Training Course

Working Groups

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ENEA Research Centre

E. Clementel

FC-Hy Guide

Working Groups

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Working Groups

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Working Groups

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Working Groups

Provisions Worked Out in Groups

- Provision 3: Product system description
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Provision 3: Product system description

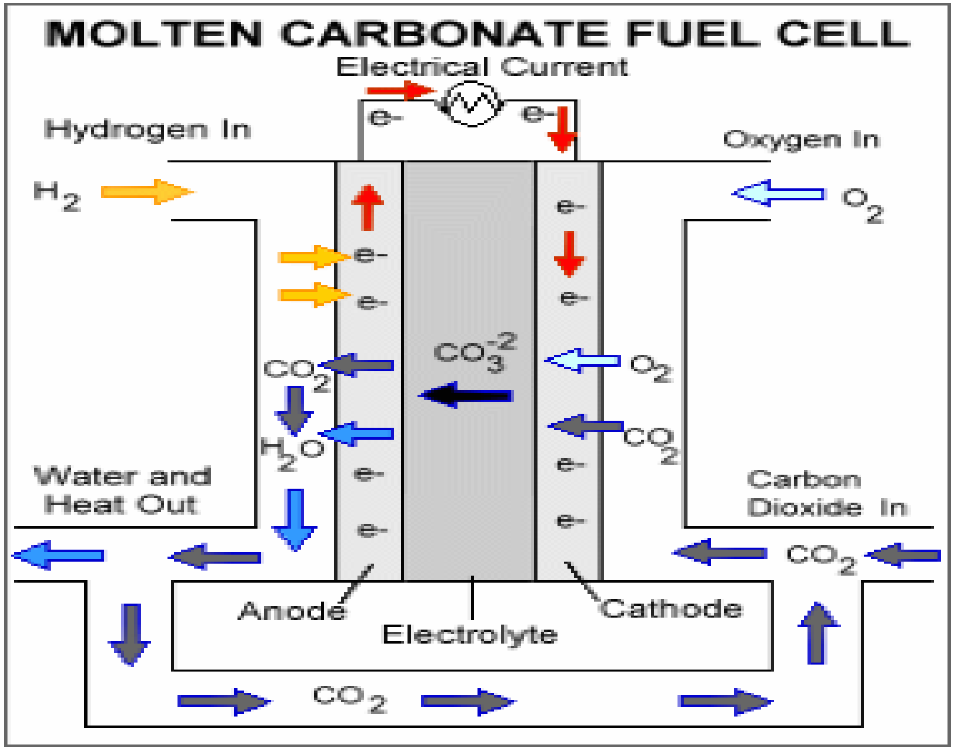
The author of the LCA study shall provide a general description of the FC life cycle, including the main components, the production processes and the use phase. To show the evaluated system, a process flow diagram shall be included. Generally the description of the FC (stack or system) has to include information on:

- *Technology used*
- *Year of construction*
- *Type of production site (laboratory, pre-commercial, commercial scale)*

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.

Provision 3: Product system description

Molten Carbonate Fuel Cells (MCFCs) are high-temperature fuel cells, that operate at temperatures of 650° C



anode: $H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$

cathode: $CO_2 + ½ O_2 + 2e^- \rightarrow CO_3^{2-}$

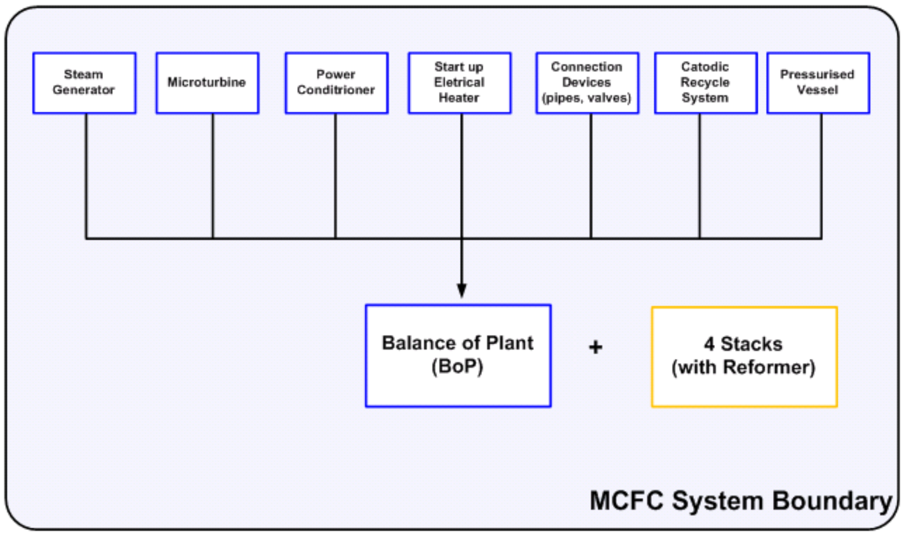
global reaction: $H_2 + ½ O_2 \rightarrow H_2O$ + electricity + heat

Provision 3: Product system description

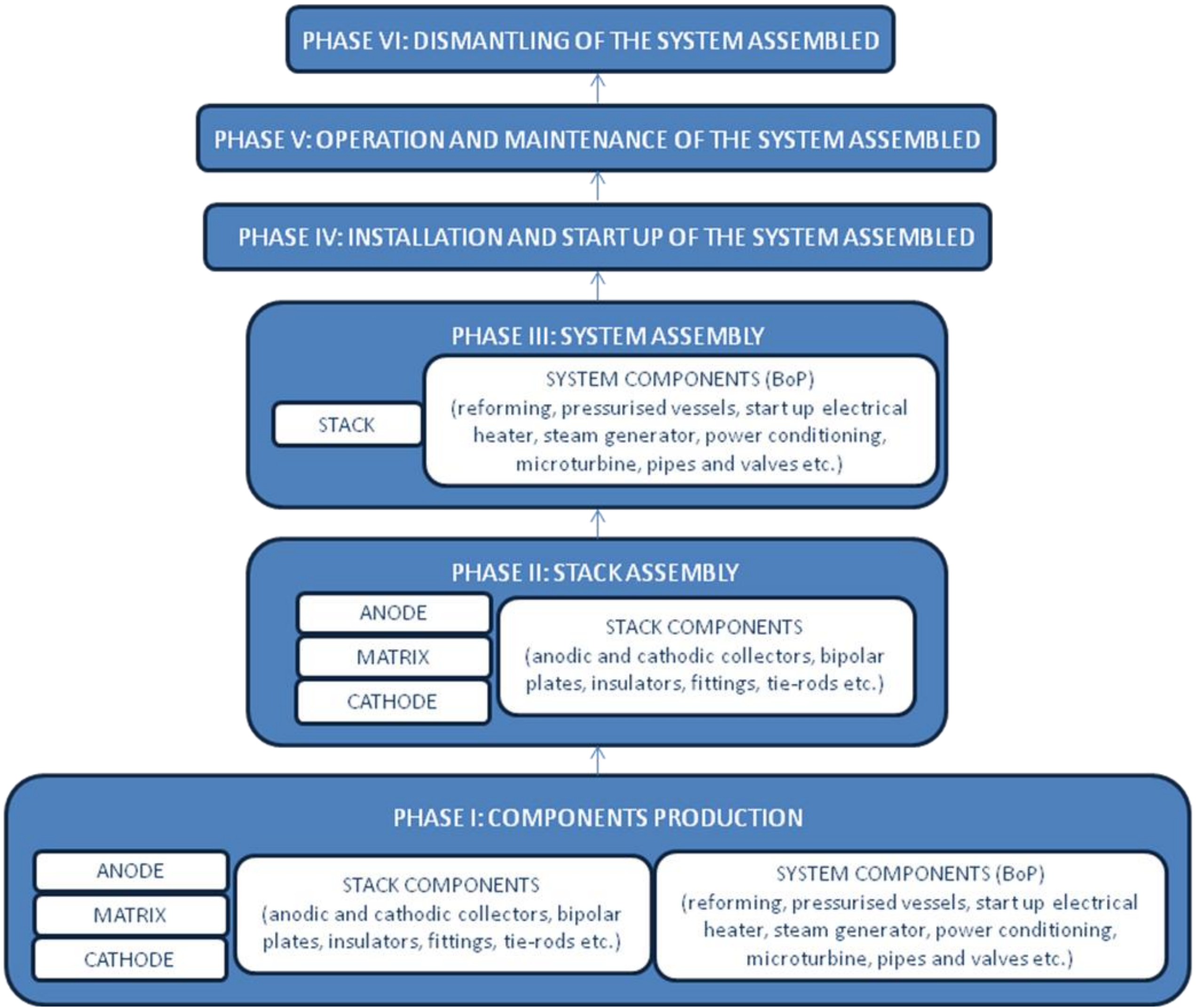
Each active cell comprises one ***anode***, one ***cathode*** and three ***layers of matrix.***

Each stack consists of ***230 active cells***, assembled together by means of specific steel components, such as ***anodic and cathodic collectors***, ***bipolar plates***, ***tie-rods***, ***fittings*** etc.

The BoP includes ***reformer***, ***pressurized vessels***, start up ***electrical heater***, ***steam generator***, ***power conditioner, pipes***, ***valves***, ***cathodic recycle system*** and ***microturbine***).



Provision 3: Product system description



Provision 4: Goal of the LCA study

The goal of the study shall be clearly defined in the report according to the goal and scope definition of the ISO 14044 standard.

GOAL:

- evaluation of the generated impacts
- identification of the most significant and sensitive steps that can be improved in their environmental performance by means of careful monitoring and strict environmental rules
- identify the technological challenges and weaknesses of production and use chains:
  - the breakdown of production and use processes into steps
  - the detection of unsolved problems, risks, environmental aspects related to specific production and use patterns
  - bottlenecks affecting the whole performance

SPECIFIC ASPECTS:

Intended applications; Method, assumption and impact limitation; Reasons for carrying out the study; Target audience; Comparison intended to be disclosed to the public; Commissioner of the study

Group 1

Provision 6: Method, assumption and impact limitation

Sufficient consistency of methods, assumptions as well as data throughout the LCI/LCA study shall be assured. Any inconsistencies shall be documented and consequences on the conclusion of the study documented.

MAIN ASSUMPTIONS MADE:

- LHV (lower heating value) is used for energy calculations.
- The CML 2001 is used for Life Cycle Impact Assessment
- The study meets the data quality requirements of ILCD Handbook (and ISO 14040:2006 and 14044:2006). Only very recent data have been entered (last 5 years).
- the selection of impact categories derives from the specific characteristics of FCs:

Global Warming (GWP), Acidification (AP), Eutrophication (EP), Photochemical Oxidation (POP), Ozone Layer Depletion (ODP), Human Toxicity (HTP) and Abiotic (ADP), Water Depletion (WDP). Other impact categories related to, e.g., radioactivity and noise are considered irrelevant and therefore excluded.

- According to previous studies in literature, industrial machinery and plant buildings are considered negligible compared to FC components and operational inputs, although the technology is not yet in its mature phase.

Provision 6: Method, assumption and impact limitation

•The three case studies refer to the the same functional unit, same system boundaries, same data degree of accuracy, same LCIA methods

HOWEVER

In the comparison among MCFCs, SOFCs and PEMFCs, some limitations due to scale factors and to differences in the operational conditions (temperature, used fuel, power output and use pattern) have to be considered.

For instance:

- PEMFCs are for mobile application (vehicles) while SOFCs and MCFCs are stationary
- PEMFCs are low temperature, while SOFCs and MCFCs are high temperature
- MCFCs use 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 comparison of the LCA studies.

Provision 11: Scope of the LCA study

The scope firstly defines the object of the LCA study. The object may be either an FC stack or a whole FC system. They cover all the single components and process steps, such as the active components (anode, cathode, matrix) and the steel parts.

Our study include:

- Function and Multifunctionality
- Functional unit and reference flow
- Units
- System boundaries
- Definition of relevant flows
- Cut-off criteria
- Life Cycle Impact Assessment methods and categories
- Type and sources of required data and information
- Data quality requirements (primary, secundary, geographic)
- Comparisons criteria
- Review aspects
- Reporting

Provision 11: Scope of the LCA study

The objects of MCFC LCA study are:

- MCFC stack (125 kWel);
- Complete system (4 stacks + BoP-Balance of Plant, 500 kWel) over its complete turnover time (20 years);
- Complete system operation for electricity production fueled by natural gas.

Each active cell comprises one ***anode***, one ***cathode*** and three ***layers of matrix.***

Each stack consists of ***230 active cells***, assembled together by means of specific steel components, such as ***anodic and cathodic collectors***, ***bipolar plates***, ***tie-rods***, ***fittings*** etc.

The BoP includes ***reformer***, ***pressurized vessels***, start up ***electrical heater***, ***steam generator***, ***power conditioner, pipes***, ***valves***, ***cathodic recycle system*** and ***microturbine***).

Group 1

Provision 12: Functional unit

- ***FC stack:*** *The functional unit shall be 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:*** *The functional unit shall be "production of a certain amount of electricity and useful thermal energy in a given number of years", expressed in* MJ_{ex}*. 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* MJ_{el}*.*

The service life span shall be chosen with respect to the expected lifetime and in context to the time the facility is already running, and adequately supported with experimental results and/or other technical analysis. It is suggested to define the service life using a 10% of degradation of the FC performance.

Group 1

Provision 12: Functional unit

***MCFC stack and System (4 stacks + BoP*)**

In the analyzed system, electricity and heat are the main outputs: both an electric power output and a thermal power output can be provided. Considering both the production of the MCFC stack module, the stack+BoP system, and finally its operating phase, different functional units should be chosen, calculated on the basis of the delivered electricity and heat. The following equation applies to the output power, in order to convert energy to exergy:

Total Power output (kW_{ex}) = Electric Power (kW_{el}) + ε* Thermal Power (kW_{th}).

where ε =1-(Ta/Tm) is the Carnot factor. T_a is the ambient temperature and Tm the thermodynamic mean temperature between T_o (temperature of delivered heat) and T_r (return flow temperature).

A similar equation applies to delivered electricity and heat:

Exergy delivered (kWh_{ex}) = Electricity delivered (kWh_{el}) + ε* Heat delivered (kWh_{th})

HOWEVER:

in the present case study the system's usable heat output is not converted into an actually used service by means of cogeneration devices. Therefore, the only valuable product taken into account is electricity. The functional units chosen are therefore only referred to the electric power capacity of the manufactured stack (125 kW_{el}) and system (4 stacks + BoP, 500 kW_{el}).

Provision 12: Functional unit

MCFC System's operation

Since the thermal output is not used, the functional unit for the operating MCFC system refers the electricity generated by a TWINSTACK module in its lifetime.

Considering

* an electrical power output of 500 kW,

* an expected number of operative hours per year of 8000 hours

* an estimated lifetime of 20 years,

the system functional unit was calculated as:

power output (500 kW) x service time (20 years per 8000 hours/yr= 160000 hours) =

= 80 GWh_{el} (2.89E+08 MJ_{el}).

This value was chosen as the operating system's functional unit.

Group 1

Provision 15: Multifunctionality

FCs are a typical example of multifunctional process as their main products are electricity and heat. The use of the produced heat shall be analysed in order to identify if an allocation problem exist.

Allocation alternatives:

- Allocating to mass, energy, exergy, economic value of products
- System expansion and no allocation
- Only one product considered

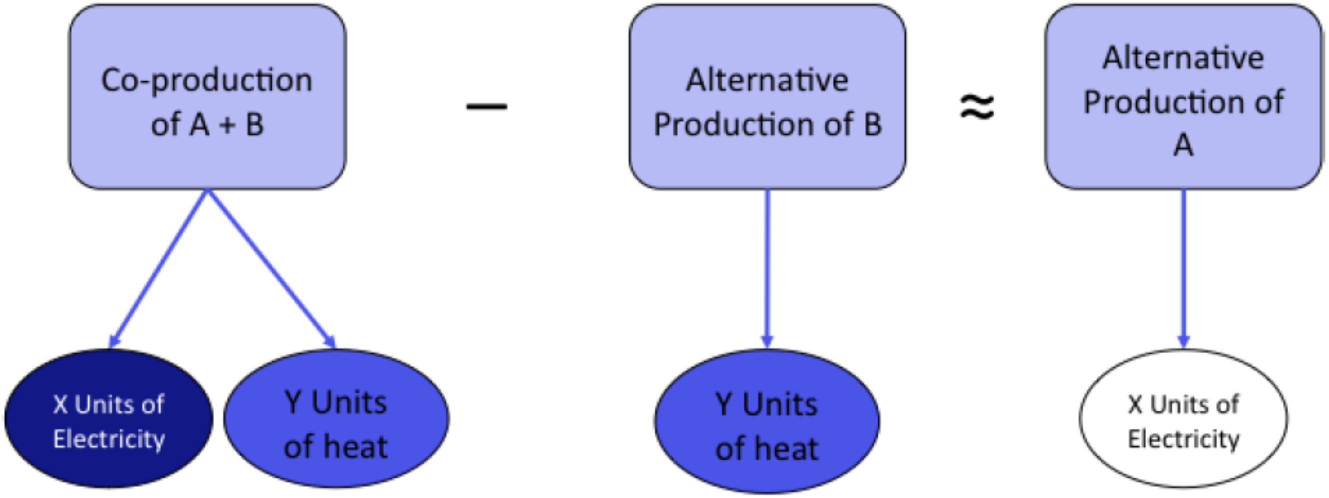
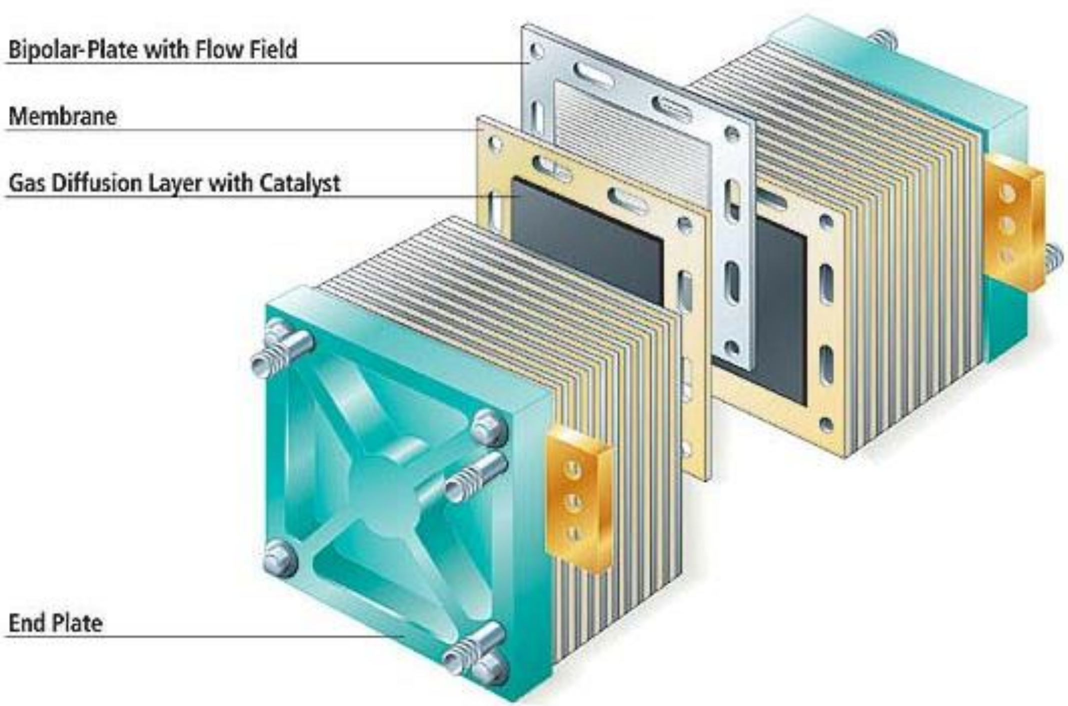


Figure 6: System expansion for solving multifunctionality (Source: JRC 2010) (modified)

Group 3

Provision 16: System boundaries

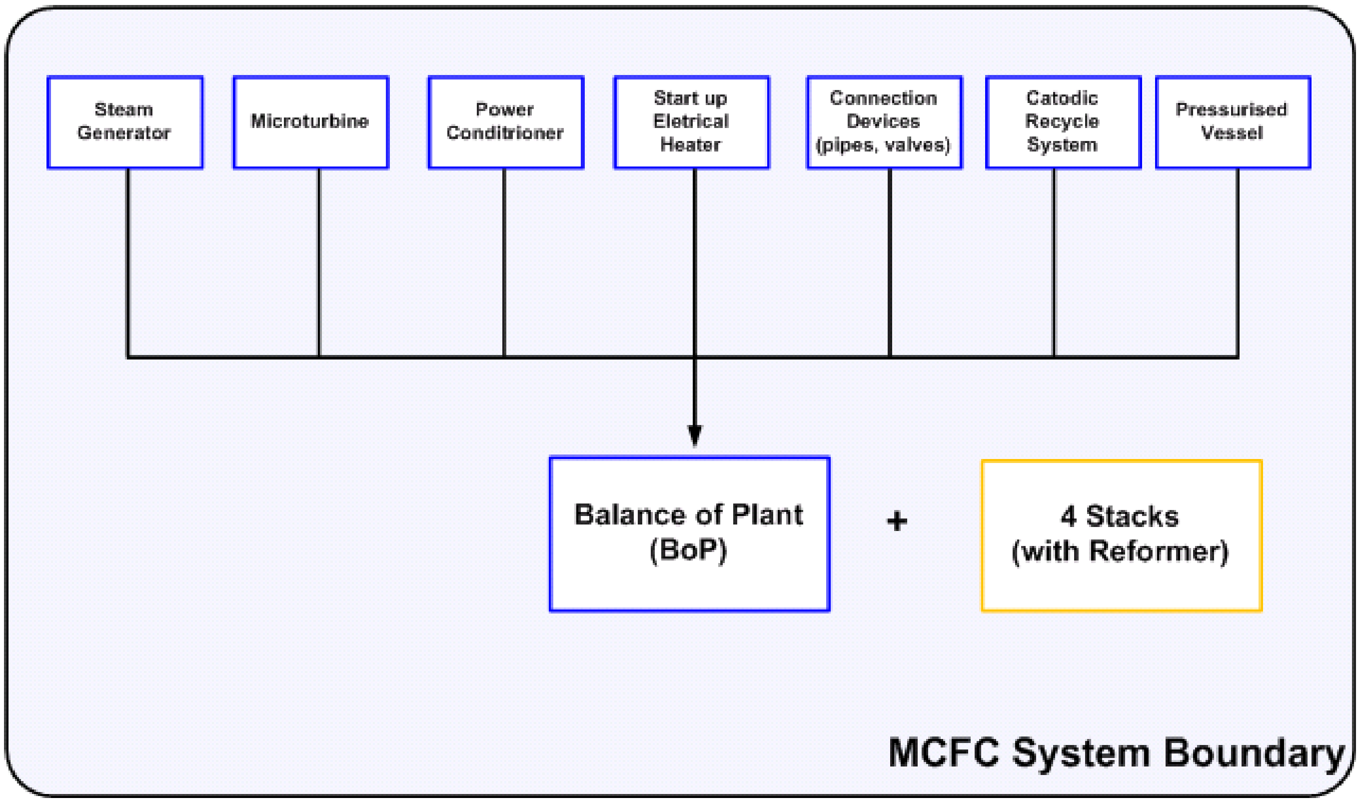
The system boundaries of an LCA on FC are defined according to the assessed product system. In the case of FC system mostly a "cradle to grave" view is applied. Cradle to gate is instead used in the case of FC stack, where the absence of the BoP makes it impossible to assess the use phase. In both cases, the production of the fuel is not included.



System 1

MCFC stack (125 kWel), includes the production phase, analysed starting from the extraction of resources and the supply of energy and chemicals in the preparation phase, also properly accounting of the related emissions.

Provision 16: System boundaries

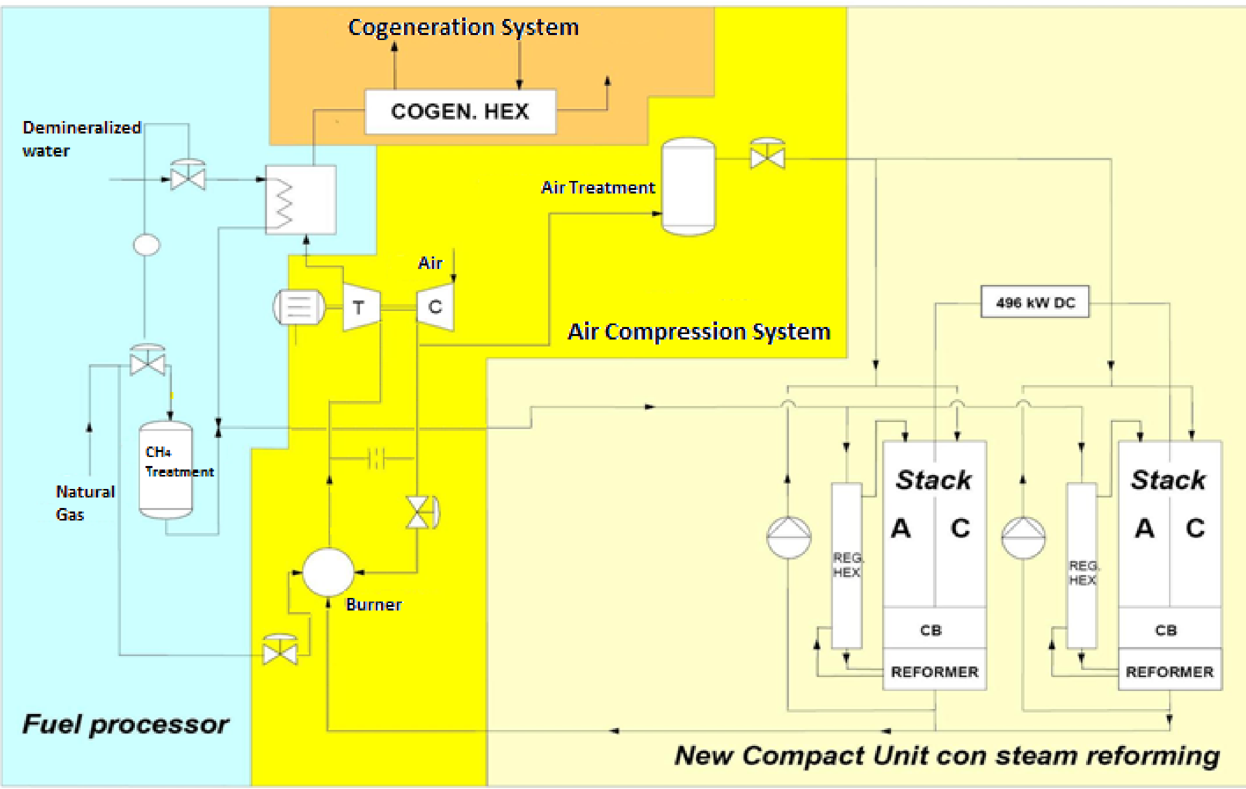


System2:

500 kWel MCFC Boundary as for the system 1, also for BoP components (mining, manufacturing, etc.)

Provision 16: System boundaries

System3: TWINSTACK+ Fuel. Boundary includes fuel extraction and processing



- ✓Pink area: stacks and reformers,
- ✓Yellow area:air compressor, an exhaust gases burner and a small turbine supporting the air compressor and the natural gas pre-heating step;
- ✓Light blue area: natural gas input and pretreatment;
- ✓Orange area: the cogeneration heat exchanger, for potential use of waste heat.

Provision 18: Cut-off criteria

All cut-offs shall not go beyond 2 % of mass or energy balance of the entire system (foreground and background). If the Cut-off is too coarse the system boundaries might be reconsidered.

In this LCA study all the cut-offs are set at 2%.

Inputs that contribute less than 2% to the mass or energy of the total product system's inputs as well as less than 2% to the environmental impacts are not accounted for.

Environmental impacts calculated with and without 2% cut-off do not differ significantly in most impact categories. In some cases the difference is larger. For this reason the choice of the cut-off percentage remains up to the experience of the LCA analyst, who may decide to adopt a smaller cut-off in order to highlight and discuss the importance of selected inputs to specific categories.

Provision 18: Cut-off criteria

Impact category	Unit	MCFC stack (without cut-off)	MCFC stack (with 2% cut-off)
Abiotic depletion	kg Sb eq	3.56E+02	3.53E+02
Acidification	kg SO_2 eq	1.46E+03	1.45E+03
Eutrophication	kg PO_4^{---} eq	1.76E+02	1.70E+02
Global warming (GWP100)	kg CO_2 eq	5.05E+04	4.96E+04
Ozone layer depletion (ODP)	kg CFC-11 eq	1.78E-02	1.76E-02
Human toxicity	kg 1,4-DB eq	3.96E+05	3.70E+05
Photochemical oxidation	kg C_2H_4	6.01E+01	5.79E+01

MCFC stack (125 kWel)

MCFC system (500 kWel), supposed to be operating for 20 years (including 16 stacks and 4 reformers)

Impact category	Unit	MCFC system (without cut-off)	MCFC system (with 2% cut-off)
Abiotic depletion	kg Sb eq	2.71E+04	1.03E+04
Acidification	kg SO_2 eq	1.37E+06	1.37E+06
Eutrophication	kg PO_4^{---} eq	2.18E+04	2.09E+04
Global warming (GWP100)	kg CO_2 eq	3.78E+06	3.50E+06
Ozone layer depletion (ODP)	kg CFC-11 eq	5.27E-01	5.24E-01
Human toxicity	kg 1,4-DB eq	2.08E+07	1.87E+07
Photochemical oxidation	kg C_2H_4	5.50E+04	5.48E+04

Provision 19: Life Cycle Impact Assessment

Scoping the LCA study, the LCIA methods to be applied shall be defined. When available, the methods, models and characterisation factors identified in the Guidance document under preparation by the JRC-IES, through the European Platform on LCA, shall be used. Until then, the CML impact assessment methods shall be used (CML 2001). Within the CML-method the Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP) and Abiotic Depletion (ADP) (van Oers et al., 2001) shall be used.

Provision 19: Life Cycle Impact Assessment

The midpoint CML impact assessment methods are recommended by JRC-IES to convert all the inputs and outputs flows, collected and reported in the inventory, into impact indicator related to human health, natural environment and resource depletion.

The ***CML 2 baseline 2000*** applied to the MCFC study is a mid-point method developed by the Centre of Environmental Science at Leiden University. This method provides characterisation and normalisation factors updated on a regular basis, which can be profitably used to quantify environmental impacts for different impact categories.

This study considers the impact categories of:

- Global Warming Potential (GWP)
- Acidification Potential (AP)
- Eutrophication Potential (EP)
- Photochemical Oxidation Potential (POCP)
- Abiotic Depletion (ADP)
- Ozone Layer Depletion (ODP)
- Human Toxicity (HTP)

Provision 20: Type and sources of data and information

Inputs and outputs to and from the foreground system to other technical systems shall be included. All resources from nature and emissions to nature of the foreground and background system should be taken into account. Exceptions are allowed in accordance with the cut- off criteria (section 6.3.3). Data used shall reflect the technology actually used, depending also on the region where the process occurs. If specific data is not available, comparable data can be used. The closing of data gaps with comparable data shall be described in the LCA report.

Provision 20: Type and sources of data and information

Data used in this LCA study reflect the most recent technology used by Ansaldo Fuel Cells in the production of MCFCs and were provided by Ansaldo itself within a collaborative agreement (primary data). Therefore, most of the input and output flows to and from the foreground system as well as resources from nature and emissions to nature of the foreground and background system are qualitatively and quantitatively assessed based on the information provided by the producer. In the case of the background systems, data from existing databases, mainly Ecoinvent Unit Processes library, are used. Some of the data not accessible from the company were obtained from recently published scientific literature. Other sources of data were ENEA and FN-Fabbricazioni Nucleari, operating in Italy for the design, manufacture and commercial development of MCFCs.

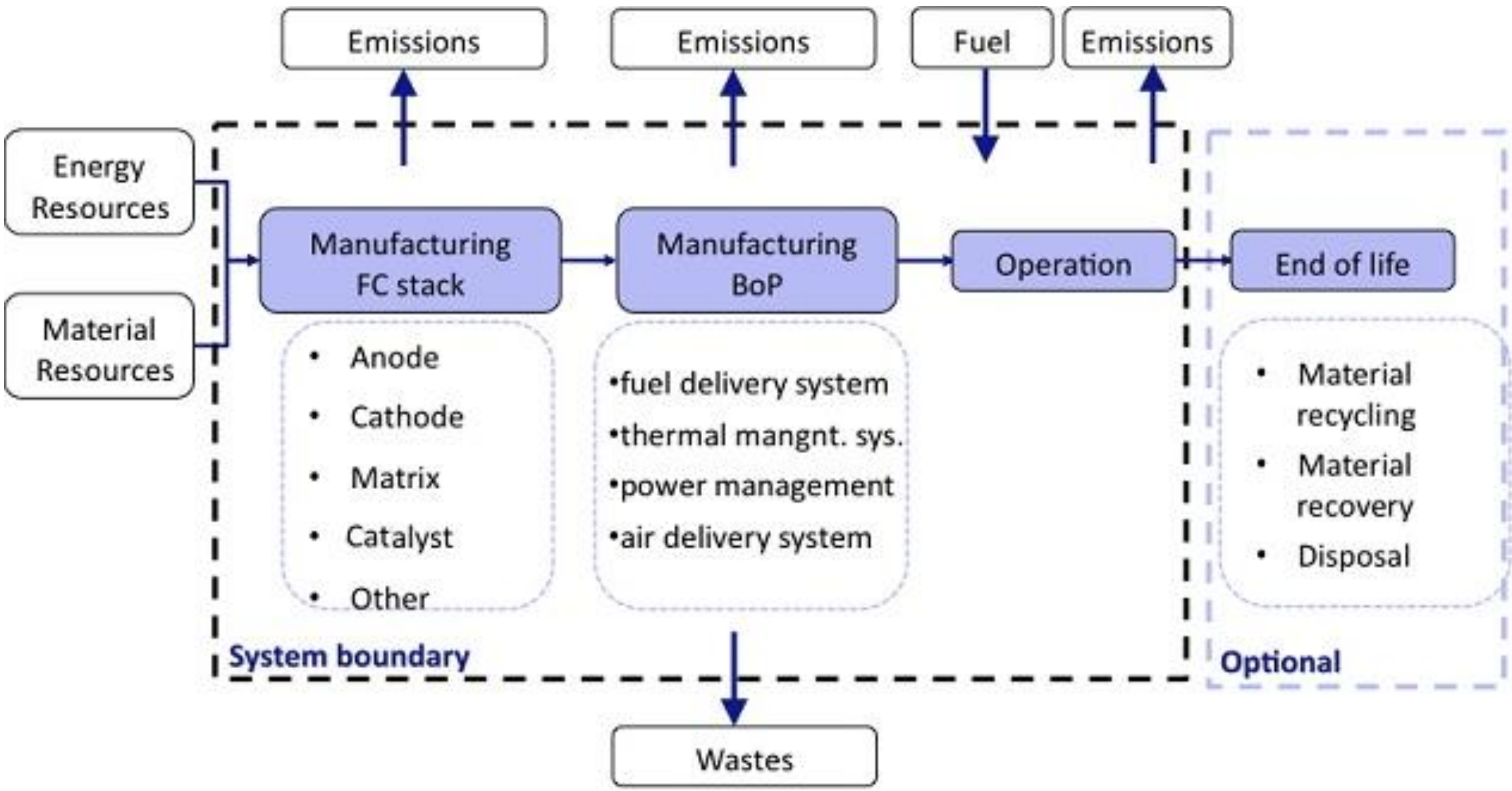
FOREGROUND PROCESSES	BACKGROUND PROCESSES
• anode production	• mineral extraction
• cathode production	• mineral manufacturing
• matrix production	• raw materials supply
• other stack components production	• energy supply
• BoP components production	• electricity mix
• stack assembly	• natural gas supply
• system assembly	
• energy requirements	

Group 3

Provision 25: Identifying processes within the system boundaries

It has to be defined which foreground and background processes are taken into account in the LCA. Foreground processes are identified 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 module, start-up and maintenance. For the fuel cell system, the foreground includes also the manufacturing of the BoP. Details are provided in figures 11 14, 15 and 16. The background system comprises related upstream processes (supply chain of energy and materials) and downstream processes as well. The important upstream processes like raw material extraction shall be included; the related infrastructure may be included. It is recommended to use already existing aggregated data e.g. from ELCD, which comprises complete upstream processes (e.g. energy supply), including the infrastructure. The infrastructure (e.g. means of transportation or pipelines) may be included in line with the cut-off criteria (section 6.3.3).

Provision 25: Identifying processes within the system boundaries



Provision 25: Identifying processes within the system boundaries

In all cases (**MCFC stack, MCFC system , TWINSTACK)** the system boundaries include foreground and background flows.

- Foreground flows include all processes related to the production and use of the MCFC itself, consisting of all the main production processes like the manufacturing of anode, cathode and matrix and their assembly for the MCFC stack, the manufacturing of the Balance of Plant and the start-up of the MCFC system.
- Background flows deal with almost all material and energy flows to and from the foreground system, such as infrastructure processes for the supply of the energy, power plants, power lines, mining, etc. Raw materials, used resources, primary products, additives, auxiliary materials and energy entering the system and electricity, heat, emissions to air, emissions to water, residues, waste and energy leaving the system have to be all taken into account as background data.

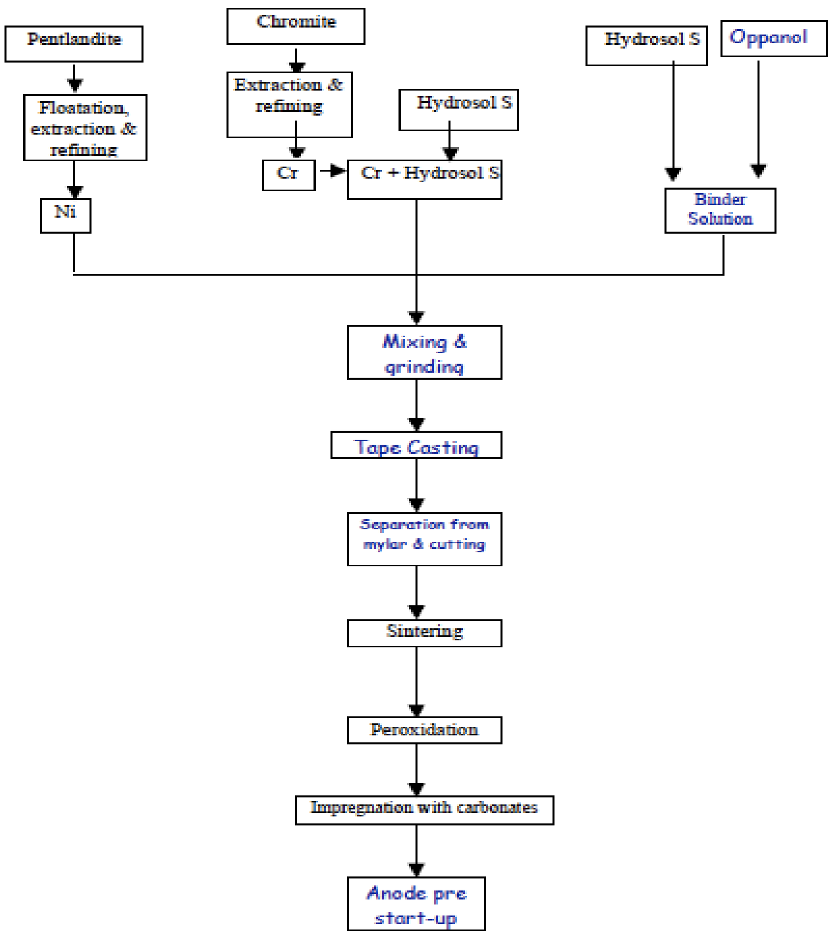
Group 3

Provision 25: Identifying processes within the system boundaries

FOREGROUND PROCESSES	BACKGROUND PROCESSES
• anode production	• mineral extraction
• cathode production	• mineral manufacturing
• matrix production	• raw materials supply
• other stack components production	• energy supply
• BoP components production	• electricity mix
• stack assembly	• natural gas supply
• system assembly	
• energy requirements	

Group 3

Provision 25: Identifying processes within the system boundaries



Provision 30: Classification and characterization

The following impact categories already identify in the scope phase shall be evaluated: global warming potential, acidification potential, eutrophication potential, photochemical ozone creation potential, abiotic depletion. When available, the methods, models and characterisation factors identified in the Guidance document under preparation by the JRC-IES, through the European Platform on LCA, shall be used. Until then, the CML impact assessment method shall be used, with the most updated version:

- *Global warming potential (GWP) (IPPC, 2007); kg CO2 eq.*
- *Acidification potential (AP) (Huijbregts, 1999); kg SO2 eq.*
- *Eutrophication potential (EP) (Huijbregts, 1992); kg PO4- eq.*
- *Abiotic depletion (AD) (van Oers et al., 2001); kg antimony eq.*

The method is implemented in all the major software tools available in the market. 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. A comparison across the impact categories shall not be done. Summing up shall not be done across impact categories.

Provision 30: Classification and characterization

The software tool used for the classification and characterization of the MCFC technology was SimaPro 7.3 and, among the methods available within this software, the method CML 2000 was selected.

The classification is the step in which the elementary flows are assigned to one or more of the selected impact categories, whereas the following step is characterization, i.e. the definition of how much impact an emission contributes with regard to a specific impact category.

The CML 2000 method automatically calculates the results multiplying the inventory values by appropriate characterization factors. Each factor has a different unit, depending on the specific impact category considered, and thus the results from different categories cannot be neither directly compared nor summed up. The units used for the characterization factors make reference to a specific chemical species or item, the environmental burden of which is known based on previous studies and is taken as reference impact.

Species that contribute to the same category as the reference species are evaluated in proportion to the impact generated (e.g. a species that contributes to global warming 10 times more than CO2 is credited a Global Warming Potential Factors of 10 g CO2-equivalent, so that its mass is converted into an equivalent mass of CO2 by multiplying by the G.W.P.F.).

Provision 30: Classification and characterization

Impact category	Unit	MCFC stack (without cut-off)	MCFC stack (with 2% cut-off)
Abiotic depletion	kg Sb eq	3.56E+02	3.53E+02
Acidification	kg SO_2 eq	1.46E+03	1.45E+03
Eutrophication	kg PO_4^{---} eq	1.76E+02	1.70E+02
Global warming (GWP100)	kg CO_2 eq	5.05E+04	4.96E+04
Ozone layer depletion (ODP)	kg CFC-11 eq	1.78E-02	1.76E-02
Human toxicity	kg 1,4-DB eq	3.96E+05	3.70E+05
Photochemical oxidation	kg C_2H_4	6.01E+01	5.79E+01

MCFC stack (125 kW_{el})

MCFC system (500 kW_{el}), supposed to be operating for 20 years (including 16 stacks and 4 reformers)

Impact category	Unit	MCFC system (without cut-off)	MCFC system (with 2% cut-off)
Abiotic depletion	kg Sb eq	2.71E+04	1.03E+04
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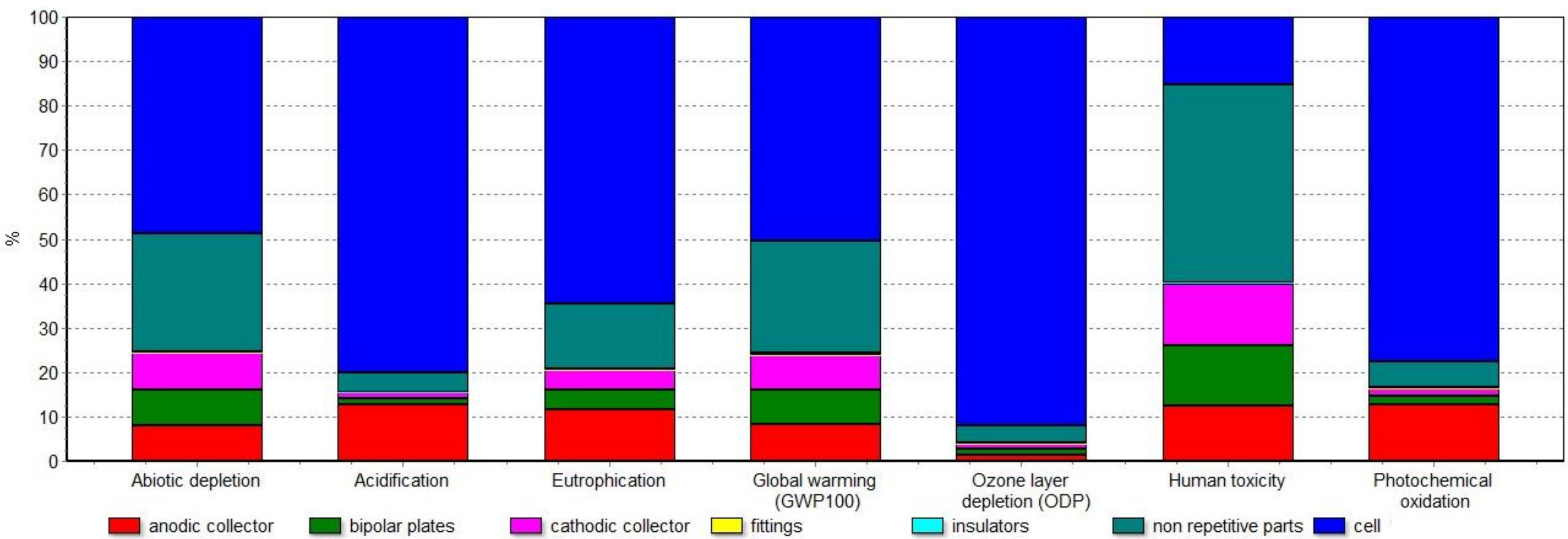
Eutrophication	kg PO_4^{---} eq	2.18E+04	2.09E+04
Global warming (GWP100)	kg CO_2 eq	3.78E+06	3.50E+06
Ozone layer depletion (ODP)	kg CFC-11 eq	5.27E-01	5.24E-01
Human toxicity	kg 1,4-DB eq	2.08E+07	1.87E+07
Photochemical oxidation	kg C_2H_4	5.50E+04	5.48E+04

Provision 30: Classification and characterization

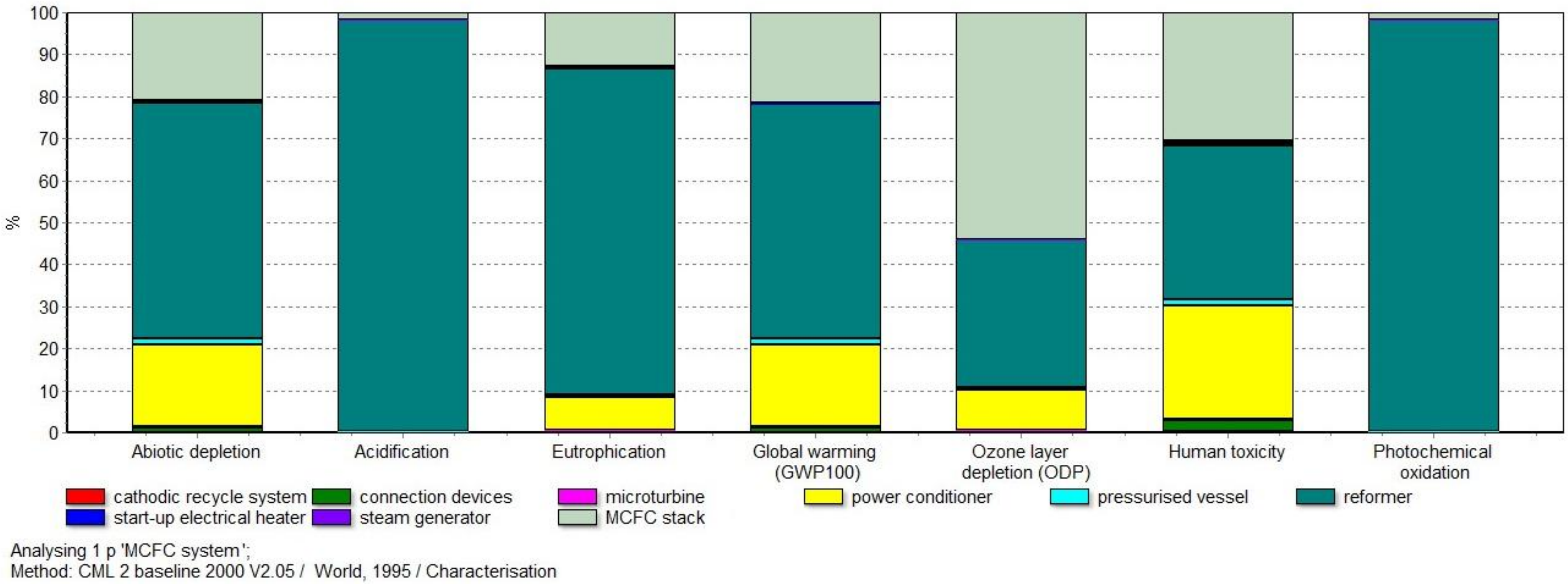
MCFC stack



Analysing 1 p 'MCFC stack';
Method: CML 2 baseline 2000 V2.05 / World, 1995 / Characterisation

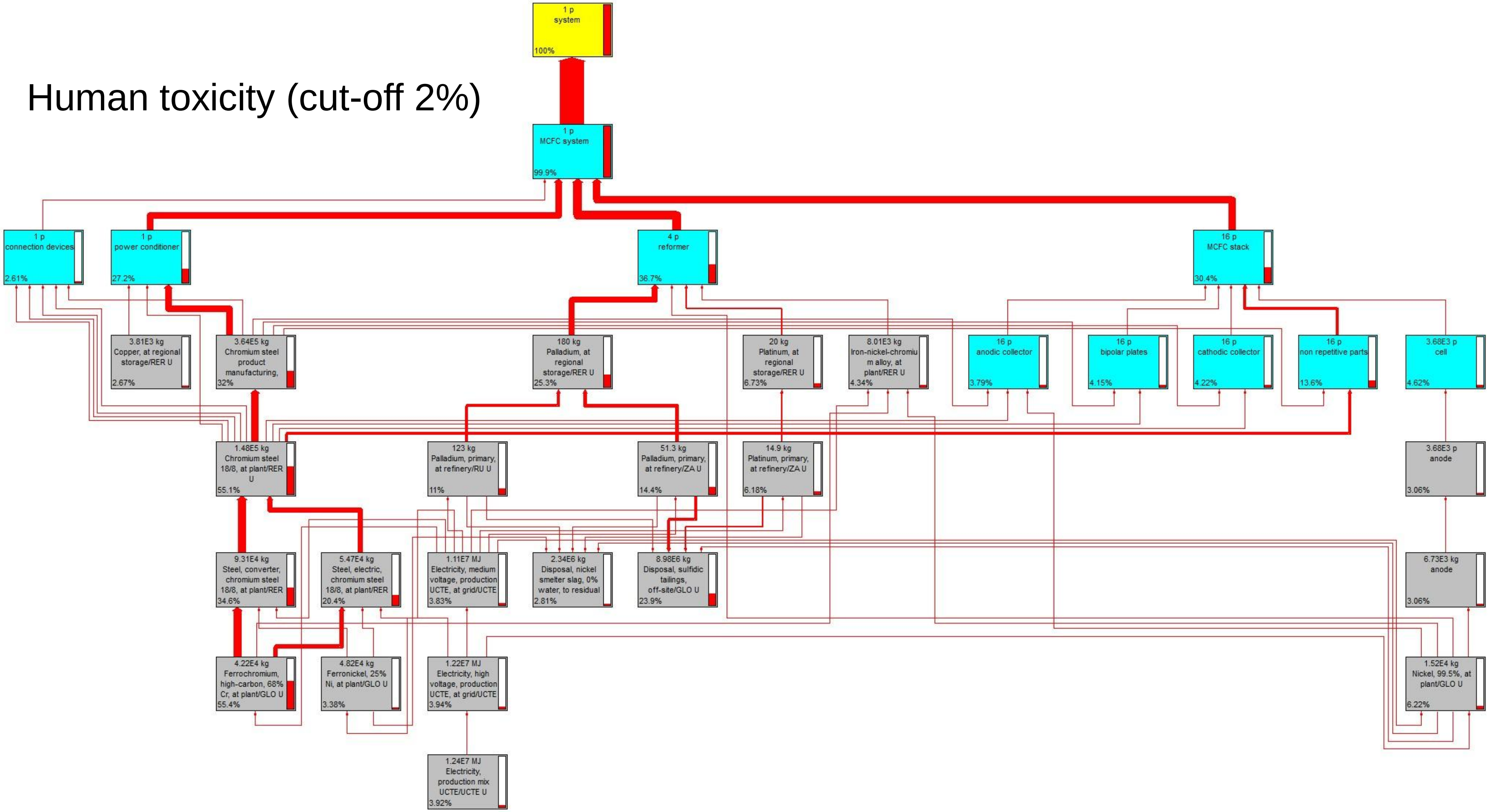
Provision 30: Classification and characterization

MCFC system



Provision 30: Classification and characterization

Human toxicity (cut-off 2%)



Provision 34 : Evaluation of results

- ***Completeness check:*** *Evaluate LCI model completeness (process coverage):*
  - *for comparative assertion, the cut-off shall always be met also by mass and energy, in addition to environmental impact*
  - *the final achieved degree of completeness shall be reported. If the aimed at or necessary completeness cannot be achieved, it shall be decided whether the scope or even the goal needs to be revised or redefined.*
- ***Sensitivity check:*** *identify the sensitive among the significant issues and analyse the sensitivity of these for the overall results:*
  - *evaluate the sensitivity of the LCIA results to key flows, process parameter settings, etc.*
  - *improve robustness of sensitive data, parameter, assumptions*
  - *report final achievements.*
- ***Consistency check:*** *Especially for comparative studies, check whether differences in data quality are consistent with the goal and scope of the studies, check whether the impact assessment steps have been consistently applied and in line with goal and scope, evaluate the relevance of any inconsistencies identified for the results and document them.*
- ***Uncertainty check:*** *perform uncertainty calculation of data/parameters according to the available techniques- report final achievements.*

Provision 34 : Evaluation of results

Completeness check

The validity of results achieved depends, first of all, on the degree of completeness of the study. In the MCFC LCA study, all elementary flows of quantitative relevance to the overall environmental impact of the system as well as the relevant steps of the production and functioning of a MCFC system are included.

- The cut-off criteria adopted (2%) can be considered met and therefore the goal and scope of the present study are accomplished.
- Foreground data about the active components manufacturing processes, their assembly into a stack, the production of Balance of Plant and the assembly of the system itself, and finally its operation phase are based on data provided by producer companies.
- Background data are gathered from updated datasets recommended by the Joint Research Centre of the European Commission and commercially available.

Provision 34 : Evaluation of results

Completeness check

Data missing:

- Some data regarding the energy consumption in the assembly phase were not accounted for, due to a lack of primary data, and should be included in future studies in order to achieve a better level of completeness.
- The disposal phase was not evaluated, due to lack of enough and reliable research on FC decommissioning.

Provision 34 : Evaluation of results

Sensitivity check

Sensitivity check aims at determining the robustness of the results of a LCA study and allows to determine what level of accuracy is necessary for a flow to make the analysed system sufficiently useful and valid. Sensitivity analysis can also indicate which input/output values are reasonable to use in the analysis. Sensitivity analysis is helpful in making decisions or recommendations, since it provides information such as:

- how robust is the scenario proposed in the face of different values of process parameters;
- under what circumstances the scenario proposed would change;
- how the optimal scenario changes in different circumstances.

Provision 34 : Evaluation of results

Sensitivity check

	IMPACT CATEGORY	SENSITIVITY PARAMETER	CONTRIBUTION TO THE IMPACT
Cell	Acidification	Nickel Secondary nickel	91.30% 2.25%
Stack (125 KW_{el})	Global warming	Electricity, medium voltage, production IT* Electricity, medium voltage, average production EU°	29.50% 24.40%
System (500 KW_{el})	Ozone layer depletion	Palladium Secondary palladium	30.10% 2.01%
System + Naural Gas	Abiotic depletion	Natural gas (Industry Data, SimaPro) Natural gas (Ecoinvent, average EU°)	94.10% 99.70%

Provision 34 : Evaluation of results

Consistency check

Assumptions, methods and data were double-checked for consistency throughout both the LCI and LCIA study.

- Inventory data result to be consistent in terms of time-related, geographical and technological representativeness.
- Mass and energy flows have been double-checked in relation to the size and power of the system, with special attention to the consistency at the different scales (single cell, 125 kW stack, 500 kW module and operation over time).
- The data used in the different steps and scales are internally consistent.
- The impact assessment results are consistent and in line with the goal and scope initially defined.

Provision 34 : Evaluation of results

Uncertainty check

LCA data are always characterized by a given level of uncertainty that depends on source of data and processing steps. Uncertainty can refer to:

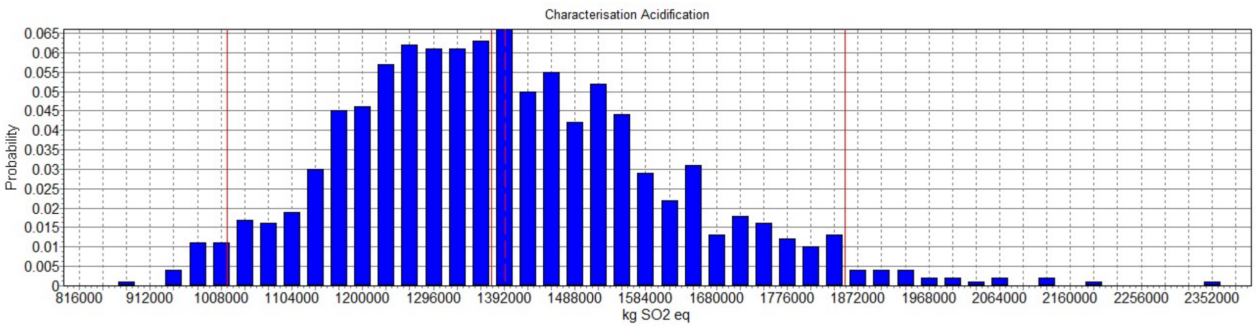
- ***Foreground data:*** primary data is related to the confidentiality of data provided by the producer, to the accuracy in data collection and processing or to the level of process optimization applied in the producer company.
- ***Background data:*** accuracy and updating of the database used and it cannot be easily checked by the analyst.

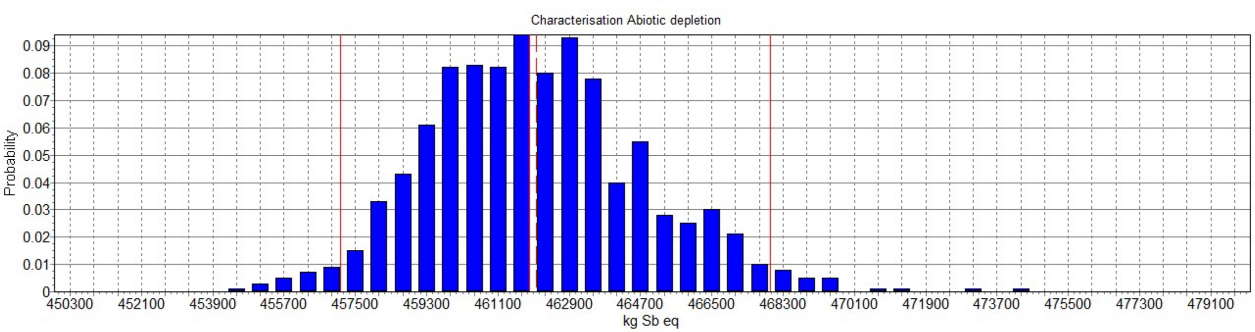
Provision 34 : Evaluation of results

Uncertainty check

In the MCFC study the main uncertainty and its consequences on results were addressed in our study through Monte Carlo analysis, within the SimaPro 7.3 software.

The Monte Carlo analysis was carried out with a confidence interval of 95% and a fixed number of runs (1000).





Results appear robust against uncertainty and possible errors. Finally, the assessment is multi-level and detailed enough to be able to provide an overview of the improvement potentialities based on technical and use recommendations.

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