited ***to core technologies*** in FCH technologies considered in the project: PEMFCs, SOFCs, alkaline and PEM electrolysers. Nevertheless that most critical materials of FCH technologies are present in the fuel cell or the electrolyser stack (core technologies) there are also BoP components included in the study to give better understanding of the component's and material's environmental and health impacts.

In the study limitations are physical and methodological. **Methodological** are set up regarding considered technologies (PEM and alkaline electrolysers, PEM and Solid Oxide fuel cells). **Physically** study is oriented to 4 units (2 for electricity and heat production, 2 for hydrogen production) with appropriate BoP components. No additional special installation (containers, middle term storages, etc.) is considered. Basic units are defined as units of specific power. Hydrogen production is included just as technology (energy and mass consumption), with no physical facility modelled. Hydrogen production methods are limited to electrolysis from PEM (PEMWE) and alkaline electrolyser (AWE). In the end of life phase three scenarios are included: ***worst case – landfill*** scenario, best case with ***maximum re-usage*** of components and parts and ***realistic scenario*** based on the data of industry partners involved in dismantling and recycling.

2.6 Study applicability and target audience

The study is mainly targeted to specific industry parties that are working in dismantling and recycling area, to decision makers that constitute legislation, research area that are responsible for guidelines and studies and also to general public to get better understanding of the impacts of hydrogen technologies.

3. The scope of the LCA study

3.1 Functional unit

The functional unit is defined as 1kWh of exergy. In the case of PEMWE and AWE that means the exergy of the produced hydrogen and in the case of PEMFC and SOFC that means exergy of electricity and heat in the case of SOFC.

3.2 Multi functionality

Figure 1 shows a sketch of a FC system in operation with its inputs and (useful) outputs, i.e. heat and electricity. Producing more than one output, the system is characterized as a multi-functional process.

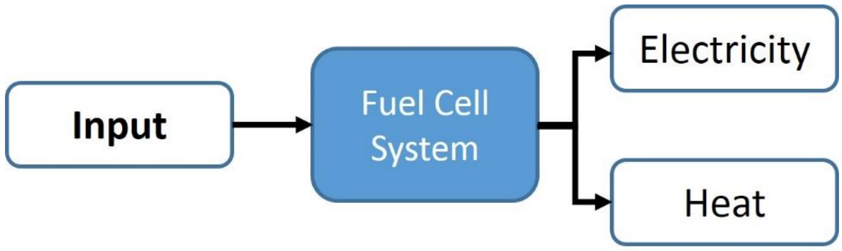

Figure 1 – Sketch of a FC unit as a multi-functional process, [1]

In [1], different approaches on how to treat multi-functionality are described. Different systems will be compared that satisfy a certain amount of electricity and heat demand. Environmental burdens will be calculated and allocated to each the energy flow. Therefore exergy content of heat flow of each system will be calculated to account multi-functionality of the systems.

3.3 System boundaries

In Figure 2 an overview of the life cycle stages and system boundary for considered systems with **fuel cells (PEMFC, SOFC)** is given. The scope is from cradle to grave with emphasis on EoL stage, where several scenarios are possible:

- ✓ Reuse as parts/material in the same product (avoiding of virgin mass flow);
- ✓ Reuse in other product (allocation of environmental impacts – mass allocation method)
- ✓ Recycling of materials in the same product (avoiding of virgin mass flow, additional energy input for recycling);
- ✓ Recycling in other product (allocation of environmental impacts – mass allocation method);
- ✓ Energy extraction process (avoiding energy input – electricity, producing heat, higher environmental impacts);
- ✓ Landfill of parts and system (higher environmental impacts – worst case scenario, [1]);

The main focus is given to ***foreground system***: supply of resources, EoLA and waste and release management. Advisory board will define LCI for manufacturing stage, typical operation regime, energy (exergy) efficiency of reference PEMFC, CHP and exergy efficiency of reference SOFC system.

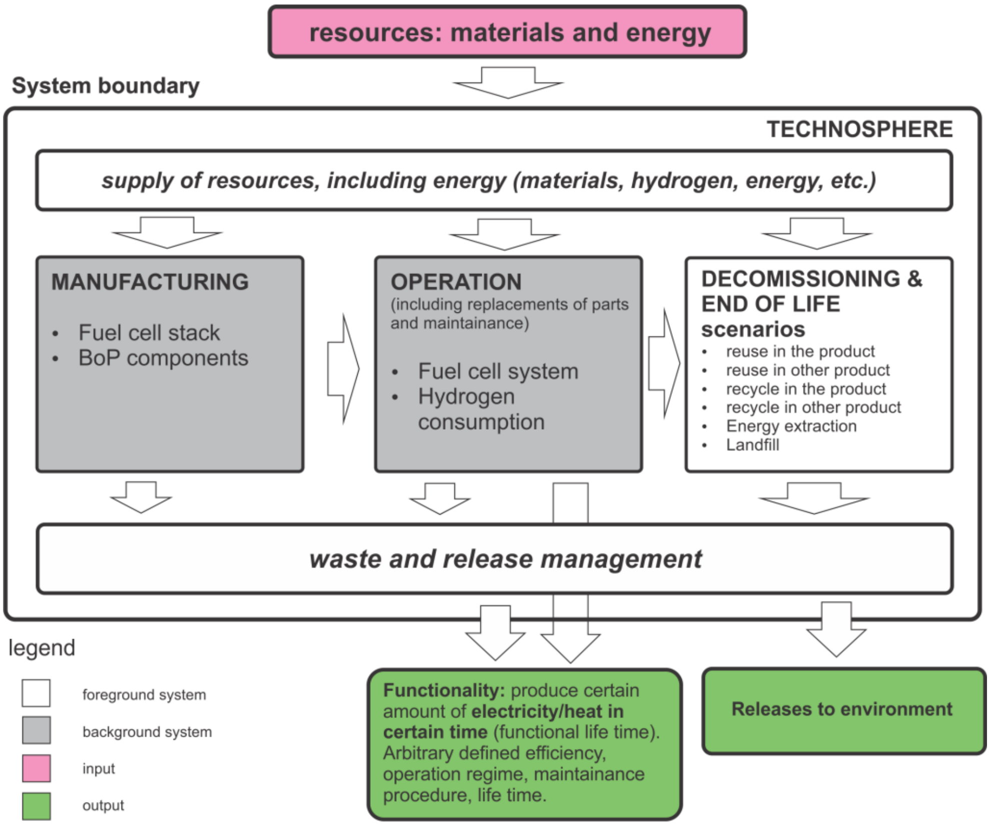

Figure 2 – Overview of the life cycle stages and system boundary of the fuel cell (PEMFC, SOFC)

In Figure 2 system boundaries of technosphere are defined. Inflows and outflows are defined in the form of energy and mass flows. The grey coloured parts of the system is not a main focus of the project, but important in terms of LCA analysis. Therefore ***background system*** will be defined by advisory board of HyTechCycling as some reference system on the basis of data from manufacturers.

In Figure 3 an overview of the life cycle stages and system boundary for considered systems with **electrolyzers** (polymer - PEMWE and alkaline - AWE) is given. The scope of the study will be from cradle to grave with emphasis on EoL stage with scenarios:

- ✓ Reuse as parts/material in the same product (avoiding of virgin mass flow);
- ✓ Reuse in other product (allocation of environmental impacts – mass allocation method)
- ✓ Recycling of materials in the same product (avoiding of virgin mass flow, additional energy input for recycling);
- ✓ Recycling in other product (allocation of environmental impacts – mass allocation method);
- ✓ Energy extraction process (avoiding energy input – electricity, producing heat, higher environmental impacts);
- ✓ Landfill of parts and system (higher environmental impacts – worst case scenario, [1]);

Advisory board will define LCI for manufacturing stage, typical operation regime, energy (exergy) efficiency of reference PEM and alkaline electrolyzer.

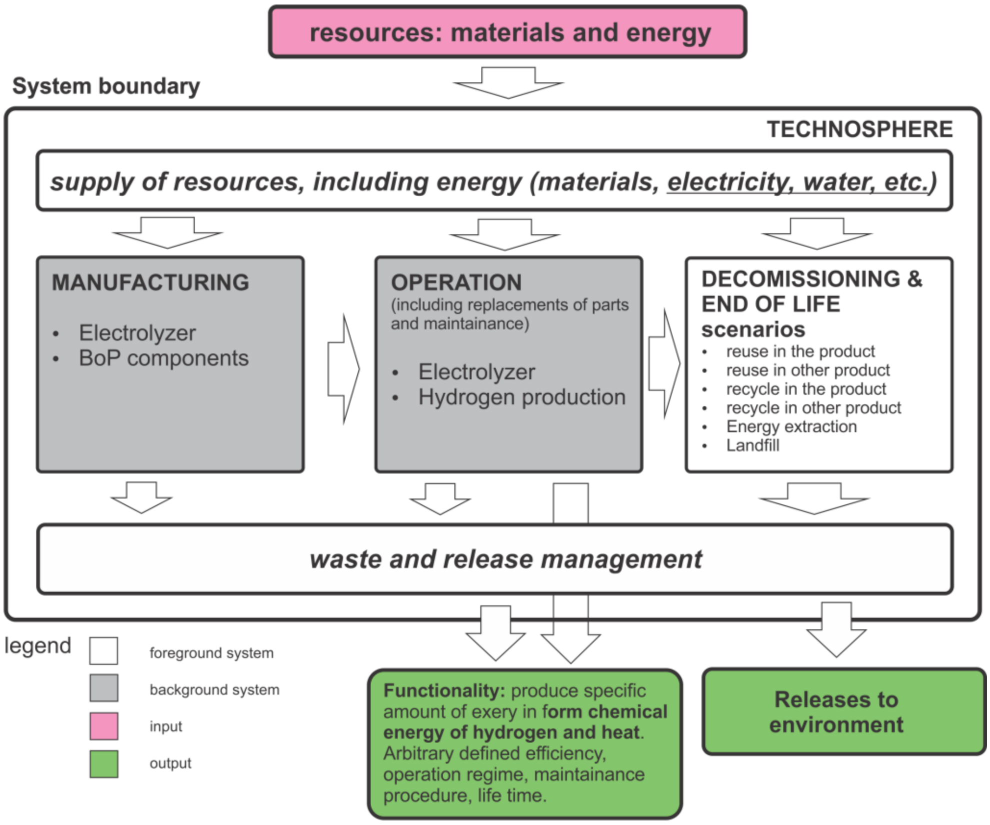

Figure 3 – Overview of the life cycle stages and system boundary of the electrolysers

In the EoL phase the LCI will represent the main challenge of the project. A "cradle to grave" approach is taken: The LCA includes manufacturing, operation (including fuel supply) and maintenance of the systems, decommissioning of the systems and end of life phase. In end of life phase scenario analysis will done for each considered technology and options defined with further LCI analysis.

The geographic reference is Europe. Given that Europe is not self-sustaining in terms of fuels and materials needed in the systems' life cycles, the geographical scope is extended to cover those countries that Europe's supply relies upon (e.g. certain metals, including platinum and zirconium).

3.4 Considered technologies combinations: hydrogen production & electricity generation

In the study we are dealing with hydrogen production (PEMWE; AWE) on one side and hydrogen consumption and electricity generation on other side (PEMFC, SOFC). In order to evaluate each considered technology both sides have to be included, so the best way was to combine both technologies as showed in Figure 4. The left side represents the source of electricity to power electrolyser: electricity mixes are chosen so the first mix is RES based electricity mix, the second one is fossil fuel based electricity mix and the third one is realistic somewhere in the middle of first two (EU28 mix or EU25 mix). The middle part of the Figure 4 is hydrogen production technology with 2 considered technologies in the project (AWE and PEMWE) plus natural gas reforming as a production methodology currently used most frequently in the world, [18]. The right part of the Figure 4 is electricity/heat generation with considered fuel cells in the project (SOFC and PEMFC).

With this approach **4 basic cases** are available: PEMWE-PEMFC, PEMWE-SOFC, AWE-PEMFC, AWE-SOFC. In addition three (3) electricity mixes are used to power electrolyser, plus additional natural gas reforming for hydrogen production, result in 14 different cases for life cycle assessment study.

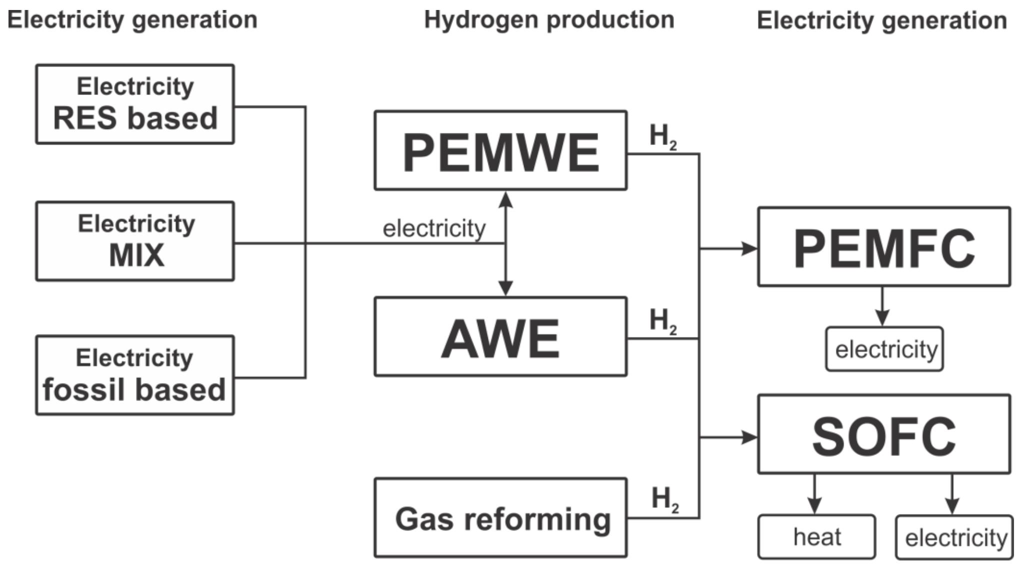

Figure 4 – The structure of the considered system with all considered technologies.

3.5 Definition of relevant flows

A flow is an input or output from a process or product system. There are several types of flows. Elementary flows are defined in ISO 14040 as "material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material and energy leaving the system being studied that is released into the environment without subsequent human transformation" (ISO 2006a), [3]. This means that an elementary flow is, for example, crude oil or hard coal resource as an input, or CO_2 emission released to air as a non-further treated output, [1].

HyGuide defines a list of flows (materials, energy, emissions) which should be included, [1] in the study. The example and a list for for fuel cells is reproduced in Table 1 and for electrolysers in Table 2.

Table 1 – Potentially relevant flows for fuel cells which should be included

Unit of manufacturing	Components	Input	Output
FC stack	Anode, cathode, matrix, electrolyte	Raw powders, chemicals, electrolyte chemical compounds + electricity for manufacturing	emissions
Stack assembled	Above components + steel parts (e.g. anodic and collectors plates, bipolar plates)	Energy for manufacturing processes	emissions
System assembled	Above components + BoP + energy required	Above inputs + materials for BoP manufacturing +electricity consumption	emissions
System assembled operation phase	Above components	Fuel consumption (H_2, O_2)	emissions, electricity
System EoL	Above components	Materials included above + energy needed for decomposition, recycling	emissions

Table 2 – Potentially relevant flows for electrolyser which should be included

Unit of manufacturing	Components	Input	Output
EL stacks	Anode, cathode, matrix, electrolyte	Raw powders, chemicals, electrolyte chemical compounds + electricity for manufacturing	emissions
Stack assembled	Above components + steel parts (e.g. anodic and collectors plates, bipolar plates)	Energy for manufacturing processes	emissions
System assembled	Above components + BoP + energy required	Above inputs + materials for BoP manufacturing + electricity consumption	emissions
System assembled operation phase	Above components	Fuel consumption (H_2O, Electricity, KOH)	emissions, H_2, 0_2
System EoL	Above components	Materials included above + energy needed for decomposition, recycling	Emissions, wastes

3.6 Cut – off criteria

The recommendation given in HyGuide is to adopt a 2% cut-off value on each relevant environmental impact category, [1]. We have to rely mainly on secondary data sources mostly from the Ecoinvent and Thinkstep GaBi professional database. The influence of specific data related choices on the results are analyzed through a sensitivity analysis.

4. Life Cycle Impact Assessment method

Life cycle assessment (LCA) is a methodological tool used to quantitatively analyze the life cycle of products/activities. ISO 14040 and 14044 provide a generic framework. After goal and scope has been determined, data has been collected, an inventory result is calculated. This inventory result is usually a very long list of emissions, consumed resources and sometimes other items. The interpretation of this list is difficult. An LCIA procedure is designed to help with this interpretation.

In the GaBi thinkstep database[4] content you will find all major Impact Assessment methodologies, such as: TRACI 2.0, CML 1996, 2001, and 2007, Ecoindicator 95 and 99, Ecological Scarcity Method (UBP), EDIP, USEtox and ReCiPe. These methodologies are extensively described in Appendix. Using these impact methodologies you can see your results in terms of several LCIA impact potentials.

Most frequently used LCIA methods listed are described in Appendix: Life Cycle Impact Assessment methods and environmental indicators. In many LCA studies CML 2001 LCIA method is used that represents the midpoint approach, but in last period ReCiPe method is used more frequently because it combines both the midpoint and the endpoint approach. This enables easier interpretation but sometimes it can also produce certain inconsistency due to misinterpretation of the results. On the basis of the ReCiPe method the midpoint and endpoint indicators are explained more in detail in the following section.

The basic approach in the HyTechCycling will be midpoint approach (CML2001, ReCiPe) that will give useful information for industry sector that deal with disassembly of systems and recycling of FCH technologies. The possible use of end point approach is in this case just to present results to general public and/or policy makers if results are in the line with midpoint approach.

4.1 Indicators

The primary objective of the ReCiPe method, is to transform the long list of Life Cycle Inventory results, into a limited number of indicator scores. These indicator scores express the relative severity on an environmental impact category. In ReCiPe we determine indicators at two levels:

- **Eighteen midpoint indicators**
- **Three endpoint indicators**

Midpoints are considered to be links in the cause-effect chain (environmental mechanism) of an impact category, prior to the endpoints, at which characterization factors or indicators can be derived to reflect the relative importance of emissions or extractions, [19]–[21]. While midpoint indicators do not account for potential damages they may cause to the final targets, endpoint indicators are damage-oriented. They must be understood as issues of environmental concern, such as human health, extinction of species, and availability of resources for future generations, [22].

[4] M. Baitz et al., "GaBi thinkstep Database & Modelling Principles," PE International, no. November. pp. 1–178, 2017.

For example, let's consider the cause-effect chain for a toxic chemical. Emission of the chemical into the groundwater will allow it to flow into a lake, where the chemical concentration might increase to a dangerous level. Fish could start dying, decreasing the overall fish population. In the end, the fish species might go extinct (Figure 5), [23].

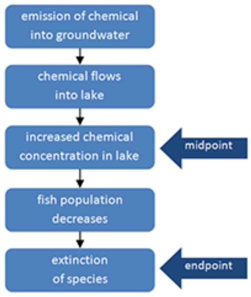

Figure 5 – Example of a cause-effect chain [23]

An endpoint method looks at environmental impact at the end of this cause-effect chain. In this example, at the extinction of a species. A midpoint method looks at the impact earlier along the cause-effect chain, before the endpoint is reached. In our example, a midpoint method might look at the increased concentration of the chemical in the lake water, [23].

ReCiPe uses an environmental mechanism as the basis for the modelling. An environmental mechanism can be seen as a series of effects that together can create a certain level of damage to for instance, human health or ecosystems. For instance, for climate change we know that a number of substances, increases the radiative forcing, this means heat is prevented from being radiated from the earth to space. As a result, more energy is trapped on earth, and temperature increases. As a result of this we can expect changes in habitats for living organisms, and as a result of this species may go extinct.

From this example it is clear that the longer one makes this environmental mechanism the higher the uncertainties get. The radiative forcing is a physical parameter that can be relatively easily measured in a laboratory. The resulting temperature increase is less easy to determine, as there are many parallel positive and negative feedbacks. Our understanding of the expected change in habitat is also not complete, etc. So the obvious benefit of taking only the first step is the relatively low uncertainty (see Figure 6).

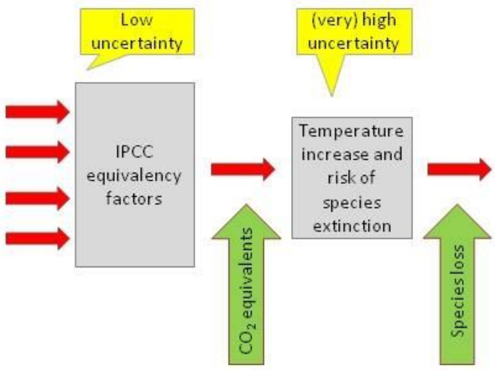

Figure 6 – Example of a harmonised midpoint-endpoint model for climate change, linking to human health and ecosystem damage, [24]

In ReCiPe we indeed calculate **eighteen of such midpoint indicators**, but also calculate three much more uncertain endpoint indicators. The motivation to calculate the **endpoint indicators**, is that the large number of midpoint indicators are very difficult to interpret, partially as there are too many, partially because they have a very abstract meaning. How to compare radiative forcing with base saturation numbers that express acidification? The indicators at the endpoint level are intended to facilitate easier interpretation, as there are only three, and they have a more understandable meaning. The idea is that each user can choose at which level it wants to have the result:

- Eighteen robust midpoints, that are relatively robust, not easy to interpret, but better for industry and research sector;
- Three easy to understand, but more uncertain endpoints, where the explanation has to be done carefully so there is no misleading:
    - ✓ Damage to Human health
    - ✓ Damage to ecosystems
    - ✓ Damage to resource availability

The user can thus choose between uncertainty in the indicators, and uncertainty on the correct interpretation of indicators. Figure 7 provides the overall structure of the method:

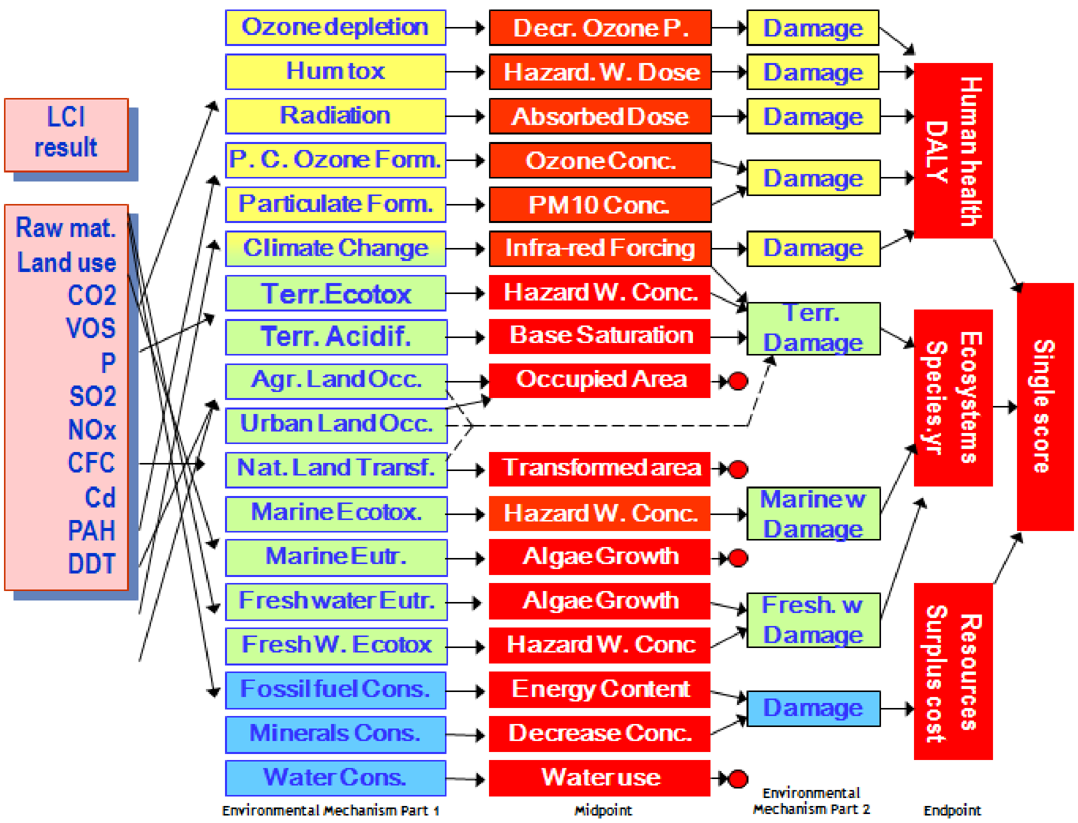

Figure 7 – Relationship between LCI parameters (left), midpoint indicator (middle) and endpoint indicator (right) in ReCiPe 2008, [25]

4.2 Characterization

The CML2001 and ReCiPe methods are included in major LCA software environments and databases and also in the Eco-invent database. The characterization factors are also available as a MS Excel spreadsheet with midpoint and endpoint characterization factors.

4.3 Cultural perspectives

Each method (midpoint, endpoint) contains factors according to the three cultural perspectives. These perspectives represent a set of choices on issues like time perspective or expectations that proper management or future technology development can avoid future damages.

- ✓ *Individualist*: short term, optimism that technology can avoid many problems in future.
- ✓ *Hierarchist*: consensus model, as often encountered in scientific models, this is often considered to be the default model.
- ✓ *Egalitarian*: long term based on precautionary principle thinking.

To conclude the chapter of the life cycle assessment method has to be stressed that in the first step midpoint approach with CML2001 or ReCiPe methodology will be used with possible use of end point approach, where this would seems helpful in interpretation and generalization of the results. More detailed list of used environmental indicators will be provide in the context of D4.2 – Life Cycle Inventory.

5. Questionnaire for advisory board

In the next step exact input data will be needed regarding:

- input materials,
- energy flows needed in manufacturing stages of considered FCH technologies
- defined power of system components
- life time of system components
- energy efficiencies in different operating regimes
- reference operating regime in FCH technology life time
- maintenance linked with material and energy consumption
- other mass flows into environment caused by operation
- possible recycling processes
- other recycling possibilities
- etc.

So the first step in the D4.2 or after D4.1 is to structure exact questionnaire for advisory board or industry collaborating in the project to define all influential parameters (some stresses out above) in detail.

6. Conclusions

This document is defining basic concepts and LCA approach in the technology manufacturing, operational and end of life phase of considered FCH technologies. The LCA follows the FC related guidance document from relevant projects, standards and guidelines.

The scope of the study will be from cradle to grave with all considered technologies included. Since we are studying 2 technologies for hydrogen production (PEMWE, AWE) within the project, those two production methodologies will be used in LCA numerical cases. For electricity/heat generation PEMFC and SOFC technologies are considered that brings 4 basic LCA cases in the LCA study with possible changes in input data.

In end of life phase, that is the core of the study, the approach will be to include maximum possible re-usage, recycling in the same product, recycling in other product and the last possibility will be landfill as a worst case.

The functional unit is set to be 1kWh of exergy in the form of electricity, heat and fuel depends in which part of life cycle phase we are analysing results.

The life cycle impact assessment methodology will be primary midpoint approach method (CML2001 and ReCiPe) with possible endpoint approach if seemed useful. List of environmental indicators will be divided to global, regional and local environmental indicators to address different technological impacts.

This document serves as a guideline for D4.2 that covers LCA of materials represented in FCH technologies that will cover extended life cycle inventory for considered FCH technologies.

7. References

[1] P. Masoni and A. Zamagni, “Guidance Document for performing LCAs on Fuel Cells and Hydrogen Technologies (FC-Hy Guide),” 2011.

[2] “International Organisation for Standardisation (2006) ISO 14044: Environmental management - Life cycle assessment - Requirements and guidelines,” 2006.

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Appendix

Life Cycle Impact Assessment methods and environmental indicators

There are many (Life Cycle Assessment methods developed through LCA history. Some used in last period are briefly presented here, [4]:

- CML 2001
- EDIP 2003
- Impact 2002+
- ReCiPe
- TRACI 2.1
- UBP 2013
- USEtox
- Eco-Indicator 99

Since the approach used for the study has to be set within this deliverable some of the LCIA methods will be described that are most commonly used.

CML 2001

Description:

CML 2001 is an impact assessment method which restricts quantitative modelling to early stages in the cause-effect chain to limit uncertainties. Results are grouped in midpoint categories according to common mechanisms (e.g. climate change) or commonly accepted groupings (e.g. Eco toxicity).

Characterization:

CML 2001 is developed by the Institute of Environmental Sciences, Leiden University, The Netherlands, and is published in a handbook with several different authors, see literature below. The main principles behind the methodology are not being further developed. A Microsoft Excel spreadsheet with characterization factors for more than 1700 different flows can be downloaded from the CML website. The characterization factors are updated when new knowledge on substance level is available. Several additional characterisation factors are calculated by PE and LBP-Gabi following the principles described in the CML 2001 methodology documents.

Normalisation and weighting:

Normalisation factors for CML 2001 are available for the Netherlands, Western Europe, EU and the World. The normalisation factors are calculated via total substance emissions and characterisation factors per substance, and are hence following the substance level updates as described above. This data is scaled from the original CML 2001 normalisation via gross domestic product [26], [27].

EDIP: Environmental Development of Industrial Products

The "Environmental Development of Industrial Products (EDIP)" is a method that was developed by the Institute for Product Development (IPU) at the Technical University of Denmark.

EDIP 2003 is the update of the EDIP 1997 LCIA method methodology and covers a larger part of the environmental mechanism and lies closer to a damage-oriented approach. EDIP 2003 considers the characteristics of the receiving environment in an effort to increase the relevance of the calculated impacts, [28]–[32].

IMPACT 2002+ Method

Description:

The Life Cycle Impact Assessment methodology IMPACT 2002+ suggests a feasible implementation of a combined midpoint/damage approach. These combinations will link all types of Life Cycle Inventory (LCI) results, the elementary flows and other interventions, throughout the 14 midpoint categories summed up to four damage categories.

New concepts and methods have been developed within IMPACT 2002+ for the comparative assessment of human toxicity and eco-toxicity. Human Damage Factors are calculated for carcinogens and non-carcinogens, employing intake fractions, best estimates of dose-response slope factors, as well as severities. The transfer of contaminants into the human food is no more based on consumption surveys, but accounts for agricultural and livestock production levels. Indoor and outdoor air emissions can be compared and the intermittent character of rainfall is considered. Both human toxicity and ecotoxicity effect factors are based on mean responses rather than on conservative assumptions.

Other midpoint categories are adapted from existing characterising methods (Eco-Indicator 99 and CML 2001). All midpoint scores are expressed in units of a reference substance and related to the four damage categories human health, ecosystem quality, climate change, and resources, [33]–[35].

ReCiPe LCA methodology

Description:

The ReCiPe LCA methodology was created by RIVM, CML, PRé Consultants, Radboud Universiteit Nijmegen and CE Delft. The group of authors include the developers of the CML 2001 and Ecoindicator 99 methodologies, [36]**.**

ReCiPe can be seen as a fusion of the two methodologies, taking the midpoint indicators from CML and the endpoint indicators from Ecoindicator.

Cultural Perspective:

All mid- and endpoint indicators are available in three versions taking into account three different cultural perspectives:

- **Individualist** (I) is based on the short-term interest, impact types that are undisputed, technological optimism as regards to human adaptation. Uses the shortest time frame e.g. a 20 year timeframe for global warming, GWP20
- **Hierarchist** (H) is based on the most common policy principles with regards to time-frame and other issues. Uses the medium time frame e.g. a 100 year timeframe for global warming, GWP100
- **Egalitarian** (E) is the most precautionary perspective, taking into account the longest time-frame, impact types that are not yet fully established but for which some indication is available, etc. Uses the longest time frame e.g. a 500 year timeframe for global warming, (GWP500) and infinite time for ozone depletion (ODPInf)

Characterization:

ReCiPe determine indicators at two levels; midpoint and endpoint indicators. The idea is that the user can choose the level of the results:

- Eighteen midpoint indicators; low uncertainty but difficult to interpret. The midpoint indicators are similar to what is used in the CML methodology: Climate change, acidification, eutrophication etc.
- Three endpoint indicators; easy to understand but more uncertain. The endpoint indicators are similar to what is used in the Ecoindicator 99 methodology: Damage to Human health, ecosystems, and resource availability.

Normalisation is developed both for the midpoint and endpoint indicators.

Weighting is not developed for the mid-point indicators by the ReCiPe authors. The midpoint values can be weighted using the PE LCIA Survey 2012. Using this only makes sense combined with a normalisation hereby bringing the impacts to the same unit of person-equivalents.

The endpoint indicators can be weighted using the ReCiPe weighting factors developed by the authors or using the weighting factors developed in the PE LCIA Survey 2012

TRACI Method

Description:

The U.S. Environmental Protection Agency developed an Impact Assessment methodology called TRACI, short for "Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts". The aim is to assist in enabling Impact Assessment for sustainability, Life Cycle Assessment, industrial ecology, process design and pollution prevention, [37]***.***

Within the TRACI methodology the impact categories were characterised at the midpoint level, including a higher level of societal agreement concerning the certainties of modeling at this point in the cause-effect chain. Research in the impact categories of acidification, smog formation, eutrophication, human health cancer, human health noncancer, human health criteria pollutants were developed specifically for US conditions by using the input data consistent with US locations. The impact categories used in the TRACI methodology are the following: Ozone depletion, global warming, smog formation, acidification, eutrophication, human health cancer, human health noncancer, human health criteria pollutants, eco-toxicity, fossil fuel depletion, land use and water use.

The TRACI is primarily a midpoint approach. The methodology draws simple cause-effect chains to show the point at which each impact category is characterised.

The TRACI methodology reflect current state of developments, consistency with EPA regulations and policy as well as best-available practice for life-cycle impact assessment (LCIA) in the United States.

UBP 2013, Ecological Scarcity Method

Description:

The Ecological Scarcity Method permits impact assessment of life cycle inventories according to the 'distance to target' principle , [38].

Eco-factors, expressed as eco-points per unit of pollutant emission or resource extraction, are normalized towards current emissions/levels in Switzerland, and weighted according to Swiss national policy targets or international targets supported by Switzerland. For global warming, the Kyoto protocol governs the reduction target, and the IPCC factors translate into the other greenhouse gases. [UBP 2013]

The eco-factors are implemented in 18 different environmental impacts (e.g. global warming, water pollutants, pesticides into soil, etc.). The 18 sub-values are already translated into the same unit and can be summarized to give a single score result.

USEtox

Description:

USEtox is developed under the United Nations Environment Program (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative, directly involving the model developers of CalTOX, IMPACT 2002, USES-LCA, BETR, EDIP, WATSON and EcoSense,[39]–[42].

The USEtox model operates on two scales; the continental scale and the global scale. The continental scale consists of six compartments: Urban air, rural air, agricultural soil, natural soil, freshwater, and coastal marine water. The global scale has the same structure, but without the urban air.

USEtox calculates characterisation factors for human toxicity and freshwater ecotoxicity via three steps:

- Environmental fate, where the distribution and degradation of each substance is modelled
- Exposure where the exposure of humans, animals and plants are modelled and
- Effects, where the inherent damage of the substance is researched

Human effect factors relate the quantity taken in to the potential risk of cancerous and non-cancerous effects expressing cases per kg of chemical emitted. The final unit is comparative toxic units (CTUh).

Effect factors for freshwater ecosystems are based on species-specific data of concentration at which 50% of a population displays an effect, expressed as an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF m3-day/ kg). The final unit is comparative toxic units (CTUe).

The model provides both recommended and interim characterisation factors for human health and freshwater ecotoxicity impacts.

Eco-Indicator 99 Method

Description

The data for the impact categories "Eco-Indicator 99" are according to information from Pre Consultants, which are collected and published in a spreadsheet by the Institute of Environmental Sciences, Leiden University, the Netherlands, [43]–[45].

Normalisation factors Eco-Indicator 99

The Normalisation factors "Eco-Indicator 99" are based on published information from Pre Consultants. Background information can be found in the report: "The Eco-Indicatior 99 - A damage orientated method for Life Cycle Assessment".

Impact categories

A short description of the most commonly used impact categories has been included in this document as an additional support for those beginner LCA practitioners.

Acidification

Acidic gases such as sulphur dioxide (SO_2) react with water in the atmosphere to form “acid rain”, a process known as acid deposition. When this rain falls, often a considerable distance from the original source of the gas (e.g. Sweden receives the acid rain caused by gases emitted in the UK), it causes ecosystem impairment of varying degree, depending upon the nature of the landscape ecosystems. Gases that cause acid deposition include ammonia (NH_3), nitrogen oxides (NO_x) and sulphur oxides (SO_x).

Acidification potential is expressed using the reference unit, kg SO_2 equivalent. The model does not take account of regional differences in terms of which areas are more or less susceptible to acidification. It accounts only for acidification caused by SO_2 and NO_x. This includes acidification due to fertilizer use, according to the method developed by the Intergovernmental Panel on Climate Change (IPCC). CML has based the characterisation factor on the RAINS model developed by the University of Amsterdam.

Impact category	**Acidification**
Definition	Reduction of the pH due to the acidifying effects of anthropogenic emissions
Impact indicator	Increase of the acidity in water and soil systems
Considerations	• Acidifying potential of oxides of nitrogen and sulphur
Damage categories (endpoint)	Damage to the quality of ecosystems and decrease in biodiversity
Unit	Kg SO_2 equivalent

Climate change

Climate change can be defined as the change in global temperature caused by the greenhouse effect that the release of “greenhouse gases” by human activity creates. There is now scientific consensus that the increase in these emissions is having a noticeable effect on climate. This raise of global temperature is expected to cause climatic disturbance, desertification, rising sea levels and spread of disease.

Climate change is one of the major environmental effects of economic activity, and one of the most difficult to handle because of its broad scale. The Environmental Profiles characterisation model is based on factors developed by the UN’s Intergovernmental Panel on Climate Change (IPCC). Factors are expressed as Global Warming Potential over the time horizon of different years, being the most common 100 years (GWP100), measured in the reference unit, kg CO_2 equivalent.

Impact category	**Climate change**
Definition	Alteration of global temperature caused by greenhouse gases
Impact indicator	Disturbances in global temperature and climatic phenomenon
Considerations	• Greenhouse gases[2] and their global warming potential (GWP), e.g. methane, sulphur hexafluoride, etc.
Damage categories (endpoint)	Crops, forests, coral reefs, etc. (biodiversity decrease in general) Temperature disturbances Climatic phenomenon abnormality (e.g. more powerful cyclones, torrential storms, etc.)
Unit	Kg CO_2 equivalent

Depletion of abiotic resources

There are many different sub-impacts to be considered in this case. In a general way, this impact category in referred to the consumption of non-biological resources such as fossil fuels, minerals, metals, water, etc.

The value of the abiotic resource consumption of a substance (e.g. lignite or coal) ***is a measure of the scarcity of a substance***. That means it depends on the amount of resources and the extraction rate. It is formed by the amount of resources that are depleted and measured in antimony equivalents in some models or water consumption (in m^3), kg of mineral depletion and MJ of fossil fuels.

Impact category	Depletion of abiotic resources
Definition	Decrease of the availability of non-biological resources (non- and renewable) as a result of their unsustainable use
Impact indicator	Decrease of resources
Considerations	• Distinctions between renewable and non-renewable resources
Damage categories (endpoint)	Damage to natural resources and possible ecosystem collapse
Unit	Depending on the model: • Kg antimony equivalent • Kg of minerals • MJ of fossil fuels • m^3 water consumption

Ecotoxicity

Environmental toxicity is measured as three separate impact categories which examine ***freshwater***, ***marine*** and ***land***. The emission of some substances, such as heavy metals, can have impacts on the ecosystem. Assessment of toxicity has been based on maximum tolerable concentrations in water for ecosystems. Ecotoxicity Potentials are calculated with the USESLCA, which is based on EUSES, the EU's toxicity model. This provides a method for describing fate, exposure and the effects of toxic substances on the environment. Characterization factors are expressed using the reference unit, kg 1,4-dichlorobenzene equivalent (1,4-DB), and are measured separately for impacts of toxic substances on:

- Fresh-water aquatic ecosystems
- Marine ecosystems
- Terrestrial ecosystems

Impact category	Ecotoxicity
Definition	Toxic effects of chemicals on an ecosystem
Impact indicator	Biodiversity loss and/or extinction of species
Considerations	• Toxicological responses of different species • Nature of the chemicals in the ecosystem
Damage categories (endpoint)	Damage to the ecosystem quality and species extinction
Unit	Depending on the model: • Kg 1,4-DB equivalent • PDF (Potentially Disappeared Fraction of species) • PAF (Potentially Affected Fraction of species)

Eutrophication

Eutrophication is the build-up of a concentration of chemical nutrients in an ecosystem which leads to abnormal productivity. This causes excessive plant growth like algae in rivers which causes severe reductions in water quality and animal populations. Emissions of ammonia, nitrates, nitrogen oxides and phosphorous to air or water all have an impact on eutrophication. This category is based on the work of Heijungs, and is expressed using the reference unit, kg PO_{43}- equivalents.

Direct and indirect impacts of fertilisers are included in the method. The direct impacts are from production of the fertilisers and the indirect ones are calculated using the IPCC method to estimate emissions to water causing eutrophication.

Impact category	Eutrophication
Definition	Accumulation of nutrients in aquatic systems
Impact indicator	• Increase of nitrogen and phosphorus concentrations • Formation of biomass (e.g. algae)
Considerations	Transportation of the nutrients (air, water, wash-off from land)
Damage categories (endpoint)	Damage to the ecosystem quality
Unit	Depending on the model: • Kg PO_4^{3-} equivalent • Kg N equivalent

Human toxicity

The Human Toxicity Potential is a calculated index that reflects the potential harm of a unit of chemical released into the environment, and it is based on both the inherent toxicity of a compound and its potential dose. These by-products, mainly arsenic, sodium dichromate, and hydrogen fluoride, are caused, for the most part, by electricity production from fossil sources. These are potentially dangerous chemicals to humans through inhalation, ingestion, and even contact. Cancer potency, for example, is an issue here. This impact category is measured in 1,4-dichlorobenzene equivalents.

Impact category	Human toxicity
Definition	Toxic effects of chemicals on humans
Impact indicator	Cancer, respiratory diseases, other non-carcinogenic effects and effects to ionising radiation
Considerations	• Toxicological responses of humans • Nature of the chemicals in the human body
Damage categories (endpoint)	Human health
Unit	Depending on the model: • Kg 1,4-DB equivalent • DALY (Disability-adjusted life year)[3]

Ionising radiation

Ionising radiation is an impact category in LCA related to the damage to human health and ecosystems that is linked to the emissions of radionuclides throughout a product or building life cycle. In the building sector, they can be linked to the use of nuclear power in an electricity mix.

The category takes into account the radiation types α-, β-, γ-rays and neutrons. The characterization model considers the emissions and calculation of their radiation behaviour and burden based on detailed nuclear-physical knowledge. The unit the impact is given is kg of uranium-235 (U235).

Impact category	Ionising radiation
Definition	Type of radiation composed of particles with enough energy to liberate an electron from an atom or molecule
Impact indicator	Effects of the radiation (health decline, cancer, illnesses, etc.)
Considerations	• Radiation behaviour of the substances • Toxicological responses of humans and other species
Damage categories (endpoint)	Human health and ecosystem quality
Unit	Depending on the model: • Kg U^{235} equivalent • DALY

Land use

The study is based on the UNEP/SETAC land use assessment framework (Milà i Canals et al., 2007, Koellner et al., 2012) and focuses on occupation impacts, i.e. the use of land. The damage is expressed as “potentially disappeared fraction of species” (PDF) per m^2 or m^2a (square metre of land per year). To finally calculate land use impacts in LCA studies, these characterization factors have to be multiplied with the land occupation:

Occupation impact = Land occupation (m^2a) * Characterization factor (PDF/m^2)

Impact category	Land use
Definition	Impact on the land due to agriculture, anthropogenic settlement and resource extractions
Impact indicator	Species loss, soil loss, amount of organic dry matter content, etc.
Considerations	• Analysis of the land area to be altered • Observations of biodiversity that could be damaged
Damage categories (endpoint)	Natural resource (non- and renewable) depletion
Unit	Depending on the model: • PDF/m^2 • m^2a

Ozone layer depletion (Stratospheric ozone depletion)

Ozone-depleting gases cause damage to stratospheric ozone or the "ozone layer". There is great uncertainty about the combined effects of different gases in the stratosphere, and all chlorinated and brominated compounds that are stable enough to reach the stratosphere can have an effect. CFCs, halons and HCFCs are the major causes of ozone depletion. Damage to the ozone layer reduces its ability to prevent ultraviolet (UV) light entering the earth's atmosphere, increasing the amount of carcinogenic UVB light reaching the earth's surface. The characterisation model has been developed by the World Meteorological Organisation (WMO) and defines the ozone depletion potential of different gases relative to the reference substance chlorofluorocarbon-11 (CFC-11), expressed in kg CFC-11 equivalent.

Impact category	Ozone layer depletion
Definition	Diminution of the stratospheric ozone layer due to anthropogenic emissions of ozone depleting substances
Impact indicator	Increase of ultraviolet UV-B radiation and number of cases of skin illnesses
Considerations	• Atmospheric residence time of ozone depleting substances • EESC (Equivalent Effective Stratospheric Chlorine)
Damage categories (endpoint)	Human health and ecosystem quality
Unit	Kg CFC-11 equivalent

Particulate matter

Particulate Matter is a complex mixture of extremely small particles. Particle pollution can be made up of a number of components, including acids (such as nitrates and sulphates), organic chemicals, metals, and soil or dust particles. A multitude of health problems, especially of the respiratory tract, are linked to particle pollution. PM is measured in PM10 equivalents, i.e. particles with a size of 10 µm.

Impact category	Particulate matter
Definition	Suspended extremely small particles originated from anthropogenic processes such as combustion, resource extraction, etc.
Impact indicator	Increase in different sized particles suspended on air (PM10, PM2.5, PM0.1)
Considerations	• Environmental behaviour of the particles
Damage categories (endpoint)	Human health
Unit	Kg particulate matter

Photochemical oxidation (Photochemical ozone creation potential)

Ozone is protective in the stratosphere, but on the ground-level it is toxic to humans in high concentration. Photochemical ozone, also called "ground level ozone", is formed by the reaction of volatile organic compounds and nitrogen oxides in the presence of heat and sunlight. The impact category depends largely on the amounts of carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxide (NO), ammonium and NMVOC (non-methane volatile organic compounds). Photochemical ozone creation potential (also known as summer smog) for emission of substances to air is calculated with the United Nations Economic Commission for Europe (UNECE) trajectory model (including fate) and expressed using the reference unit, kg ethylene (C_2H_4) equivalent.

Impact category	**Photochemical oxidation**
Definition	Type of smog created from the effect of sunlight, heat and NMVOC and NOx
Impact indicator	Increase in the summer smog
Considerations	• Meteorology, the chemical composition of the atmosphere and emissions of other pollutants
Damage categories (endpoint)	Human health and ecosystem quality
Unit	Depending on the model: • Kg ethylene equivalent • Kg NMVOC • Kg formed ozone