"Performing Life Cycle Assessment for Hydrogen and Fuel Cell Technology"

LCM 2011, Berlin, 1 September 2011

FC-Hy Guide

Examples of application of FC Guide to: Solid Oxide Fuel Cell (**SOFC**), Proton Exchange Membrane Fuel Cell (**PEMFC**), Molten Carbonate Fuel Cells (**MCFC**)

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Presentation outline

- Background information on the case studies and the project
- Guidance document applied to SOFC, MCFC, PEMFC:
  - Goal and Scope of study
  - Life Cycle Inventory Analysis
  - Life Cycle Impact Assessment
  - Interpretation of results
- Next steps

The problem

- The Fuel Cells and Hydrogen Joint Undertaking (FCH-JU):
  - "*Sustainability is a key driver of the FCH JU activities and it is necessary to assess the new developments towards these goals.* ***Life Cycle Assessment will therefore be applied throughout the FCH JU on a programme level.***"
- However, the present main critics addressed to LCA are:
- **Weak comparability** among different studies on the same product
- **Complexity** of the method, which hampers its applicability in the industrial context.

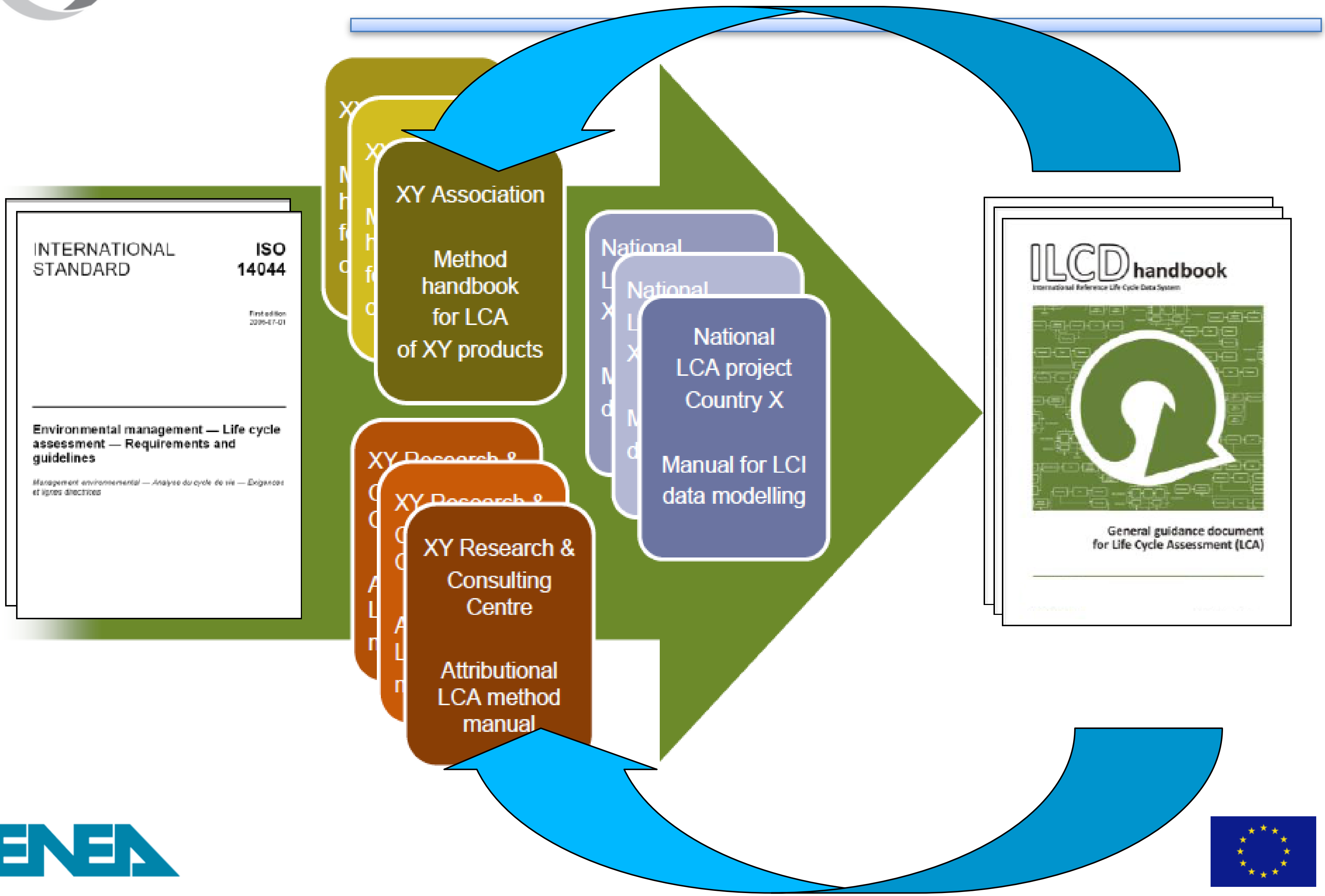
Weak comparability

- ISO standards leave high degree of freedom to practitioners: **subjectivity** linked to some methodological choices (e.g. allocation, system boundary definition, modelling, etc.)
- ILCD Handbook (HB) addresses this question, providing **guidance** on all the LCA process, from the definition of the Decision Context, to specific requirements for review process
- However, ILCD HB is necessarily still **generic** as it applies to all possible sectors, technologies, decision contexts, LCA applications

Complexity

- LCA is necessarily a **complex method**, as in a generic life cycle system many parameters can affect the final results
- However, when a sufficient **knowledge** of a specific product/technology/system is available, the practitioner can **focus** her/his efforts on the real **relevant aspects** of the life cycle
- This is the only possible way to reduce the complexity of an LCA study, keeping a sufficient **scientific robustness** of the results (**relevance** of results)

ILCD Handbook



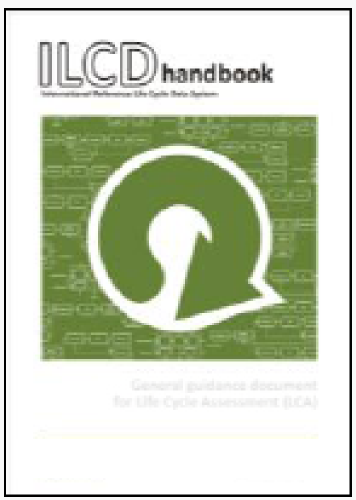
Third tier of harmonisation

3rd tier

FC-Hy Guide
Guidance document for performing LCAs on Fuel Cell Technologies
FC-Guide

Specific guidance for a product group.

2nd tier



Review

Life Cycle Inventory

Life Cycle Impact Assessment

General guide for Life Cycle Assessment
- General guide for Life Cycle Assessment (LCA) – Detailed guidance (this document)
- General guide for Life Cycle Assessment (LCA) – Provisions and action steps

Documentation, Nomenclature, Terminology

Provisions depending on the decision context and application

1st tier

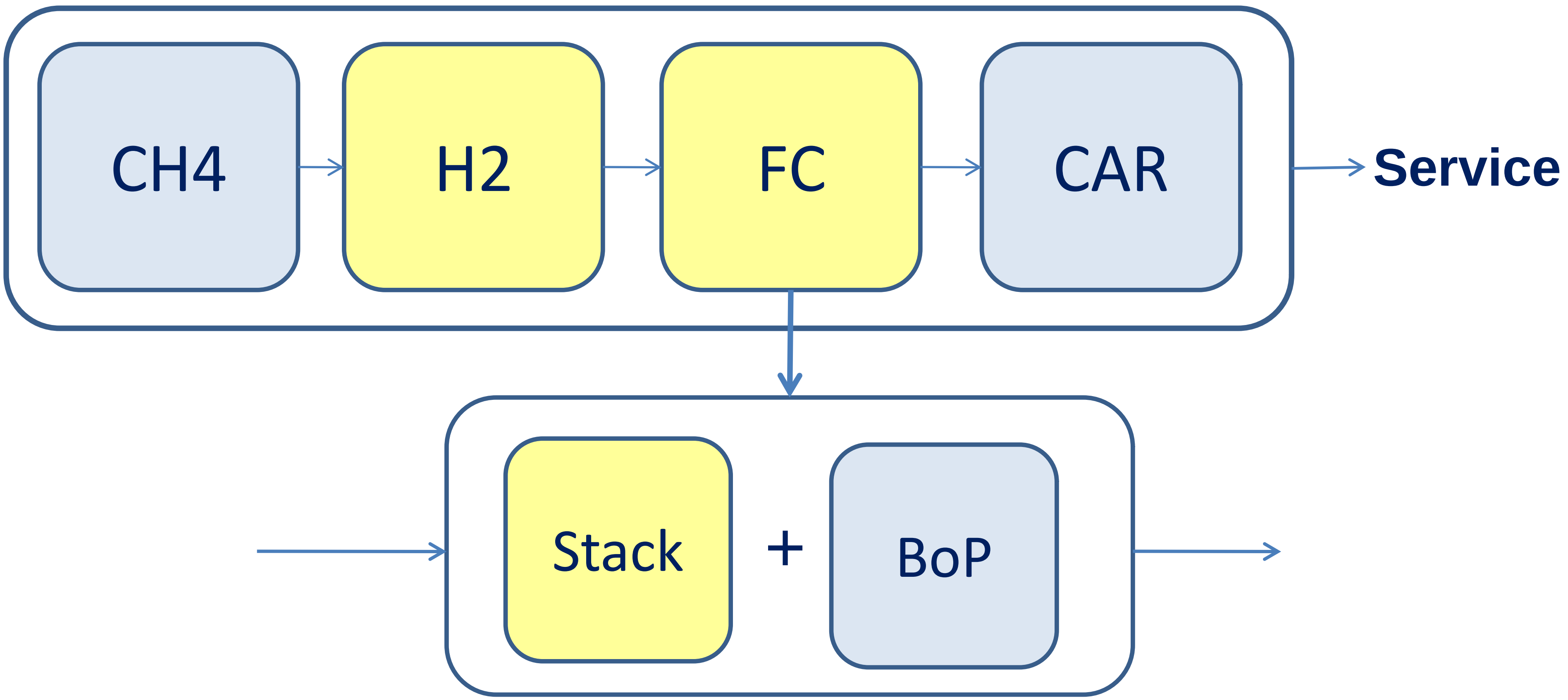
ISO 14040, 14044

General rules

Output

- Prepare and make available to the final user **knowledge and a pre-elaborated set of information**, ready to be used:
  - **FC Guide** (information and provisions)
  - **Templates**: Data collection, Data documentation, Reporting
  - **Examples** from case studies
  - **Training**
- Target: technology developers, LCA practitioners
  - "*less and correct*"

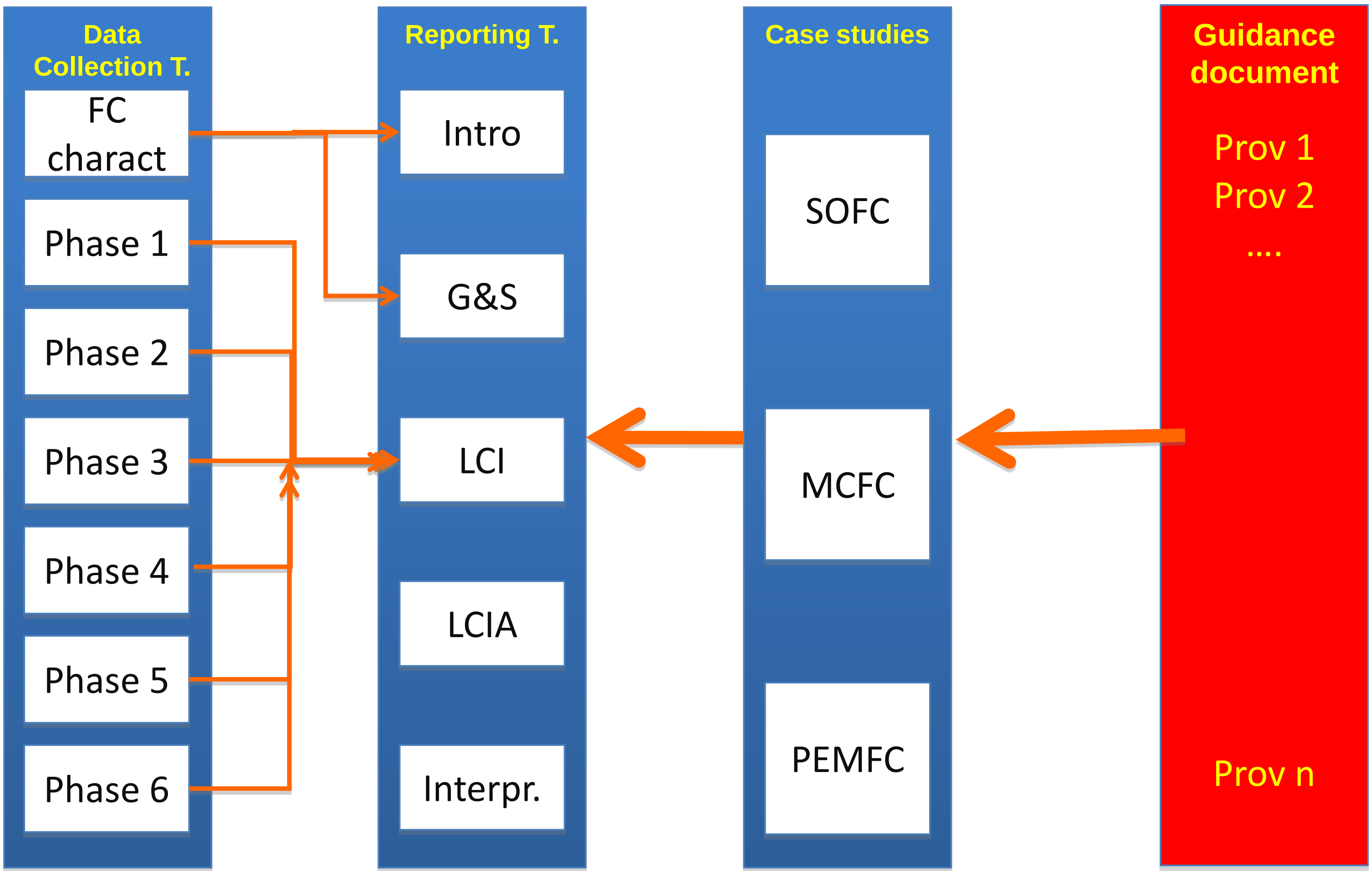
How to use the information given in the Guidance Document



Other background information

- Studies performed by FC experts, not directly involved in drafting the Guidance Document
- “Exercises”: not always primary data from producers were available
- Studies developed following an andvanced draft of the guidance document, not the final version
  - Time constraints of the project: work in parallel
  - Comments from the open consultation included, but comments from review panel not yet included
  - Exemples not complete. In particular:
    - data quality aspects not included yet
    - Limitation in the interpretation phase

Presentation Structure



Introduction to FC technologies

Provision 1 – Product related information

Shall – Describe the FC system or stack. Information on the main properties given by stating the FC standard being met.

Shall – If no standard is applicable: see table below

Data collection template

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	

Introduction to FC technologies: SOFC

Product information	Value/description
Trade name	Hexis (stack)
Type of electrolyte	Solid Oxide
Primary function	Production of electricity and heat in domestic level
Electrical power	1 kWel (stack), 2 kWel (system)
Thermal power	4.7 kWth (system)
Efficiency	Electric: 25%; Thermal: 58,8%
Rated voltage, Current	N/A (Operational point: V=700mV, I= =.3 A/cm2 @82% utilization
Operating temperature	800-950° C
Weight (estimated)	100 kg (stack), 250 kg (system)
Dimensions (system)	2.1*0.6*0.77 m
Fuel used	Natural gas. Specifications according to DIN 51857
Expected service lifetime	40.000 h (stack operational target)
Intended use	Covering power and heat demand of a single family dwelling, in parallel to electric grid connection and a peak gas boiler

Introduction to FC technologies: MCFC

Product information	Value/description
Trade name	TWINSTACK®
Type of electrolyte	Molten carbonate salt mixture (Li2CO3 and K2CO3)
Primary function	Production of electricity and heat
Electrical power	500 kW (system)
Thermal power	300 kW
Efficiency	Electric: 25%
Rated voltage, Current	700 V
Operating temperature	650° C
Weight (estimated)	49.5 E3 kg (system) (4500 Kg each stack)
Dimensions (system)	11*5.5*19 m
Fuel used	Natural gas. LHV 3.45° 7 J/m3, sulphur content 35 mg/Nm3
Expected service lifetime	40.000 h
Intended use	Electricity rpoduction

System description

Provision 3 – Produt system description

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

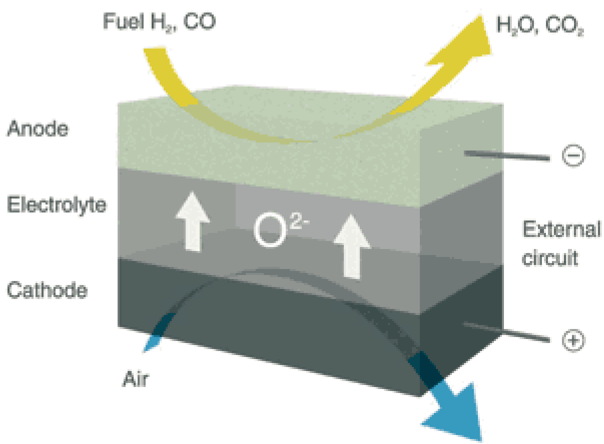
-year of construction

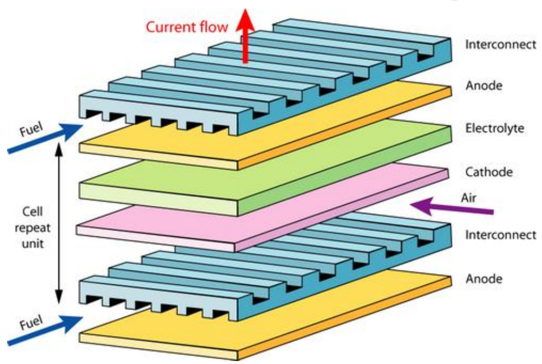
-type of production site (laboratory, pre-commercial, commercial scale)

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.

System description: SOFC

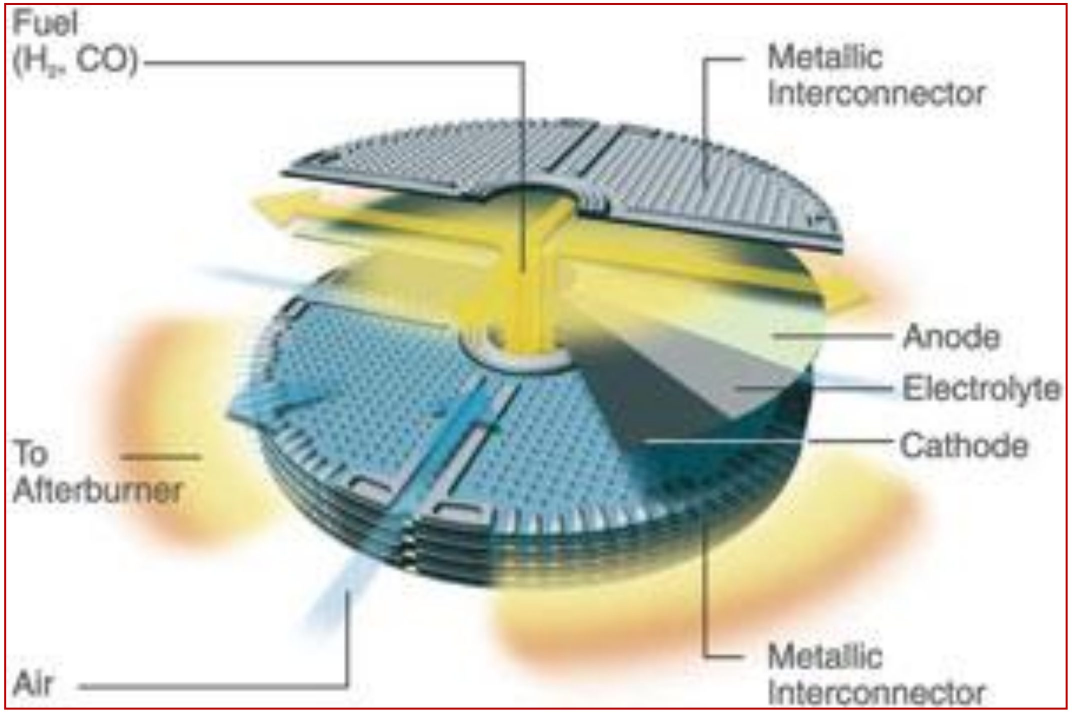
Operating principles





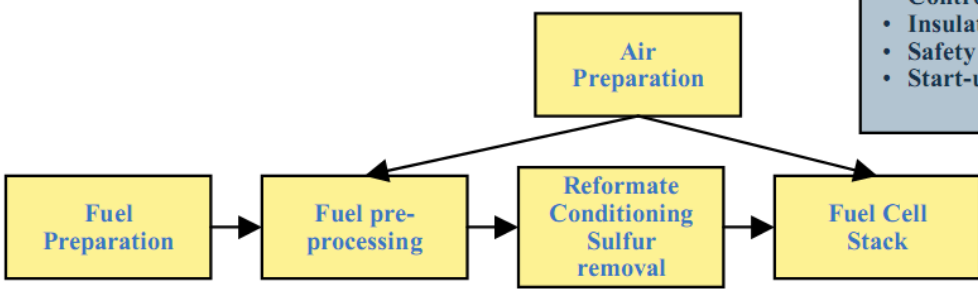
planar

Cell configuration



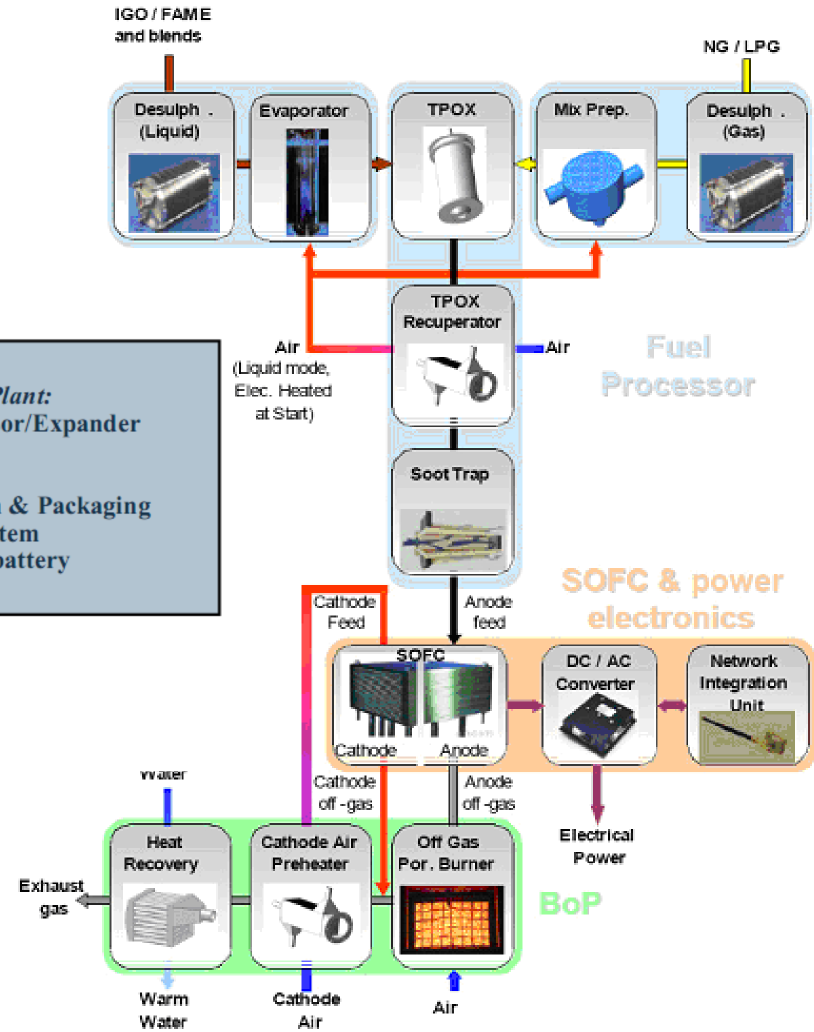
SOFC-based system

SOFC-Based System



Balance of Plant:

- **Compressor/Expander**
- **Pumps**
- **Controls**
- **Insulation & Packaging**
- **Safety system**
- **Start-up battery**



LCA studies: Goal definition

- Test the FC Guidance document with full-scale real cases
  - Help carrying out the definition of relevant LCA features in order to make the FC Guidance Document more product-specific
    - Identify which data are more critical for the final result of the study
    - allocation,
    - cut-off,
    - impact categories, etc.
  - Check whether the provisions are clearly understandable by the target audience;
- Provide examples to support future implementation of the FC Guidance

Goal & Scope definition: Intended application

Provision 5: Intended application(s)

Shall: Clearly state the intended application, 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 specific modules of the FC
- benchmarking of a specific FC against the product group's average.

LCA studies: goal and scope definition

	MCFC	SOFC	PEMFC
Scope	MCFC stack (125 kWel) MCFC system (4 stacks + BoP, 500 kWel), including its operation for electricity production fueled by natural gas	SOFC stack (1 kWel) SOFC system (2 stacks+ BoP, 2 kWel), including its operation for electricity production fueled by natural gas	PEMFC system (1 stack s+ BoP, 1200 W), including its operation for electricity production fueled by hydrogen

Intended application

Internal use

- Results will help FC producing companies optimizing the production and use steps by identifying the crucial parameters affecting the performance of the whole system

External use

- The study contributes to develop step-by-step guidance for the applicastion of LCA to different types of FC technologies

Method, assumptions and limitations

- CML update 2010 method
- low percentage of primary data
- waste created during the manufacturing phase were not considered
- recycling and energy recovery not included
- transportation of materials from the manufacturing plant to the fuel cell system manufacturing plant not considered
- Machinery and plant buildings are negligible
- Data gaps: assumptions based on experience and use of data of similar products

Target audience and decision context

Target audience

- Users familiar with LCA but not necessarily expert
- Technicians dealing with technical and environmental decisions for full scale implementation of FC technology in the market
- FCH JU project officers

Decision context

- Situation A micro level (negligible changes in the background system)

Short parenthesis: why situation B is not covered by the guidance document

- 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.).
- Situation A covers the scope of the FCH JU required applications.

Functional unit and reference flow

Provision 12 – Functional unit (FU)

FC stack

Shall - The FU 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 FU is the "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}.

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.

Provision 13 – Reference flow

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

Functional unit and reference flow

SOFC

Stack: 1 SOFC stack (1 kWel), containing 50 cells, casing, flanges and insulations

System: 2 stacks + BoP, 1 MJex (2 kWel, 4.7 kWth), estimated life time: 20 years

MCFC

Stack: 1 MCFC stack (125 kWel)

System: 4 stacks + BoP, 500 kWel, estimated lifetime of 20 years (80 GWel)

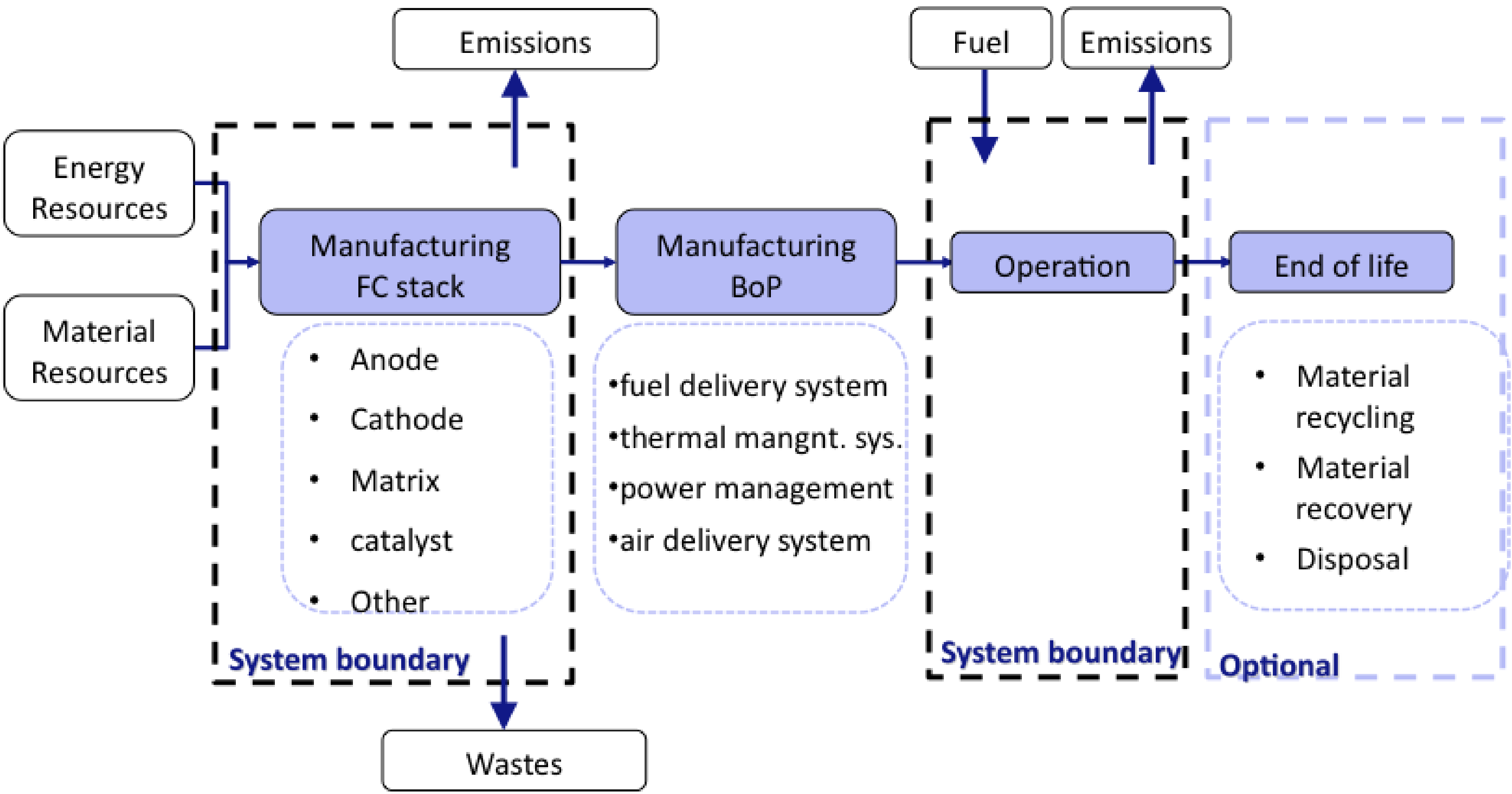
System boundaries

Provision 16 – System boundaries

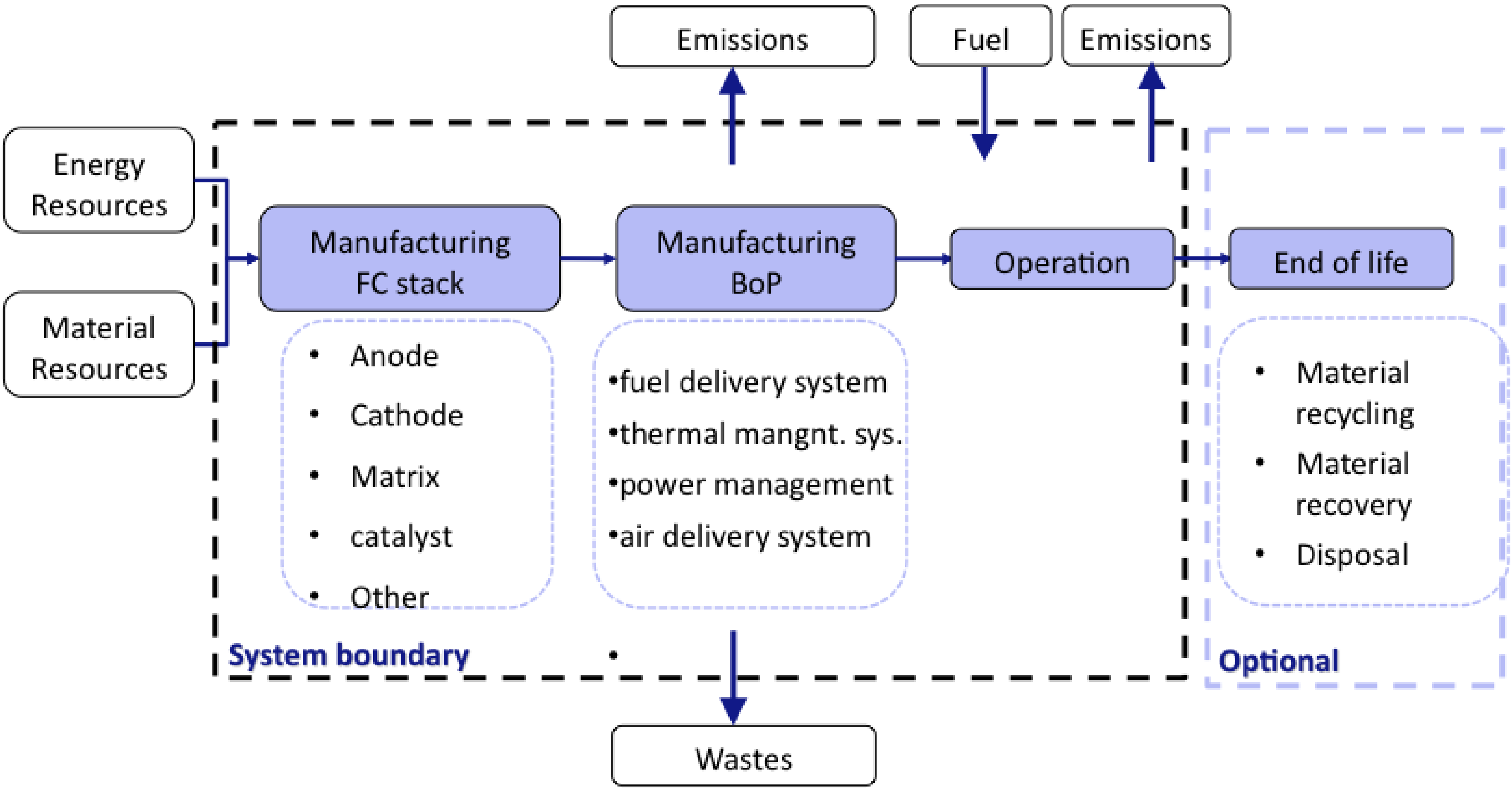
Should - The system boundaries of a LCA on a FC are defined according to the product system under assessment. In the case of a FC system a "cradle to grave" approach is mostly applied. However a cradle to gate approach is used in the case of a FC stack, where the absence of the BoP makes it impossible to assess the use phase.
End of life is optional and can be kept out of the boundaries of the study. However, it shall be described qualitatively.

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

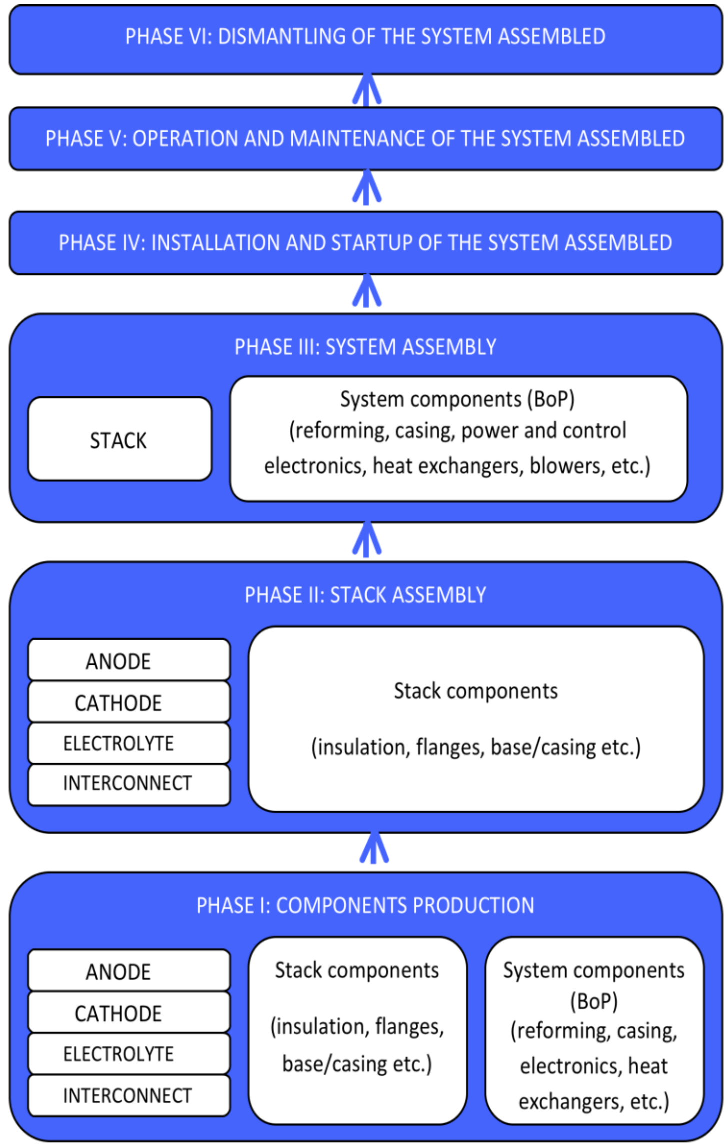
System boundaries - stack



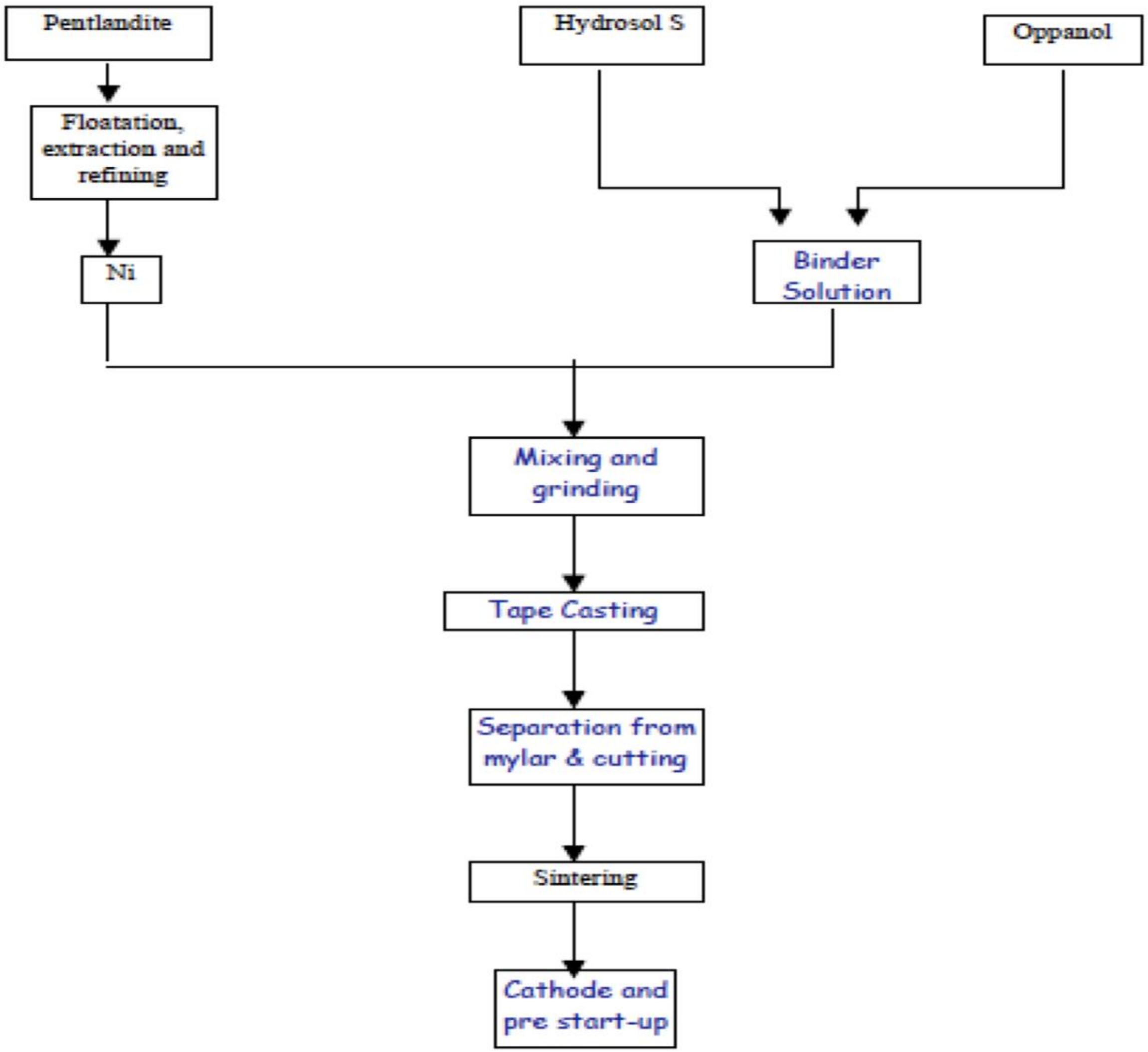
System boundaries - system



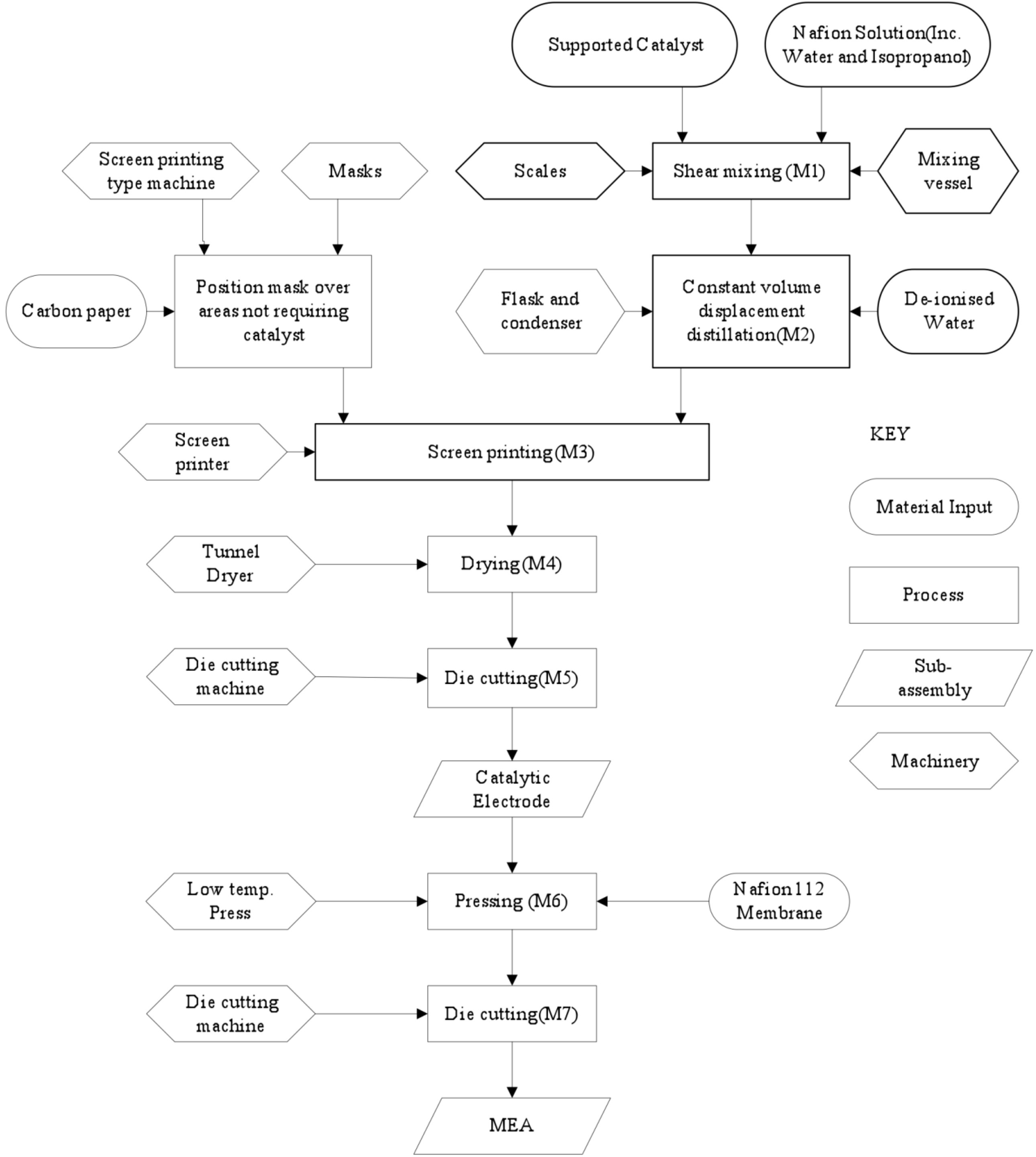
FCs: system flow diagram



Example: MCFC Cathode production



Example PEMFC: Membrane Electrode Assembly



Definition of relevant flows and cut-offs

Provision 17 – Definition of relevant flows

Shall – Include at least the following potential relevant flows:

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

Provision 18 – 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 cut-off or excluded from the study

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Relevant flows for SOFC

Unit of product	Components	Input	Output
Solid Oxide Fuel cell	Anode, cathode, electrolyte, interconnect	Main materials (Doped $LaMnO_2$, YSZ, **NiO**, **Ferrochromium 68% Cr**), secondary materials – solvents, binders, etc. (PVB - Polyvinyl butyral, Ethanol, Trichloroethylene, Polyethylene glycol, Dibutyl phthalate), electricity consumption for manufacturing.	Emissions
SOFC stack (1 kWel)	The above plus stack casing – base, flanges and insulation	The above plus corresponding materials (Steel AISI 303, Iron-NI-Cr alloy, SiO_2, TiO_2, Al_2O_3).	Emissions
SOFC system (2 kWel)	The above plus, reforming, casing, piping, start up components, heat exchangers, power conditioning, afterburner, control, remaining BoP components	The above plus BoP components (TPOX reactor, Gas phase de-S, mixing chamber, electrical resistance, inverter, porous type burner, electronics for control units, blowers, soot trap and corresponding materials (Steel AISI 301, Al_2O_3, SiC, Cast iron, Granulated Activated Carbon, Steel, low alloyed, Steel AISI 303, PM2000, Steel AISI 430, Iron-nickel-chromium alloy, Aluminum, Copper, Plastics, Polyethylene, ABS)	Emissions
Assembled system and start-up		Electricity and natural gas consumption	Emissions
System operation phase and maintenance		Fuel consumption	Emissions

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Relevant flows for MCFC

Unit of product	Components	Input	Output
Molten Carbonate Fuel Cell	Anode, cathode, matrix, electrolyte	Metal powders (Ni, Cr, $LiAlO_2$), electrolyte chemical compounds (Li_2CO_3, K_2CO_3), binders (hydrosol S, oppanol, fish oil, antifoam, Ketjenflex, Butavar B98), solvents (ethanol, isobutanol, tetrachloroethylene), polymer (mylar), industrial gases (N_2, H_2, CO_2, H_2O) energy inputs for anode, cathode and matrix manufacturing processes.	Emissions to air (N_2, H_2, CO_2)
Stack assembled (125 kW_{el})	Above components plus steel parts (anodic and cathodic collectors, bipolar plates, fittings)	Above inputs plus stainless steel (AISI 310, AISI 316L), chromium steel products manufacturing inputs	Above outputs plus chromium steel products manufacturing outputs
System assembled (500 kW_{el})	Above components plus Balance of Plant (reformer, pressurized vessels, start up electrical heater, steam generator, power conditioner, microturbine, pipes and valves, cathodic recycle system)	Above inputs plus iron-nickel-chromium alloy (Incoloy 800H), carbon steel, cast iron, copper, aluminum, silica sand, titanium dioxide, aluminum dioxide, palladium, platinum, magnesium oxide, steel, aluminium and copper products manufacturing inputs	Above outputs plus steel, aluminium and copper products manufacturing outputs
System assembled operation phase	Above components plus natural gas	Above inputs plus natural gas supply inputs	Above outputs plus natural gas supply outputs

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Relevant flows for PEMFC

Unit of product	Components	Input	Output
Fuel cell	Anode, cathode, membrane, gas diffusion layer, gasket, bipolar plates	Electricity consumption; Chemicals (raw powders and solvents. E.g. Cr powder, Pt powder, isopropanol, de-ionized water); Materials (Nafion, Graphite, Polypropilene, Teflon)	Emissions
Fuel cell stack	Fuel cells, endplates, insulators, tie-rods, buss plates, manifolds, fittings	Electricity consumption; Materials (Aluminium alloy, PTFE, Steel, Copper, Stainless steel)	Emissions
Fuel cell system	Fuel cell stack, compressor, fan, heat exchanger, electronics, wiring, housing, valves, fittings, piping, electromotors, voltage converter, nuts and bolts	Electricity consumption; Materials (Copper, Steel, Stainless steel, Cast iron, Aluminium, Plastic)	Emissions
Assembled system and start-up		Electricity consumption	Emissions
System operation phase and maintenance		Fuel consumption	Emissions

Identifying processes within the system boundaries

Provision 25 – identifying processes within the system boundaries

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 module, start-up and maintenance. For the fuel cell system, the foreground also includes the manufacturing of the BoP.

Shall: Include the important upstream processes such as raw material extraction.

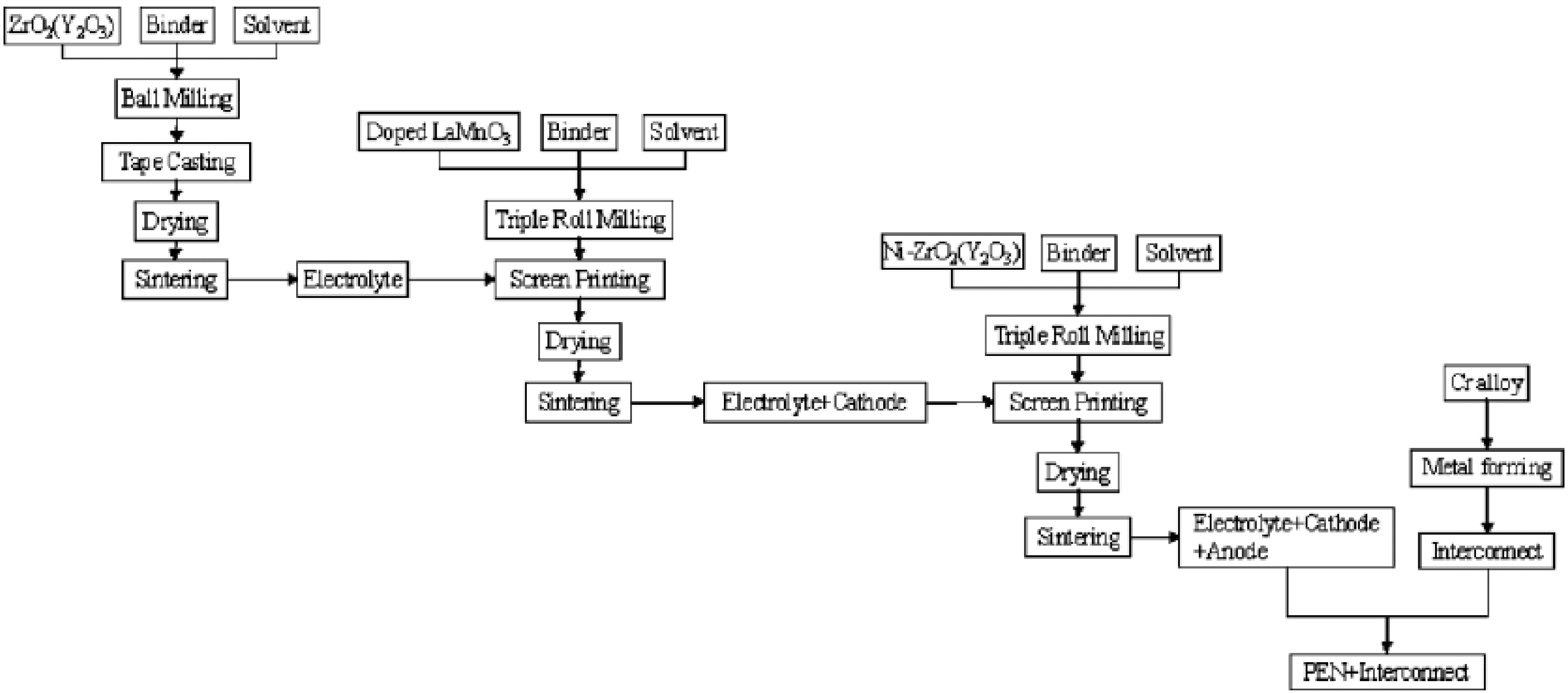
Should: The related infrastructure may be included. It is recommended existing aggregated data be used e.g. from ELCD, which comprises complete upstream processes (e.g. energy supply), including the infrastructure. The infrastructure (e.g. means of transportation or pipelines) may be included in line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

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 boundaries of the study.

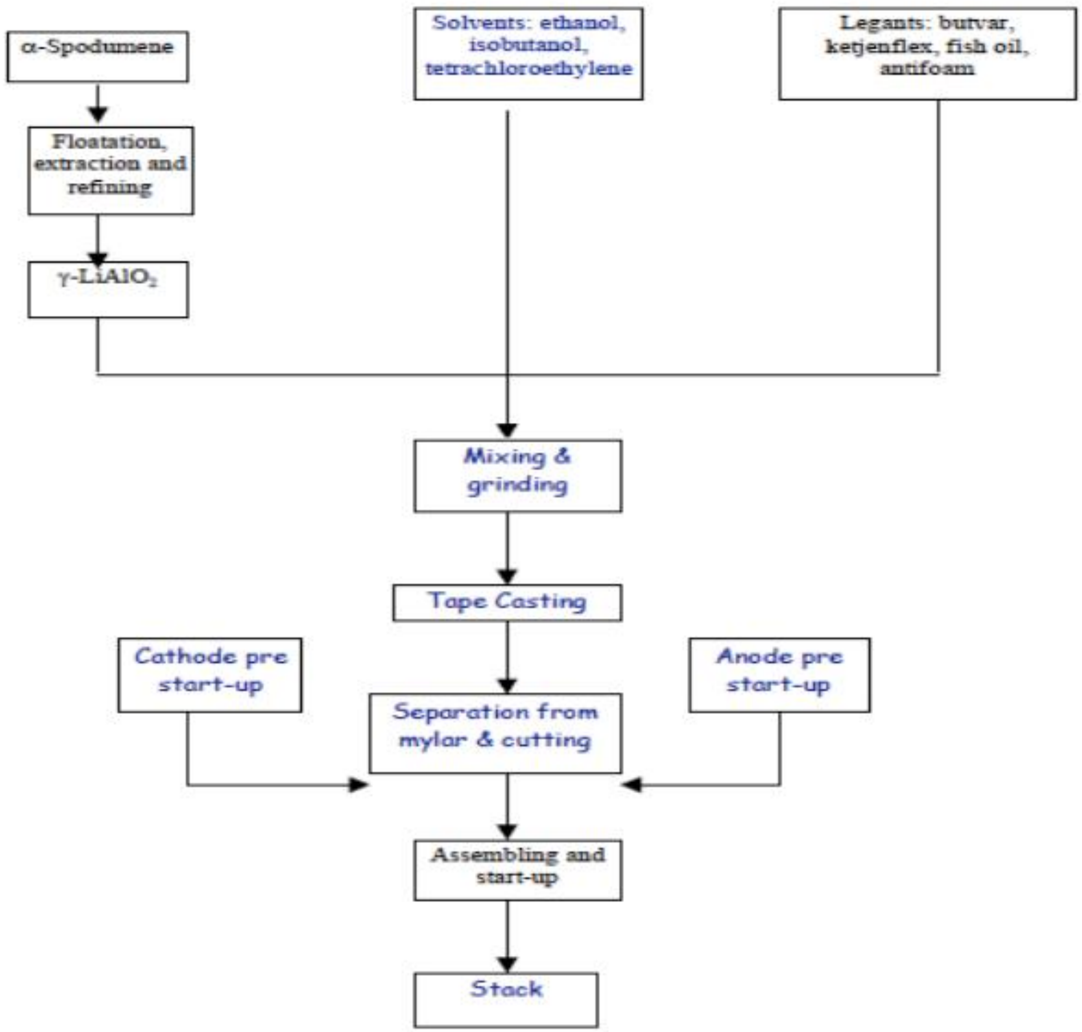
Shall: If not included in the study boundaries, a qualitative description of the end of life.

Identifying processes: SOFC



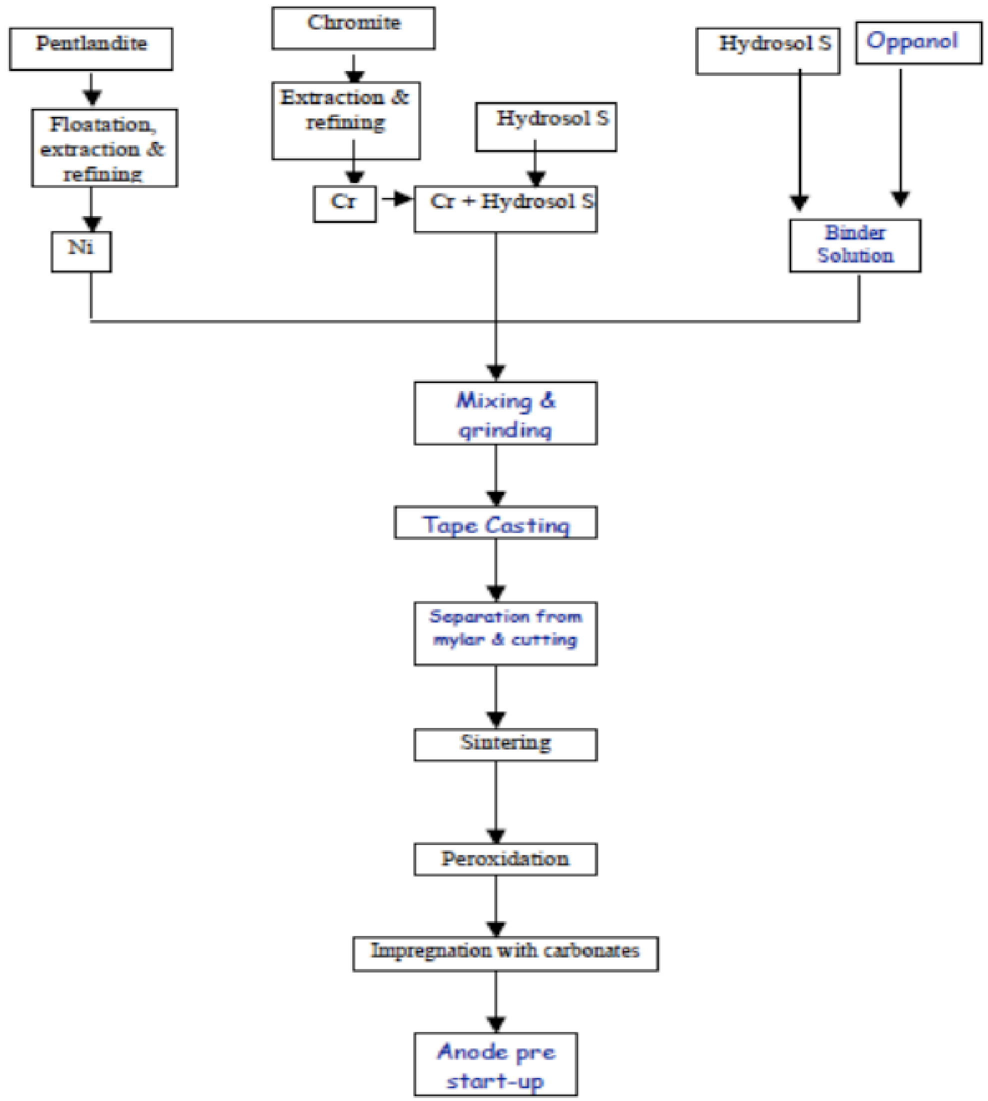
SOFC cell manufacturing process

Identifying processes: MCFC



MCFC – matrix industrial production and stack assembly

Identifying processes: MCFC



MCFC – Anode production

Data collection

Provision 26 – Data collection

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 secondary 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.

Shall: Data used shall reflect the technology actually used.

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: If data gaps arise, state in the report how they are filled and how they are consistent with the primary data collected.

Should: If data gaps arise, use the following methods for filling them:

- Literature research
- Generic data that are similar
- Information gained from manufacturers
- Information gained from technical experts or process operators.

Data collection

Provision 27 – Selection of generic LCI

Shall: Generic data can be applied for a variety of processes and materials that are frequently used. Depending on the technology under evaluation this could include fossil fuel supply, electricity, thermal energy supply, auxiliary materials, catalyst material or transport processes, etc. Use the following databases for generic data (by order 1, 2, 3):

1. The European Reference Life Cycle Database (ELCD)
2. Data from the International Reference Life Cycle Data System Data Network (ILCD Data Network)

If there are no applicable data in above list available

3. Databases using the ILCD format (http://lca.jrc.ec.europa.eu/lcainfohub/databaseList.vm)

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.

Data collection MCFC: components (Phase I)

(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)					

Data collection: MCFC components (Phase I)

Anode Preparation	Process Energy (MJ)	Process energy intensity (MJ/kg)
powders' preparation		
binder solution preparation		
mixing and grinding		
tape casting		
sintering		
pre-oxydation		
carbonate impregnation		

Cathode Preparation	Process Energy (MJ)	Process energy intensity (MJ/kg)
powders' preparation		
binder solution preparation		
mixing and grinding		
tape casting		
sintering		

Matrix Processes	Process Energy (MJ)	Process energy intensity (MJ/kg)
powders' preparation		
binder solution preparation		
mixing and grinding		
tape casting		

Data collection MCFC: assembly into a stack (Phase II)

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)		

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

Processes	Process Energy (MJ)	Process energy intensity (MJ/kg)
Injection moulding		
Stamping		
Machining		
Al coating for bipolar plate		
Ni coating for anodic and cathodic collectors		
Other metal coating (specify)		
Structural foam		
Aluminium casting		
Die cutting		
Aluminium stamping		
Machining		
Assembly (manual)		
Assembly (robotic)		

Data collection MCFC: assembly into a system (Phase III)

Components	Materials	Amount (g/unit of product)	Energy inputs (MJ/kg)
Reformer	Steel		
	Ni		
	Zn		
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)		

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

Processes	Process Energy (MJ)	Process energy intensity (MJ/kg)
Metal forming		
Welding		
Catalyst preparation		
Assembly (manual)		
Assembly (robotic)		

Data collection MCFC: Installation and start up (Phase IV)

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		

Data collection MCFC: operation and maintenance (Phase V)

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

Data collection MCFC: dismantling (Phase VI)

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)	

Multifunctionality

Provision 28 – Multifunctionality

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.

Multifunctionality

SOFC

Electricity: 0.7715
Heat: 0.2285
The following equation was applied:
$MJex = MJel + \varsigma_{th} * MJth$
where $\varsigma_{th} = 1-(Ta/Tm)$ is the Carnot factor.
Ta=10° C , Tr =30° C, To =80° C
Tm=50.977° C, and $\varsigma_{th} = 0.12603$

SOFC system consumes (at full capacity) 8 kW of natural gas, producing 2 kW of electricity and 4.7 kW of heat. The co-generated energy flows are equivalent to 2.5923 kW of exergy and the corresponding allocation factors are: Electricity: (2/2.5923) = 0.7715; Heat: (0.5923/2.5923) = 0.2285.

MCFC and PEMFC

Electricity: 100%
Heat is considered as a waste emission to the environment.

Re-use, recycling, and energy recovery

Three main scenarios:

- **Disposal**: If no information is available, the worst case scenario of disposal is applied (no credit 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 (credit for 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

Impact assessment - characterization

Provision 30 – Characterisation

Shall: Evaluate the following impact categories previously identified in the scope phase: global warming potential, acidification potential, eutrophication potential, photochemical ozone creation 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:
- Global warming potential (GWP) (IPPC 2007); kg CO_2 eq.
- Acidification potential (AP) (Huijbregts 1999); kg SO_2 eq.
- Eutrophication potential (EP) (Huijbregts 1992); kg PO_4^- eq.
- Abiotic depletion (AD) (van Oers et al. 2001); kg Sb eq.

This methodology is implemented in all the major software tools available on 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.

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)
Land use

Shall: Do not perform a comparison across the impact categories

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

Impact assessment - SOFC

Impact category	Unit	Total	SOFC Cell	Stack casing-base	Flanges	Insulation
Abiotic depletion	kg Sb eq	3,76E+00	2,36E+00	6,90E-01	5,68E-01	1,46E-01
Acidification	kg SO2 eq	1,73E+01	1,80E+00	4,72E+00	1,06E+01	1,36E-01
Eutrophication	kg PO4--- eq	2,58E-01	1,07E-01	3,63E-02	9,91E-02	1,55E-02
Global warming (GWP100)	kg CO2 eq	5,26E+02	3,11E+02	1,07E+02	9,02E+01	1,80E+01
Ozone layer depletion (ODP)	kg CFC-11 eq	7,60E-05	6,62E-05	1,58E-07	6,44E-06	3,20E-06
Human toxicity	kg 1,4-DB eq	5,63E+03	3,73E+03	6,42E+00	1,89E+03	7,48E+00
Photochemical oxidation	kg C2H4	7,03E-01	7,19E-02	2,05E-01	4,20E-01	5,80E-03

SOFC stack, assembled

Impact assessment - SOFC

Impact category	Unit	Total	SOFC System	SOFC system fuel supply	SOFC system operation
Abiotic depletion	kg Sb eq	1,79E-03	1,13E-05	1,78E-03	0,00E+00
Acidification	kg SO2 eq	1,76E-04	3,65E-05	1,19E-04	2,05E-05
Eutrophication	kg PO4--- eq	1,59E-05	8,83E-07	1,02E-05	4,86E-06
Global warming (GWP100)	kg CO2 eq	2,10E-01	1,52E-03	3,44E-02	1,74E-01
Ozone layer depletion (ODP)	kg CFC-11 eq	2,57E-08	1,69E-10	2,55E-08	0,00E+00
Human toxicity	kg 1,4-DB eq	1,95E-02	1,15E-02	7,99E-03	4,50E-05
Photochemical oxidation	kg C2H4	1,29E-05	1,67E-06	1,04E-05	8,46E-07

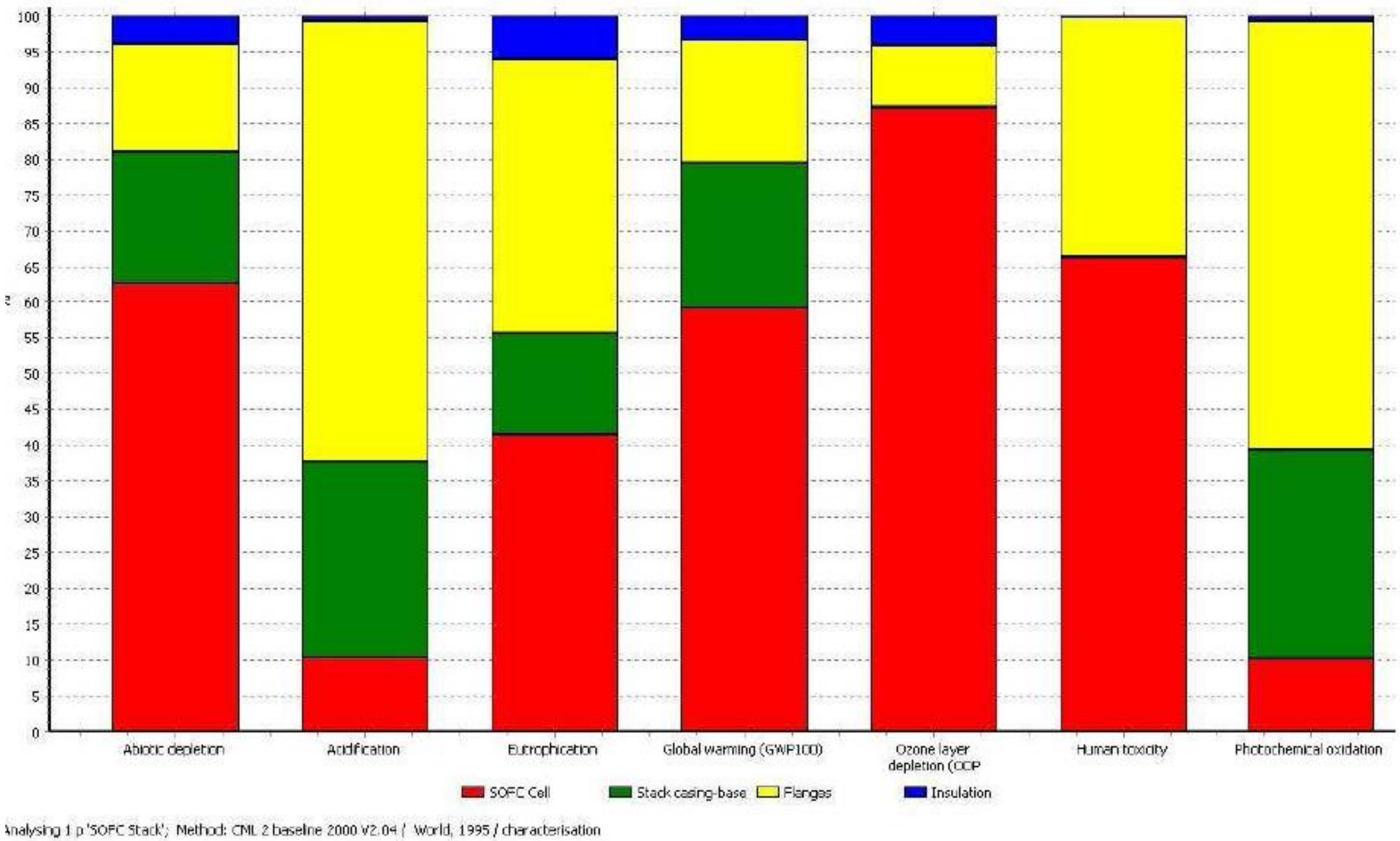
SOFC system (1 kWel)

Interpretation of results – Identification of significant issues

Provision 33 – Idnetification of significant issues

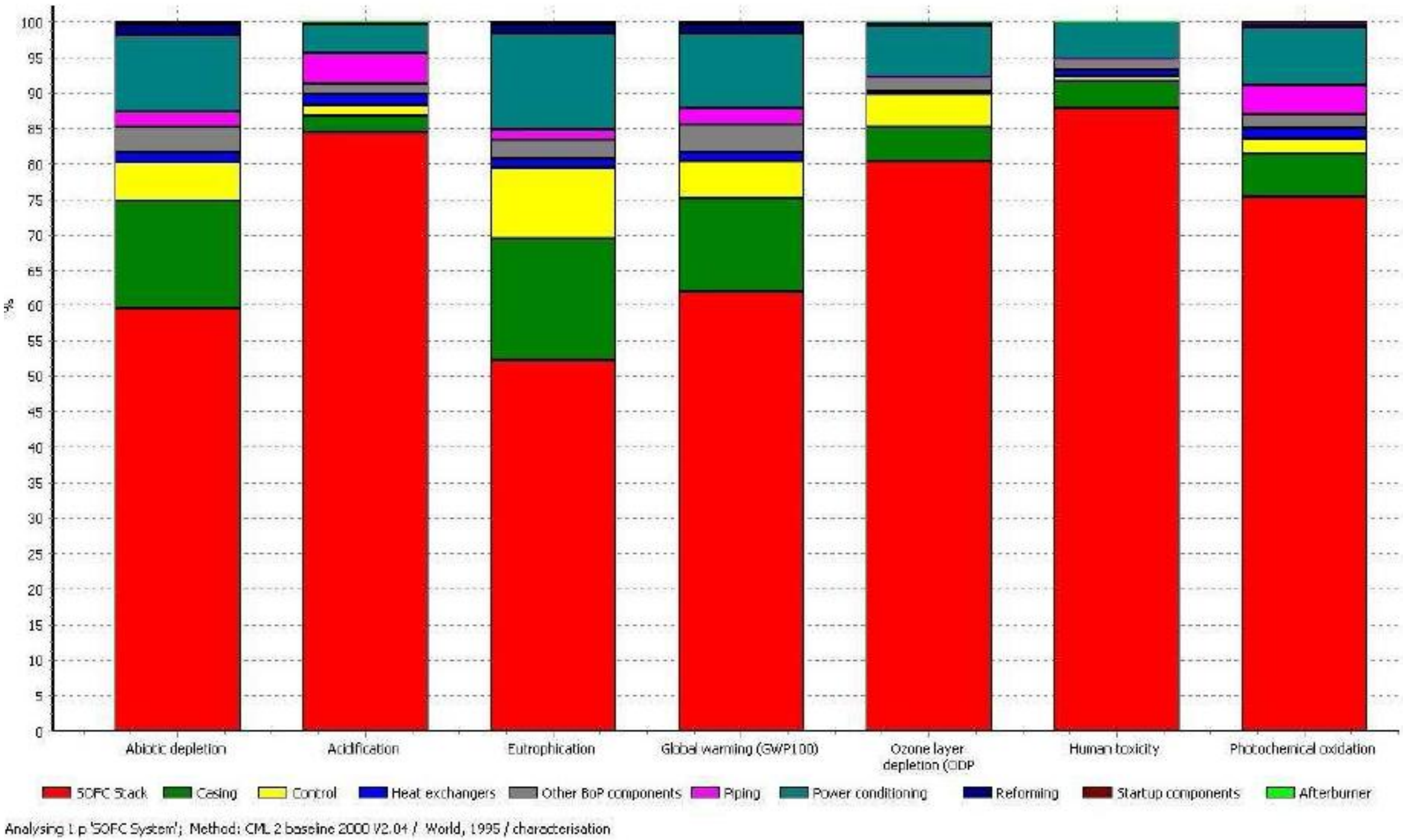
Shall – Idnetify the significatn issues by quantifying which processes/flows are major contributors to the total impact.

Should – Stacked column or pie-charts can be used.



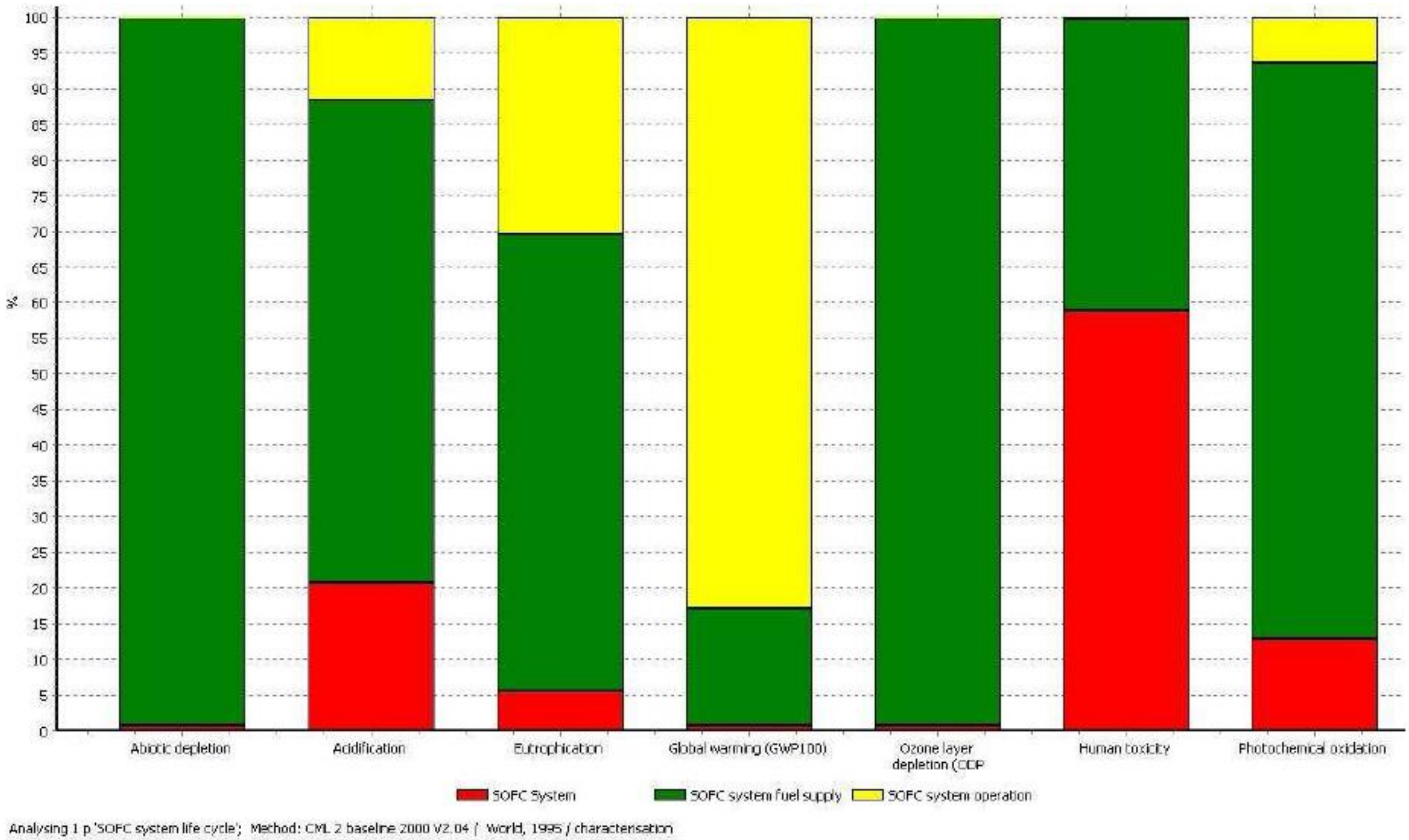
SOFC – one single stack components

Interpretation of results – Identification of significant issues



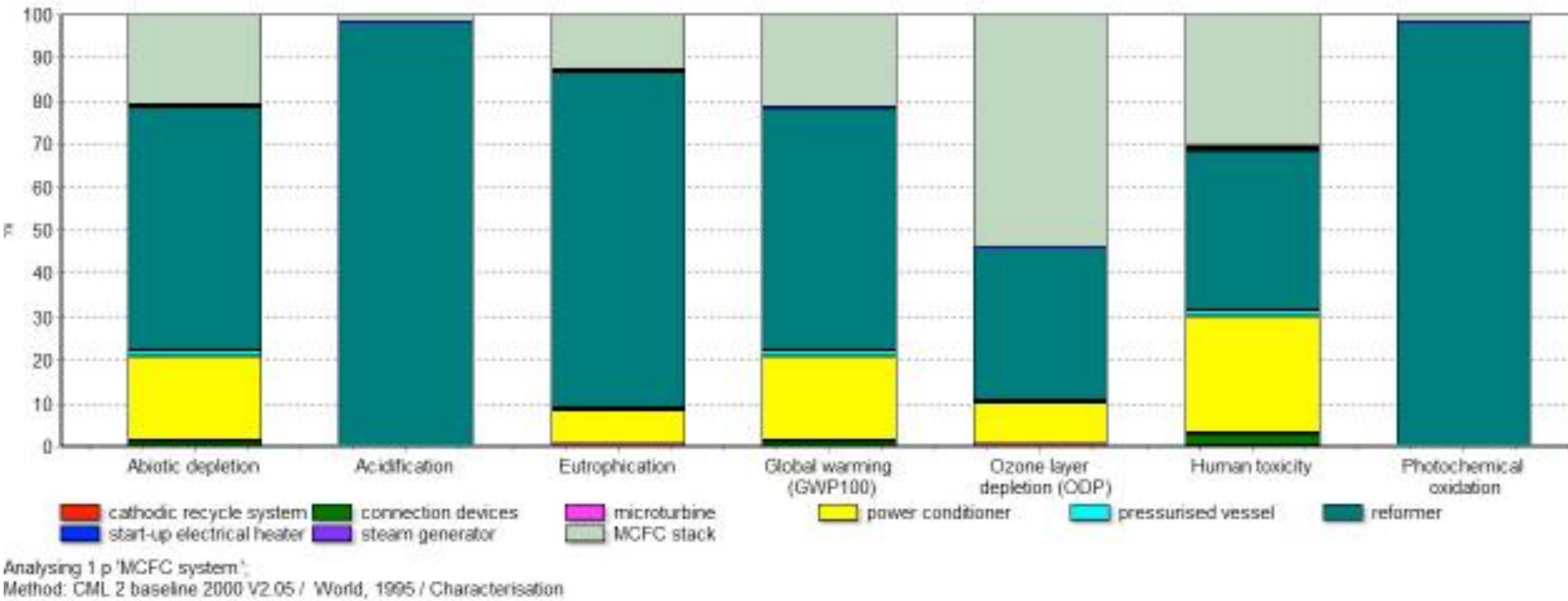
SOFC – system components

Interpretation of results – Identification of significant issues



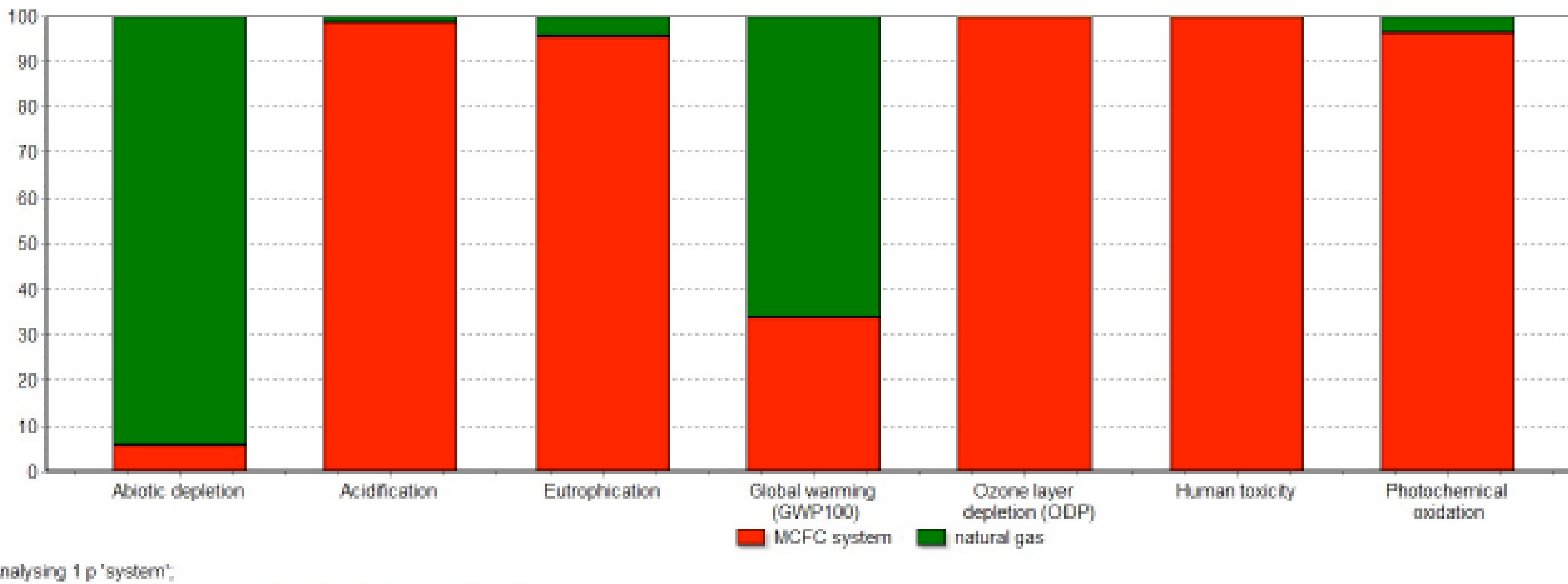
SOFC – system, operation and fuel supply

Interpretation of results – Identification of significant issues



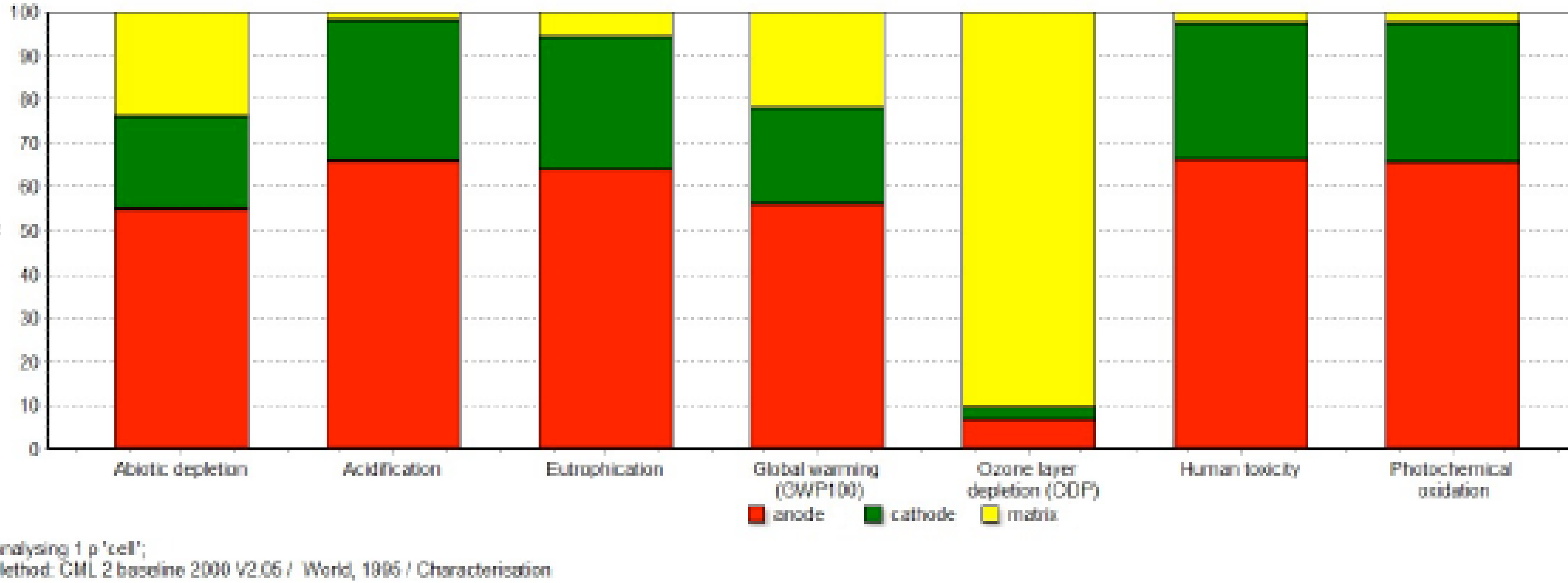
MCFC – contribution (%) of system components (system=16 stacks + 4 reformers)

Interpretation of results – Identification of significant issues



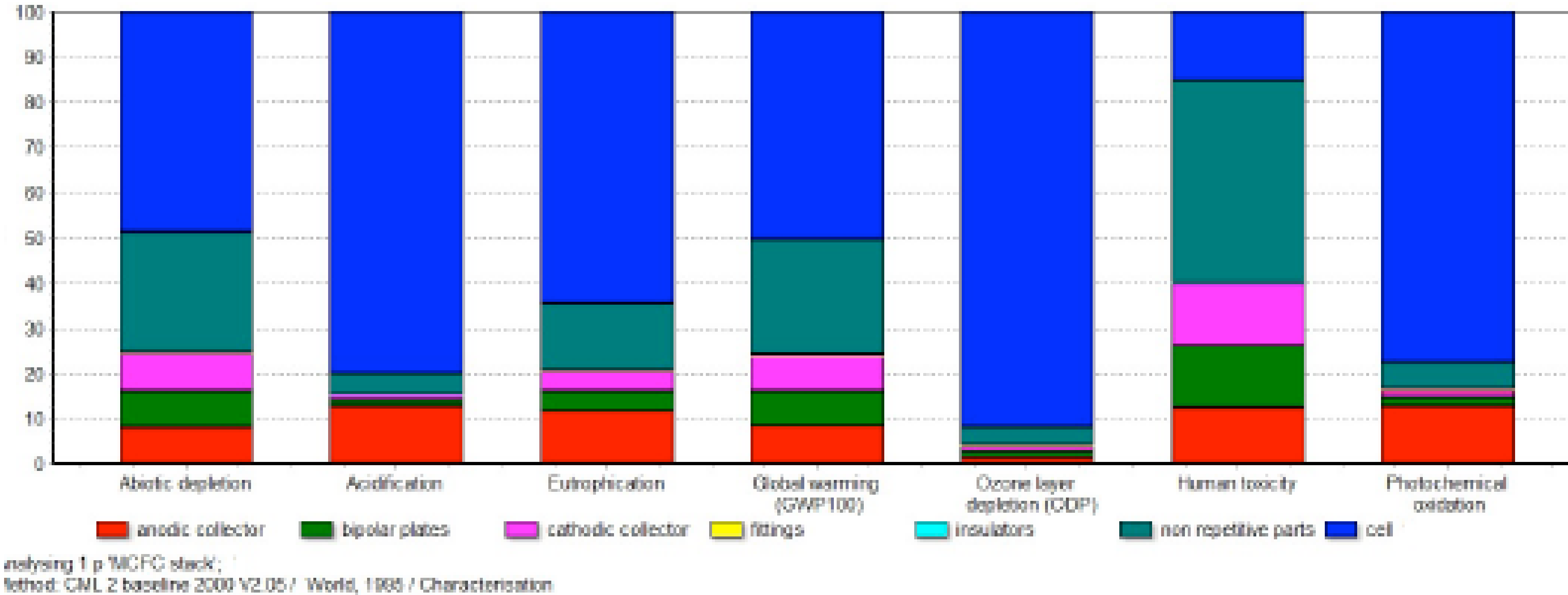
MCFC – contribution (%) of operating system for electricity production

Interpretation of results – Identification of significant issues



MCFC – contribution (%) of a single cell components

Interpretation of results – Identification of significant issues



MCFC – contribution (%) of one single stack components

FC-Hy Guide

Significant issues

Palladium, platinum
Iron-nickel-chromium alloy

	SOFC	MCFC	PEMFC
System fuel supply	Fuel supply	MCFC system (stack + BoP)	PEMFC system and fuel supply
System	Stack (50-85%)	Reformer	Stack
	Power conditioning (+ control electronics 10-25%)	Power conditioning	PEM components (voltage converter)
		Stack	
Stack	Anode	Anode (>50%)	MEA
	Electrolyte	Cathode (20%)	Gasket
	Cathode	Matrix	Buss plates
	Interconnect	Stainless steel parts	

Chromium steel
copper

platinum

tetrafluoroethylene

Nickel, ferrochromium

tetrachloroethylene

nickel

Conclusions, limitations and recommendations

MCFC

- Optimize electricity use in the production processes
- Find a good substitute for palladium and/or increase the recycling rate.
- Limit the use of tetracloroethylene in the matrix
- Decrease the use of chromium steel in the reformer and power conditioner
- Adopt a non-fossil energy source to produce the MCFC system

SOFC

- The manufacturing processes of the SOFC need to be consolidated and optimised
- Improve the overal efficiency
- Adopt a non-fossil energy source to produce the SOFC system
- Decrease the use of chromium alloys in cell manufacturing
- Limit the use of tetracloroethylene in cell manufacturing

PEMFC

- Reducing/recycling platinum
- Recycling/reuse of the other materials in the production of the system
- Reduce the use of tetrafluoroethylene in the gasket and membrane manufacturing
- Reduce copper in manufacturing the ancillary components and in BoP
- Hydrogen needs to be produced using renewable sources.

Future options: materials and non-fossil energy source

Next steps

- Review of the LCA studies
- Feedback from the case studies to the Guidance document and make it more product-specific
- Publication on the website http://www.fc-hyguide.eu/

PLEASE NOTE:

the FC-Hy Guide are "living" documents that well be updated taking on board the lessons learned by their applications

Supporting material and information

- **FC-Hy project** (http://www.fc-hyguide.eu/welcome)
  - FC and Hy Guidance document
  - Supporting material: Data collection template, Reporting template, LCA review reporting template, Documentation of the data set according to ILCD
  - Examples of case studies
  - Presentations of the training course
- **ILCD Handbook** (http://lct.jrc.ec.europa.eu/)
- **ELCD database** (http://lct.jrc.ec.europa.eu/assessment/data). About 300 data sets:
  - End-of-life treatment 45
  - Energy carriers and technologies 173
  - Materials production 63
  - Systems 14
  - Transport services 22

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