Fuel cell and Hydrogen – Joint Undertaking

FC-Hy Guide

Guidance Document for performing LCAs on Fuel Cells and H_2 Technologies

GUIDANCE DOCUMENT FOR PERFORMING LCA ON FUEL CELLS

Deliverable D3.3 – Final guidance document

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Abstract: This document gives guidance for conducting a LCA study on fuel cells. Adapted from the ILCD Handbook and the ISO 14040 series, the document gives an overview of how to carry out a LCA on fuel cells. This is done by delivering a specific set of rules with clear specifications about the information and issues that have to be considered and reported in a LCA study on fuel cells.

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List of Abbreviations

AC	Alternating current
AoP	Areas of Protection
AP	Acidification Potential
BoP	Balance of Plant
CML	Centre of Environmental Science - Leiden University
CO2	Carbon Dioxide
DC	Direct current
DMFC	Direct Methanol Fuel Cell
EC	European Community
ELCD	European Reference Life Cycle Database
EP	Eutrophication Potential
FC	Fuel CellFCs Fuel Cells
FCS	Fuel Cell System
FCH JU	Joint Undertaking on Fuel Cells and Hydrogen
FU	Functional Unit
GD	Guidance Document
GHG	Greenhouse Gas
GWP	Global Warming Potential
HTP	Human Toxicity Potential
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JRC-IES	Joint Research Centre – Institute for Environment and Sustainability
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MCFC	Molten Carbonate Fuel Cell
MJ	Megajoule
NCV	Net calorific value
NOX	Nitrogen Oxides

ODP	Ozone Depletion Potential
PAFC	Phosphoric Acid Fuel Cell
PE	Primary Energy
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PO43-	Phosphate ion
POCP	Photochemical Ozone Creation Potential
SI	International System of Units
SO2	Sulphur Dioxide
SOFC	Solid Oxide Fuel Cell
URL	Uniform Resource Locator
URI	Uniform Resource Identifier
yr.	year

List of key terms

Term	Definition
Allocation [or: Partitioning]	Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems (ISO 2006b).
Attributional modelling [or: descriptive, book-keeping]	LCI modelling frame that inventories the inputs and output flows of all processes of a system as they occur. For instance, modelling process along an existing supply-chain is of this type (JRC 2010a).
Average data	Data combined from different manufacturers or production sites for the same declared unit. NOTE Average can relate to a number of issues such as technologies, products, sites, countries, and/or time.
Co-product	Any of two or more products coming from the same unit process or system (ISO 2006b).
Comparative assertion	Environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function (ISO 2006b).
Comparative life cycle assessment	Comparison of LCA results for different products, systems or services that usually perform the same or similar function (JRC 2010a).
Consequential modelling	LCI modelling principle that identifies and models all processes in the background system of a system in consequence of decisions made in the foreground system (JRC 2010a).
Data set	Collection of data appropriate for a specific LCA, LCI or for information modules
Decision context	The decision-context is a key criterion for determining the most appropriate methods for the LCI model, i.e. the LCI modelling framework (i.e. “attributional” or “consequential”) and the related LCI method approaches (i.e. “allocation” or “substitution”) to be applied (JRC 2010a).
Disclosed to the public	The audience is not specifically limited and hence includes non-technical and external audience, e.g. consumers (JRC 2010a).
End-of-life product	Product at the end of its useful life that will potentially undergo reuse, recycling, or recovery (JRC 2010a).

Environmental impact	Potential impact on the natural environment, human health or the depletion of natural resources, caused by the interventions between the technosphere and the ecosphere as covered by LCA (e.g. emissions, resource extraction, land use) (JRC 2010a).
Generic data	Surrogate data used if no system specific data are available. They are developed using at least partly other information then those for the specific process, like for example stoichiometric data or other calculation models, patents, expert judgement. Generic processes can aim at representing a specific process or system or an average situation.
Life Cycle Assessment (LCA)	Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO 2006a).
Life Cycle Impact Assessment (LCIA)	Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (ISO 2006a).
Life Cycle Inventory (LCI) data set	Data set with the inventory of a process or system. Can be both unit process and LCI results and variants of these (JRC 2010a).
Multi-functional process	Process or system that performs more than one function. Examples: Processes with more than one product as output (e.g. NaOH, Cl2 and H2 from chlorine-alkali electrolysis) (JRC 2010a). See also: "Allocation" and "System expansion"
Primary data	Primary data are data determined by direct measurement, estimation or calculation for the process or system under study.
Secondary data	Secondary data are data collected from literature or other published media.
Situation A	“Micro-level decision support": Decision support, typically at the level of products, but also single process steps, sites/companies and other systems, with no or exclusively small-scale consequences in the background system or on other systems. I.e. the consequences of the analysed decision alone are too small to overcome thresholds and trigger structural changes of installed capacity elsewhere via market mechanisms (JRC 2010a)

Situation B	"Meso/macro-level decision support": Decision support for strategies with large-scale consequences in the background system or other systems. The analysed decision alone is large enough to result via market mechanisms in structural changes of installed capacity in at least one process outside the foreground system of the analysed system. One example is decision support for strategies (e.g. raw materials strategies, technology scenarios, policy options, etc.) (JRC 2010a).
Situation C	“Accounting”: Purely descriptive accounting / documentation of the analysed system (e.g. a product, need fulfilment, sector, country, etc.) of the past, present or forecasted future, and without implying a decision-context that would account for potential additional consequences on other systems. Two sub-cases need to be differentiated: In Situation C1 ("Accounting, with system-external interactions"), existing interactions with other systems are included in the LCI model (e.g. considering recycling benefits or avoided production for co-products). Note that these "interactions" refer to existing interactions with other systems only. This is in contrast to the additional consequences that are assumed to occur under Situation A and B, and that are assumed to be caused by the analysed decision. Situation C2 accounts for the analysed system in isolation, i.e. interactions with other systems are not accounted for, but cases of recycling and co-production are solved inside the system model (by allocation) (JRC 2010a)
Specific data	Data representing a single process (e.g. a specific technology as operated on a given site) or system. It exclusively contains data that have been collected at the represented process.
Substitution	Solving multi-functionality of processes and products by expanding the system boundariesboundary and substituting the not required function with an alternative way of providing it, i.e. the process(es) or product(s) that the not required function supersedes. Effectively the life cycle inventory of the superseded process(es) or product(s) is subtracted from that of the analysed system, i.e. it is "credited". Substitution is a special (subtractive) case of applying the system expansion principle (JRC 2010a).

System	Any good, service, event, basket-of-products, average consumption of a citizen, or similar object that is analysed in the context of the LCA study. Note that ISO 14044:2006 generally refers to "product system", while broader systems than single products can be analysed in an LCA study; hence here the term "system" is used. In many but not all cases the term will hence refer to products, depending on the specific study object. Moreover, as LCI studies can be restricted to a single unit process as part of a system, in this document the study object is also identified in a general way as "process / system" (JRC 2010a).
System expansion	Adding specific processes or products and the related life cycle inventories to the analysed system. Used to make several multifunctional systems with an only partly equivalent set of functions comparable within LCA (JRC 2010a).
Unit process	Smallest element considered in the life cycle inventory analysis for which input and output data are quantified. (ISO 2006a) In practice of LCA, both physically not further separable processes (such as unit operations in production plants) and also whole production sites are covered under "unit process". See also "Unit process, black box", "Unit process, single operation", and "System" (JRC 2010a).
Unit process, black box	A unit process that includes more than one single-operation unit processes (JRC 2010a).
Unit process, single operation	A unit process that cannot be further sub-divided into included processes (JRC 2010a).

PART I - GENERAL INFORMATION

1. About this document

This document provides detailed technical guidance on how to conduct Life Cycle Assessment (LCA) (according to the ISO 14040 and 14044 standards) for fuel cells (FCs) and hydrogen production technologies. It builds on the International Reference Life Cycle Data System (ILCD)1, coordinated by the Joint Research Centre – Institute for Environment and Sustainability (JRC-IES), through the European Platform on LCA. This system promotes the availability, exchange and use of consistent and quality-assured life cycle data and methods for robust decision support in policy making and in business. The ILCD Handbook2 is applicable to a wide range of different decision-contexts and sectors, and therefore needs to be translated to product-specific criteria, guidelines and simplified tools to foster LCA applications in the specific industry sectors.

The FC-HyGuide project responds to this need by providing a Guidance Document (GD) on how to perform every step of a LCA for hydrogen (H_2) production and fuel cell technologies.

The GD is foreseen to be applied to all projects funded by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) requesting LCA in the field of H_2 production and fuel cell technologies. By providing information on how to deal with key methodological aspects of LCA (for example definition of a functional unit, system boundary, allocation rules, relevant impact categories, etc.), the GD will allow each hydrogen production and fuel cells technology developers to assess their own technology, and make the information available in the ILCD Data Network. The availability of data sets will therefore be increased and future LCA studies in this field supported.

The intended audience of this document is primarily, the FC technology developers working on projects funded by the FCH JU. However, the document can be relevant for any LCA study of FCs. It also provides a first example of ILCD sectoral guidance document.

The applicability of the provisions given in the GD is limited to micro-level decision-context situations in the ILCD Handbook3 (Situation A). Situation A applies to decisions or studies which have only a minor relevance in a particular industry sector so micro level decision support causes none or negligible change in the background system (further information on

[1] The ILCD consists primarily of the ILCD Data Network and the ILCD Handbook. The ILCD Data Network is a web-based, decentralised network of Life Cycle Inventory (LCI) data sets.

[2] The ILCD Handbook is a series of technical guidance documents in line with the ISO 14040 series. It includes explicit and goal-specific methodological recommendations, multi-language terminology, nomenclature, a detailed verification/review frame and further supporting documents and tools.

[3] Regarding the decision-contexts, the ILCD Handbook identifies three typologies: micro-level (typically questions related to specific products, with no structural consequences outside the decision-context), meso/macro-level (questions at strategic level, such as raw materials strategies, technology scenarios and policy options, for example, which have structural consequences outside the decision-context) and accounting (descriptive documentation of the system under analysis).

background system can be found in section 6.3.1). This guidance document is made for the geographical scope of Europe. A non-exhaustive list of possible applications includes: evaluating the production of fuel cells (stack(s) and/or system), identification of Key Environmental Performance Indicators of fuel cell production for the purposes of Ecodesign/simplified LCA; hot spot analysis of a specific product; comparison of specific goods or services; benchmarking of specific products against the product group's average; development of life cycle based Type I Ecolabel criteria; development of a life cycle based Type III environmental declaration (e.g. Environmental Product Declaration) for fuel cells and development of a carbon footprint etc.

Situation B would cover "Meso/macro-level decision support", i.e. life cycle based decision support at a strategic level (e.g. raw materials strategies, technology scenarios, policy options), which are assumed to have structural consequences outside the decision-context (they are supposed to change available production capacity). This GD does not cover this decision context because possible FC applications are strongly context-dependent and thus more specific rules than those defined in ILCD Handbook cannot be defined. In fact the FC can be applied in a wide range of applications, ranging from stationary to portable, and can use different fuel production processes. Each application of the FC stack or system into the final application has to be evaluated on a case-by-case basis.

For the time being, some of the provisions reported in this GD are not detailed enough to allow for being unambiguously applied, due to the lack of more precise information. In fact, the still limited amount of life cycle information on the FC technology does not always allow extending the validity of choices, assumptions and results made to the entire product group. Thus, this GD should be conceived as a living document that will be further refined and detailed when more information from case studies will be available.

1.1. ILCD-compliance statement

The GD is compliant with the ILCD Handbook with reference to situation A, which means the provisions and explanations given are in line with those of the ILCD Handbook with respect to five aspects: data quality, method, nomenclature, review and documentation

- Data quality
  Data quality relates to completeness, representativeness (technological, geographical and time-related), precision/uncertainty, methodological appropriateness and consistency.
- Method
  The method relates to the appropriateness of the LCI modelling and other method provisions, and the consistency of their use.
- Nomenclature
  Nomenclature relates to correctness and consistency of nomenclature which has been used (appropriate naming of flows and processes, consistent use of ILCD reference elementary flows, use of units etc.) and terminology (use of technical terms).
- Review

Review relates to the appropriateness and correctness of the review type, review methods and documentation. This includes ensuring that the methods used to carry out the LCA are consistent with this guidance document (i.e. the document reported below), and are scientifically and technically valid. The data used must be appropriate and reasonable in relation to the goal of the study, and the interpretations reflect the limitations identified and the goal of the study. The study report is also transparent and consistent.

- Documentation
  Documentation relates to several topics: documentation extent (appropriate coverage of what is reported); form of documentation (selection of the applicable forms of reporting and documentation); documentation format (selection and correct use of the data set format or report template, and review documentation requirements).

If all the provisions are implemented, an LCA study conducted using this guide will be ILCD compliant.

2. How to use this document

This guidance document consists of two parts.

Part I (sections 1, 2 and 3) provides general information on the document, explaining its purpose and structure. A general description of LCA is also provided in section 3 to briefly introduce the methodology to the users.

Part II represents the core of the document. It provides detailed guidance on how to perform LCA for fuel cell and hydrogen production technologies. The methodological aspects include the definition of the functional unit, the system boundary selection, allocation rules and selection of impact indicators. They are explained with reference to the technological systems under study. A specific set of rules about the information and topics that have to be considered and reported in a LCA study are described in parallel to the methodological aspects in Part II. Some of the methodological aspects and general elements of a LCA study are mandatory some are optional. To distinguish between these two methodological elements “shall” is used for all mandatory parts and “should” is used for recommended but optional elements.

The guidance document is completed with five annexes. Annex I provides LCA study reporting templates (i.e. how to report the results and conclusions of the LCA in a complete and accurate way, without bias to the audience). Annex II shows the meta-documentation fields for the ILCD format to be filled out within the data sets. Annex III provides a specific data collection template. Annex IV includes a review reporting template, and Annex V gives examples from case studies on fuel cells and hydrogen production which will assist users in the application of the guidance document.

3. Introduction to LCA

Life Cycle Assessment (LCA) is an analytical tool to assist making environmentally relevant decisions concerning product systems. The scope of LCA encompasses development, production, use, disposal and recycling of products for specific applications. LCA is an established, internationally-accepted method that is defined in two ISO Standards (14040/14044). The ISO 14040 defines a LCA as follows:

"LCA is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its entire life cycle" (ISO 2006a).

The core of the LCA methodology is thinking in product systems and accounting for several environmental goals simultaneously. This methodology helps to keep decision-makers aware of potential shift of burdens that may occur when applying particular individual solutions. The following paragraphs briefly describe the methodology, while greater detail is provided in PART II of this document.

In LCA, the entire life cycle of the product in question is described. This description includes the extraction of resources, the production of materials and intermediates from the resources, the assembly of the product from the materials, the use of the product, and the end of life (Figure 1). The compilation of all relevant processes (connected by material and energy flows) across the life cycle of the product and relevant processes from other contributing products is referred to as the product system. The purpose of building the product system is to identify the intended benefit from the product to be delivered.

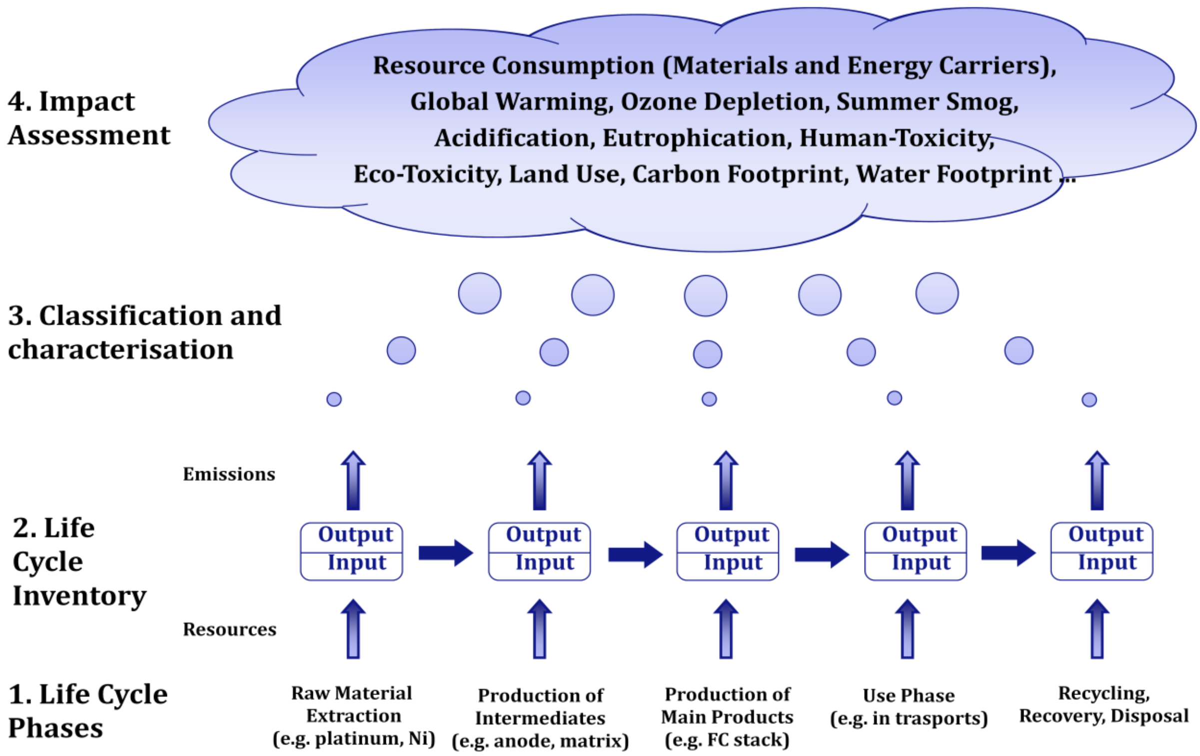

Figure 1: Overview of the LCA methodology

Performing a LCA is divided into several steps. Most of them are done sequentially, but there are also iterative parts where the previous steps have to be reconsidered. These steps are:

- Goal definition
- Scope definition
- Inventory analysis
- Impact assessment
- Interpretation

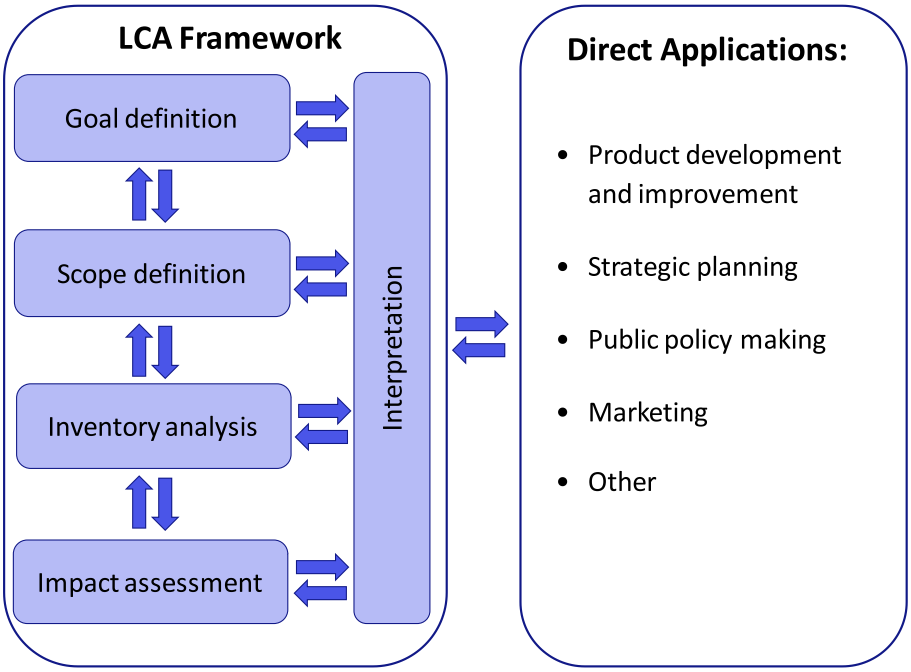

Figure 2: Methodology of LCA taken from ISO 2006a and JRC 2010a (modified)

Figure 2 illustrates a simplified overview of LCA methodology derived from the ISO standard 14040. The main phases (goal definition, scope definition, inventory analysis, impact assessment and interpretation) are shown. The interpretation interacts with all the phases. Moreover in the figure the iterative character of a LCA is shown. In fact, once the goal of the work is defined, the initial scope settings are derived that define the requirements on the subsequent work. However, as during the life cycle inventory phase of data collection and during the subsequent impact assessment and interpretation more information becomes available, the initial scope settings will typically need to be refined and sometimes also revised.

1. Goal definition

During the goal definition several aspects have to be defined:

- Intended application(s)
- Method, assumptions and impact limitations
- Reasons for carrying out the study and decision-context(s). Decision-contexts are goal situations under which the study is carried out and are defined by the intended

application and by the specific decision to be supported.
- Target audience(s)
- A statement as to whether the results are intended to be used in comparative studies which will be made public
- Commissioner(s) of the study.

2. **Scope definition**

During the scope phase the following aspects should be defined:
- The function, functional unit and the reference flow
- Life Cycle Inventory modelling (multi-functionality)
- System boundary and cut-off criteria
- Life Cycle Impact Assessment methods and categories
- Type, quality and sources of required data and information
- Data quality requirements
- Comparisons between systems
- Critical review needs
- The intended reporting.

3. **Life Cycle Inventory**

A model of the product system is conceived to represent the interaction of the product system with the environment. The model is commonly programmed in a dedicated LCA software tool and covers each step of the life cycle from the raw material extraction through to the product's end of life in a series of interconnected steps called processes. Interaction with the environment is represented as elementary flows crossing the system boundary, e.g. resources taken from nature and introduced into the product system or emissions arising from combustion, physical, thermal or chemical conversion processes which are vented into the environment. The elementary flows which make up the interaction of a product system with the environment are compiled. This compilation is referred to as the Life Cycle Inventory (LCI). Up to this point, the focus has been on the product system. It shifts towards the environment in the next step.

4. **Impact Assessment**

The large number of resources and emissions that make up the LCI is translated into a handful of environmental impact categories in the Life Cycle Impact Assessment (LCIA) step. Each flow from the LCI is grouped into one or more categories. Within each category, the flows are aggregated using equivalence factors called characterisation factors. These factors are based on the physical and chemical properties of the impact-causing substances, as well as on the fate of the flows once they leave the product system towards the environment. The aggregated value is called a "potential impact" and is most commonly given in kg equivalent of a certain reference substance for the respective category. For example, the unit of the impact "Global Warming Potential" (GWP) is kg carbon dioxide equivalent (kg CO_2-eq.). Methane (CH_4) has a 25 (IPCC 2007) times greater impact on global warming than carbon dioxide (CO_2) within 100 years span concerning greenhouse gas impacts, so it is characterised with a factor of 25 when aggregating GWP.

5. **Interpretation**
   Robust conclusions and recommendations relating to the goal and scope of the study are developed in the last phase. The results of the other phases are considered collectively and analysed in terms of the accuracy achieved and the completeness and precision of the data and the assumptions that were used.

Grouping and weighting, i.e. aggregation of all the environmental impacts into one single environmental value so as to tell which option is “best” when comparing product systems is often requested. However it is important to note that the aggregation of independent impact categories requires normative decisions. ISO 14044 specifies in section 4.1 that “It should be recognized that there is no scientific basis for reducing LCA results to a single overall score or number” (ISO 2006b). Grouping and weighting is based on subjective assessments rather than scientific findings and is therefore generally not recommended and forbidden for comparisons. When comparing, a complete set of indicators has to be used, e.g. it is not allowed to use Carbon Footprint alone for comparison. Most reports cover multiple impact categories, which allow trade-offs between different environmental impacts to be recognised and considered.

Decision-makers can use LCA to gain sound information on which to base decisions. The strength of the methodology lies in the two core aspects mentioned at the beginning of this text: thinking in product systems and accounting for all relevant impact categories. This ensures that shifts of environmental burdens between life cycle stages (or between impact categories) are recorded and decision makers can modify their processes to optimise the overall environmental benefits. The ability for multi-dimensional evaluation of system solutions is especially crucial when particular technology efficiencies have been maximised and substantial improvements can only be achieved through such system solutions.

Provision 1: The iterative approach to LCA

Shall: Take an iterative approach to LCA, expecting two to four iterations towards completing the study:

- Define the goal at the beginning of the study:
- Derive the scope definition accordingly
- Compile easily available LCI data for the foreground and background system
- Calculate the LCIA results
- Identify significant issues and perform first sensitivity, consistency and completeness checks on this initial model
- Based on this go to the next iteration: Start with fine-tuning or revising the scope (in some cases even the goal), improve the life cycle model accordingly, etc.
- Starting from the beginning of the study, document the details of the initial goal and scope definition, key LCI and LCIA items, and the key initial results of the sensitivity, consistency and completeness checks. During subsequent iterations, use this preliminary core report as work in progress and constantly revise, fine-tune and complete it towards the final report

Shall: If a review is performed, identify and involve critical reviewer(s) and - if required or desired - interested parties, from the beginning of the study.

PART II - GUIDANCE ON PERFORMING LCA OF FUEL CELLS

This section provides comprehensive information for experts such as technical engineers, decision-makers in industry and government policy on how to perform an LCA of fuel cells, both stack and system. Therefore, the methodological background is explained in detail, and each important step of an LCA – mandatory or optional – is described. The information on the methodological background is adapted according to ISO 14040, 14044 and the ILCD Handbook (ISO 2006a), (ISO 2006b), (JRC 2010a). The specific rules (including technical description and the information which has to be reported) are provided alongside the methodological information.

4. *Introduction to fuel cell technologies*

Fuel cells (FCs) are devices that convert hydrogen-containing fuels into electricity and thermal energy via an electrochemical process. They are considered a valuable alternative way of electrical energy production due to two main aspects: the low level of emissions during the process and the high conversion efficiencies. Other important features that make FCs attractive are:

- Modular structure, that makes them suitable for different applications;
- Flexibility, i.e. the ability to work with different type of fuels, and
- Silent operation.

Although the operating principle is the same for all types of cells, materials used and the operating conditions vary considerably. The different types of FCs exist can be classified into several categories depending on the combination of type of fuel and oxidant, the type of electrolyte and the temperature of operation. The most common classification is by the type of electrolyte used and includes:

- Polymer electrolyte membrane fuel cell (PEMFC)
- Phosphoric acid fuel cell (PAFC)
- Molten carbonate fuel cell (MCFC)
- Solid oxide fuel cell (SOFC)
- Direct methanol fuel cell (DMFC).

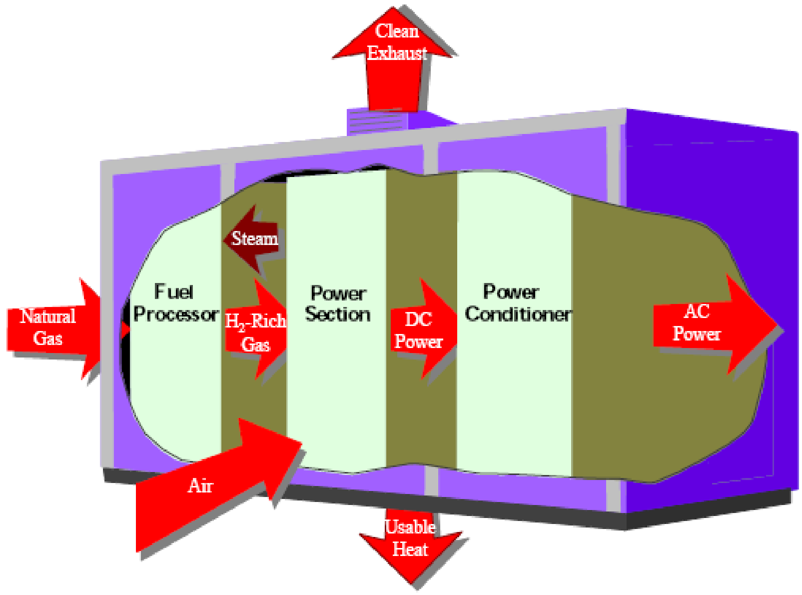

Figure 3: Schematic view of a generic fuel cell system (Source: Gasik 2008)

Figure 3 shows a simple example of a fuel cell system. The system commences with fuel processing where a conventional fuel (natural gas, other gaseous hydrocarbons, methanol, naphtha, or coal) is cleaned and then converted into a gas containing hydrogen. Energy conversion occurs when DC electricity is generated by means of individual fuel cells combined in stacks or bundles. A varying number of cells or stacks can be matched to a particular power application. Finally, power conditioning converts the electric power from DC into regulated DC or AC for consumer use (AAVV 2004).

FCs are complex systems, with a wide range of functions, depending on the specific applications (e.g., stationary, transport, portable) and a wide range of possible fuel production processes (e.g., hydrogen produced by water electrolysis can use electricity from any sources, MCFC have an integrated reforming process, etc.). Thus, any approach to the environmental assessment of FCs needs to take into consideration this variability and to be flexible enough to allow for assessment of the technology at different levels.

For this reason this FC Guidance Document recommends a modular approach, based on the modularity concept of the ISO 14025. It consists of analysing the FC technology system in terms of its main parts, which may represent the whole or a portion of the life cycle of the complete product being analysed. Modules can be subsequently combined to evaluate complex systems, see Figure 4. In this figure, each box represents a specific technical system necessary for the functioning of the FC, and each of them can be a module in the overall LCA study.

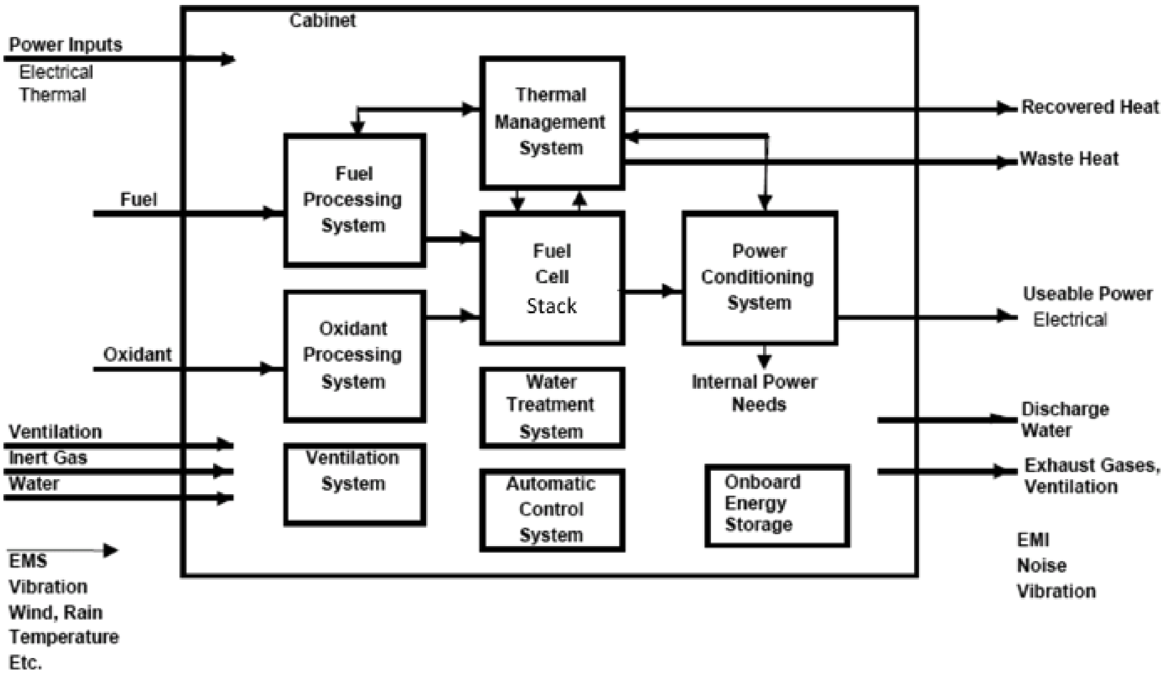

Figure 4: Schematic representation of a Fuel Cell system and its components (Source: EC/TS 62282-1)

Two modules have been identified for the LCA studies of a FC, and therefore within the scope of this document:

- FC stack (in Figure 4 it is named FC Module);
- FC system .

The FC stack consists of individual cells that are combined in a modular format by electrically connecting the cells to form units with the desired output capacity. The cell consists of:

- Contact layer;
- Cathode gas distribution layer;
- Electrolyte (in matrix);
- Anode gas distribution layer;
- Catalyst layer;
- Contact layer.

The stack consists of the following components:

- Interconnected/end plate;
- Seal gasket;
- Current collector;
- A number of individual cells;
- Current collector;
- Seal gasket;
- Interconnect components.

The stack is completed by the top end plates and stack thermal insulation (Gasik 2008).

The FC System as a whole comprises the stack together with the Balance of Plant (BoP, all the blocks in Figure 4 besides the fuel cell module). The cell stack is terminated by the manifold plate which connects the stack to the BoP. The BoP supplies fuel and air, ensures constant stack temperatures, manages required gas/fluid recycling, and provides infrastructure for start-up and shut-down as well as ancillary systems for total system control and power conditioning. The precise arrangement of the BoP depends largely on the fuel cell type, the fuel choice, and the end use of the system. Specific operating conditions and requirements of individual cell and stack designs also determine the characteristics of the BoP.

Because the system configuration is so strongly dependent on a range of conditions, it is not possible to provide guidance for conducting a LCA for a FC system applicable to each specific application. Therefore this document identifies and considers a basic structure of the BoP, the equipment necessary for the operation of the fuel cell (points 1 and 2 below). The use of the FC system for a special application is not considered (point 3 below). The three elements of the BoP are (AAVV 2004):

1. *Essential BoP* supports all system operating modes such as cold start, cool-down to ambient temperature, standby, power-up from standby, cool-down to standby, load following and emergency shut-down:
   - Air delivery system (blower, compressor, metering, pipe work, humidification, pre-heat)
   - Fuel delivery system (fuel pump/blower, metering, fuel cleaning4, fuel processing, humidification, cooling/pre-heat)
   - Thermal management system – air or water cooled (heat exchangers, after/start-up burner, steam generator)
   - Recycle streams (water5, fuel, C02, liquid electrolyte)
2. ***Ancillary BoP supports power management and system control:***
   - Power conditioning 6(DC-DC, DC-AC inversion)
   - Control system and instrumentation (sensor, hardware, software)
3. ***External BoP is application specific and maximizes energy efficiency:***
   - Housing/pressure vessels
   - Waste heat recovery

[4] Except when pure fuels are used, some fuel preparation is required, usually involving the removal of impurities and thermal conditioning. In addition, many fuel cells that use fuels other than pure hydrogen require some fuel processing, such as reforming, in which the fuel is reacted with some oxidant (usually steam or air) to form a hydrogen-rich anode feed mixture (AAVV 2004).

[5] While water is a reaction product, water is needed in some parts of the fuel cell. To avoid having to feed water in addition to fuel, and to ensure smooth operation, water management systems are required in most fuel cell systems (AAVV 2004).

[6] Since fuel cell stacks provide a variable DC voltage output that is typically not directly usable for the load, electric power conditioning is commonly required.

- Electricity and thermal storage

In the case of a LCA of a FC system, if a LCA of the FC stack is readily available and it is compliant with the FC Guide document methodology and standards, it can be used as an "information module" in the LCA study of the FC system, and the LCA of the BoP and the missing life cycle stages (transport, use phase, etc.) can be added following the example provided by Appendix B of ISO 14025.

4.1. Product information requested and standards to use

Provision 2: Product related information

Shall: briefly describe the FC system or stack. Information about the major properties need to be given by stating the FC standard being met, such as the IEC/TS 62282-1ed2.0 (2010-04) Fuel cell technologies - Part 1: Terminology; IEC 62282-2ed1.1 Consol. with am 1(2007-03) Fuel cell technologies - Part 2: Fuel cell modules; IEC 62282-2 ed1.0 (2004-07) Fuel cell technologies - Part 2: Fuel cell modules.

Shall: if no standard is applicable, state the following properties and characteristics:

- Trade name
- Type of electrolyte used
- Primary functions (production of electricity, heat, etc.)
- Electrical power (rated output)
- Thermal power (if applicable)
- Efficiency
- Rated voltage
- Rated current
- Range of temperatures and operating temperature
- Weight
- Dimensions
- Fuel used and its technical specifications
- Expected service life
- Description of the intended use.
- System boundary definition

4.2. Producer's information requested and description of the product system

Provision 3: Description of FC producer and product system

Should: Provide a short description of the organisation, including:

- Overall FC production capacity
- Number of sites
- Geographical coverage by region (Europe, North America, etc.) of the production sites
- Information on products- or management system-related certifications (e.g. ISO Type I ecolabels; ISO 9001- and 14001-certificates, EMAS-registrations etc.)
- Other relevant work the organization wants to communicate (e.g. SA 18000, supply-chain management, social responsibility- SR etc.).

Shall: Provide a general description of the FC life cycle, including the main components, the production processes and the use phase. To show the system under evaluation, a process flow diagram shall be included. Generally the description of the FC (stack or system) has to include information on:

- Technology used
- Year of construction
- Type of production site (laboratory, pre-commercial, commercial scale)
- On-site electricity or heat production (if existing);
- Production capacity;
- Actual production and total market production
- Technical service life;
- Type of storage.

If the study evaluates only components or a part of the production chain, only these components/parts have to be described but the product system which they are part of shall be named.

5. Goal of the LCA study on fuel cells

The goal definition is always the first step when performing a LCA. It includes:

- Definition of the intended application
- The reasons for carrying out the study
- The target audience
- Disclosure statement if the results are intended to be used in comparative assertions disclosed to public.

Provision 4 : Goal of the LCA study

Shall: Unambiguously define the goal of the study according to the goal definition in the ISO 14044 standard.

5.1. Intended application(s)

Provision 5: Intended application(s)

Shall: Unambiguously state the intended application (in the case of more than one application, state all), indicating if it is for internal (to the organization commissioning the study) use or for external use (results of the LCA to be disclosed to the public). Specific purpose could be (non exhaustive list):

Internal use:

- Identification of Key Environmental Performance Indicators (KEPI) for Ecodesign
- Hotspots analysis of a specific FC

External use:

- Development of life-cycle based Type I Ecolabel criteria
- Development of a life-cycle based Type III environmental declaration (e.g. Environmental Product Declaration - EPD)
- Calculation of a carbon footprint

Internal/external use:

- Comparison of environmental aspects of the FC
- Benchmarking of a specific FC against the product group's average.

5.2. Method, assumptions and impact limitations

Provision 6: Method, assumption and impact limitation

Shall: Assure sufficient consistency of methods and assumptions as well as data throughout the LCI/LCA study.

Document any inconsistencies and document consequences of these inconsistencies on the conclusion of the study.

Some examples:

- use of the upper or lower calorific value in the energy calculations
- comparing fuel cells, use of the same product use pattern, same system boundary, data with similar degree of accuracy, same LCIA methods
- exclusion of some impact categories

5.3. Reasons for carrying out the study

The drivers and the motivation for the study have to be detailed. In the case of a FC, the reasons might be e.g. to include environmental information in the product development to make a decision out of this information for the next steps, or to increase market share through environmental claims or giving decision support for legislation on funding of FC as an energy production system.

Provision 7: Reasons for carrying out the study

Shall: Unambiguously state the reasons for carrying out the study.

5.4. Target Audiences

The target audience determines how the report is constructed. For example, the audience may be “technical” or “non-technical”. For technical experts or researchers in the field of FC production, the technical detail level of the report is high. For politicians and decision-makers the report is supposed not to focus on the technical details but more on explaining the results in a non-technical manner not withstanding its technical base. Beside of the general distinction in technical/non-technical there might be various other possibilities how the target audience can orientate the format of a report. Some might want an EPD for example; this makes the whole study follow the relevant PCR. It may be internal audience then the format might be an executive summary plus a power point. Defining the target audience and hence the report format allows to better foresee the resources needed for the study.

Provision 8: Target audience

Shall: Unambiguously state the target audience of the study.

Should: Consider the audience when deciding how the report is written:

- Technical audience: experts or researchers in the field of FC production will focus the report on the technical details.
- Non-technical audience: politicians and decision makers will focus the report on the results and on the overall implications from a life cycle perspective.

Should: Consider specific formats, that might be demanded e.g. when writing an environmental product declaration.

5.5. Comparison intended to be disclosed to the public

If the intention of the LCA study is a comparison of production technologies, it is important to include the statement that the study is comparative. In this case, for instance, the system boundary has to be defined consistently and the functional unit has to be the same.

If the study is to be disclosed to the public, this also has to be stated in this context. These statements will influence the need of the critical review. More details on the critical review procedure for comparative assertions are given in section 11.

Provision 9: Comparison intended to be disclosed to the public

Shall: Include the statement if the study is comparative.

Shall: include the statement if the study is to be disclosed to the public

5.6. Commissioner of the study

The commissioner and the (co)financier of the study have to be stated in the report as well as other actors involved in the study such as other persons, groups, companies, organisations etc. This might be important, when e.g. the producer of a FC (stack and/or system) finances a study that compares his own system with the system of a competitor. In such a case, the LCA credibility might suffer, if the financer is not announced beforehand.

Provision 10: Commissioner of the study

Shall: Unambiguously identify the commissioner of the study and name all organisations that have any relevant influence on the study

Should: The person who carried out the LCA study should be named also.

6. Scope of the LCA Study on fuel cells

During the scope phase the object of the LCA study is defined, i.e. the exact product or system under investigation. The object of the LCA study may be either a FC stack or a whole FC system. These include all the single components and process steps, such as the active components (anode, cathode, matrix) and the steel and other material parts. In the LCA study, the object is defined in terms of functional unit and/or reference flow.

This phase, together with the Interpretation, is the most important one of the LCA methodology since it requires several resources for unambiguously defining what the LCA study is about and for whom. In fact, the depth and the breadth of LCA can differ considerably depending on the goal and scope of a particular LCA and errors made in this phase have strong consequences on the results (adapted from Fullana et al. 2011).

6.1. Function, functional unit and reference flow

The function of a Fuel Cell is the production of electricity and (in many cases) useful heat. Some specific FC can have additional functions (such as the production of water). Additional functions are not covered by this document.

The functional unit (FU) is a “quantified performance of a product system for use as a reference unit” (ISO 2006a). Generally a functional unit shall be precise and quantifiable.

To measure the performance of a FC with a single parameter, when both electricity and thermal energy are valuable products of the FC, the concept of exergy is adopted. In thermodynamics, the exergy of a system is the maximum useful work during a process that brings the system into equilibrium with a heat reservoir. Here the exergy is simply defined as the sum of electricity (in MJ) plus the useful thermal energy (in MJ) times a Carnot coefficient.

$$MJ_{ex} = MJ_{el} + ς_{th} * MJ_{th}$$

where:
MJex: exergy
MJel: electrical energy
MJth: thermal energy
ςth =1-(Ta/Tm).
Ta: ambient temperature and Tm the thermodynamic mean temperature of To (temperature of delivered heat) and Tr (return flow temperature).

$$kW_{ex} = kW_{el} + ς_{th} * kW_{th}$$

where:
kWex: exergy power
kWel: electrical power
kWth: thermal power
ςth =1-(Ta/Tm).

Ta: ambient temperature and Tm the thermodynamic mean temperature of To (temperature of delivered heat) and Tr (return flow temperature).

Other specific parameters need to be also defined, such as the nominal exergy power, the voltage of the electricity and the temperature of the thermal energy.

Provision 11: Functional unit

FC STACK

Shall: The functional unit is the power capacity of the manufactured stack expressed in kW (energy if electricity is the only valuable product, exergy if both electricity and heat are valuable products; in this case the share of electricity and heat shall be declared).

FC SYSTEM

Shall: The functional unit is the “production of a certain amount of electricity and useful thermal energy in a given number of years” , expressed in MJex. The share of electricity and heat shall be declared.

If the thermal output of the FC is not used, the FU is only the production of electricity, expressed in MJel.

Shall: Choose a service life span consistent with the expected lifetime and taking into account the time the facility has already been running, adequately supported with experimental results and/or other technical analysis.

Should: Define the service life using a -10% of degradation of the FC performance.

A reference flow is linked to the functional unit and sometimes, but not always, it is the same as the functional unit. The reference flow is a “measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit” (ISO 2006b).

Provision 12: Reference flow

Shall: The reference flow is the number of FC stacks or whole systems, required to produce the amount of energy or exergy defined in the functional unit.

6.2. Life Cycle Inventory modelling

Provision 13: Units

Shall: Use the International System of Units (SI) in the Life Cycle Inventory modelling.

Shall: Use an attributional modelling approach in LCA studies of FC systems and/or stacks, in line with the requirements of the ILCD Handbook for the decision context (Situation A). The requirements of attributional modelling will be described in the next sections.

6.2.1. Multi-functionality

A multi-functional process is a process or system that performs more than one function. FCs are a typical example of a multi-functional process as their main products are electricity and heat, and in some cases also water.

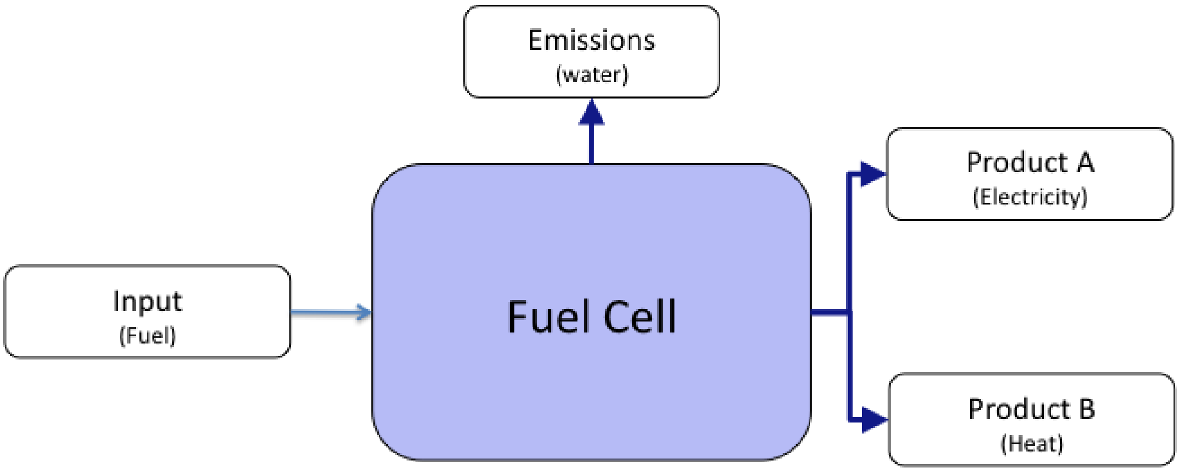

Figure 5: Schematic of a FC as multi-functional process

The main flows of the FC are displayed in Figure 5. The input is the fuel. The products are electricity and heat. A staged approach can be used to address the environmental impacts for each product in an appropriate manner.

The ISO 14044 and the ILCD handbook show a hierarchy of possible solutions for solving the issue of multi-functionality in the case of an attributional modelling approach (ISO 2006b) (JRC 2010).

The first approach is to subdivide the processes into several small processes. In case of the FC, the process cannot be subdivided further as it is only one process delivering several products.

The second approach outlined in the ILCD handbook is a system expansion. System expansion means to add or subtract a process with another function to make the original process comparable to other systems (Figure 6).

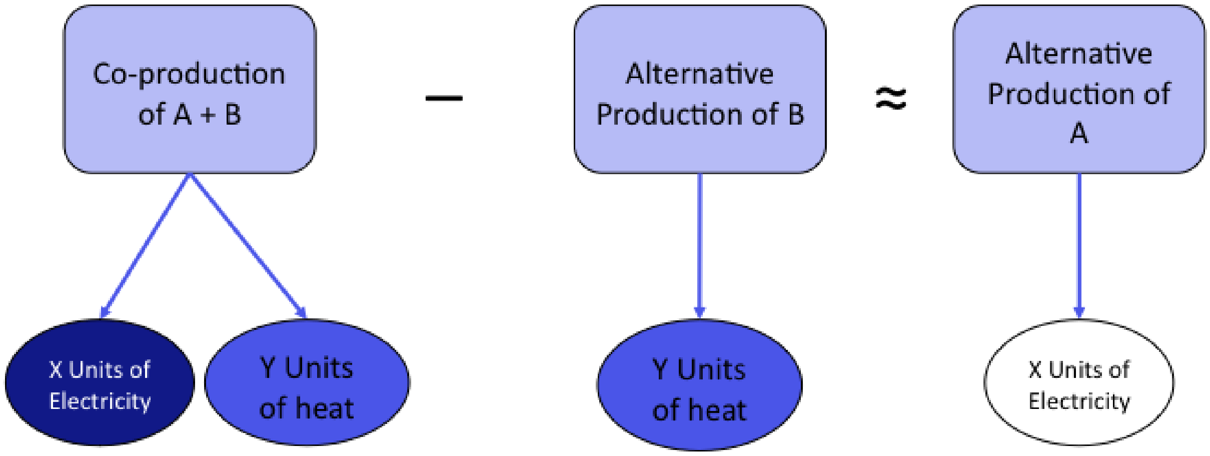

Figure 6: System expansion for solving multi-functionality (Source: JRC 2010) (modified)

In the case of a FC this method could be applied but the problem arises with the definition of the alternative system of producing heat.

The third approach is allocation. Allocation is "partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems" (ISO 2006a). This means that the impacts are separated into the different products using an allocation factor. The allocation factor can derive from mass, energy, price or other values.

The effect of the allocation or system expansion methods on the reliability of the final results and conclusion has to be determined by a sensitivity analysis. This analysis will show whether a chosen approach significantly influenced the results or not. In this way faults and misinterpretations can be avoided.

Provision 14: Multi-functionality

Shall: Analyse the use of the heat produced during the process in order to identify if an allocation problem exists.

6.3. System boundary and cut-off criteria (completeness)

6.3.1. System boundary

The ISO 14040 defines the system boundary as a "set of criteria specifying which unit processes are part of a product system" (ISO 2006a). This means that the process steps to be included and excluded in the LCA study need to be clearly defined.

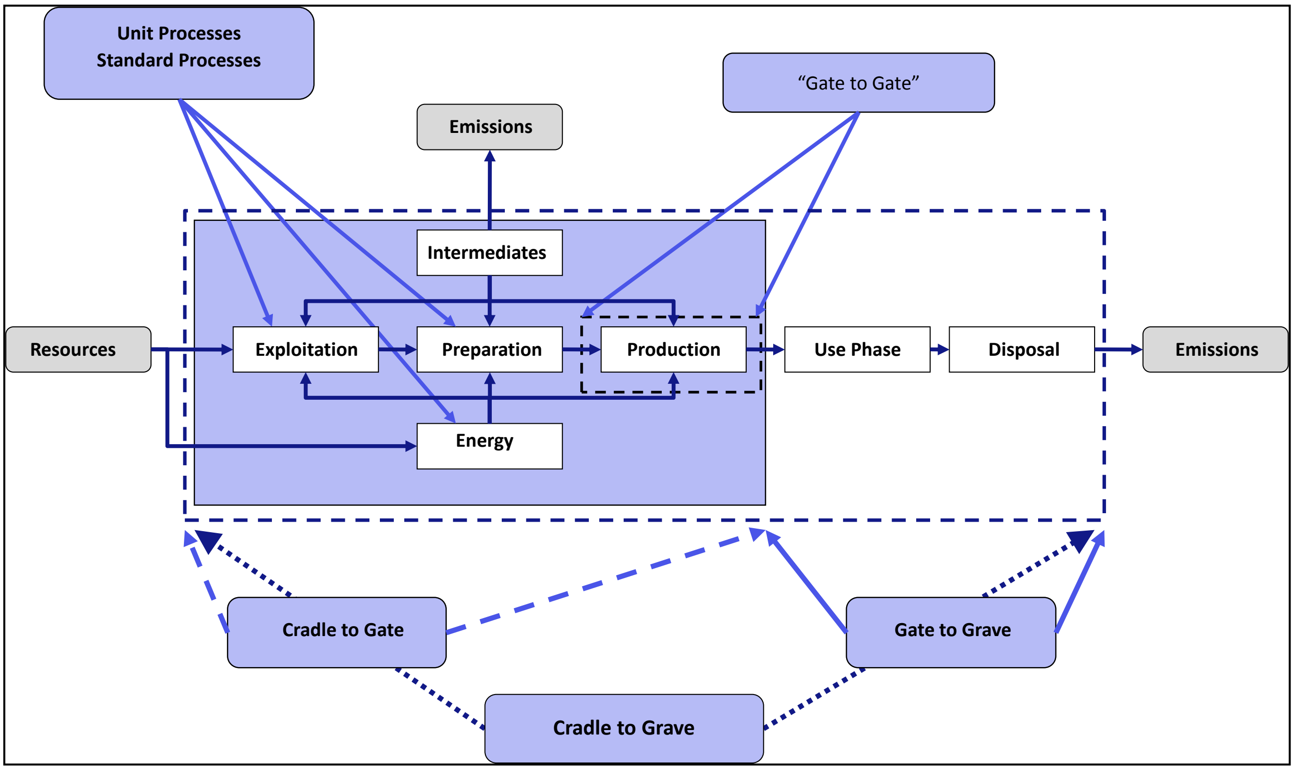

Figure 7: Possible system boundary in the life cycle of a product

Figure 7 shows an overview of how different system boundary can be defined. In the case of a FC system a "cradle to grave" view is generally applied. However, cradle to gate is commonly used in the case of a FC stack, where the absence of the BoP makes it impossible to assess the use phase. In both cases, the production of the fuel is not included. All relevant flows crossing the system boundary are included.

The FC system is divided into foreground and background system (Figure 8). The foreground system comprises the main process steps and the related infrastructure processes such as the manufacturing e.g. of the anode, cathode and the matrix. The foreground system is supported by the background system which is made up of processes such as the infrastructure processes for the supply of the energy including the power plants and power lines. The foreground and the background systems are included in the system boundary.

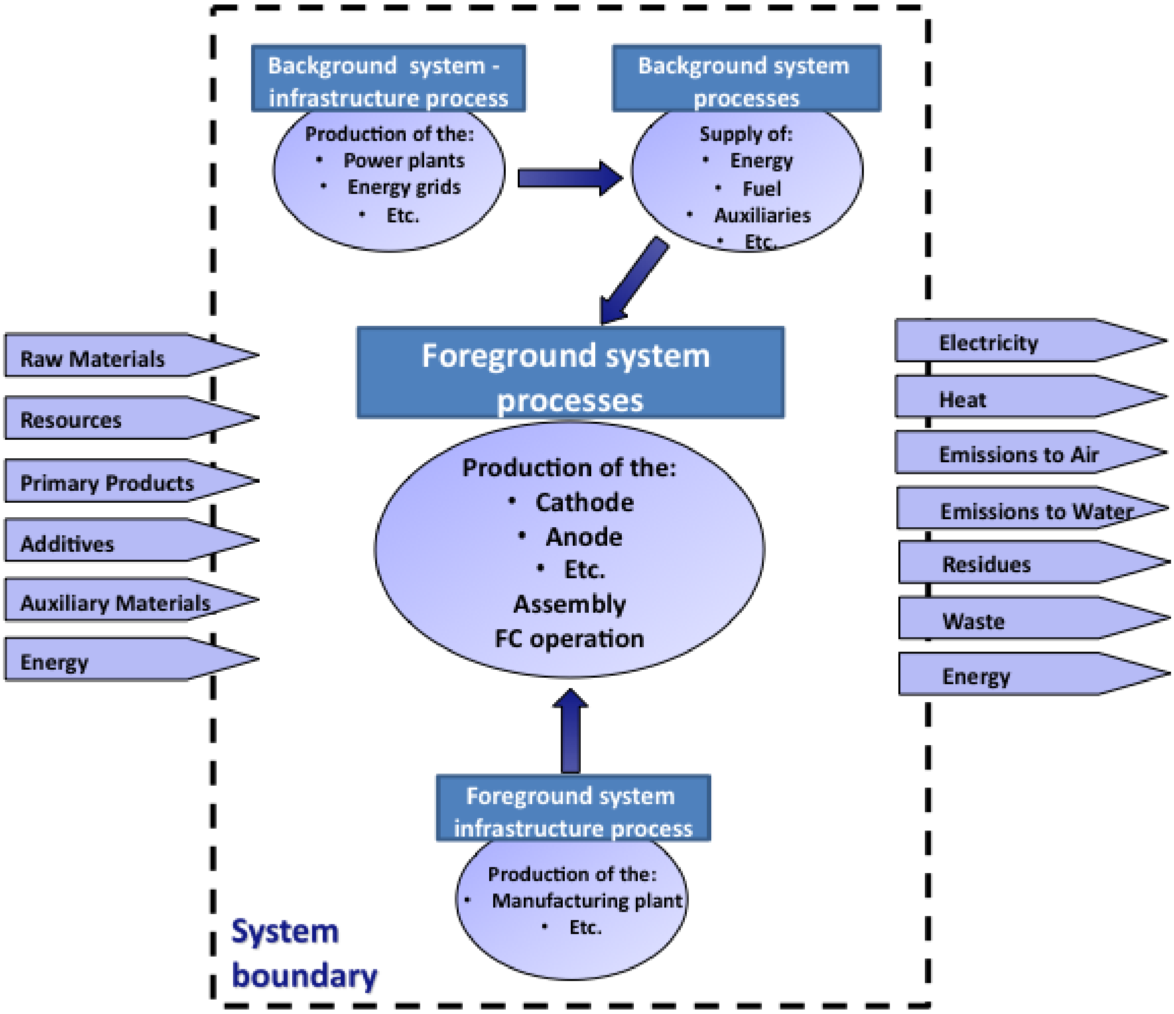

Figure 8: Foreground and Background system

The **foreground system** comprises all processes related to the production and use of the FC itself (Figure 9). In the case of a fuel cell stack, this includes in the first place the main production processes such as the manufacturing of the anode, cathode and the matrix, their assembly and maintenance. In the case of a fuel cell system, the foreground also includes the manufacturing of the BoP and the start-up system.

In the foreground process all relevant materials and energy flows of the usage are assessed. These are basically all flows going to and coming from the production process. Examples are the power demand, the amount of input flows such as the fuel (hydrogen or syngas) and emissions. Depending on the level of detail the main production process can be broken down into further processes.

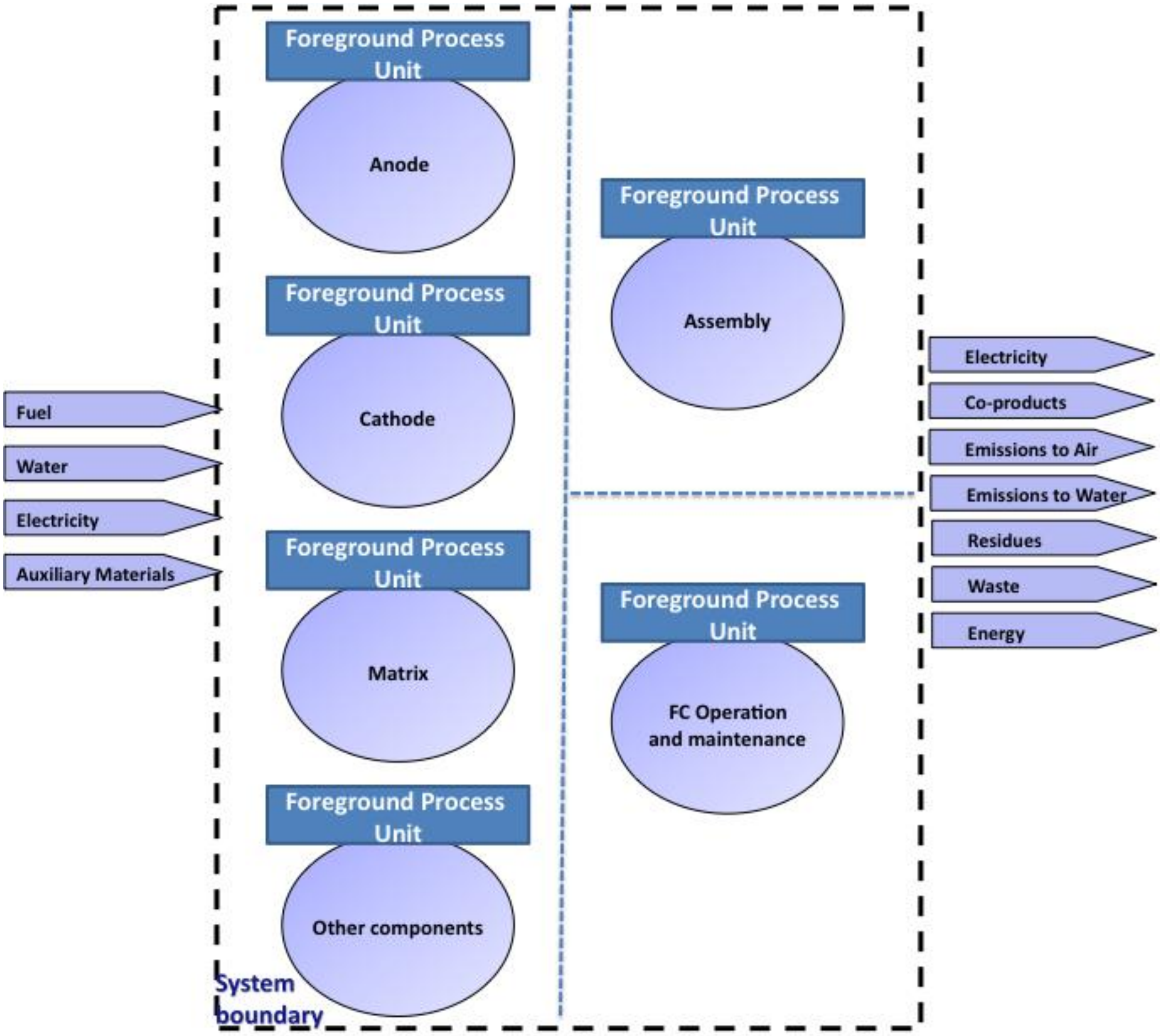

Figure 9: Foreground system

The foreground system's infrastructure is, as the name implies, the infrastructure that is related to the foreground process. Generally it considers the manufacturing of capital goods (e.g. the manufacturing plant). For the manufacturing of the facility electrical energy as well as materials such as steel, aluminium and other auxiliaries are needed. The life time of the equipment has to be considered in order to take into account the maintenance and replacement. If the life time of a machine is shorter than that of the whole facility, the impact of the production of this machine has to be considered more than once.

In the case of a FC, previous studies have shown that machinery and plant buildings can be considered of negligible importance compared to the contribution to the LCI of the components that are used in the final product, i.e. the fuel cells (Pehnt 2003a, b; Lunghi and Bove 2003; Lunghi et al. 2004a).

The background system supports the foreground system and its processes. It deals with almost all material and energy flows going to and coming from the foreground system. In practise it is not recommended to collect primary data for all background processes or to use hundreds of single unit processes and set up background systems individually. Rather, it is recommended that secondary data for the background system from existing high quality databases are used. This enables LCA studies to be completed in a timely manner.

Secondary data from databases have to include the entire supply chain of the corresponding background process. For instance the data set for the electricity supply includes the extraction of resources, production and distribution of the electricity generated. This means that if 1 kWh of electrical energy is consumed, the secondary average data set used shall include all relevant impacts and emissions for the provision of this energy.

The background system's infrastructures are the facilities for fulfilling the function of the background processes. Generally the background system's infrastructure (e.g. the manufacturing of the power plant or the fossil fuels production infrastructure) is included in the secondary data sets used for modelling the background system. They only have to be considered individually if something is constructed exclusively for the FC under study.

Provision 15: System boundary

Shall: The system boundary shall be consistent with the goal of the study (ISO 2006a)

Shall: Show the chosen system boundary in a flow chart

Should: The system boundary of a LCA on a FC is defined according to the product system under assessment. In the case of a FC system a "cradle to grave" approach is mostly applied. However a cradle to gate approach is used in the case of a FC stack, where the absence of the BoP makes it impossible to assess the use phase.

Shall: In both cases, the production of the fuel is not included.

6.3.2. Definition of relevant (energy, material and elementary) flows

A flow in general is an input or output from a process or product system. There are several types of flows. The elementary flow for example is defined in the 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). In essence this means that an elementary flow is for example crude oil or coal as input with CO_2 emission to air as an output.

Which product flows are relevant within the FC system depends on which FC technology is being assessed (flows being relevant for a MCFC e.g. K2CO3 might be irrelevant for a PEMFC).

Generally, all flows having an impact on the overall results are relevant.

Modelling a MCFC, for example, the electricity consumption for the manufacturing of the FC has to be adequately determined. Due to the different technologies in use it is not really possible to give general information as to which flows are relevant. However consumption of electricity and materials based on non-renewable resources are usually of environmental relevance. Specific process emissions and wastes might also be of environmental significance.

The cost of a material or energy being consumed can also provide a hint as to relevance. The environmental emissions and waste of a process have to be accounted for as completely as possible. Depending on the type of substances or materials, even small quantities may have large impact potential. These could include hazardous substances, or very small quantities of materials which are essential to the total process.

Provision 16: Definition of relevant flows

Shall: Decide which input and output flows are relevant based on the actual FC system and the individual goal and scope of the study.

Should: The following potential relevant flows for fuel cells should be included:

Unit of product	Components	Input	Output
Fuel cell stack	Anode, cathode, matrix, electrolyte	Chemicals (raw powders - e.g. Cr - and solvents, electrolyte chemical compounds) + electricity consumption for manufacturing processes	Emissions
Stack assembled	Above components + steel parts (e.g. anodic and cathodic collectors, bipolar plates)	Energy for manufacturing processes, materials (e.g. steel, copper)	Emissions
System assembled	Above components + BoP	Above inputs + materials (e.g. copper, aluminium, palladium, platinum, cast iron) + electricity consumption	Emissions
System assembled operation phase	Above components	Fuel consumption	Emissions

Shall: Document and justify any exclusion of flows listed in the above -recommended list.

Should: The accuracy of the quantitative data for the relevant flows has to be as exact as possible or as practically feasible, as this will determine the quality of the study results.

6.3.3. Cut-off criteria

In practice, accounting for 100 % of all inputs and outputs is sometimes not achievable since the effort required to acquire complete data would be very high. If the additional data would only give a negligible gain in accuracy, the additional effort would not be justified.

The ISO standard takes account of this situation by defining cut-off criteria. The ISO 14040 defines cut-off criteria as "specification of the amount of material or energy flow or the level of environmental significance associated with unit processes or product system to be excluded from a study" (ISO 2006a). In other words, all inputs that contribute more than a predefined percentage of mass or energy (e.g. 1% or 2%) of the total product system's inputs have to be considered in the study.

With regard to the environmental significance, any inputs should be included that contribute to a predefined amount of the environmental impact. These cut-off criteria can also be used for outputs such as emissions to the environment.

The choice of several cut-off criteria as described above is very helpful to assess the environmental impacts. Criteria based on mass alone, for example, could omit important inputs because the magnitude of impact is not only proportional to the mass input, but depends also on the individual materials. The cut-off rules imply that the total input amount is approximated, because if the total were to be known, there would not be any need for a cut-off. The higher the percentage of cut-offs, the higher the overall uncertainty of the final result.

The cut-off rules applied have to be clearly noted in the report and the expected uncertainty within the results has to be estimated, as systems can be assessed as having less environmental impact if rough cut-offs are applied.

Provision 17: Cut off criteria

Shall: Adopt a 2% cut off value on each relevant environmental impact category. Any different value shall be justified and its effects on the final results shall be checked through a sensitivity analysis.

Should: Show which flows are cutoff or excluded from the study.

6.4. Life Cycle Impact Assessment methods and categories

Life Cycle Impact Assessment (LCIA) aims at "understanding and evaluating the magnitude and significance of the potential environmental impacts" (ISO 2006a). Here inputs and outputs of elementary flows that have been collected and reported in the Life Cycle Inventory (LCI) are translated into impact indicator results related to human health, natural environment and resource depletion. The results of the LCIA should not be interpreted as a prediction of actual environmental effects but rather as indicators of potential environmentally relevant impacts.

The impact assessment phase consists of mandatory (classification and characterization) and optional (normalization, grouping and weighting) steps. Weighting step is based on value-choices and is not scientifically based. Thus, for guaranteeing an impact assessment free of value choices and assumptions, in FC applications non-normalized and non-weighed results have to be shown.

From the practical point of view, the impact assessment phase does not involve the LCA practitioners directly, but indirectly in that they choose the impact categories and the LCIA methods to be applied.

Choice of relevant impact categories and impact assessment methods

An impact category is defined as a “class representing environmental issues of concern to which life cycle inventory analysis results may be assigned” (ISO 2006b). This definition means various emissions are assigned to an impact category such as “Global Warming Potential”.

When referring to impact categories it has to be clarified if mid- or endpoint categories are being used (Figure 10). Categories at midpoint level require modelling the impact using an indicator located along the impact pathway, but not at the end. Examples include Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP), Human Toxicity (cancer and non-cancer related), Respiratory Inorganics, Ionising Radiation, Eco Toxicity, Land Use, Water Footprint, and Resource Depletion.

Category endpoints are defined as an “attribute or aspect of natural environment, human health, or resources, identifying an environmental issue giving cause for concern” (ISO 2006b). Categories at the endpoint level require modelling all the way to the impact on the entities described by the Area of Protection (AoP) i.e. on human health, on the natural environment and on natural resources. This extensive modelling then allows for cross-comparison of different impact categories within AoP on a natural or social science basis, and possibly taking into account all substance-specific differences.

The endpoint categories are more easily understood, because they are closer to what ultimately matters to society. The major uncertainties associated with modelling the impact pathway from midpoint to endpoint, however, represent a drawback that shall be considered. Conversely, midpoint categories are in line with the current environmental policy theme and can be modelled quite accurately. Moreover, the midpoints allow easier identification of the contribution of different processes, as the result is not completely aggregated.

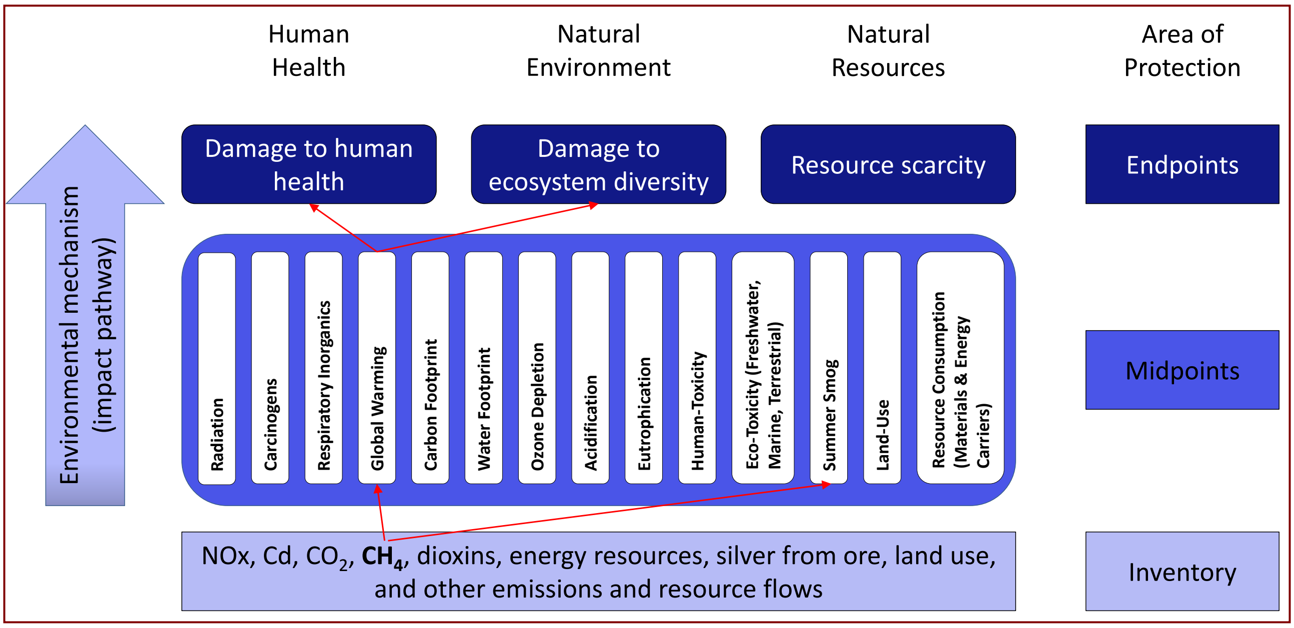

Figure 10: Schematic steps from Life Cycle Inventory to impact category (JRC 2010a) (modified)

In general impact assessment categories should therefore be chosen using an approved methodology, in conjunction with the scientific literature and general European policy goals.

The European Parliament and Council published "The Sixth Environment Action Program of the European Community 2002-2012" (European Parliament and the Council 2002) that forms the basis for the choice of the impact categories considered. The environmental priorities within this program are:

- Climate change
- Nature and biodiversity
- Environment, health and quality of life
- Natural resources and wastes

When describing climate change, the GWP is a generally and globally accepted impact category. To consider the varying greenhouse gas effect a time horizon of 100 years is chosen, also known as "GWP100". For example, in the case of a PEMFC stack, major contributions to this category are made by the gas diffusion electrode, which also contributes to acidification, and by the plates, which contribute also to energy resources. In the case of MCFC, a significant contribution to this category is made by the anode, which is responsible also for relevant impacts in terms of acidification and eutrophication.

With regard to the priority of nature and biodiversity, the protection of the environment from harmful pollutants is the primary goal. The impact categories AP and EP are the most relevant in this context. The key pollutants in these impact categories are SOX and NOX which have been in the past, and in many cases still are, the main sources for damage to forest and soil.

The protection of human health and the improvement of the quality of life are amongst other measures addressed by controlling ground level ozone levels. The impact category

POCP addresses the issue of summer smog formation especially in densely populated urban areas.

Abiotic depletion includes natural resources (including energy resources) such as iron ore and crude oil which are regarded as non-living. This category is relevant to a FC since they use high value materials (for example MCFCs use materials such as aluminium, nickel, chromium and lithium for electrodes, stainless steel for bipolar and casing), both from the environmental and economic point of view (Alkaner and Zhou 2006).

The use of secondary energy carriers, such as electricity, has to be documented separately. Aside from primary energy, other resources like land-use are recommended to be addressed as well. Land-use is an impact category under development at the moment that can be addressed when available. It will likely comprise several indicators addressing implications of different land-use types (Beck 2010).

Biodiversity (end-point) is also one of the major topics from policy side. Biodiversity are not calculated as such, but are represented by those mid-point categories, that affect biodiversity negatively, pre-dominantly eco-toxicity, Acidification Potential, Eutrophication Potential, Global Warming Potential, Ozone Depletion Potential and land-use. Methodology addressing biodiversity directly is under development. As soon as this methodology becomes available it is recommended to use it for LCA studies on fuel cells.

Provision 18: Impact categories to be used

Shall: Use the following midpoint impact categories:

- Global Warming Potential (GWP)
- Acidification Potential (AP)
- Abiotic depletion (AD)
- Eutrophication Potential (EP)

Shall: In addition to these environmental impact categories use the following environmental indicators:

- Non-renewable Primary Energy Demand (PED non-renewable)
- Renewable Primary Energy Demand (PED renewable)

Should: The following impact categories could be used additionally

- Ozone depletion potential
- Human toxicity
- Respiratory inorganics
- Ionising radiation
- Ecotoxicity (freshwater, marine, terrestrial)
- Photochemical ozone formation
- Ecotoxicity
- Land use

Scoping the LCA study, the LCIA methods to be applied shall be defined.

Different Life Cycle Assessment methods exist which are either midpoint or endpoint oriented. These include CML, ReCiPe, LIME and IMPACT 2002+. These methods are presently under evaluation by the JRC-IES, through the European Platform on LCA. A guidance document is being developed which will provide recommendations on methods that should be used in LCIA. 7

In general terms, the following criteria have been defined for selecting the impact assessment methods:

- Scientific robustness, which also takes into account the level of uncertainty;
- Development that has occurred over time;
- Method’s application in LCA practice
- European environmental policy goals

In order to guarantee the comparability among the LCA studies on FC technologies, it is necessary to define one impact assessment method for the impact categories selected. Among the several valuable options, the midpoint CML method8 (latest development) has been selected to be applied to the FCs for the following pragmatic reasons, free from any judgment of superiority:

- it meets adequately the criteria described above;
- it is implemented in most (if not all) the LCA software available;
- It has been widely used for the last 20 years.

Provision 19: Choice of impact assessment methods

Shall: Select the relevant environmental impact categories, models and characterisation factors from ILCD Handbook “Recommendations based on existing environmental impact assessment models and factors for Life Cycle Assessment” available at http://lct.jrc.ec.europa.eu/. (currently in draft version)

Shall: Use the CML impact method (latest development, http://cml.leiden.edu/software/data-cmlia.html) until the JRC recommendations are published.

6.5. Type and sources of required data and information

The quality of the data determines the quality of the whole study. In general there are two types of data used in a LCA study. Those are on one hand primary inventory data for the main processes, i.e. input and output data of stack production e.g. amount of energy and

[7] A comprehensive list of Life Cycle Assessment methods is given in the document “Recommendations based on existing environmental impact assessment models and factors for Life Cycle Assessment”, available in a draft version at http://lct.jrc.ec.europa.eu/.

[8] Developed by the Centre of Environmental Science at Leiden University (CML) (CML 2011), it provides characterisation and normalisation factors published on a regular basis,

materials. On the other hand, in addition to the primary data, secondary data are necessary, e.g. the inventory of the electricity consumed in the production of a material.

Provision 20: Type and sources of data and information

Shall: Require the inclusion of inputs and outputs to and from the foreground system to other technical systems.

Shall: Take into account all resources from nature and emissions to nature of the foreground and background system. Exceptions are allowed in accordance with the cut-off criteria (section 6.3.3).

Shall: Require the use of data reflecting the technology actually used and on the region where the process occurs.

Shall: Require the description in the LCA report of the closing of data gaps using comparable data.

6.6. Data quality requirements

In terms of FC production, the data quality refers to how the data are measured. It is recommended that a long term measurement is undertaken. If this is not possible, it is recommended to measure the same value several times and prepare an average. If the measured data are averaged it has to be stated how often they were measured and how precise the measurements are, which means stating if all the measured values were close to each other or if not how wide the deviation is. These aspects have to be considered by planning the data collection (section 7.2)

Data quality assessment has to focus on primary data and - for the overall LCA results - relevant secondary data.

Provision 21: Data quality requirements

Shall: Define the data quality requirements according to the goal and scope of the study

Shall: where the study is intended to be used in comparative assertions to be disclodsed to the public, apply all the quality requirements listed in clause 4.2.3.6.2 of ISO 14044

Shall: Use primary data for the foreground system of the FC

Shall: For consistency in comparative studies, use the European mixes (EU-27) for electricity, natural gas and other energy carriers

Should: In addition to the EU-27 mixes, specific mixes (country, company etc.) regarding electricity, natural gas and other energy carriers can be used, but not as an alternative.

Should: In addition to the EU-27 mixes, specific mixes (country, company etc.) regarding electricity, natural gas and other energy carriers can be used, but not as an alternative.

Should: Secondary data, e.g. production of materials, should reflect the European average (see section 7.3 for more details)

Should: Use primary data for the related infrastructure (if the infrastructure is assessed)

Shall: for comparative assertions disclosed to the public, the quality requirements from ISO 14044 apply.

Shall: The data/data sources used shall be documented in a transparent way so to enable another practitioner to reproduce the results.

Data quality requirements for LCI datasets

When LCI datasets are delivered, as a result of the LCA study, and they have to be made available to the ILCD Data Network, further requirements on data quality have to be fulfilled. More in detail, the following data quality indicators have to be used: Technological representativeness (TeR), Geographical representativeness (GR), Time-related representativeness (TiR), Completeness (C), Precision / uncertainty (P), Methodological appropriateness and consistency (M). They are described in the table below.

Table 1: Overall inventory data quality (validity) and its main 6 aspects

INDICATOR/ COMPONENT	DEFINITION/COMMENT
Technological representativeness (TeR)	"Degree to which the data set reflects the true population of interest regarding technology, including for included background data sets, if any." *Comment*: i.e. of the technological characteristics including operating conditions.

Geographical representativeness (GR)	"Degree to which the data set reflects the true population of interest regarding geography, including for included background data sets, if any." *Comment*: i.e. of the given location / site, region, country, market, continent, etc.
Time-related representativeness (TiR)	"Degree to which the data set reflects the true population of interest regarding time / age of the data, including for included background data sets, if any." *Comment*: i.e. of the given year (and - if applicable – of intra-annual or intra-daily differences).
Completeness (C)	"Share of (elementary) flows that are quantitatively included in the inventory. Note that for product and waste flows this needs to be judged on a system's level." *Comment*: i.e. degree of coverage of overall environmental impact, i.e. used cut-off criteria.
Precision / uncertainty (P)	"Measure of the variability of the data values for each data expressed (e.g. low variance = high precision). Note that for product and waste flows this needs to be judged on a system's level." *Comment*: i.e. variance of single data values and unit process inventories.
Methodological appropriateness and consistency (M)	"The applied LCI methods and methodological choices (e.g. allocation, substitution, etc.) are in line with the goal and scope of the data set, especially its intended applications and decision support context. The methods also have been consistently applied across all data including for included processes, if any." *Comment*: i.e. correct and consistent application of the recommended LCI modelling framework and LCI method approaches for the given Situation A, B, or C.

The quality levels defined in the ILCD Handbook (Annex A: Data Quality concept and approach) have to be used for documenting what has been achieved for the final data and for each of the data quality indicators. Moreover, the overall data quality has to be calculated by summing up the achieved quality rating for each of the quality components, according to the formula provided in Annex A of ILCD.

Entry-level requirements exist and can be applied for the first years of building up the ILCD Data Network. These are simplified/less demanding compared to full ILCD-compliance. The reader shall refer to the document “Compliance rules and entry-level requirements” (available at http://lca.jrc.ec.europa.eu/lcainfohub/datasets/html/external_docs/ILCD-Data-Network-Compliance-Entry-level-Version1-March2010.pdf) for details.

6.7. Comparisons between systems

Comparative studies are aimed at evaluating the superiority, inferiority or equality of the compared alternatives. In the comparison among the different types of FCs, some limitations due to scale factors and to differences in the operational conditions (temperature, used fuel, power output) have to be considered. For instance, MCFCs are fed by methane internally reformed to hydrogen, while SOFCs and PEMFCs are directly fed by H2 from previous reforming, thus adding to the difficulty of a direct comparison9. This would require a different pattern for hydrogen fuel (replacement of reformers by an electrolyzer for all the systems investigated) and consequent removal of reformers from the analysis10.

For these reasons, the following aspects shall be taken into consideration:

- The equivalence of the functional unit of compared alternatives.
- If some of the aspects of the FU differ between the systems, it shall be ensured that the functions are still seen as sufficiently comparable by the main stakeholders affected by the LCA study and the product users.
- The selection of the compared alternatives.
- In selecting alternatives, existing or widely used alternatives that may perform environmentally better than the compared ones shall not be left out.
- Durability
- The technical life-time of the alternatives shall be considered. This is a key aspect for FCs since, being technologies still under development, notably improvements are expected that will increase the FCs life-time.
- Methodological assumptions and data consistency
- Consistency shall be assured in FU and reference flow definition, selection of system boundary, requirements on data (technological, temporal, geographic representativeness), allocation principles, LCIA methods.

[9] The direct use of hydrogen deriving from electrolysis of water is not excluded in the future of MCFCs.
[10] The electrolyzer might be powered by excess electricity in low demand hours.

Provision 22: Comparison between systems

Shall: If different systems are compared the definitions made in the scope phase have to be addressed consistently:

- The LCI model shall be constructed analogously using the same rules for system boundary, LCI modelling principles and methodological approaches
- Methodological and data assumptions shall be analogous
- Completeness, accuracy and precision of the data (data quality aspects) shall be sufficiently similar. Equivalence of FU (or only insignificantly different) – including specifically the durability, consistency in system boundary, data quality requirements, allocation, LCIA methods.

Shall: If different systems are compared, harmonise the following aspects:

- comparison between systems shall be made on the basis of the same function(s), quantified by the same functional unit(s) in the form of their reference flows
- Uncertainty calculations shall be made either as best/worst case scenario or as stochastic uncertainty and accuracy calculation
- The cut-off shall be the same for mass and energy, additionally to the overall environmental impact
- Identical parts can be excluded of all models, similar but not identical parts shall remain in the model
- Use the European mix for electricity for comparing technologies in different countries.
- A LCIA shall be performed
- A critical review shall be undertaken (section 6.8)

Should: In selecting alternatives, include potentially environmentally better market relevant and available alternatives. If these are not included, this shall be highlighted in: conclusions and recommendations; executive and technical summary of the report.

6.8. Identification of critical review needs

The critical review is defined as a "process intended to ensure consistency between a Life Cycle Assessment and the principles and requirements of the International Standards on Life Cycle Assessment" (ISO 2006a). It is aimed at ensuring whether:

- The methods used to carry out the LCA are consistent with ILCD Handbook (and thereby also with ISO 14040 and 14044:2006) and scientifically and technically valid;
- The data used are appropriate and reasonable in relation to the goal of the study;
- The interpretations reflect the limitations identified and the goal of the study
- The study report is transparent and consistent (JRC 2010).

This means that the LCA undertaken shall be cross checked by a third party expert that has not been involved in the original LCA study guaranteeing consistent and reliable results. For studies that compare different FC stacks and are to be made public, a panel of three independent experts if required.

Whether a critical review is necessary or not depends on the items defined in the goal and scope phase:

- The intended application and decision context.
- The reason for carrying out the study.
- The intended target audience (internal or external, technical or non-technical).

It is recommended that an independent external review of studies of FCs be conducted. This means the reviewer is not involved in the study and not part of the organization that performed or commissioned the study.

Provision 23: Identification of critical review needs

Shall: A critical review is necessary if the study compares systems and is intended to be disclosed to the public.

Should: LCA studies for internal use only do not require a critical review, it is optional but recommended.

Shall: If the study intends to compare different FC stacks or systems and is intended to be disclosed to the public, the critical review shall be done by a panel of independent external reviewers to reach a higher level of assurance. The panel consists of an independent expert acting as a chairperson and at least two other independent experts, selected by the chairperson.

Shall: For comparative studies, open invitations shall be extended to additional interested parties to be involved in the review process (e.g. government agencies, non-governmental organizations or affected industries).

Shall The opinion of these 'additional interested parties" is to be considered in the review and be included in the review report.

Shall: Assure the independence, qualifications and experience of the reviewers. The reviewer/s shall be experienced in LCA methodology, verification and audit practice and shall have technical expertise related to the FC/FC system under analysis.

Should: For reviewer qualification, please refer to the document "Reviewer qualification for Life Cycle Inventory data sets" (JRC 2010b).

6.9. Intended reporting

Reporting is the step of the LCA in which the results, data, methods, assumptions and limitations shall be completely and accurately reported without bias. Moreover, the report needs to be presented in sufficient detail to ensure reproducibility of the results and to provide the required information to reviewers to judge the quality of the results and appropriateness of conclusions and recommendations.

The report has to be adjusted depending on the intended application and audience of the report (companies, trade associations, government agencies, environmental groups, scientific/technical communities, and other non-government organizations, as well as the general public / consumers). There are three levels of reporting depending on the final purpose of the study:

- a report for internal use,
- a report for a third party (i.e. an interested party other than the commissioner or the LCA practitioner performing the study)
- a report for the purpose of comparative studies and to be disclosed to the public

Provision 24: Intended reporting

Shall: Decide which form of reporting shall be used:

- Detailed report
- Data set
- Data set plus detailed report
- Non-technical executive summary.

Shall: Decide which level of reporting shall be used:

- Internal
- External (but limited, well defined recipients)
- Third-party report, publicly accessible
- Report on comparisons, publicly accessible.

Shall: Documentation of the methods and assumptions, together with data/data sources used, shall be sufficiently to enable a LCA practitioner to reproduce any conclusions or recommendations drawn.

Should: It is recommended that the third party report should document the results in an appropriate and clear manner. Even though this level of reporting does not require the inclusion of confidential information, however confidential information needs to be made available for reviewers, as a separate document under a confidentiality agreement.

7. Life Cycle Inventory Analysis of the study on fuel cells

After the goal and scope definition the next phase is the Life Cycle Inventory Analysis (LCI). It is defined as the "phase of Life Cycle Assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle" (ISO 2006b). This means that the data collection, the data processing and modelling are done during the LCI. Figure 11 shows the scheme for inventory analysis according to the ISO 14044.

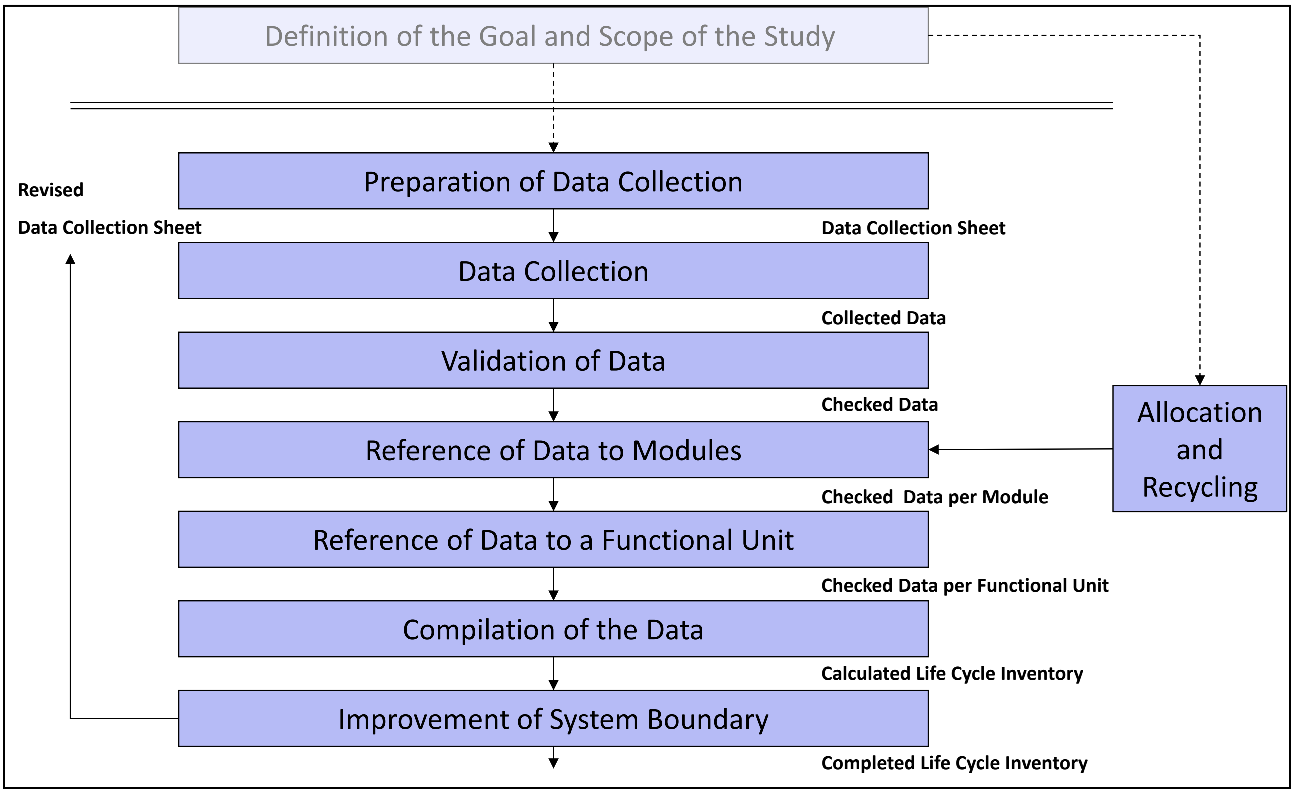

Figure 11: Simplified procedures for Lice Cycle Inventory Analysis (LCIA) (Source: ISO 2006b) (modified)

The first step is to define what data are needed. The next step is validating the data with e.g. existing secondary data. As a preliminary step for the modelling, the data are processed by referencing them to the functional unit. Using these processed data, a model is created in a LCA software11. Based on the data entered, the software compiles the Life Cycle Inventory. Reflecting the iterative nature of LCA, the LCI might be calculated several times following refinements of the data and the LCI model.

The use of such software makes modelling a product system faster, easier and provides a means to avoid errors when introducing hundreds of data in the calculations and when performing the calculations themselves.

Based on the data collected, material and energy flows can be assigned to each single process step and a detailed process chain analysis of the entire system can be done.

[11] There are various LCA software systems available. A detailed list can be found in the LCA directory of the European Platform of LCA http://lca.jrc.ec.europa.eu/lcainfohub/directory.vm

However, it must be ensured that a detailed data collection for each process step has been carried out and that the data have been measured under the same framework conditions (e.g. timeframe). If this is not done, reliable and consistent results can't be generated. After all numbers of materials and energy are assigned to the dedicated processes, where they are going to as an input or coming from as an output, the software uses these data to compile the final results in terms of e.g. the environmental indicators.

The Life Cycle Inventory Analysis comprises several procedural steps and methodological aspects, which are described below. These steps are:

- Identification of the processes within the system boundary
- Definition of the handling of multi-functional processes
- Data collection
- Modelling

7.1. Identifying processes within the system boundary

System boundary has been defined in the scope phase, identifying the foreground and the background systems. Here, the process units to be assigned to the foreground and background are identified, according to the attributional modelling.

Attributional modelling depicts the system as it can be observed/measured, linking the single processes along the flow of matter, energy and services, i.e. the existing supply chain.

LCA studies on a FC stack have to be carried out as a cradle-to-gate assessment, starting from the extraction of raw materials through to the production of the fuel cell stack and its start-up and maintenance. Including the end of life of a fuel cell stack or system is optional and could be kept out of the boundary of the study. However, it has to be described qualitatively.

A detailed overview of the life cycle steps including their boundary towards nature and other technical systems is shown in Figure 12 and Figure 13. The flows and substances entering from other systems and leaving the FC under evaluation towards other systems vary, depending on the type of FC.

Depending on the level of detail, the main production process can be broken down into further processes. An example is provided in Figure 14, which shows the anode production process. The level of detail in process modelling (e.g. whether a production process is described at the level of individual machines or production lines, at plant level or at sector level) depends, on the one hand, on the needs of the user and on the other hand on the data availability.

In the context of LCA, process data are required with the aim of suggesting improvements to the processes and systems under investigation. Thus, the degree of detail required in process data depends on the level at which the processes being investigated can be influenced. If changes to the process can only be made at a plant level, detailed information on machine level is unnecessary, unless the process is multifunctional and allocation of individual sub-processes to the different functions is needed.

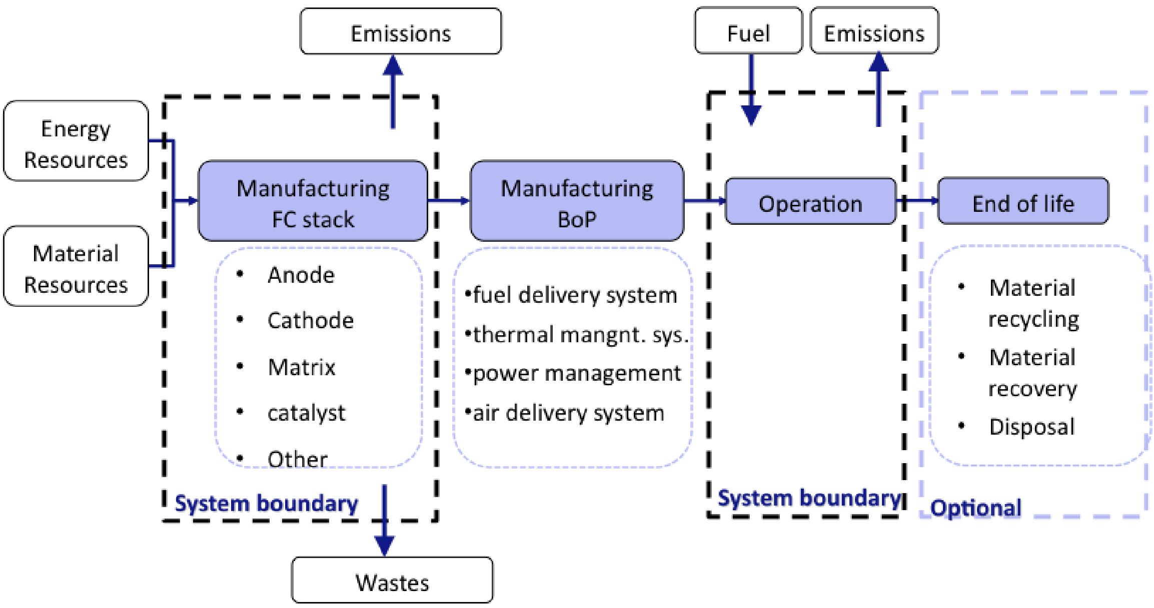

Figure 12: Boundary and processes for FC Stacks

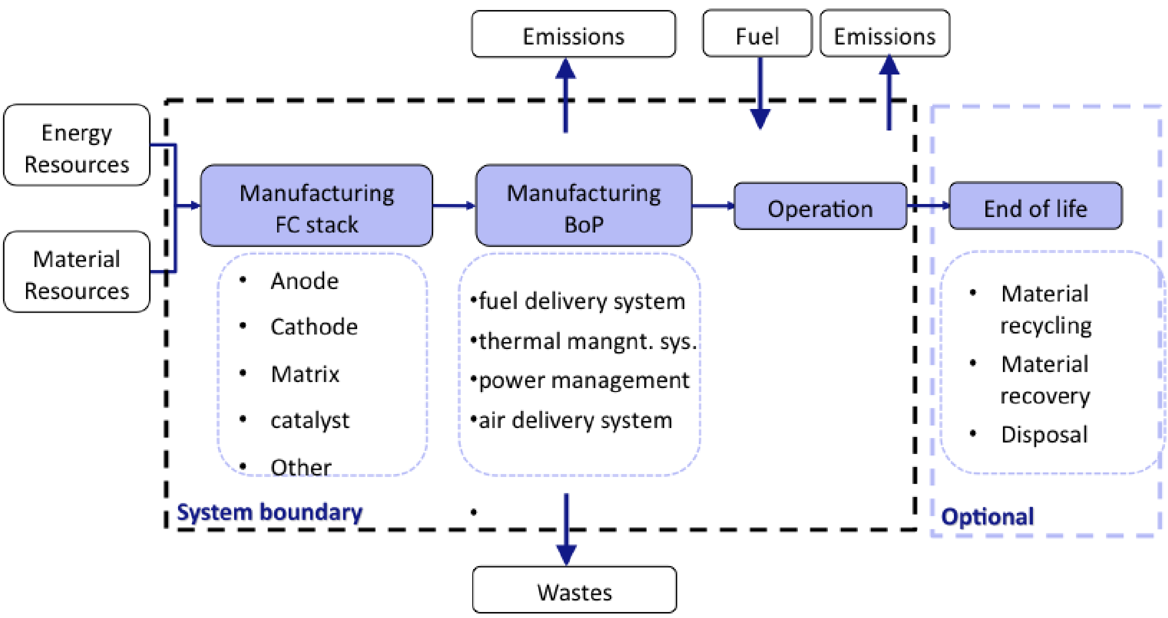

Figure 13: Boundary and processes for FC Systems

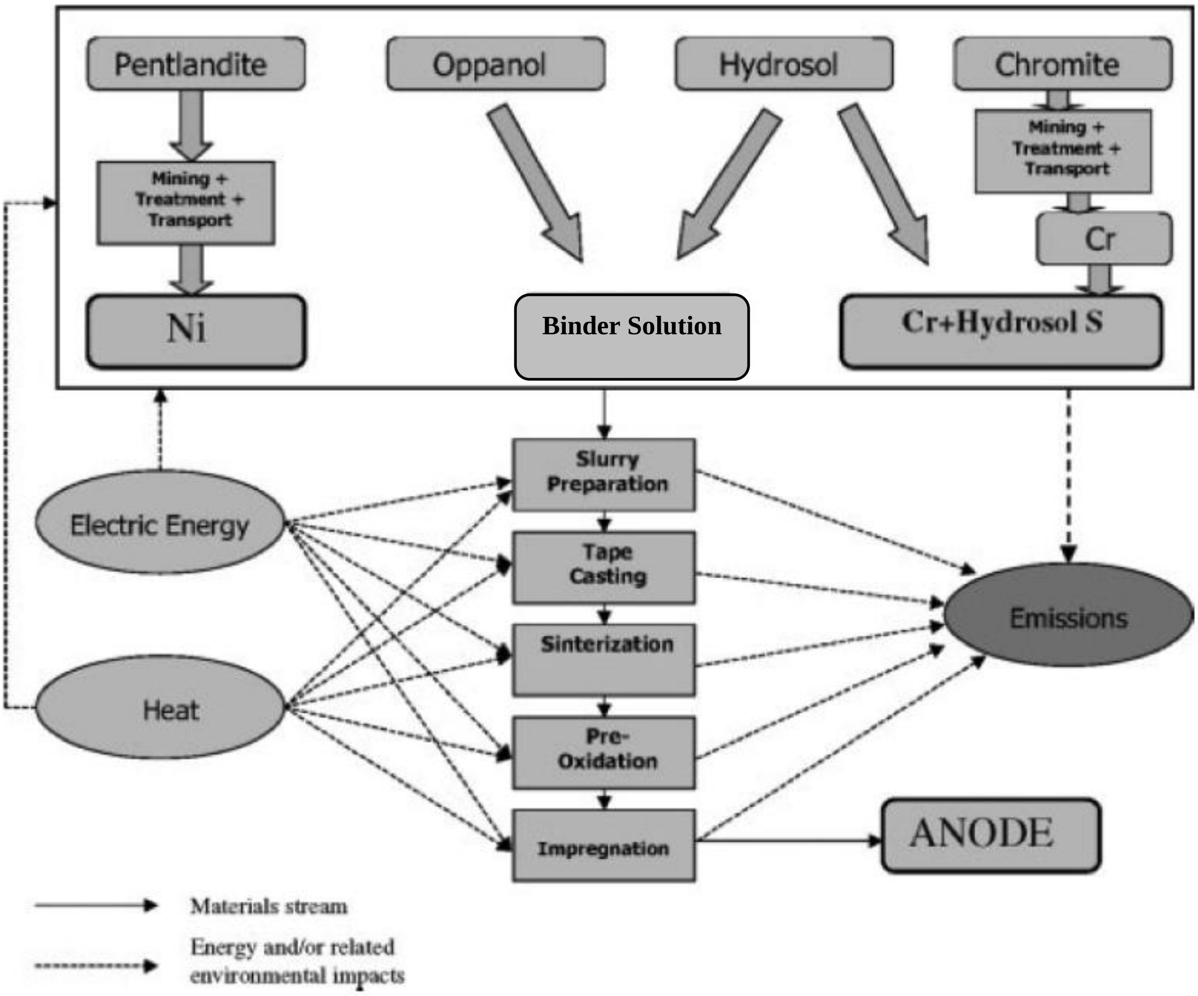

Figure 14: An example of further detailing the processes in the flow diagram. The anode production process (Source: Lunghi and Bove 2003)

Provision 25: Identifying processes within the system boundary

Shall: Define which foreground and background processes are taken into account in the LCA.

Shall: Identify the foreground processes following a supply-chain logic. For the fuel cell stack they include e.g. the manufacturing of the anode, cathode and the matrix, their assembly in a FC stack, start-up and maintenance. For the fuel cell system, the foreground also includes the manufacturing of the BoP. Details are provided in Figures 12, 13 and 14.

Shall: Include the important upstream processes such as raw material extraction and always identify processes using electricity, fossil and/or renewable resources.

Should: The related infrastructure ((e.g. means of transportation or pipelines) may be included in line with the cut-off criteria (section 6.3.3). It is recommended the use of existing secondary aggregated data, e.g. from ELCD, which comprises complete upstream processes (e.g. energy supply), including the infrastructure.

Shall: Exclude the use phase of the fuel cell in specific applications (on-site electric power for households and commercial buildings; supplemental or auxiliary power to support car, truck and aircraft systems; etc.). It can be easily added in follow up studies using this guide.

Should: The end of life of the fuel cell stack and system is optional and could be kept out of the boundary of the study.

Shall: If not included in the study boundary, a qualitative description of the end of life.

7.2. Planning data collection

The data collection is a very important step within the LCA. The quality of the data determines the quality of the whole study. Therefore the data collection is supposed to be done with care and precision. It can be time consuming and resource intensive to assure the data quality. It is strongly recommended a data collection system be established as a set of procedures as laid out in the provisions at the end of this section (ENEA 2004).

As stated above, the following types of data are used in a LCA study: primary data (i.e. at the operated processes) on the one hand, secondary data (from other sources than operated processes) on the other side. Both can be specific, generic and/or average. An example of specific data would be the input and output data of a FC such as amount of fuel consumed and net amount of electricity and useful thermal energy produced. When specific data are not available, generic (or surrogate) data can be used. An example of average data is for example the inventory of the electricity consumed as background data, as a result of data combined from different production sites in a defined geographic area.

The data have to be representative for regular operations of the process. This means that it has to be representative of normal operations in relation to the following factors:

- One start-up and shut-down sequence should be included
- Regular maintenance shall be included
- Auxiliaries shall be included

- If seasonal influences exist they shall be included (either measured or estimated) and balanced out
- The period measured shall be long enough to cover business as usual without irregularities.

For example, if unusually frequent start-up and shut downs of the production unit due to the development stage of the technology are included in the operational data, this might lead to non-representative energy consumption figures. In any case the origin of the data used is to be clearly documented so that the representativeness of the data being used can be assessed. For example, is it measured or calculated data? If it is measured: over what period of time was it measured? It also has to be clarified if the data are representative of a small-scale prototype or a large-scale production facility. In some cases, seasonal or geographical influences might need to be considered.

If possible the operating data measured shall cover one year of operations so that irregularities are averaged. Measured data covering shorter periods of time may also be used if considered representative for regular operation. If no or only limited measured data are available, design data may also be used. It is important that the origin and time period covered by the data is documented in the report. Moreover, data which are not attributable to regular operations shall be included but marked as such.

The selected processes have to be appropriate for their application. For example a process covering a small delivery truck below 7.5 t, should not be used to typify carriage of heavy goods. Another example is electricity supply. Voltage level should be considered as the distribution losses increase with decreasing voltage level. The following aspects need to be considered as well:

- The data should be representative for the technology as it is applied and for geographical and temporal coverage
- The data supplier and the quality of the background data should be known
- Consistency, i.e. the processes under investigation should be modelled using the same methodology and where processes are similar, the same system boundary.

For better guidance and for assistance in performing the workflow a data reporting template has been prepared. This template is available in Annex II.

Provision 26: Data collection

Shall: The data collection shall be done considering the following factors:

- One start-up and shut-down sequence should be included
- Regular maintenance shall be included
- Auxiliaries like pressurised air, etc. shall be included
- If seasonal influences exist they shall be included (either measured or estimated) and balanced out
- The period measured shall be long enough to cover business as usual operations without irregularities.

Shall: Collect site specific data of the foreground system of the FC and the related infrastructure valid for the reference year or the reference period.

Should: Process steps related to the background system may be site specific if available. Data on the production of materials and energy carrier should reflect the geographical region where they are purchased.

Shall: State the time (or time period) of measuring the primary data. In case of calculation or estimation, the time (or time period) of the data to which the assumptions refer have to be stated as well. Also most of the data available are only valid for a certain time period. If secondary data are used, especially for the background system, the age of the data and therefore the time-representativeness has to be documented and shall be suitable for the study

Should: Use the actual production technology in determining the input flows, - and take into account the region where they are purchased. If data are not available, comparable data should be used.

Shall: Document also data which are not attributable to regular operations

Should: Establish a data collection system:

- Identification of the data that need to be collected
- Planning when, where, and how data are to be collected and by whom
- Identification and treatment of data gaps
- The actual data collection (measurement or retrieval from book, experience, expert, etc.)
- Documentation of the resulting data, together with possible sources of error, bias or lack of knowledge
- Validation of the data collection system, the data collected and their documentation
- Communication of the data and their documentation.

Regarding the collection, documentation and inventory of data related to emissions and wastes (e.g. how to inventory future long term emissions, whether or not inventorying sum indicators like AOX or COD), no specific requirements apply to the case of FCs. Thus, for a full

ILCD-compliance, the provisions listed in the ILCD Handbook, sections 7.4.3 to 7.4.5 have to be applied, together with those on “Nomenclature and other conventions”, given in the respective separate guidance (JRC 2010c).

7.3. Selection of secondary Life Cycle Inventory data

Beside primary inventory data as described in the sections above, secondary data are needed, e.g. for energy carriers or auxiliary materials (e.g. nitrogen) consumed in daily life and business which are used in LCA studies generally. This aggregated data can usually be taken from existing (often established and differently reviewed) databases.

The electricity supply for example, is usually taken from the national grid. So an aggregated dataset which covers the country specific average for power generation, distribution and losses can be used to improve the time-efficiency of the study. Depending on the power plant technology (efficiency, exhaust cleaning technologies utilised, etc.) and the energy carriers used, the inventory data for the supply of 1 kWh of grid electricity can vary considerably from country to country. For example a country with a high share of hydropower has generally less harmful emissions than a country with e.g. coal based power generation. Due to this difference using different power grid mixes can result in totally different results. For the sake of comparability among studies using this guide the EU-27 mix is mandatory.

In the same way other secondary data can be applied for a variety of processes and materials that are frequently used. Depending on the technology under evaluation this could be the fossil fuel supply, electricity, thermal energy supply, auxiliary materials, catalyst material or transport processes, etc.

Provision 27: Selection of secondary LCI data

Shall: Consider the following criteria for selecting secondary data:

- The data shall be representative for the applied technology and for geographical and temporal coverage
- The data supplier and the quality of the secondary data shall be known
- The data shall be modelled consistent i.e. the processes used shall be modelled using the same methodology and for similar processes the same system boundary

Shall: The secondary data (generic, average or specific) shall be consistent with the primary data collected.

List of databases

There are multiple databases available that offer Life Cycle Inventory data with varying coverage and quality.

It is mandatory to use already existing secondary data sets from the European Reference Life Cycle Database (ELCD) or from the data network of the International Reference Life Cycle Data System (ILCD) as the first choice (JRC 2010d), (JRC 2010e). Data sets from these databases comprise complete LCI results, also known as secondary processes (e.g. “EU-27 natural gas, at consumer" or "EU-27 electricity grid mix, at consumer, 230V"). If data are not available from these two sources, high quality data sets from consistent databases using the ILCD format are recommended. A detailed list of the available databases can be found in the LCA directory on the European Platform of LCA (http://lct.jrc.ec.europa.eu/).

Provision 28: Choice of databases for secondary data

Shall: Use the following databases for secondary data (by order 1, 2, 3):

1. The European Reference Life Cycle Database (ELCD)
2. If there are no applicable data in above mentioned database available, use the following priorities:
3. ILCD compliant data sets, e.g. from the International Reference Life Cycle Data Network
4. ILCD entry level data sets, e.g. from the International Reference Life Cycle Data Network
5. 4.Databases using the ILCD format (http://lca.jrc.ec.europa.eu/lcainfohub/databaseList.vm)
6. If the data needed are not available in databases using ILCD format, the following sources can be used: other LCA databases than those listed above; recipes and formulations; patents; stoichiometric models; legal limits; data of similar processes, etc.

Shall: In case of comparative assertions to be disclosed to the public, the choice of databases used in the two studies shall be consistent one another. Any deviation shall be documented.

Dealing with data gaps

A suitable data set may not exist in any of the above mentioned databases. In this case it is recommended a literature search is undertaken to fill the data gap(s).
Other options are available if it is not possible to carry out a literature search due to factors such as time restrictions. One option is to use secondary data similar to the data set needed. If, for instance, a data set for a certain alloy is not available, than a data set for a similar alloy might be used even though they have a slightly different material composition.
Another option for dealing with data gaps is to ask the manufacturers or technical experts/process operators directly for information.

Provision 29: Filling data gaps

Shall: If data gaps arise, state in the report how they are filled

Shall: Check the relevancy of initially missing data in the following way and relevant gaps shall be filled if possible and as detailed below:

- Should: Identify relevance of initially missing data by using conservative estimation in a first screening
- Should: Dealing with relevant initially missing data if the screening shows relevance, focus on try to get better data
- Shall: Filling data gaps with estimates of defined and minimum quality. Documentation should be done in a transparent and consistent way. Data gaps shall generally be filled with methodologically consistent data. Only data that increases the overall quality of the final inventory of the analysed system shall be used to fill data gaps.

Shall: If data estimates cannot be made available that would meet above requirements, the data gaps shall be kept and documented on missing quality instead.

Should: Use the following methods for filling data gaps:

- Literature research
- Secondary data that are similar regarding the environmental profile
- Information gained from manufacturers
- Information gained from technical experts or process operators.

7.4. Dealing with multi-functional processes

FCs are a typical example of a multi-functional process as their main products are electricity and heat and in some cases, also water. In some cases heat is a valuable product, as the temperature is sufficiently high to make it usable in other processes. A way to avoid allocation problems in this case is to adopt exergy as the functional unit, as exergy is a measure of the combination of electricity and usable heat produced by the FC.
In other situations, heat is not a valuable product either because the fluid temperature is too low to permit the recovery of the heat energy, or because the FC is used in a context where heat is not required. In this case, heat can be considered as a waste emission to the environment.

Provision 30: Dealing with multi-functionality

FCs are a typical example of a multi-functional process as their main products are electricity and heat. Two scenarios are possible:

Scenario 1: Heat is a valuable product, as the temperature is sufficiently high to make it usable in other processes.

Shall: Adopt exergy as functional unit as a way to avoid allocation problems, as exergy is a measure of the combination of electricity and usable heat produced by the FC.

Scenario 2: Heat is not a valuable product either because the fluid temperature is too low to permit the recovery of the heat energy, or because the FC is used in a context where heat is not required.

Shall: Consider heat as a waste emission to the environment.

Shall: Determine by a sensitivity analysis (see section 9.2.2) the effect of the allocation or of any other solutions used for the multi-functionality on the reliability of the final results and conclusions.

7.5. Consideration of re-use, recycling, and energy recovery

The end of life of a fuel cell stack and system is an optional study and could be kept out of the boundary of the study. However, it shall be described qualitatively. Three main scenarios are envisaged:

- Disposal: If no information is available, the worst case scenario of disposal is applied, i.e. the product as a whole is considered to be disposed of without getting any credits for re-use or recycling.
- Recycling: If the producer of the FC has in place a take-back policy, the re-use and/or recycling options can be considered. The disassembly and recycling processes shall be described and credits for impacts avoided through component re-use, material recycling and/or recovery can be claimed.
- Legislation: When European or national legislation is applicable, the minimum percentages of recycling and/or energy recovery mandatory by law can be applied for calculating the credits for impacts avoided, taking into account the impacts related to disassembly and recycling processes.

With the present state of technological development, not many attempts and progresses have been made to dismantle and recycle the active parts of Fuel Cells and thus, the use of recycled materials for the manufacturing is not a common practice. In principle, shredding and removing the different materials that make up the stack, the power conditioner, and other parts, would be an important choice, considering that there is a large amount of valuable materials within the FCs: copper, iron, steel and aluminium in the BoP, nickel in anodes and cathodes, chromium in anodes, etc.

It would be advisable to develop recycling patterns for the recovery of these very valuable metals by means of conventional technologies, and their inclusion in the end of life recycling scenario.
If recycling processes are included in the study, their modelling has to follow the provisions of ILCD Handbook in Annex C (JRC 2010a).

7.6. Calculation of Life Cycle Inventory results

After the multi-functionality has been addressed and the data collected, the inventories of all unit processes included are scaled in relation to their share in the overall product system and are aggregated over e.g. life cycle stages or over the whole product system.
All relevant interim products and wastes generated inside the system are to be completely modelled. The final LCI results have to represent only the product prescribed by the functional unit.

Provision 31: Calculation of LCI results

Shall: Determine for each process within the system boundary how much of its reference flow is required for the system to deliver its functional unit and/or reference flow; scale the inventory of each process accordingly.

Shall: Keep track of the not aggregated inventory for the identification of the significant issues

Should: Aggregate (sum up) the scaled inventories of all processes within the system boundary for that system.

8. Impact assessment

The impact categories to be covered in the life cycle impact assessment and the LCIA methods to be applied (together with the normalisation and weighting set, if included) are defined in the scope phase of a LCA.
This section explains how to address the three steps of the life cycle impact assessment, with reference to the FC (both stack and system): classification and characterisation, normalisation (optional), grouping and weighting (optional).

8.1. Classification and Characterisation

Mandatory elements in the LCIA are classification and characterization. Classification is the assignment of the various emissions into impact categories.
Most elementary flows can be assigned to one impact category but in some cases a single attribution is not possible. For example methane does have an impact on global warming as well as on the photochemical ozone creation potential. Therefore during classification, the emissions are assigned to both impact categories.
Characterisation means the definition of how much impact an emission has with regard to a pre-defined reference substance of an impact category. This is expressed by means of a characterization factor.

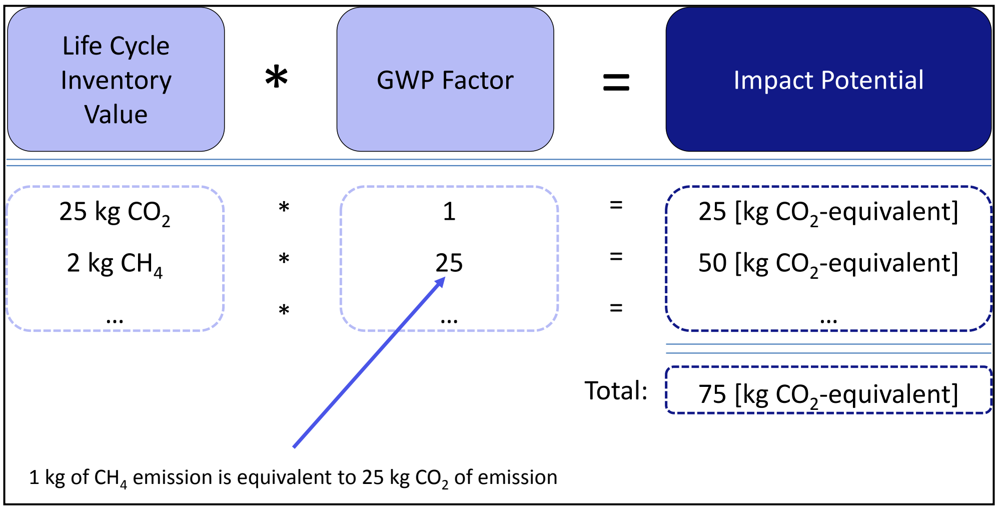

Figure 15: Characterisation of methane

Figure 15 shows an example of the characterisation of methane for GWP according to the IPCC (IPCC 2007). Methane has an environmental impact for GWP that is 25 times stronger than that of CO2 within 100 years time span. As the GWP is calculated in kg CO2 equivalents the characterisation factor of methane is 25. The results for each characterised indicator can be summed up within each impact category.
In relation to this element of the LCIA procedure, the practitioner needs only to apply the impact assessment method selected in the previous step. The software will automatically calculate the results by multiplying the inventory results by the characterization factors.

The LCA practitioner and the final user of the results should be careful in analysing the results of the characterisation step, bearing in mind that a comparison across the impact categories cannot be done at this stage. In fact, they have different units and therefore cannot be directly compared to identify which are most relevant or summed up.

Provision 32: Classification and characterisation

Shall: Evaluate the following impact categories previously identified in the scope phase: global warming potential, acidification potential, eutrophication potential, abiotic depletion.

Shall: When available, use the methods, models and characterisation factors identified in the Guidance document under preparation by the JRC-IES, through the European Platform on LCA. Until this Guidance document is available, use the most up-to-date CML impact assessment methodology. If the assessment is performed with spreadsheets in Excel, the list of characterisation factors is available at the following address http://cml.leiden.edu/software/data-cmlia.html.

Shall: In addition to these environmental impact categories, use the following environmental indicators:

- Non-renewable Primary Energy Demand (PED non-renewable)
- Renewable Primary Energy Demand (PED renewable)

Should: The following impact categories could be used additionally

- Ozone depletion potential
- Human toxicity
- Respiratory inorganics
- Ionising radiation
- Ecotoxicity (freshwater, marine, terrestrial)
- Photochemical ozone formation
- Ecotoxicity
- Land use

Shall: Do not perform a comparison across the impact categories

Shall: Do not perform a summing up across impact categories.

8.2. Normalisation (optional)

Normalisation is an optional element of the ISO standard, and means to “calculate the (relative) magnitude of category indicator results relative to reference information” (ISO 2006b). As the absolute values of the environmental indicators are of different order of magnitudes, the results may be shown relative to some reference information (e.g. country wide emissions).

After normalisation the results are given relative to the reference e.g. XX % GWP of the reference system, such as EU-27, YY % AP. Hence the results of a FC production are compared with the environmental impact indicator of the chosen reference system (e.g. total EU-27 or an individual European member state, e.g. Italy). Normalised environmental impact indicator results can be displayed in one graph. In the case of the determination of the environmental profile of FC production, normalisation is not needed since the results in the form of absolute values are easier to comprehend.

Provision 33: Normalisation

Should: Normalisation as optional element of LCIA is not recommended in the case of FC production. However, it may be applied to support the interpretation of the results of the study.

Shall: If normalisation is undertaken, document the decision in the scope definition and report it transparently.

Shall: If normalisation is applied the following points shall be included:

- Show also the non-normalised results
- Do not aggregate the normalised results
- Different reference systems (e.g. EU-27, DE etc.) have to be used for normalisation.

8.3. Grouping and Weighting (optional)

Grouping is defined as "the assignment of impact categories into one or more sets as predefined in the goal and scope definition, and it may involve sorting and/or ranking" (ISO 2006b). Grouping is an optional element to either sort impact categories on a nominal basis or rank the impact categories in a given hierarchy (based on value choices)

Weighting is "the process of converting indicator results of different impact categories by using numerical factors based on value-choices" (ISO 2006b). This means that all impact categories are summed up into a single figure. Weighting steps are based on value-choices and are not scientifically based. Different individuals, organizations and societies may have different preferences; therefore it is possible that different parties will reach different weighting results based on the same indicator results or normalized indicator results. In an LCA it may be desirable to use several different weighting factors and weighting methods, and to conduct sensitivity analysis to assess the consequences on the LCIA results of different value-choices and weighting methods. In comparative studies for release to a third parties or the public, it is not allowed to use weighting.

In the context of this specific guidance document on FC production, grouping and weighting is not recommended.

Provision 34: Grouping and Weighting

Should: The grouping and weighting elements in the case of FC production are not recommended.

Shall: Do not use grouping and weighting in studies leading to comparative assertions **intended to be disclosed to the public.**

Shall: If grouping and weighting is undertaken, the following provisions apply:

- Document the decision in the scope definition and report it transparently
- To obtain weighted LCIA results, multiply the (typically normalised) LCIA results by the weighting set. This shall be done separately for each impact category.
- The resulting weighted LCIA results can be summed up across the impact categories
- Show also the non-grouped and weighted results.

Shall: if the weighting is applied, use several different weighting factors and weighting methods, and conduct sensitivity analysis to assess the consequences on the LCIA results of different value-choices and weighting methods

9. Interpretation and quality control of the study on fuel cells

The Life Cycle Interpretation phase is defined as the “phase of Life Cycle Assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations” (ISO 2006a). Using this definition, the interpretation phase serves different purposes. One is supporting the iterative character of LCA, as shown in Figure 16. Figure 16 also illustrates the relationships between the different elements within the interpretation phase and other phases of LCA.

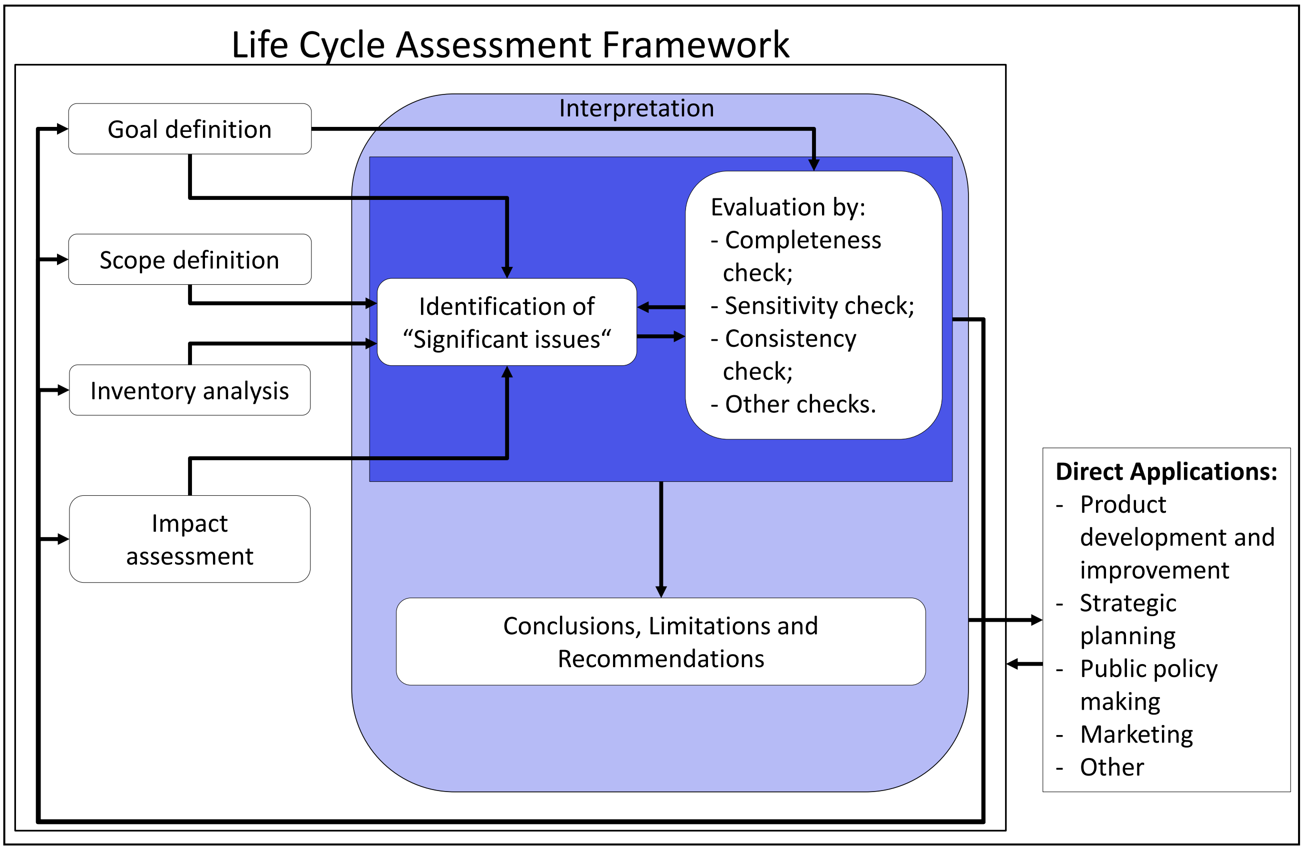

Figure 16: Relationship between elements within the interpretation phase and other phases of LCA (ISO 2006b) (modified)

This is done by interpreting the results to critically check the goal and scope definition and to reconsider either the inventory phase or the goal and scope definition, if deemed necessary. For example, if during the completeness check of the LCA of a FC, data on important flows are found to be impossible to be available within the conditions of the study, the goal and scope definition has to be reconsidered and this has to be stated in the section about limitations (section 5.2).

Another task to be carried out within the interpretation phase is a consistency check. In general the consistency check is based on the law of conservation of mass and energy. For example, the law of conservation of mass states that the mass going into a system is the same as the mass coming out of a system.

The interpretation covers three areas:

- identification of significant issues (i.e. key parameters, impact categories, etc);
- evaluation of the results through completeness, sensitivity, consistency and uncertainty checks;
- drawing conclusions, limitations and recommendations.

9.1. Identification of significant issues in the Life Cycle Inventory Analysis results

After the iterative steps have resulted in the final model, the results have to be used to derive reliable conclusions.

The first step is to produce graphs like e.g. stacked columns or pie charts depicting the different processes or flows contributing to e.g. Global Warming Potential. This is intended to identify the relationship of the different processes to the impact categories under consideration in terms of their contribution to that category. In simple systems it is most likely that the main contributors are intuitively obvious. For example, in a FC, with the fuel production outside the system boundary, it can be expected that the stack manufacturing is one of the main contributors.

Based on the graphs the main contributors are defined and named. They serve one of the main purposes of performing a LCA, which is the identification of environmental significant issues. These can be:

- The main contributors to the LCIA results (the most relevant life cycle stages, processes and elementary flows, and the most relevant impact categories);
- The main choices that affect the accuracy of the final results of the LCA (for example cut-off criteria, system boundary settings, etc.).

It is important to do this analysis for all impact categories under consideration, since it is not always the same process step that has issues of relevance for each of the impact categories.

Provision 35: Identification of significant issues

Shall: Identify the significant issues by quantifying which processes/flows are major contributors to the total impact.

Should: Stacked columns or pie-charts can be used.

9.2. Evaluation of results

As part of the interpretation phase of a LCA, the evaluation step serves the purpose of establishing the foundation for drawing the conclusions and providing recommendations. It involves:

- Completeness check
- Sensitivity check
- Consistency check
- Uncertainty check.

9.2.1. Completeness check

The completeness check is aimed at determining the degree to which the study is complete and whether the cut-off criteria have been met. If the cut-off criteria are not met, additional or better data are to be used. In general, the completeness check is based on the law of conservation of mass and energy which states that the mass and energy going into the system is the same as the mass and energy going out of the system. It is very important to be aware of the fact that during the operation of a FC there may be non-measured mass flows: this can be e.g. water evaporation or exhaust gases. The same check shall be done for the energy balance. The energy check is intended to identify potentially large differences as this is a hint for incomplete or incorrect modelling.

The degree of completeness achieved has to be primarily judged impact category by impact category.

Provision 36: Completeness check

Shall: For performing the completeness check, the following points have to be done:

- Report the degree of completeness achieved
- Add a justification if the excluded flows and processes satisfy the cut-off criteria
- If incompleteness is found either try to solve it (use additional or higher quality data) or adjust the Goal and Scope.

Should: Use the conservation law for the completeness check regarding:

- Mass (please be aware of potential non-recorded mass flows, e.g. exhaust gases)
- Energy (please be aware of potential non-recorded energy flows, e.g. waste heat).

9.2.2. Sensitivity check

A sensitivity analysis is conducted in a LCA to assess the final results and conclusion. It is defined in the ISO 14040 as “systematic procedures for estimating the effects of the choices made regarding methods and data on the outcome of a study” (ISO 2006a). Generally it is an additional check for how stable the results are in the different phases of the LCA. In this way, the reliability and consistency of the whole study and its results can be verified and guaranteed.

As already mentioned above, sensitivity analyses are also undertaken to understand how cut-off criteria have affected the results. A sensitivity check may also be done to estimate the effect of uncertainties in the data and of allocation methods. If a sensitivity analysis of estimations due to data gaps shows a high variance in the results, data collection has to be intensified. In the same way, allocation methods used the appropriateness of the definition of goal and scope and the results of all other phases of the study can be validated. A sensitivity analysis has to be done when a LCA is used to compare products and is intended to be disclosed to the public or allocation is used for solving multi-functionality. The interpretation phase in this type of report has to include statements based on sensitivity analyses.

Provision 37: Sensitivity check

Shall: A sensitivity check has to be done if the study is comparative or if system expansion or allocation is used for solving multi-functionality.

Should: For performing the sensitivity check the following steps are recommended:

1. Define different parameters which might have high impact on the results
2. Define certain limits of the parameters according to expected minimum and maximum values
3. Vary the parameters and record their impact on the results.

Should: Using the Monte-Carlo Simulation for the sensitivity check

Shall: if any results of the sensitivity check do not meet the requirements of the goal and scope, the goal and scope shall be reviewed and reported in the “limitations” chapter (section 5.2).

9.2.3. Consistency check

The consistency check is aimed at investigating whether the assumptions, methods, and data have been applied consistently throughout the LCI and LCIA study.

Inventory data issues of relevance here cover the consistency of the time-related, geographical and/or technological representativeness of data, the appropriateness of the chosen unit process and the completeness and precision of the data.

Impact assessment issues of relevance are the consistent application of the LCIA elements, including optional normalisation and weighting. Examples for the FC are the use of the upper or lower calorific value in the energy calculations, or the exclusion of some impact categories.

Provision 38: Consistency check

Shall: Perform a consistency check.

Shall: for comparative studies, check whether differences in data quality are consistent with the goal and scope of the study.

Should: Additionally check the following points

- Check whether the impact assessment elements have been consistently applied and are in line with the goal and scope
- Evaluate the relevance of any inconsistencies identified for the results and document them.

9.2.4. Uncertainty check

Uncertainty in a LCA study is related to several aspects, among which are data, methodological choices and models used in the impact assessment. In this document only the aspects related to data/parameters are addressed in relation their precision, since the others have been addressed under the “sensitivity check”.

Uncertainty in parameters results from incomplete knowledge about the true value of a parameter and it is generally due to measurement errors in input data.

Several techniques exist to evaluate this uncertainty, such as Monte Carlo Analysis, Bayesian statistics, analytical uncertainty propagation methods, semi-quantitative expert judgement, etc.

It is important to remember that the quantitative precision of the data is an important component, but structural and modelling aspects of both the LCI and the LCIA play an important and often dominant role, which cannot be addressed directly or quantitatively in uncertainty calculation.

Provision 39: Uncertainty check

Shall: perform an uncertainty check

- Perform uncertainty calculation of data/parameters according to the available techniques
- Report findings of the uncertainty check.

9.3. Conclusions, limitations and recommendations

The interpretation phase provides information to detail the limitations of the study. All known limitations within the goal and scope of the study have to be reported. This might be a self-imposed limitation such as e.g. limiting the study to Carbon footprint only. Alternatively, it might be that some flows are either not recorded correctly or if recorded not modelled correctly as there is no data available. This happens with rare materials or uncommon chemicals for example.

After detailing the limitations, recommendations can be prepared. Recommendations have to be logical, reasonable and plausible and based on the conclusions. An over-interpretation of the results (for example exaggerating small or insignificant differences, or deriving general conclusions from specific case studies) should be avoided, together with the risk of inappropriately claiming equality of alternatives under comparison. Over-interpretation can happen for example when comparing FC systems resulting in different outputs, such as different thermal energy quality (temperature). A useful practice to help avoid these mistakes is stating the reasons for the differences at the same time as the results and recommendations.

In making recommendations, additional environmental information not resulting from LCA studies has to be taken into consideration, if relevant. Examples are any hazardous (a subset of solid wastes that pose substantial or potential threats to public health or the environment) or toxic substances (a chemical or mixture that can cause illness, death, disease, or birth defects), wastes or other substances used or released. Any other environmental impacts that may be occurring and could be important to be mentioned shall be reported, even if they can't be quantified yet.

Examples of recommendations:

- Focus FC stack improvement on one or more specific components (for example anode, which is one of the most significant issues) that contribute a major share to the overall impact and have potential for improvement;
- Replace a supplier with another supplier with a less impactful production system or supply-chain.

Finally, the validity of the study has to be reported.

Provision 40: Conclusions, limitations and recommendations

Shall: Analyse and report the results obtained with the corresponding worst and best case assumption scenarios.

Shall: Report complete and accurate results and conclusions of the LCA study without bias to the intended audience using the report template given in Annex I of this document.

Shall: Avoid the following common mistakes, while deriving conclusions:

- Exaggerating small or insignificant differences
- Deriving general conclusions from specific case studies
- Being too confident about differences based on assumptions or uncertainties.

Shall: While deriving conclusions on comparisons consider the differences within the different systems.

Shall: Recommendations shall be made in a conservative way.

Shall: Use the report template when reporting about the FC (stack and system).

Shall: Document sources used for the foreground and background data, in line with scientific standards.

Shall: Take into account additional environmental information (if available) that has not been evaluated within the life cycle assessment study.

Shall: Report the validity of the study.

Should: Limit the validity to 3 years, due to the fast pace of improvements in FC technology. Revise the study whenever a major modification to FC production occurs.

10. Reporting of the fuel cell study

Reporting is the step of the LCA in which the results, data, methods, assumptions and limitations have to be reported completely and accurately without bias. Moreover, they have to be presented in sufficient detail to ensure reproducibility of the results and to provide the required information to reviewers to judge the quality of the results and appropriateness of the conclusions and recommendations.

The nature of the report has to be appropriate to the intended application and audience of the report (companies, trade associations, government agencies, environmental groups, scientific/technical communities, and other non-government organizations, as well as the general public/consumers). The third party report is recommended as it documents the results in an appropriate and clear manner. This level of reporting does not require the inclusion of confidential information, which however needs to be made available for reviewers, as a separate document, under a confidentiality agreement.

The report consists of four parts:

- Executive Summary: for a non-technical audience. It has to give brief information about the goal and scope, the results and recommendations. This is to provide the information that is especially relevant for decision-makers
- Technical Summary, for technical audience and LCA practitioners. It condenses the major information of the report for LCA practitioners in a more technical manner.
- Body of Report: which reflects the procedure of the LCA study and thus includes detailed information on Goal and Scope (description of the system under analysis, methods applied, system boundary and cut-offs, functional unit, comparison between systems (if intended), etc.), inventory analysis (information about all inputs and outputs, description of the foreground system, calculation of LCI results, etc.), impact assessment (calculated LCIA results, impact categories under consideration, normalization and weighting factors, etc.) and interpretation (interpretation of significant issues, sensitivity check, conclusions and recommendations, etc.).
- Annex: includes elements that would interrupt the reading flow of the main part of the report and are also of a more technical nature. It could include a data collection template, or overview of all assumptions made.

In addition, a confidential report can be included as a fifth part also. It would contain those data and information that are confidential or proprietary and cannot be made externally available. However, this information is necessary in case of a critical review and has to be provided to the reviewer (details on critical review are available in section 11). Such a critical review has to be conducted if the study involves a comparison of products or is intended to be published. The report structure and content for assertive and non-assertive comparative studies on FCs, intended to be disclosed to the public, have to fulfil some additional requirements. These additional requirements are e.g. an analysis of the material and energy flows, justifying their inclusion resp. exclusion or the assessment of completeness and representativeness as well as the description of the equivalence of the compared system (JRC 2010a).

The report templates given in the Annex I of this guidance document provide a detailed report structure for LCA studies on FCs, including main report, third party review report and a report for comparative studies.

Provision 41: Reporting

Should: Use the report template in Annex I.

Shall: Include the following parts in the report: Executive Summary, Technical Summary, Main content, Annex (if any).

Should: Include Annex in the report, if necessary

Shall: Report for comparative studies: Reporting on assertive and non-assertive comparative studies intended to be disclosed to the public, the following additional reporting shall by done in addition to the requirements to reports for internal use and third party reports (ISO 2006b):

- Analysis of material and energy flows to justify their inclusion or exclusion;
- Assessment of the precision, completeness and representativeness of data used;
- Description of the equivalence of the systems being compared in accordance with ISO 14044 and related provisions in this document
- Description of the critical review process;
- Evaluation of the completeness of the LCIA;
- Statement as to whether international acceptance exists for the selected environmental categories and a justification for their use;
- Explanation for the scientific and technical validity and environmental relevance of the category indicators used in the study;
- The results of the uncertainty and sensitivity analyses;
- Evaluation of the significance of the differences found.

11. Critical review of the study on fuel cell

Whether a critical review is necessary or not depends on the items defined in the goal and scope phase (see section 6.8):

- The intended application and decision context.
- The reason for carrying out the study.
- The intended target audience (internally or externally, technical or non-technical).

A critical review has to be done, if the study compares systems or will be disclosed to the public. If the study involves a comparison and is intended to be published a critical review conducted by a review panel of at least 3 persons has to be done. LCA studies for internal use only do not require a critical review, and this phase is optional.

The independence, qualification and experience of the reviewers have to be assured (JRC 2010c). The reviewer(s) need experience in LCA methodology, verification and audit practice, and must have technical expertise related to the hydrogen production system analysed.

The review report template to be used is shown in Annex IV.

Provision 42: Critical review

Should: For internal studies a critical review is not mandatory, but recommended.

Shall: If the study intends to compare different FC stacks or systems and is intended to be disclosed to the public, the critical review shall be done by a panel of independent external reviewers (at least 3) in order to reach a higher level of assurance. The panel consists of an independent expert acting as a chairman and at least two other independent experts, selected by the chairman.

Shall: For comparative studies, involve additional interested parties (e.g. government agencies, non-governmental organizations or affected industries) in the review process by open invitation.

Shall: Include the comment of the reviewer(s) in the review report or justify an eventual rebuttal.

Shall: If a critical review is conducted, the reviewer shall be:

- Independent
- Experienced in LCA methodology
- Experienced in verification and audit practice
- Have technical expertise related to the hydrogen production system under analysis.

Should: If one reviewer does not have all the above mentioned experience, it is possible to replace the reviewer by a review team.

Should: The reviewer may be integrated in the study from the beginning.

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ANNEX I - LCA STUDY REPORTING TEMPLATE ON FUEL CELLS

<table>
<tr><td>Executive Summary</td><td>Provide a short summary for a non-technical audience.</td></tr>
<tr><td>Technical Summary</td><td>Provide a short summary for a technical audience. Note with which standards the study is compliant e.g. ISO 14044 and/or ILCD.</td></tr>
<tr><td colspan="2">Main Part</td></tr>
<tr><td colspan="2">1. Product group</td></tr>
<tr><td>1.1. Product information requested and standards to use (see provision 2)</td><td>Briefly describe the FC system or FC stack. Information about the major properties needs to be given by stating the FC standard met.

Mandatory:
• Trade name
• Type of electrolyte used
• Primary functions (production of electricity, heat, etc.)
• Electrical power (rated output)
• Thermal power (if applicable)
• Efficiency
• Rated voltage
• Rated current
• Range of temperature and operating temperature
• Weight
• Dimensions
• Fuel used and its technical specifications
• Expected service life time
• Description of the intended use.
• System boundary definition</td></tr>
<tr><td>1.2. Producer's information requested and description of the system (see provision 3)</td><td>Provide information about the FC producer, including:
• Overall FC production capacity; number of sites; geographical production coverage by region (Europe, North America, etc.).

Provide a general description of the FC life cycle, including the main components, the production processes and the use phase.

For example:
Production technology used; location of the site; year of construction; type of production site (laboratory, pre-commercial, commercial scale); on-site electricity or heat production (if existing); production capacity;</td></tr>
</table>

	technical service life; type of storage. If the study evaluates only components or a part of the production chain, only these components/parts have to be described but the product system which they are part of shall be named.
2. Goal of the Life Cycle Assessment study on FCs and FC Systems	
2.1. Intended application(s) (see provision 5)	Unambiguously define the goal and scope of the study according to the goal and scope definition of the ISO 14044 standard. Describe the intended application(s), indicating if it is for internal use (internal to the organization commissioning the study) or for external use (results of the LCA to be disclosed to the public), e.g.: *Internal use:* • Identification of Key Environmental Performance Indicators (KEPI) for Ecodesign • Hotspots analysis of a specific FC *External use:* • Development of life-cycle based Type I Ecolabel criteria • Development of a life-cycle based Type III environmental declaration (e.g. Environmental Product Declaration - EPD • Calculation of a carbon footprint *Internal/external use:* • Comparison of environmental aspects of specific stack of a FC/System • Benchmarking of a specific FC against the product group's average.
2.2. Method, assumptions, limitations (see provision 6).	Detail any assumptions or limitations. Some examples: • Use of the upper or lower calorific value in the energy calculations • Comparing fuel cells, use of the same product use pattern, same system boundary, data with similar degree of accuracy, same LCIA methods • Exclusion of some impact categories
2.3. Reasons for carrying out the study (see provision 7)	Describe the reason for carrying out the study.
2.4. Target audience	Describe the target audience. For Example:

(see provision 8)	Technical / non-technical audience; decision-makers etc.
2.5. Comparisons intended to be disclosed to the public (see provision 9)	State whether the study is comparative and/or intended to be disclosed to the public.
2.6. Commissioner of the study (see provision 10)	Specify the commissioner of the study, (co)financier and/or other actors having influence on the study, including who carried out the study
3. Scope of the Life Cycle Assessment study on FCs and FC Systems	
3.1. Functional unit / Reference flow (see provisions 11 and 12)	*If FC stack*: The functional unit is the power capacity of the manufactured stack expressed in kW (energy if electricity is the only valuable product, exergy if both electricity and heat are valuable products; in this case the share of electricity and heat shall be declared). *If FC System:* The functional unit is the "production of a certain amount of electricity and useful thermal energy in a given number of years", expressed in MJex. The share of electricity and heat shall be declared. If the thermal output of the FC is not used, the FU is only the production of electricity, expressed in MJel. The reference flow is the number of FC stacks or whole systems, required to produce the amount of energy or exergy defined in the functional unit.
3.2. Multi-functionality (see provision 14).	If multi-functionality occurs state which method is chosen to solve multi-functionality.
3.3. System boundary (see provision 15).	Describe the system boundary and also show them graphically (Flow chart). List the flows taken into consideration.
3.4. Cut-off criteria (see provision 17).	State the flows which are cut-off and the expected impact of the cut-off.
3.5. LCIA methods and categories (see provisions 18 and 19)	State what impact categories and methods have been chosen and if there are any limitations.

3.6. Type and sources of data and information (see provision 20)	Describe the quality and the sources of the data and information required.
3.7. Data quality requirements (see provision 21)	Describe the data quality. **Require the use** of site specific data (primary data) of the foreground system of the FC and of the related infrastructure. **Require the use** of the European mix for electricity for cross border comparison. In addition, a specific mix can be used when appropriate, but not as an alternative. Process steps related to the background system may be site specific, if available. **The use of secondary data** (from data bases and/or literature) is acceptable.
3.8. Comparisons between systems (see provision 22)	If there are comparisons between systems, describe the differences (reference flow, scope definitions, assumptions etc.)
3.9. Identification of critical review needs (see provision 23)	State whether a critical review is required or not (internal use), and describe the specific requirements.
4. Life Cycle Inventory Analysis of the study on FCs and FC Systems	
4.1. Identifying processes within the system boundary (see provision 25)	Describe the processes being evaluated, divided into foreground and background processes. For the fuel cell stack foreground processes include e.g. the manufacturing of the anode, cathode and the matrix, their assembly in a FC stack, start-up and maintenance. For the fuel cell system, the foreground processes include also the manufacturing of the BoP) **Exclude t**he use phase of the fuel cell in specific applications (on-site electric power for households and commercial buildings; supplemental or auxiliary power to support car, truck and aircraft systems; etc.). The end of life of a fuel cell stack and system is optional and could be kept out of the boundary of the study. If not included in the study boundary, describe the end of life qualitatively.
4.2. Data collection (see provisions 26 and 29)	Describe the data collection, e.g. how long the data were measured, in which way. Describe how data gaps have been closed.
4.3. Data collection	State if the data were collected for each unit process separately or not.

(see provision 26)	
4.4. Selection of secondary LCI data (see provisions 27 and 28)	List which secondary data were used based on which database.
4.5. Dealing with multi-functional processes (see provision 30)	If multi-functionality occurs, show the possible impacts, e.g. allocation with different allocation factors.
4.6. Consideration of re-use, recycling and energy recovery	State whether there is any re-use, recycling and/or energy recovery. The end of life of a fuel cell stack and system is optional and could be kept out of the boundary of the study. However, it shall be described qualitatively. Three main scenarios are envisaged: • Disposal (worst case scenario): if no information is available, the worst case scenario is applied i.e. the product as a whole is considered to be disposed of without getting any credits for re-use or recycling. • Recycling: if the producer of the FC has in place a take-back policy, the re-use and/or recycling options can be considered. The disassembly and recycling processes shall be described and credits for impacts avoided from component re-use, material recycling and/or recovery can be claimed. • Legislation: When European or national legislation is applicable, the minimum percentages of recycling and/or energy recovery mandatory by law can be applied for calculating the credits for impacts avoided, taking into account the impacts related to disassembly and recycling processes.
4.7. Calculation of LCI results (see provision 31)	Describe how the LCI results are calculated (e.g. Excel, LCA software). If a LCA software is used indicate which one.
5. Life Cycle Impact Assessment of the study on FCs and FC Systems	
5.1. Impact assessment (see provision 32)	Replace the “XX” with your results, FU with your functional unit and prepare graphs of the results. GWP per FU: XX kg CO_2 eq. /FU AP per FU: XX kg SO_2 eq. / FU EP per FU: XX kg PO_4^- eq. / FU POCP per FU: XX kg C_2H_4 eq. / FU

	AD per FU: XX kg Sb eq. / FU PED (non-renewable) per FU XX MJ PEDnon-renewable / FU PED (renewable) per FU: XX MJ PEDrenewable / FU
5.2. Normalization (see provision 33)	State whether there is normalization applied and document the methodology.
5.3. Grouping and Weighting (see provision 34)	State whether grouping or weighting is applied and document the methods and the sensitivity analysis to assess the consequences on the LCIA results of different value-choices and weighting methods.
6. Interpretation and quality control of the study on FCs and FC Systems	
6.1. Identification of significant issues (see provision 35).	List and describe the significant issues.
6.2. Completeness check (see provision 36).	Detail the results of the completeness check.
6.3. Sensitivity check (see provision 37).	Detail the results of the sensitivity check.
6.4. Consistency check (see provision 38).	Detail the results of the consistency check.
6.5. Uncertainty check (see provision 39).	Detail the results of the uncertainty check.
6.6. Conclusions, limitations and recommendations (see provision 40).	State and explain the conclusions, limitations and recommendations.
7. Critical Review of the study on FCs and FC Systems	
7.1. Critical Review (see provision 42).	State and explain the results of the critical review or attach the report of the reviewer/s.

ANNEX II – DOCUMENTATION OF THE RESULTING DATA SET ACCORDING TO ILCD

If the LCA study on a FC should result in an ILCD entry level or ILCD compliant data set, the following meta-documentation fields of the ILCD format have to be filled out within the data set. Note that a data set in the ILCD format consists of the meta-documentation (item 1-15) and the input/output flows (item 16). Data sets in the ILCD format can be prepared by using the ILCD Editor Tool, available at http://lca.jrc.ec.europa.eu/ or by commercial software systems providing this functionality.

1. Process information	
1.1. Key data set information	
1.1.1. Base name	Naming conventions of the “ILCD - Nomenclature and other conventions” document shall be applied.
1.1.2. Treatment standard routes	Naming conventions of the “ILCD - Nomenclature and other conventions” document shall be applied. If the field has no entry, enter a blank (" "). This should occur very rarely.
1.1.3. Mix and location types	Naming conventions of the”ILCD - Nomenclature and other conventions“ document shall be applied. If the field has no entry, enter a blank (" "). This should occur very rarely.
1.1.4. Quantitative product or process properties.	Naming conventions of the “ILCD - Nomenclature and other conventions” document shall be applied. If the field has no entry, enter a blank (" "). This should occur very rarely.
1.2. Classification information	
1.2.1. Name	The classes of the file ILCDClassification.xml shall be used. Classes of additional classification systems can be added only via separate "Classification" field sets.
1.2.2. Unique class identifier	The classes of the file ILCDClassification.xml shall be used. Classes of additional classification systems can be added only via separate "Classification" field sets.
2. Quantitative reference	

2.1. Type of quantitative reference	Recommended to be of the type "Reference flow(s)".
2.2. Reference flow(s)	If "Type of quantitative reference" is "Reference flow", at least one reference flow is to be identified among the input/output product or waste flows.
2.3. Functional unit, Production period, or Other parameter	Required ("C"), if field "Type of quantitative reference", is of a type other than "Reference flow(s)". However, even if it is of a type "Reference flow(s)", it is recommended to also give one or more functional units for the reference flow(s). If it is anticipated that the data set is to be used in comparative studies, this step might be a formal requirement.
3. Time representativeness	
3.1. Ref.year	
3.2. Data set valid until:	
3.3. Time representativeness description	
4. Geographical representativeness	
4.1. Location	Must use one of the locations that are specified in the ILCDLocations.xml or other file, as referenced in the field <processDataSet@locations>. Leave empty if study is geography-unspecific such as with a technology-model data set (i.e. do only enter "GLO" if the data set represents worldwide average data).
4.2. Geographical representativeness description	
5. Technological representativeness	
5.1. Technology description including	

	background system	
5.2.	**Technical purpose of product or process**	
5.3.	**Flow diagram (s) or picture(s)**	System boundary diagram should also be placed here. Technical flow charts are recommended to improve documentation of most data sets.
6.	**Mathematical model**	
6.1.	**Model description**	This entry is required ("C") only for parameterised LCI data sets, i.e. if at least one field "Name of variable" is in use.
6.2.	**Name of variable**	This entry is required ("C") only for parameterised LCI data sets, for at least one set of "Variable / parameter" fields.
6.3.	**Formula**	This entry is empty if the "Name of the variable" is a parameter that is defined by the "Mean value" given i.e. a formula should be entered only if it actually is a variable that is calculated by a formula.
6.4.	**Mean value**	This entry is required ("C") only for parameterised LCI data sets if a "Name of variable" is given. If this is a variable, the "Mean value" is the calculated result of the "Formula" field with the given parameterisation (i.e. with the default parameter settings).
6.5.	**Comment, units, defaults**	This entry is required ("C") only for parameterised LCI data sets.
7.	**LCI method and allocation**	
7.1.	**Type of data set**	Note the differences between "LCI result" and "Partly terminated system" data sets.
7.2.	**LCI method principle**	Ensure that the entry is consistent with the approach stated in the section “Compliance declarations” and the entry/ies in the field ”LCI method approaches“. Note that for data sets for Situations A, B, C1 or C2 of the ILCD Handbook, this information is to be entered in the field "Compliance declarations".
7.3.	**Deviation from LCI**	Enter "None", if no deviations.

	method principle/explanations	
7.4.	**LCI method approaches**	Ensure that the entry fits with the approach stated in the section “Compliance declarations” and the entry/ies in the field “LCI method principle”.
7.5.	**Deviations from LCI method approaches / explanations**	Enter "None", if no deviations.
7.6.	**Modelling constants**	
7.7.	**Deviation from modelling constants / explanations**	Enter “None", if no deviations.
8. Data sources, treatment, and representativeness		
8.1.	**Data cut-off and completeness principles**	Ensure that the cut-off and completeness requirements as defined for the data quality level stated in sub-section “Validation/Data quality indicators” and the section “Compliance declarations” are met.
8.2.	**Deviation from data cut-off and completeness principles/explanations**	Enter "None", if no deviations.
8.3.	**Data selection and combination principles**	Ensure that the method requirements as defined for the data method type and quality level stated in the section “Compliance declarations”, are met. For “LCI results” and “partly terminated systems” data sets also check the “Included processes”.
8.4.	**Deviation from data selection and**	Enter "None", if no deviations

combination principles/explanations	
8.5. Data treatment and extrapolations principles	Ensure that the technological, geographical and time representativeness requirements as defined for the data quality level in sub-section "Validation/Data quality indicators" and the section “Compliance declarations”, are met. Also check with entries given in the respective “… representativeness“ sections.
8.6. Deviation from data treatment and extrapolations principles/explanations	Enter "None", if no deviations.
8.7. Data source(s) used for this data set	Provide citations/reference of all relevant data sources, including for the relevant ("key") processes included in the background system, if any.
8.8. Percentage supply or production covered	Consider which market-relevant technologies are actually and explicitly addressed/included in the inventory of this data set., especially for generic and average data sets,
8.9. User advice for data set	
9. Completeness	
9.1. Completeness product model	Ensure that the cut-off and completeness requirements as defined for the data quality level in sub-section "Validation/Data quality indicators" and the section “Compliance declarations” are met.
9.2. Supported impact assessment methods	Usability of this field pending finalisation of the implementation of the "LCIA method data set". If specific data sets are unavailable, a reference to an empty default "LCIA method data set" can be entered.
9.3. Completeness type	
9.4. Value	

10.Validation	
10.1. Type of review	Ensure that the review type meets the requirements of the "review compliance" in section "Compliance declarations". The ILCD generally requires an independent review for externally provided data sets; for details see "ILCD compliance" documentation.
10.2. Scope name	Ensure that the review scope meets the requirements of the "review compliance" in the section "Compliance declarations".
10.3. Method name	Ensure that the cut-off and completeness requirements as defined for the data quality level in sub-section "Validation/Data quality indicators" and the section "Compliance declarations", are met. Ensure that the review methods meet the requirements of the "review compliance" in the section "Compliance declarations".
10.4. Name of data quality indicator	Ensure that the data quality indicator matches the requirements of the "quality", "method", "nomenclature", "documentation", and "review" compliance in the section 'Compliance declarations'.
10.5. Value of data quality indicator	Ensure that the data quality indicator matches the requirements of the "quality", "method", "nomenclature", "documentation", and "review" compliance in the section "Compliance declarations".
10.6. Review details	
10.7. Reviewer name and institution	
10.8. Other review details	
11.Compliance declarations	
11.1. Compliance system name	Must reference the corresponding source data set of the most recent version of the ILCD compliance system. ###AddURI • For the definitions for use in the ILCD Data Network see the separate document "ILCD Data Network:" • Compliance rules and entry-level requirements". For general ILCD-compliance requirements for LCI data sets see also the "Specific guide for LCI data sets". Other compliance systems (e.g. of specific EPD schemes etc.) can also referenced.

11.2. Approval of overall compliance	Ensure that the overall requirements for ILCD related compliance are met. For an overview and specific settings for the ILCD Data Network see the separate document "ILCD Data Network: Compliance rules and entry-level requirements".
11.3. Quality compliance	Ensure that the quality requirements for ILCD related compliance systems are met. For an overview and specific settings for the ILCD Data Network see the separate document "ILCD Data Network: Compliance rules and entry-level requirements".
11.4. Nomenclature compliance	Ensure that the nomenclature requirements for ILCD related compliance systems are met. For an overview and specific settings for the ILCD Data Network see the separate document "ILCD Data Network: Compliance rules and entry-level requirements".
11.5. Methodological compliance	Ensure that the method requirements for ILCD related compliance systems are met. For an overview and specific settings for the ILCD Data Network see the separate document "ILCD Data Network: Compliance rules and entry-level requirements".
11.6. Review compliance	Ensure that the review requirements for ILCD related compliance systems are met. For an overview and specific settings for the ILCD Data Network see the separate document "ILCD Data Network: Compliance rules and entry-level requirements".
11.7. Documentation compliance	Ensure that the documentation requirements for ILCD related compliance systems are met. For an overview and specific settings for the ILCD Data Network see the separate document "ILCD Data Network: Compliance rules and entry-level requirements".
12.Commissioner and goal	
12.1. Commissioner of data set	Detail the commissioner of the study, (co)financier and/or other actors having influence on the study.
12.2. Intended applications	Ensure that this is consistent with the “LCI method principle”, “Compliance declarations”, any specific requirements on reporting stated in ISO 14044, the ILCD Handbook (e.g. "third-party report"), and the “Type of data set”.

13.Data set generator / modeller	
13.1. Data set gen./modeller	
14.Data entry	
14.1. Data entry by:	
14.2. Official approval of data set by prod/operator:	Used only if official approval is given by the goods producer or service operator of the product represented by the data set. If it is not given, insert a reference to an empty default contact data set with a "No official approval" text entry.
15.Publication and ownership	
15.1. Data set version	Is typically automatically generated, but may need to be manually adjusted.
15.2. Date of last revision	
15.3. Owner of data set	
15.4. Copyright?	
15.5. License type	
15.6. Access and use restrictions	
16.Inputs and Outputs	
16.1. Reference to flow data set	
16.2. Exchange direction	
16.3. Mean amount	
16.4. Resulting	

amount	
16.5. Data source type	Required ("C") for unit process data sets only. (For other aggregated data set types the entry will almost always be "Mixed primary/secondary" and is hence non-informative).
16.6. Data derivation type/status	Required ("C") only if "Type of data set" is "unit process". Recommended also for other data set types.

ANNEX III - DATA COLLECTION TEMPLATE

Figure 18 to 23 show examples of a data collection template. For ease of use the template is prepared in Excel format, and separated in one several parts for general and specific information.

MCFC repetitive units

Legend:
cells to be filled out with requested data

Production specifications	Value	Unit	Data source
Expected cell lifetime		yrs	
Cell annual working hours		hrs	
Electric power per module		kW/module	
Number of modules, for a 500 KW plant		#	
Cells per module		#	
Cell active area		cm^2	
Outside dimensions		cm^2	
Length of anode		cm	
Width of anode		cm	
Weight of anode per square meter		kg/m^2	
Length of cathode		cm	
Width of cathode		cm	
Weight of cathode per square meter		kg/m^2	
Length of matrix		cm	
Width of matrix		cm	
Weight of matrix per square meter		kg/m^2	
Nominal cell potential, V_{nom}		V	
Nominal cell power density @ V_{nom}		W/cm^2	

MCFC stack

Production specifications	Value	Unit	Data source
Number of active cells in stack		#	
Number of anodes per stack		#	
Number of cathodes per stack		#	
Number of matrixes per stack		#	
Stack width		cm	
Stack height		cm	
Stack length		cm	
Stack mass		kg	
Stack nominal power		W	
Stack potential at nominal power output		V	
End of life power or stack potential		W or V	
Stack operating lifetime		hrs	
Stack shelf life		hrs	

Figure 17: Data collection template for the general information on MCFC. The same applies to the system.

PHASE I: Production of fuel cell components

Manufacturing of active components

(Unit of product is: 1 active component (anode, cathode, matrix)

Legend:

cells to be filled out with requested data

cells to be filled out with literature data

PRODUCTION OF ACTIVE COMPONENTS				% mass allocation of input flows to active components		
Materials		Amount (g/unit of product)	Energy inputs (MJ/kg)	anode	cathode	Matrix
Metal powders for anode, cathode and matrix	Cr powder					
	Ni powder					
	$LiAlO_2$					
	Other (specify)					
Electrolyte chemical compounds	Li_2CO_3					
	K_2CO_3					
	Other (specify)					
Binders	Hydrosol S					
	Oppanol					
	Fish oil					
	Antifoam					
	Ketjenflex					
	Butvar B98					
	Other binder (specify)					
Solvents	Ethanol					
	Isobutanol					
	Tetrachloroethylene					
	Other solvent (specify)					
Polymer	Mylar					
	Other polymer (specify)					
Industrial gases	N_2					
	H_2					
	CO_2					
	H_2O(gas)					
	Other gas					

Figure 18: Data collection template for the production of some MCFC cell components.

PHASE II: Assembly of fuel cell components into a stack

Including non-active ancillary components of Fuel Cell stack and process energy

(Unit of product is: 1 MCFC stack assembled)

Legend:

cells to be filled out with requested data

cells to be filled out with literature data

Ancillary Components	Materials	Amount (g/unit of product)	Energy inputs (MJ/kg)
Anodic collector	Ni cold rolled		
	Other coating (specify)		
Cathodic collector	AISI 310		
	Other steel (specify)		
Bipolar plate	Electroplated Al-wings		
	Other coating (specify)		
Manifold	AISI 310		
	Other steel (specify)		
Terminal disks	AISI 310		
	Other steel (specify)		
Pressure plates	AISI 310		
	Other steel (specify)		
Other steel components, piping	Steel		
	Other steel (specify)		
Vessel	Steel		
	Other steel (specify)		
ISP Housing	Polypropylene		
Insulators	PTFE		
Tie-rods	Steel		
Buss plates	Copper		
Coatings			
Fittings			
Solid Waste from production of active and structural components			
Liquid Waste from production of active and structural components			

Description of unit process (attach additional sheets if required):

Figure 19: Data collection template for the assembly of MCFC components into a stack.

PHASE III: Assembly of all components into a system
Manufacturing of Balance of Plant
(Unit of product is: 1 MCFC system assembled)

Legend:
cells to be filled out with requested data
cells to be filled out with literature data

Components	Materials	Amount (g/unit of product)	Energy inputs (MJ/kg)
Reformer	Steel		
	Ni		
	Zn		
	Other reformer (specify)		
Casing	Steel		
	Other casing (specify)		
Piping air and fuel supply	Steel		
	Other piping (specify)		
Start up components (e.g. pilot burner, electrical resistance, etc.)	Steel		
	Other start up (specify)		
Heat exchangers	Steel		
	Incoloy		
	Other heat exchangers (specify)		
Power conditioner	Aluminium		
	Purified silica		
	Copper		
	Plastics		
	Other power conditioner (specify)		
Afterburner	Steel		
	Other afterburner (specify)		
Solid Waste from production of stack and system components			
Liquid Waste from production of stack and system components			

Description of unit process (attach additional sheets if required):

Processes	Process Energy (MJ)	Process energy intensity (MJ/kg)
Metal forming		

Figure 20: Data collection template for the assembly of MCFC components, stacks plus BoP.

PHASE IV: Installation and start-up of the assembled fuel cell system

Installing a MCFC system

(Unit of product is: 1 MCFC system assembled after start-up)

Legend:

cells to be filled out with requested data (white)

cells to be filled out with literature data (yellow)

Start up Inputs	Amount (g/unit of product)	Energy inputs (MJ/kg)
Fuel for start up (specify fuel type, i.e. natural gas)		
Process water		
Electricity		
Start-up duration		

Figure 21: Data collection template for the installation and start-up of the assembled MCFC system

PHASE V: Operation and maintenance
Electricity Production
(Unit process identification: electricity production)

Legend:
cells to be filled out with requested data

System descrition and inputs	Amount	Unit
Estimated lifetime of the operative system		yr
Expected number of operative hours per year of the operative system		hr/yr
Nominal electric power output of the system		kW_e
Nominal thermal power output of the system		kW_t
Net electric power output of the system		kW_e
Net thermal power output of the system		kW_t
Exhaust gas output temperature		°C
Exhaust gas mass flow		kg/s
Exhaust gas composition (specify)		….
Sulfur content per Nm^3 of natural gas supplied		mgS/Nm^3
Electric efficiency decay factor in unit lifetime		%
Standard operative Temperature of the cells		°C
Temperature of delivered heat		°C
Return flow temperature		°C
Inverter efficiency		%
Labour		hr/yr
Steel parts to substituted along the system lifetime due to ordinary maintenance		kg/yr
Other components to substituted along the system lifetime due to ordinary maintenance		kg/yr
Electricity consumption due to maintenance and operation phase		kWh/yr
Estimate of transmission losses to national grid or to final user		%
Fuel consumption (natural gas - NG) during system operation phase		m^3
Chemicals used for maintenance		kg/yr

Figure 22: Data collection template for the operation and maintenance of MCFC system

PHASE VI: Dismantling of the stack and system/plant

Waste scenario

Legend:
cells to be filled out with requested data

System description	Specify
Please provide a short description of current options for system disposal (if available)	
Materials contained in the system which could be recycled/reused with currently available technologies (if available)	
Solid Waste from dismantling of stack and system components	
Liquid Waste from dismantling of stack and system components	

Figure 23: Data collection template for the dismantling of the MCFC stack and system

ANNEX IV - LCA REVIEW REPORTING TEMPLATE ON FC

The results of the verification should be reported in a “Review report – Judgment table” that has to follow the scheme of table below.

1. Life Cycle Assessment and LCA applications

REVIEW REPORTING			
General information			
Project name			
Review commissioner(s)			
Reviewer name(s)			
Review type applied			
Date of completion of review (DD/MM/YYYY)			
Compliance system name			
Reviewer assessment:			
Aspect	**Yes**	**No**	**Comments**
Quality compliance			
Method compliance			
Nomenclature compliance			
Documentation compliance			
Review compliance			
Compliant with ISO 14040 & 14044			
Reproducibility and Transparency			

In order to express a judgment on each of the items listed above, the following items have to be considered:

- For **quality conformity** all items under Life Cycle Inventory and Quality control
- For **method conformity** all items under goal and scope definition, LCIA and interpretation
- For **nomenclature conformity** all items throughout the study because it represents a transversal judgment. It is considered transversal as there is a specific nomenclature for all the LCA phases (e.g. for input and output flows, processes, etc)
- For **documentation conformity** all items under reporting
- **Review conformity** represents a judgment on the possibility to perform a complete

review on the basis of the requirements for verification

The reviewer has to tick “yes” if the LCA study fulfills the requirements for the conformity and “no” if the LCA study does not reach this fulfillment.

In the “comments” field the reviewer has to insert references and examples in order to justify non-conformity judgments.

The Judgment table has to be appended to a full review report. In the full report the following issues have to be covered:

- Items verified
- Methods used
- Criteria for choice of samples
- Reasons for exclusions
- Analyzed data flows
- Main results
- Suggestions for improvements

2. Life Cycle Inventory data set (ILCD Data Network - Entry-level requirements)

The review findings are to be documented in the LCI data set. The specifically applied scope and methods of review are also to be documented in the data set.

The - for Independent External Reviews optional - separate review report would carry e.g. responses of the Commissioner to the reviewer comments and further details.

REVIEW REPORTING	
General information	
Data set name	
Data set UUID and version number	
Data set locator (e.g. URI, URL, contact point, database name and version, etc.)	
Data set owner	
Review commissioner(s)	
Date of completion of review	
Reviewer name(s)	
Review type applied	
Date of review (DD/MM/YYYY)	
Compliance system name	**ILCD Data Network - Entry-level**

Reviewer assessment:			
Aspect	**Yes**	**No**	**Comments**
Quality compliance			
Method compliance			
Nomenclature compliance			
Documentation compliance			
Review compliance			
Compliant with ISO 14040 & 14044			
Reproducibility and Transparency			

All the following items should be explicitly addressed. It should be noted the findings/comments on all items are part of the "Review details" text field. Some items are also represented by separate data quality indicators, and in the validation section of the data set.

ITEMs	Quality values*	Comments
Correctness and appropriateness of the data set documentation		
An overall quality statement on the data		
Geographical representativeness of Inputs and Outputs		
Technological representativeness of Inputs and Outputs		
Time representativeness of Inputs and Outputs		
Completeness of Inputs and Outputs		
Precision of Inputs and Outputs		
Completeness of coverage of the relevant impact fields (environmental, human health, resource use)		
Plausibility of data		
Appropriateness of system boundary,		

Appropriateness of cut-off rules,		
Appropriateness of LCI modelling choices such as allocation,		
Consistency of processes included and of LCI methodology.		
If the data set comprises pre-calculated LCIA results, the correspondence of the Input and Output elementary flows (including their geographical validity) with the LCIA method(s) applied.		
Others		

Note*

Quality Values	Meaning
Very good	Meets the criterion to a very high degree, having or no relevant need for improvement. This is to be judged in view of the criterion’s contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.
Good	Meets the criterion to a high degree, having little yet significant need for improvement. This is to be judged in view of the criterion’s contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.
Fair	Meets the criterion to a sufficient degree, while having the need for improvement. This is to be judged in view of the criterion’s contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.
Poor	Does not meet the criterion to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterion’s contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.
Very poor	Does not at all meet the criterion, having the need for very substantial improvement. This is to be judged in view of the criterion’s contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.
Not evaluated / unknown	This criterion was not reviewed or its quality could not be verified.
Not applicable	This criterion is not applicable to this data set, e.g. its geographical representative can not be evaluated as it is a location-unspecific technology unit process.

If intended/foreseen the responses of the commissioner of the study to the reviewer comments:

ITEMs	Reviewer Comments	Response from commissioner
Correctness and appropriateness of the data set documentation		
An overall quality statement on the data		
Geographical Representativeness of Inputs and Outputs		
Technological representativeness of Inputs and Outputs		
Time representativeness of Inputs and Outputs		
Completeness of Inputs and Outputs		
Precision of Inputs and Outputs		
Completeness of coverage of the relevant impact fields (environmental, human health, resource use)		
Plausibility of data		
Appropriateness of system boundary,		
Appropriateness of cut-off rules,		
Appropriateness of LCI modelling choices such as allocation,		
Consistency of processes included and of LCI methodology.		
If the data set comprises pre-calculated LCIA results, the correspondence of the Input and Output elementary flows (including their geographical validity) with the LCIA method(s) applied.		
Others		

ANNEX V - EXAMPLES FROM CASE STUDIES ON FCs

The three LCA reports on MCFC, PEMFC and SOFC are available as separate documents.