D5.1 Eco-design guidelines for the PEMFC Stack

WP5 Formulation of eco-design guidelines

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EXECUTIVE SUMMARY

Hydrogen is a key lever for decarbonized mobility, providing a response to the environmental challenges. Fuel cells represent a technological revolution that is now at industrial level. The Proton Exchange Membrane Fuel Cell (PEMFC) system combines hydrogen and oxygen to provide electricity to the vehicle and discharging only water.

To tackle sustainability challenges in the deployment of new hydrogen technologies for energy, life cycle approaches have to be integrated early in the design and R&D of these technologies.

The eGHOST project is the first milestone for the dissemination and deployment of eco-design in the manufacturing of Fuel Cell and Hydrogen (FCH) systems. Its main contribution includes the development of the following **eco-design guidelines for Proton Exchange Membrane Fuel Cell (PEMFC) technology.**

This document integrates **a synthesis of the main results of the project regarding environmental, cost and social impacts evaluation of PEMFC** as well as **eco-design recommendations and products concepts for sustainability impacts improvements** all along the different life cycle phases of PEMFC systems**.**

Among relevant eco-design recommendations developed in the context of this project, we can find the following ones:

- *Reduce the Platinum content in the cells;*
- *Integrate a high rate of recycled Platinum;*
- *Reduce the mass of the MEA components;*
- *Develop refurbishment strategies for Bipolar Plates and endplates;*
- *Develop recycling streams and processes for PEMFC materials (find ways to disassemble the stack, and recycling processes for valuable materials in the stack). Envisage hydrometallurgy processes for critical raw materials recovery without compromising environmental, social and economic impact compared to the use of virgin materials.*

Section 4 of this document summarizes all eco-design recommendations identified in this project. This can be seen as a framework for PEMFC value chain actors to reach more sustainable solutions.

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ABBREVIATIONS

BoM	Bill of Materials
BPP	Bipolar Plates
EoL	End of Life
FCH	Fuel Cell and Hydrogen
GDL	Gas Diffusion Layer
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCSA	Life Cycle Sustainability Assessment
MEA	Membrane Electrode Assembly
PEMFC	Proton Exchange Membrane Fuel Cell
PFSA	Perfluorosulfonic Acid
Pt	Platinum
SLCA	Social Life Cycle Assessment
SMR	Steam Methane Reforming
WP	Work Package

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1. OBJECTIVES OF THE GUIDELINE

1.1 Eco-design challenges and hydrogen

Sustainable development is defined as "the development that meets the present needs without compromising the ability of future generations to meet their own needs" [1]. The issues raised by sustainable development are universal. Pollution of water, air and soil, resources availability, the daily erosion of biodiversity, waste and energy concerns us all, and the energy sector needs to adapt to answer these concerns. To be able to respond to these challenges, it is necessary to take into account all the components of our societies and their interactions: **the ecological, but also the social and economic aspects**.

Figure 1 - Sustainability approach with the three pillars: Environmental, Economic and Social

Ecodesign is both a principle and an approach**. The main goal is to anticipate and minimize negative environmental impacts linked to the entire life cycle of a product of a system of products.** Simultaneously, eco-design also keeps a product quality level according to its ideal usage. The principles can be found in ISO/TR14006 [2].

Eco-design approaches have been developed initially, to focus and improve the environmental aspects of sustainable development all along the life cycle of a product or a system introduced on the market. However, eco-design approaches have to integrate a global thinking where the interactions between the three aspects of sustainable development should be addressed.

Hydrogen technologies such as fuel cells and electrolysers have been identified as a game-changer in the transition to a low-carbon economy, mainly as an alternative to decarbonize heavy industry, transport and energy sectors [3]. However, several

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environmental challenges can be identified for these technologies identified for clean energy transition. Among them, we can cite their needs in specific minerals and metals resources that could increase subsequently the worldwide mineral demand over the next 20 years [4]. Another very important aspect is the type of hydrogen used: the hydrogen production can have a high environmental impact considering the SMR process (grey H2) for example [5]. The use of low-carbon or renewable hydrogen is a prerequisite to contribute to the decarbonation.

There is therefore a necessity **of the integration of a life cycle approach when designing these technologies**, in order to reduce their environmental, economic and social impacts all along their life cycle stages, from raw material extraction to end of life and avoid impacts transfer from one stage to another (*e.g. Reduction of environmental impact in use phase but increase in raw material extraction and/or end of life*) or from one environmental impact to another (*e.g. Reduction of carbon footprint but increase of metal and mineral consumption*).

Moreover, the New Industrial Strategy focuses on a Clean Hydrogen Alliance to accelerate the decarbonation of industry and maintain industrial leadership. This will boost the path towards a well-established hydrogen economy that has to be based on sustainable FCH systems with minimal impacts along their life cycle. **This will require the integration of sustainability considerations in the design of FCH products raising a new challenge for the industry since there is a lack of reference documentation about how to face this (re)design.**

1.2 The eGHOST project

The eGHOST project is the first milestone for the dissemination and deployment of eco-design in the manufacturing of Fuel Cell and Hydrogen (FCH) systems. Its main contribution was **the development of specific eco-design guidelines for two FCH products: Proton Exchange Membrane Fuel Cells (PEMFC) and Solid Oxyde Electrolyers (SOE)**, which serve as seed for the (re)design of other FCH products.

This document refers to the eco-design guidelines for the PEMFC technology and integrates a synthesis of the main results of the project regarding environmental, cost and social impacts evaluation of this technology as well as design recommendations and products concepts for sustainability impacts improvements all along the different life cycle phases**.**

In parallel of these specific guidelines, eGHOST looked to define standardized procedures and methods for all the stages of the eco-design process that will be collected in the eGHOST White Book, which has the aim of being the reference guidance document for developing guidelines for a sustainable-(re)designing of any FCH product.

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1.3 Public addressed for these guidelines

These guidelines are developed **for hydrogen value chains actors that are developing Proton Exchange Membrane Fuel Cell** and would like to understand where occur environmental, social and economic challenges allong the value chain of their products and identify actions to improve them.

With the lessons learnt during the project, these guidelines include the most feasible recommendations for each life cycle stage *(extraction of raw material, manufacturing, transport, operation and end of life)* of PEMFC technology to improve its sustainability.

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2. TECHNICAL DESCRIPTION OF PEMFC TECHNOLOGY

2.1 The Fuel Cell System

A Fuel Cell System is an electrochemical device that converts the chemical energy of a fuel and an oxidant to electric energy (DC power), heat and reaction products. The system studied here is developed on the Proton Exchange Membrane Fuel Cell (PEMFC) technology (also called polymer electrolyte membrane Fuel Cell), using hydrogen as the fuel and oxygen from the air as oxidant. The reaction produces water and electron.

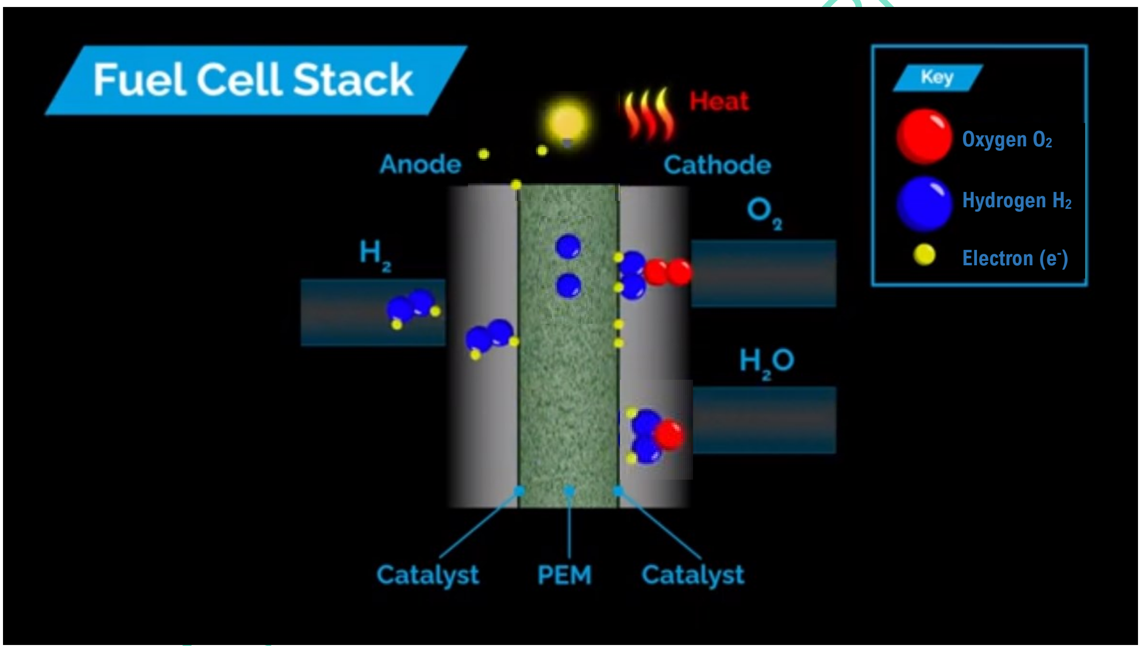

Figure 2- General principle of a Fuel Cell System

The gases (hydrogen at the anode, oxygen from the air at the anode) are conducted to the catalyst layers. Hydrogen molecules (H_2) react with the platinum of the anode catalyst to produce hydrogen ions (H^+) and electrons (e^-). At the cathode catalyst layers, hydrogen ions combine with electrons and oxygen molecules to produce water.

The PEMFC can be used in transportation like passenger cars, bus, commercial vehicles or trucks. This technology delivers power to the vehicle through its electric motor and is developped to complement electric battery technology.

The power range of PEMFC can vary between 1 to 400 kW, depending on the size and the power of the vehicle.

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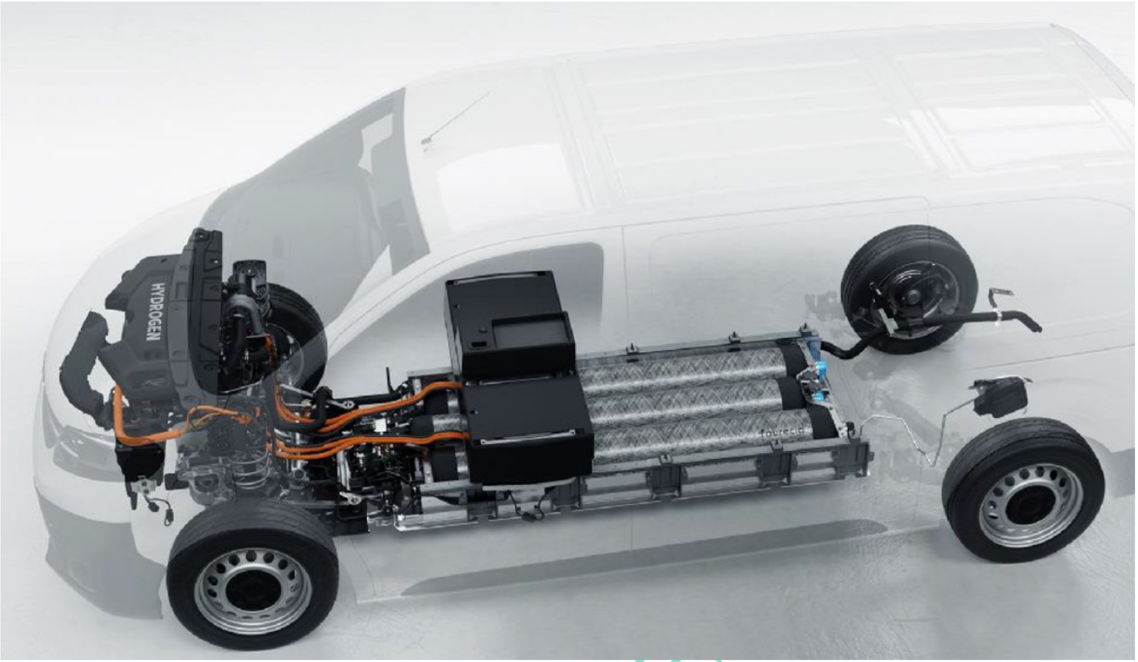

Figure 3 - Hydrogen Light Commercial Vehicle architecture

The Fuel Cell System is composed of:

- the fuel cell stack (described bellow)
- the hydrogen subsystem
- the cooling subsystem
- the air subsystem
- the power subsystem

The stacks and modules are inserted in a fuel cell power system as described in the Figure 4.

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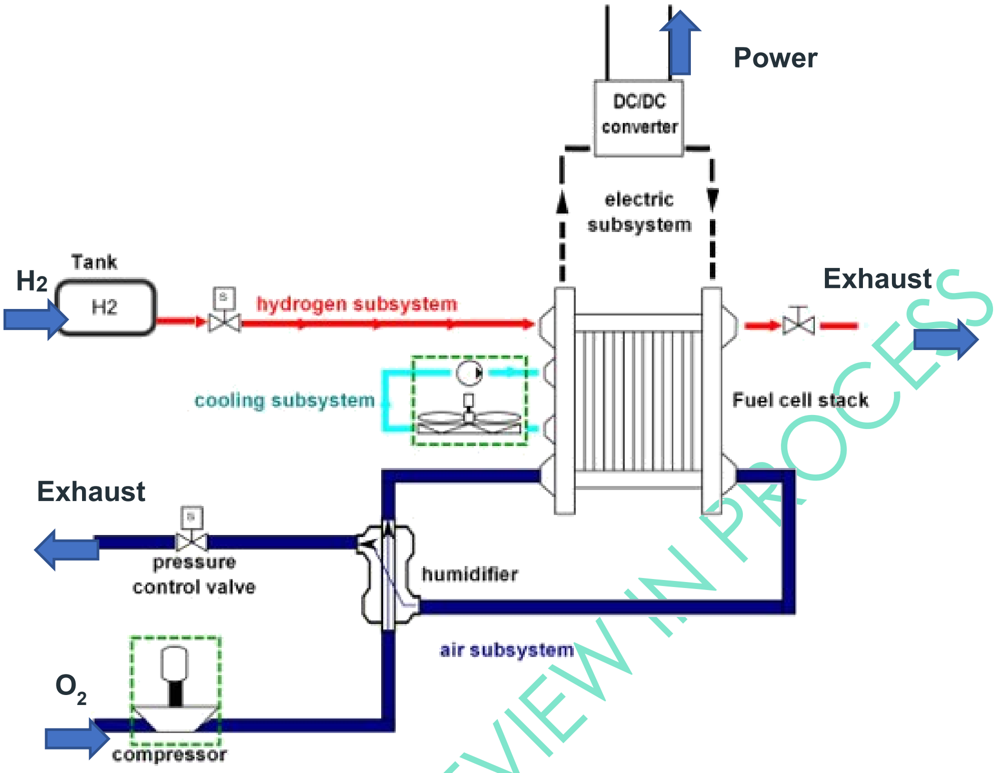

Figure 4 - Description of the different subsystems of the Fuel Cell System

2.2 The Fuel Cell Stack

The Fuel Cell stack is made of a pilling of individual cells combined in series, with endplates used to clamp the cells and also used for the air and hydrogen inlet and outlet.

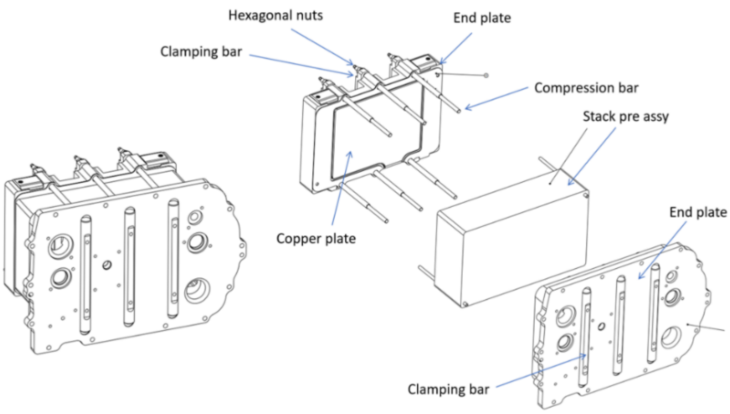

Figure 5- Exploded view of a Fuel Cell stack

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The clamping and compression bars are inserted through the endplates and fastened by nuts to immobilize them.

The Copper plates are collecting the current produced by the cells.

2.3 The Cell

A Cell is made of Bipolar Plates and Membrane Electrode Assembly (MEA).

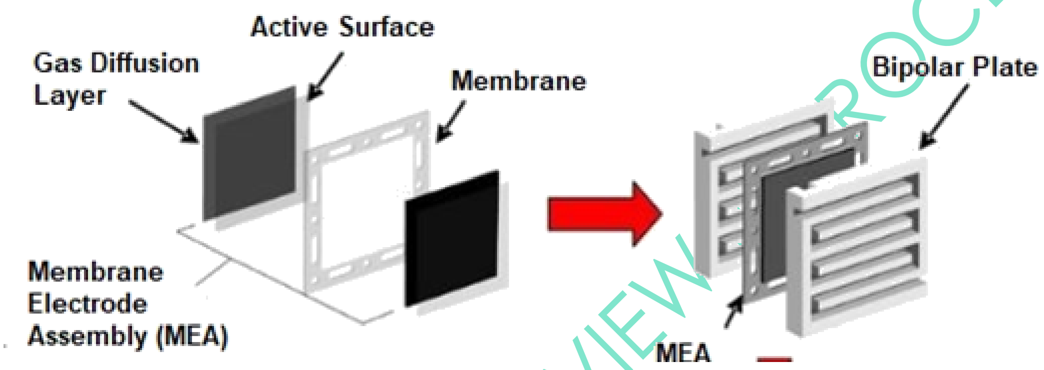

Figure 6 - From an MEA to a Cell

As described in Figure 6, a cell is made of:

- A Membrane that is used to conduct the H^+ ions and keep the hydrogen and the oxygen on each side. The material used for the membrane is fluorinated polymer (PFSA);
- A catalyst layer for the cathode and a catalyst layer for the anode, mainly composed of Platinum, and that is coated on the membrane ;
- A gas diffusion Layer (GDL) for the cathode, a gas diffusion layer for the anode, mainly composed of carbon fiber;
- A Bipolar plate (BPP) on the cathode, a Bipolar plate on the anode.

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3. ENVIRONMENTAL, COST, SOCIAL CHALLENGES OF THE PEMFC TECHNOLOGY

In the framework of the eGHOST project, a sustainability assessment of generic PEMFC technology has been realized. It includes assessment of environmental, economic and social impacts of a PEMFC system of 48kW$_{el}$.

The scope of analysis is focused **on the manufacturing phase of the stack and end of life phase**. Operation phase is not part of the scope but was simply assessed separately.

In the base case, only conventional End of Life (EoL) processes are included: landfill, incineration of the MEA and open-loop recycling of standard materials.

For cost and social assessment and due to lack of data, the end of life phase has not been considered except the rate of recycled or reused material in the manufacturing phase.

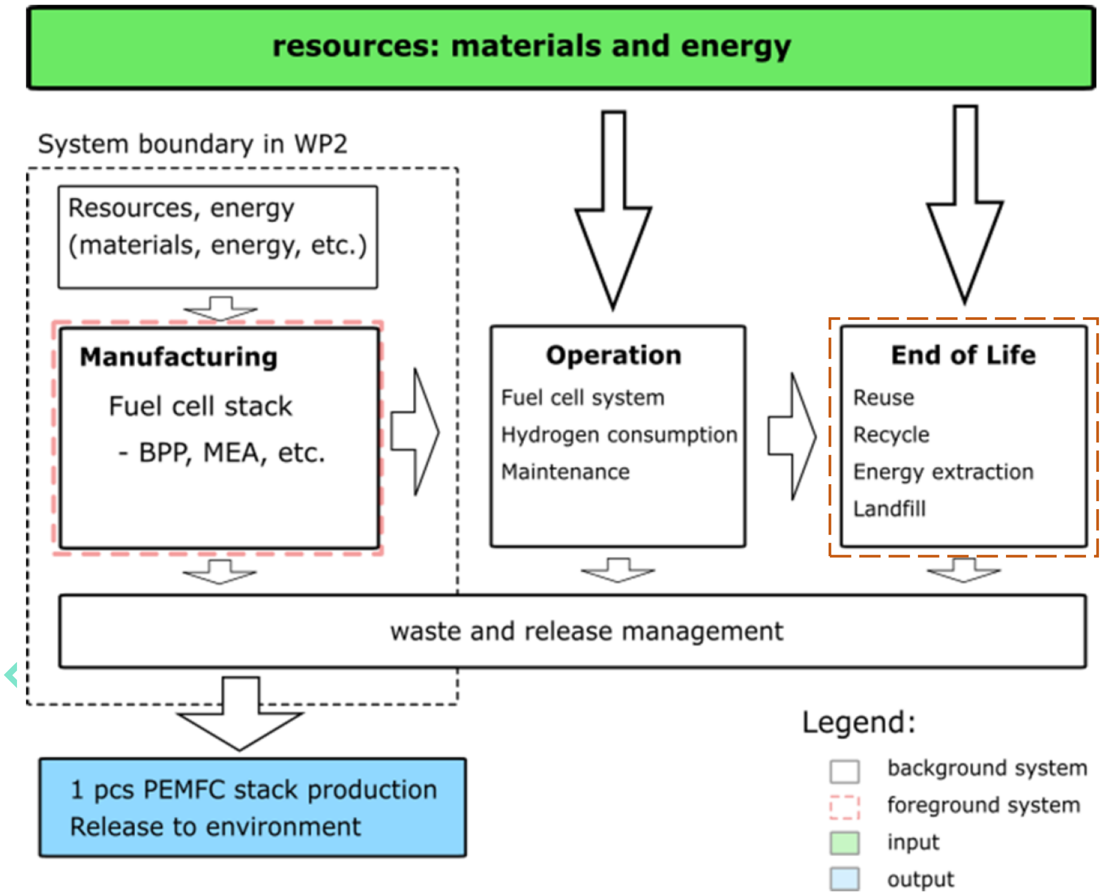

Figure 7- Inputs, outputs and system boundary for the PEMFC stack preliminary LCA study

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The detailed results as well as hypothesis of this assessment is presented in deliverable 2.3 of the eGHOST project and have been adjusted in deliverable 4.2 (public documents) [6] [5]. The following paragraphs present a summary of these results with the main identified challenges for the three sustainability pillars.

3.1 Environmental challenges for PEMFC technology

3.1.1 Environmental Life Cycle Assessment

The environmental life cycle impact assessment (LCIA) was carried out using the environmental indicators presented in Table 1. Further information on the LCA methodological choices is available in eGHOST deliverable 2.1 [7].

Table 1- Environmental impacts categories selected within the eGHOST project for environmental impact evaluation

EF IMPACT CATEGORY	INDICATOR	UNIT
CLIMATE CHANGE	Global Warming Impact Potential (GWP)	kg CO_2eq
ACIDIFICATION	Accumulated Exceedance (AE)	mol H^+ eq
EUTROPHICATION, TERRESTRIAL	Accumulated Exceedance (AE)	mol N eq
EUTROPHICATION, AQUATIC FRESHWATER	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq
EUTROPHICATION, AQUATIC MARINE	Fraction of nutrients reaching marine end compartment (N)	kg N eq
RESOURCE USE, MINERALS AND METALS	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq
RESOURCE USE, ENERGY CARRIERS	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ

For the manufacturing of the stack, the **production of platinum** is the main challenge for the environmental impacts as it is the first contributor. In fact, the extraction and refining of this metal require lots of energy, water and chemical substances due to the very low concentration of platinum in the mining ore (around 3 to 15 g /ton). It represents the most important contributor (> 63% of the stack impacts) for 6 indicators of the 7 studied: Climate change (63.5%), acidification (94.2%), Mineral and fossil resource use (86.6%), Marine and terrestrial Eutrophication (86.1 and 88.3%), despite the total mass share of Pt in the whole PEMFC stack is only 0.1%.

The **electricity** used in the manufacturing process of the stack represents also a great contribution to the impacts. It is the second contributor for climate change (13.2%), resource use (fossils) (19.9%) and for eutrophication marine and terrestrial (resp. 5.2% and 5.1%).

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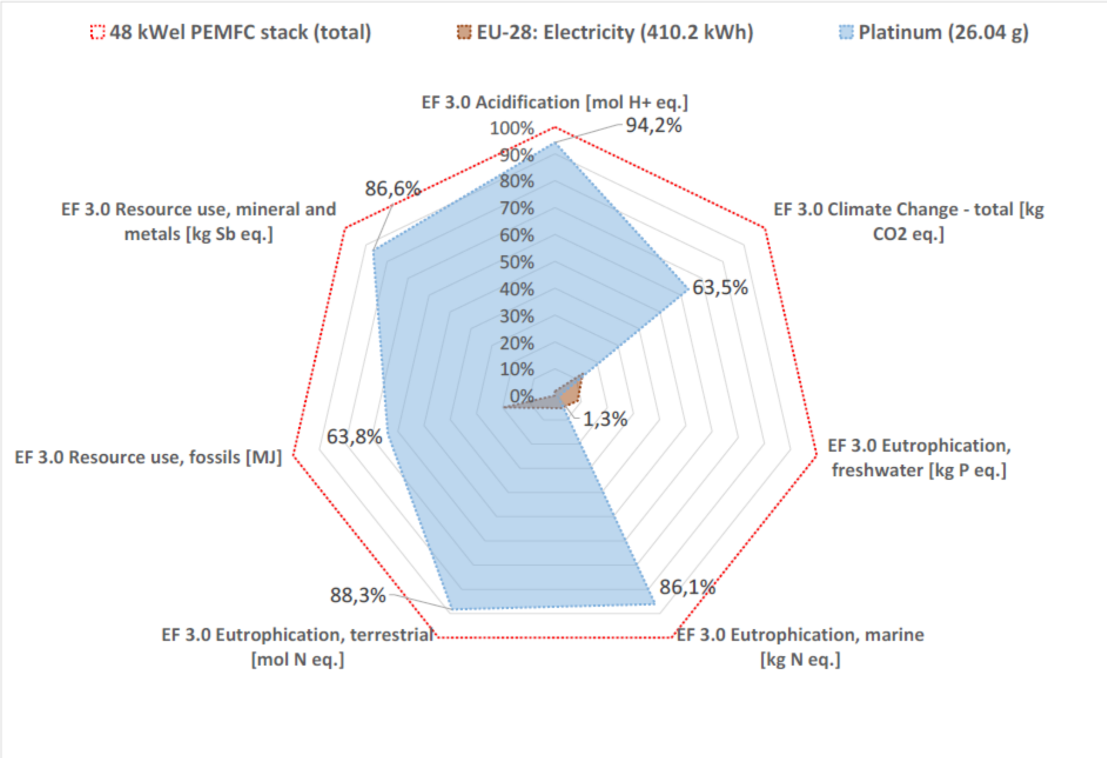

Figure 8 - Pt and electricity contribution to the potential environmental impacts of the 48kW PEMFC stack manufacture

For eutrophication, Freshwater, the **glass fiber reinforced plastic**, used for the endplates is the main contributor (61%) followed by the chromium steel (26.2%)

Nafion, a fluoropolymer mainly used in the MEA, has a non negligible impact on climate change (11,9%).

The **stainless steel** used for the BPP represents an important mass of the stack and so has an impact on each indicator.

The use phase generally has the greatest environmental impact, especially when grey hydrogen is used in Fuel Cell technologies.

This phase has been evaluated separately in the WP4 to illustrate the importance of the operation phase in the eco-design strategy of FCH technologies.

Comparing Fuel Cell life cycle with grey, and green hydrogen show that in any case, the use phase has the greatest environmental impact. However, the use of **green hydrogen** can reduce the impact on climate change by 90% compared to grey hydrogen [5].

The end of life phase shows negative impacts for all indicators studied. The impact of the processes used to recycle or incinerate the different parts is offset by to the

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avoided impacts of the materials recycled in an open-loop process. This process concerns here mainly metals: steel, copper and stainless steel. These negative impacts are low (<10%) for climate change, acidification and eutrophication marine and terrestrial.

They could be improved using close-loop recycling or reuse processes.

3.1.2 Material criticality of PEMFC technology

Critical raw materials (CRMs) are raw materials of high economic importance for the EU, with a high risk of supply disruption due to their concentration of sources and lack of good, affordable substitutes. The European Commission has created a list of critical raw materials (CRMs) for the EU, which is subject to a regular review and update. The last report on CRM list for Europe has been delivered in March 2023 [8]. **34 CRM have been identified among 70 candidate raw materials**, comprising 67 individual materials and three materials groups: ten heavy (HREEs) and five light (LREEs) rare earth elements, and five platinum group metals (PGMs).

Bauxite	**Coking Coal**	**Lithium**	**Phosphorus**
Antimony	**Feldspar**	Light rare earth elements	Scandium
Arsenic	Fluorspar	Magnesium	Silicon metal
Baryte	Gallium	**Manganese**	Strontium
Beryllium	Germanium	Natural Graphite	Tantalum
Bismuth	Hafnium	Niobium	Titanium metal
Boron/Borate	**Helium**	Platinum group metals	Tungsten
Cobalt	Heavy rare earth elements	Phosphate Rock	Vanadium
		Copper	**Nickel**

(in yellow : CRM used in the manufacturing of PEMFC technologies / HREE : Heavy rare earth elements / LREE : Light rare earth elements / PGM : Platinum Group Metal)

Figure 9- 2023 CRM list for European Commission

(in yellow : CRM used in the manufacturing of PEMFC technologies / HREE : Heavy rare earth elements / LREE : Light rare earth elements / PGM : Platinum Group Metal)

Figure 9 shows the 34 CRM of the 2023 list. Two indicators are evaluated for criticality evaluation on each material: the economic importance (EI) for Europe and the supply risk (SR) [9]. If the materials evaluated exceed a threshold on both indicators, they are identified as critical. Copper and nickel do not meet the CRM thresholds, but are included as Strategic Raw Materials in this report.

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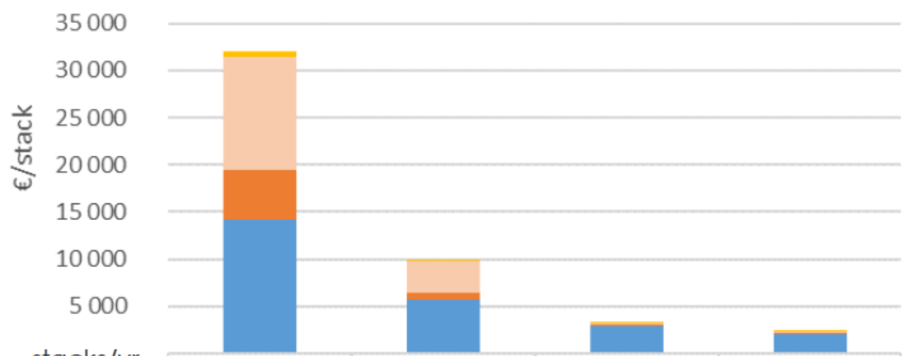
Among these CRM and strategic materials list, several can be found in the composition of the PEMFC technology:

- ***Platinum*** *(in the Catalyst layer of the MEA)*
- ***Copper***
- ***Aluminium***

3.2 Cost Challenges

According to the previous results of eGHOST project, the cost of the stack is very dependent on **the production rate**. Four production scales have been studied from laboratory to industrial: 100 stacks/year, 1 000; 10 000 and 50 000 stacks /year. The transition from laboratory to industrial scale enables to divide the cost more than ten times by acting on both process and material costs **from 32 k€ per stack at laboratory scale to 2.3 k€ per stack** at industrial scale. For 10,000 stacks and above, the process part becomes insignificant compared to **the Bill of Material that represents up to 88%** of the total cost.



stacks/yr	100	1000	10000	50000
Assembly process	578	223	35	35
BPP process	12 000	3 356	149	101
MEA process	5 180	681	223	133
Bill of materials	14 238	5 724	2 851	2 019
Total	**31,996**	**9,984**	**3,258**	**2,288**

Bill of materials | MEA process | BPP process | Assembly process

Figure 10 - PEMFC cost distribution according to production rate

For low volumes (< 1000 stack/year) the BPP process represents around 35% of the total cost.

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In the BoM, **the GDL and membrane** are the key drivers at low production rates (resp. 40% and 35%). However, their prices decrease rapidly with the economy of scale and, above 10,000 stacks per year, **the Pt catalyst** becomes the main driver with more than half of the material contribution.

On industrial scale, since the cost of the platinum catalyst within the fuel cell stacks represents a significant fraction of the total system cost, particular attention could be paid in the future to recover the Pt at the end of life of the stack. A recycling credit for Platinum recovery at end of life (around 10 years after manufacturing) is estimated to 422€ per stack.

3.3 Social challenges

For social impact evaluation, workers on the PEMFC hydrogen value chain and society have been chosen as the stakeholder categories under study. Six social impacts indicators, have been selected for social impact evaluation:

- *Children in employment*
- *Frequency of forced labor*
- *Contribution of the sector to economic development*
- *Gender wage gap*
- *Minimum wage*
- *Health expenditure*

Platinum production in South Africa is found to be the main social hotspot, arising – despite the limited amount of material used– as the major contributor to all of the social life-cycle indicators with a negative connotation. (40% for fair salary and Forced labor, and more than 80% for gender wage gap, Heath expenditure and child labor). This is due to both the high economic flow involved by platinum (as a result of its high unitary cost) and the sector-specific risk levels associated with the manufacturing country.

The production of **carbonaceous compounds** in China (used in GDL) arises as the main contributor (55%) to economic development (the only positive social indicator assessed).

Finally, the social risks associated with energy flows are found to be negligible, which is linked to the countries involved for these flows.

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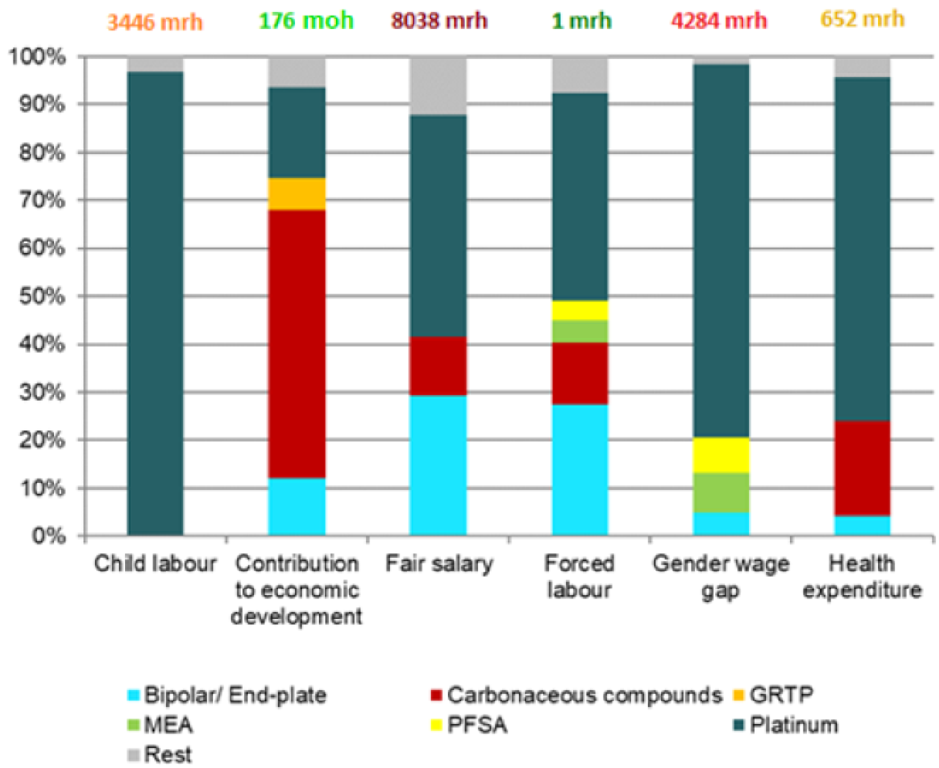

Figure 11 - Contribution to the potential social impacts for the 48 kW PEMFC stack

(mrh: medium risk hours[1]; moh: medium opportunities hours[2])

[1] Social risk is measured in medium risk hours, which is the number of worker hours along the supply chain that are characterized by a certain social risk. Therefore, higher values correspond to higher risks (i.e. more negative performance on social aspects)

[2] Social indicators may also express a positive social impact. In that case, the "risk" factor is expressed in medium opportunity hours (moh)

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4. ECO-DESIGN GUIDELINES

The basic approach for the generation of eGHOST eco-design guidelines for the PEMFC involved brainstorming sessions within the eGHOST consortium members and also technical experts from the eGHOST external working group. During these brainstorming sessions, the eco-design strategy wheel (Brezet and van Hemel, 1997) was used to generate eco-design ideas among partners and technical experts according to the different life cycle phases of the PEMFC, and to the 8 eco-design axes of the eco-design wheel (Figure 12):

1. *Selection of low-impact materials,*
2. *Reduction of intensity of use of materials,*
3. *Optimization of manufacturing techniques,*
4. *Optimization of distribution process,*
5. *Reduction of impact during use,*
6. *Optimization of product lifetime,*
7. *Optimization of end of life*
8. *New concept developments*

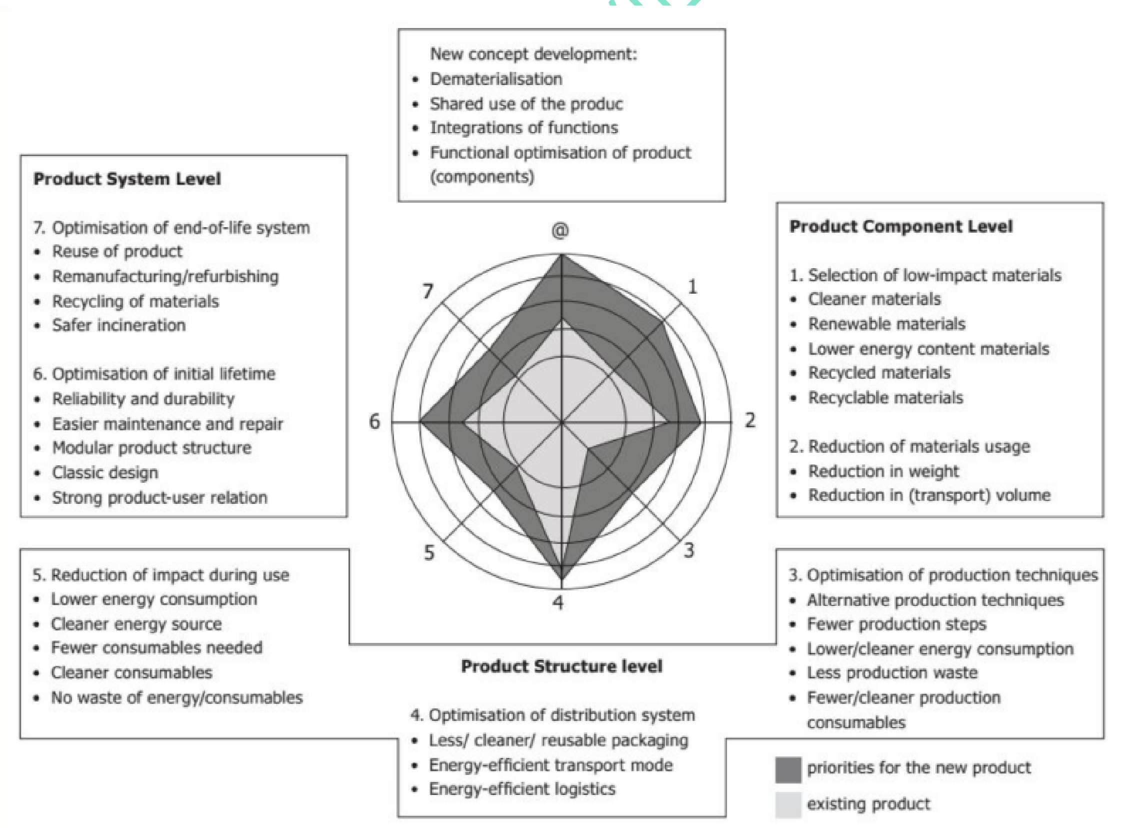

Figure 12- The eco-design strategy wheel

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The most relevant eco-design actions have then been selected by technical experts according to their technical feasibility and classified based on their temporal feasibility (medium term actions: 3 to 10 years, and long-term actions >10 years). eGHOST deliverable 3.2 integrates the global results of these workshops [10].

The final PEMFC eco-design guidelines that you will find in this document are structured in 6 different sections which represents different life cycle stages of the PEMFC systems (Materials selection, Manufacturing, Transport, Operation, End of Life, and Concepts development). Then for each section, the eco-design recommendations from the eco-design strategy wheel are presented as well as specific eco-design guidelines for PEMFC and also the actor of the value chain involved in the action. A dedicated blank section on the right of the eco-design guidelines table can be used by guidelines users to describe more precisely if they have implemented the action in their process or design and how they did it (Figure 13).

The actions defined for the two base-case FCH products were divided into **short- (within 3 years)**, **medium- (3-10 years)** and **long- (>10 years)** term actions.

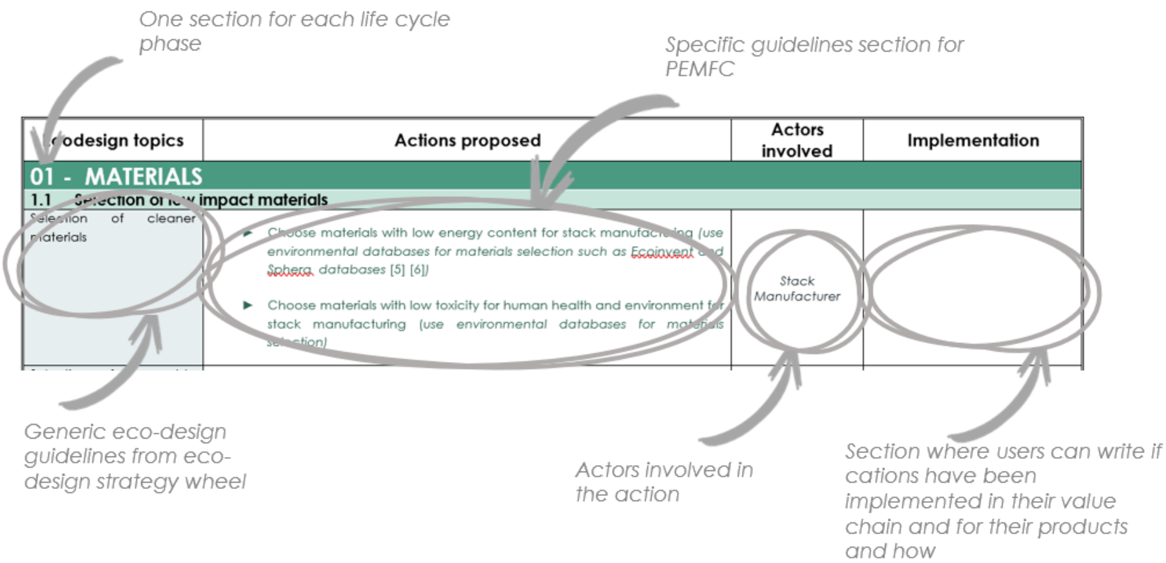

Figure 13 - Description of guidelines structure

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Table 2: Eco-design guidelines for PEMFC technology per life cycle phase

Medium term eco-design actions (3 to 10 years)
Medium to long-term eco-design actions (> 10 years)

Ecodesign topics	Actions proposed	Actors involved	Implementation
01 - MATERIALS			
1.1 Selection of low impact materials			
Selection of cleaner materials	► Choose materials with low energy content for stack manufacturing *(use environmental databases for materials selection such as Ecoinvent and Sphera databases* [11] [12]*)* ► Choose materials with low toxicity for human health and environment for stack manufacturing *(use environmental databases for materials selection)*	*Stack Manufacturer*	
Selection of renewable and sustainable materials	► **Avoid Platinum in the catalyst layer.** Still in laboratory level ► Avoid/Reduce the use of fluorinated ionomer (PFSA e.g. nafion)	*MEA manufacturer*	
Selection of materials with low energy content	► Reduce energy consumption and/or use of renewable energy for the production of the materials with EU investments (carbon footprint offsetting program for platinum production countries)	*EU countries*	
Integration of recycled materials	► **Use recycled platinum that is already available on the market** (from autocatalyst and jewelry recycling) and meets technical requirements. According to the International PGM Association, the carbon footprint of	*Catalyst manufacturer*	

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	primary Platinum is 33 300 kg CO_2eq./kgPt whereas secondary Platinum is 639 kgCO_2eq./kg Pt [13]. ► **Use recycled platinum from FCH end of life** as a closed-loop -strategy. The target is 70-80% of recycled platinum in the new products. Large volumes of technology in the market are required. According to the results of Best4Hy project, the carbon footprint of the Platinum recycled from FC with hydrometallurgy processes is around 6 220 kgCO_2eq./kgPt. ► Use a part of close-loop recycled ionomer. Still laboratory level	*MEA manufacturer*	
Integration of recyclable materials	► Make architecture of the stack easy to disassembled for recyclability ► *Avoid materials that are not recyclable*	*Stack manufacturer*	
1.2 Reduction of intensity of use of materials			
Reduction of the diversity of materials	► **Use innovative material** for electrolyte, anode and cathode to reduce the amount of critical material	*MEA manufacturer*	
Reduction of the mass of materials	► **Reduce the amount of Platinum** loading in the MEA. Prospective targets from DOE: 0.125mg/cm² [14]. ► Use of Pt alloys: Higher mass activity of catalyst due to interaction of Pt and alloying material, which can decrease the amount of Pt. Additionally, in a catalyst particle Pt is partially substituted with alloying material, which further decreases Pt loading. Check the impact potential impact transfer when substituting Platinum.	*MEA manufacturer* *Catalyst manufacturer*	

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Reduction of the volume of materials/components	▶ Improve the utilization of Platinum due to particle optimization (Shape, surface roughness can be tailored to increase the specific surface area of Pt particles) ▶ Reduce the thickness and mass of MEA components and BPP: • Membranes: from 15-20µm to 8-12µm (smaller ohmic losses). • Bipolar plates: 15-20% reduction in thickness. • Gas Diffusion Layer (GDL): from 150-300µm to 90-110µm (reduced mass transport losses). ▶ Use alternative commercial membranes : lower density and higher durability. Use PFSA-free membranes ▶ Optimize the cell power density and reduce the number of cells : for 48kW stack, from 1,66kW/kg to 4kW/kg. ▶ Reduce the overall system size/weight using less material for Balance of Plant (e.g. external housing) ▶ Optimize molding and welding processes to reduce bolts, clamps ▶ Change the stack architecture/type	*Catalyst manufacturer* *MEA and Stack manufacturer* *Stack manufacturer* *Stack manufacturer* *Stack manufacturer* *Stack manufacturer* *Stack manufacturer*	
02 - MANUFACTURING			
2.1 Optimization of manufacturing techniques			
Reduce the number of production steps	▶ Optimize number of manufacturing steps to reduce production costs	*Stack manufacturer*	
Reduce the energy consumption in production	▶ Use less energy on production lines (especially on cell sintering step which is energy consuming) to reduce environmental impacts and costs. Reduce time and temperature.	*Stack manufacturer*	

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	▶ Use low-carbon or renewable energy in the manufacturing process (for electricity, gas and heat) ▶ Revalorize thermal losses in production steps to reduce environmental impacts and costs ▶ Recover electricity produced during activation phase.	*Stack manufacturer*	
Limit and reduce production wastes	▶ Integrate internal recycling loops for production wastes as much as possible (for MEA components) to reduce environmental impacts and costs ▶ Optimize production techniques to reduce material losses and wastes (e.g. optimize the coating process) ▶ Improving defect detection technologies/ reduce rejection rate	*Stack manufacturer*	
Reduce consumables in production and use clean consumables	▶ Reduce/optimize the amount of chemicals and solvents used in all production steps ▶ Optimize the activation phase: decrease the hydrogen consumption during this step using optimized catalyst, use green hydrogen for activation.	*Stack manufacturer*	

03- TRANSPORT

3.1 Optimization of distribution process

Use less packaging and cleaner packaging	▶ Reduce the mass of packaging material ▶ Use reusable and low impact packaging and avoid non-recyclable materials	*Stack manufacturer*	

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Use transportation mode with high energy efficiency	▶ Use sustainable transportation mode for logistic, optimize the loading.	*Stack manufacturer*	
Optimize the logistic for manufacturing, installation and maintenance	▶ Facilitate local supply chains for materials and components: reduce the distance between component manufacturer and system assembly site. ▶ Reduce the frequency of distribution/ balanced production and cost optimization.	*Stack manufacturer*	
04 - OPERATION			
4.1 Reduction of impact during use			
Reduce energy consumption in use	▶ Optimize the Balance of Plant (BoP) to reduce the overall energy consumption (e.g. optimize Energy Management System) ▶ Optimize the control strategy to minimize the stack energy consumption. ▶ Reduce operating temperature of the system, to reduce energy consumption ▶ Optimize cell performance to improve the efficiency and increase the durability. ▶ Optimize the battery/stack hybridization strategy	*Stack manufacturer*	
Use clean energy and consumable sources for operation	▶ Supply the system with low carbon/green hydrogen ▶ Produce low impact steam to run the system (use steam from steam networks)	*Consumers* *Stack manufacturer*	
Use less consumables and materials for operation	▶ Use water recirculation to reduce overall water consumption ▶ Recover hydrogen leak during the purge and reintegrate them in the system.	*Stack manufacturer*	

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4.2 Optimization of product lifetime			
Improve the reliability and durability of the system	▶ Develop harmonized protocols/recommendations to start/operate the system ▶ Reduce nitrogen crossover (by optimizing the anode purging cycles and recirculation). ▶ Replacing carbon support with another material to improve cell durability. ▶ Optimize the thermal management system to increase the durability efficiency.	*Stack manufacturer*	
Ensure easy maintenance and repair	▶ Ease stack maintenance (e.g. access, cell replacement), simplify the fastening	*Stack manufacturer*	
Provide a modular structure for the system	▶ Improve stack modularity to optimize part load operation and limit degradation	*Stack manufacturer*	
Standardize reparation and maintenance procedures	▶ Develop harmonized standards to measure stack degradation	*Stack manufacturer*	
05 - END OF LIFE			
Integrate possibility of reuse of components, products	▶ Develop processes and protocols to facilitate the reuse/remanufacturing/refurbishing of valuable components (end plates, BPP, aluminum housing). These processes may include inspection of components to determine if they are suitable for washing and reuse.	*Stack manufacturer*	
Possibility for remanufacturing / refurbishing of the components	▶ Develop automated and industrialized processes for efficient stack dismantling (mechanical disassembly techniques) ▶ Design for modularity and disassembly at end of life	*Stack manufacturer*	

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Possibility of recycling	► Improve the recycling of materials, especially platinum and membrane ► Develop recycling streams and processes for PEMFC materials (find ways to disassembled the stack, and recycling processes for valuable materials in the stack). Envisage hydrometallurgy processes for critical raw materials recovery. ► Use existing recycling streams for aluminum, copper and stainless steel recovery ► Improve the total recycling rate of PEMFC systems	*Stack manufacturer and automotive recyclers*	
Safe incineration if no possibility for recycling	► Ensure safe incineration of the components if recycling is not possible	*Recyclers*	
06 – NEW CONCEPTS DEVELOPMENTS			

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All these actions have benefits for the Fuel Cell design. They can be cherry-picked in the aim to improve the global impact of the Fuel Cell.

To identify the one that should be prioritized for implementation, LCSA results were obtained for an optimistic eco-designed concept (see chapter 5) by applying some of the actions at a time.

Indeed, when calculating the sustainability benefits of eco-design actions [WP4], two main actions have been identified as important contributors for the reduction of the three issues :

- **The reduction of Platinum quantity** (A2.1 in Green on Figure 14) in the cells is the main lever for eco-design in terms of environmental, economic and social impacts. This action involves the catalyst suppliers (improve the technical characteristics of the catalyst powder), the cells manufacturers (optimize the catalyst layer thickness with the same properties, optimize the shape of the design) and the FC producer (optimize the design of the stack to improve efficiency)

- **The mass reduction of other components** (A2.3 in Blue on Figure 14) has a significant influence: minimization of the thickness.

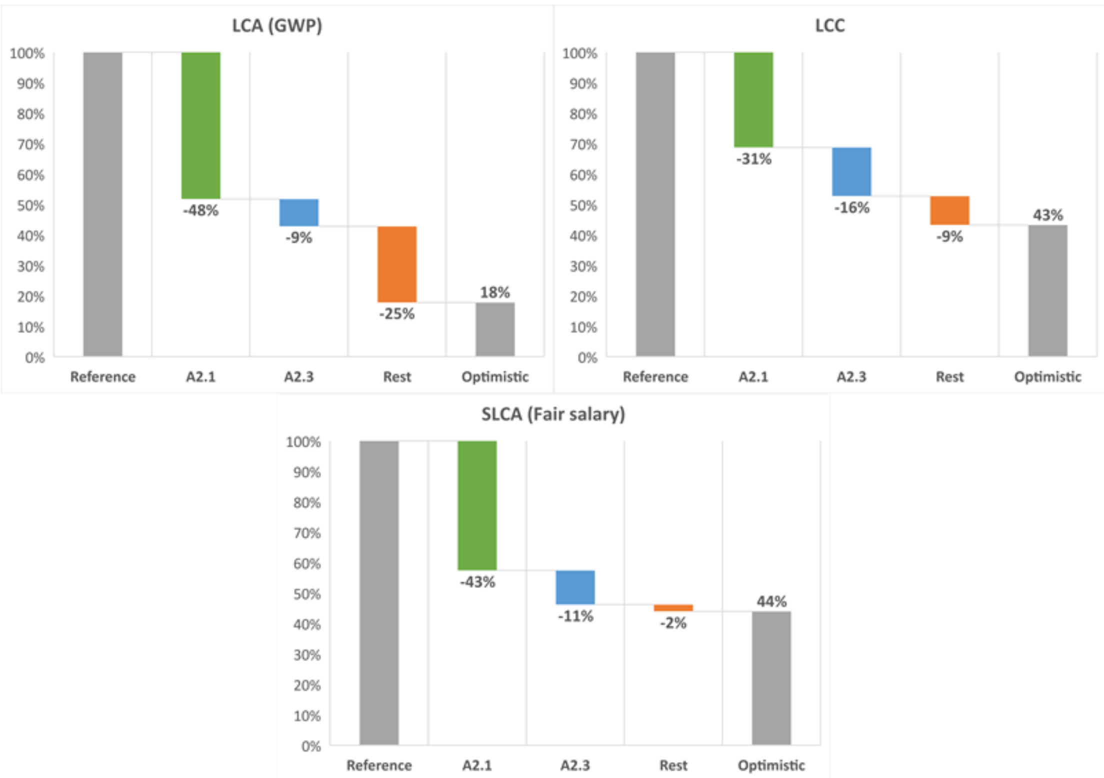

Figure 14 - Influence of eco-design actions on the sustainability profile of the PEMFC stack optimistic concept

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5. ECODESIGNED PRODUCT CONCEPTS FROM EGHOST

5.1 Description of eGHOST eco-designed products concepts

Thanks to the eco-design recommendations proposed above, four different design concepts have been developed, integrating different combinations of them. Lots of other designs could be developed choosing different combinations of actions according to the strategy of the company.

These four designs are some examples of what could be an eco-designed Fuel Cell in different perspectives: real short term, real medium/long term, optimistic and disruptive solution.

A simplified illustration is given for each concept representing the impact on the different actions for each eco-design concept proposed compared to the base case (Figure 15).

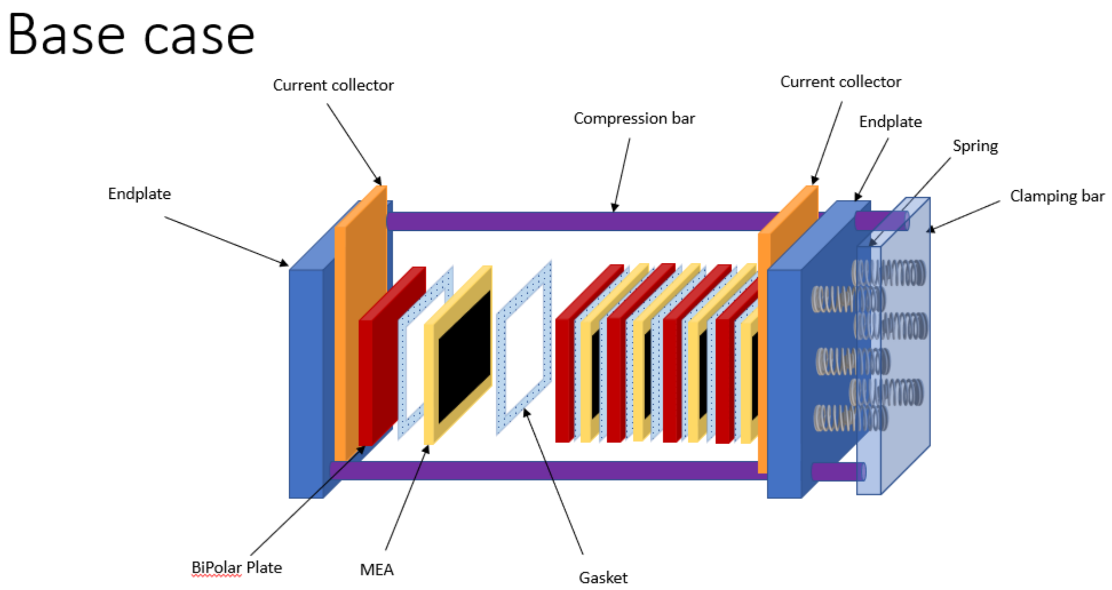

Figure 15 – Representation of stack base case

The green parts represent the share of recycled material integrated. The white parts represent the share of the parts that are reused. The different components are thinner and the stack size is decreasing for the same power delivered.

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5.1.1 Realistic short-term concept

The realistic short-term concept is based on short terms actions that will be realized and implemented in the FC industry in the near future.

It integrates a low rate of **recycled Platinum** (30%) that is already available on the global market (from different sources as autocatalyst and jewelry) that still meets technological requirements.

Anticipating the **reuse** of some parts of the stack, 30% of the **endplates** (in glass reinforced thermoplastic) are considered as reused after refurbishment.

The reduction (-50% of the quantity of platinum) of **platinum loading** is supposed to be achieved in two ways:

- A better use of platinum due to particle optimization (smaller size, shape, tailored surface roughness to increase the surface area of particles),
- The use of Pt alloyed materials which can decrease the amount of platinum itself.

Mass reduction of various materials is achieved with the reduction of membrane thickness (ionomer, -30%), GDL thickness (carbon fibers, -45%) and reduction of mass of bipolar plates (carbon composites or stainless steel, 15%). In addition, it is expected that in some case the system performance (specific power) will improve due to simultaneous improvements of the component characteristic and the reduction of the mass.

The optimization of production process is considered here with optimized catalyst coating improving the loss of material during the process and the rejection rate of components.

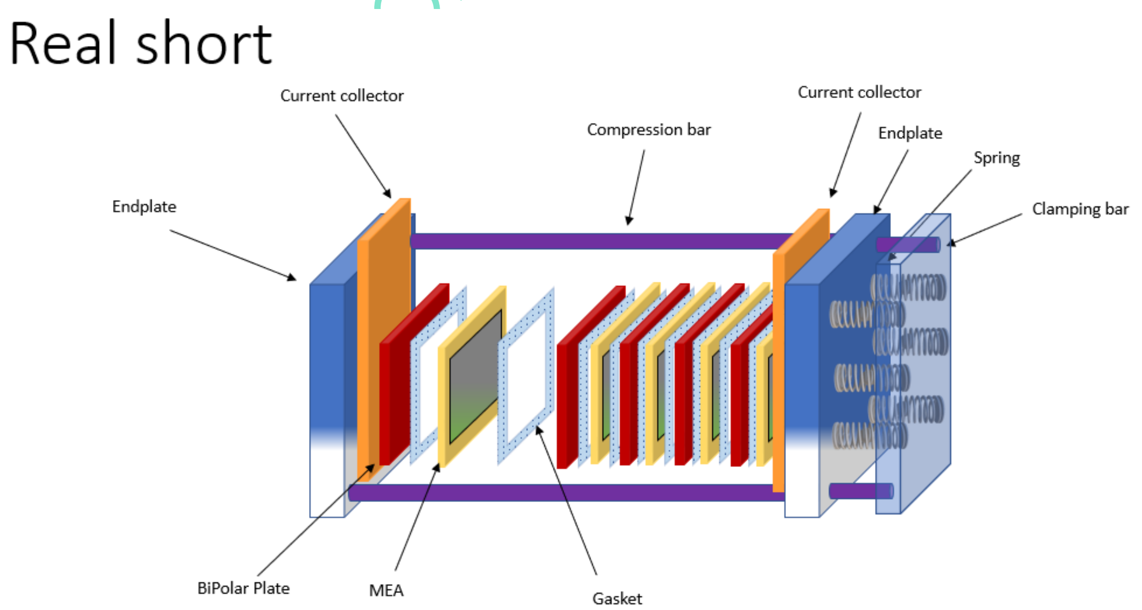

Figure 16- Representation of the real short term eco-design concept

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5.1.2 Realistic medium-to-long-term concept

The realistic medium-to-long-term concept is based on short terms actions that will be realized and implemented in the FC industry in the near future.

The supplementary actions are:

- The **increase** in **power density** is expected from 1.66 to 2.46 kW/kg due to the lower number and weight of components, alongside other technological improvements.
- The **refurbishment strategies** for the BPP : when they are not too degraded or damaged, the BPP can be reused in a new system (30% reused here).
- The **optimization of the flow channels design** on bipolar plates improve the fuel consumption, oxygen distribution and water balance systems so that the system consume less hydrogen in use.

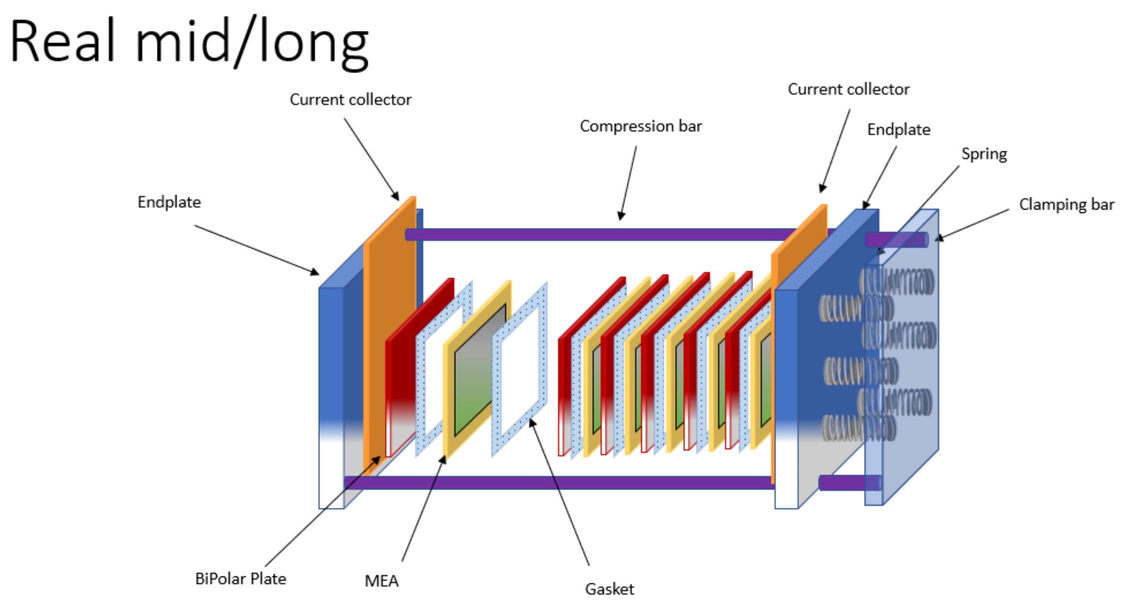

Figure 17 - Representation of the real mid/long term eco-design concept

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5.1.3 Optimistic concept

The optimistic product concept is the concept already under implementation by some top-end technological companies and/or developed at the laboratory scale. It includes all the actions foreseen in the realistic concept except when the new ones produce a better performance under the same aspect.

The paramount action is to significantly **increase the use of recycled platinum (70% - 80%)** in the fuel cell catalyst (closed-loop recycling).

Additionally, offsetting carbon footprint due to investments in mining process in platinum production countries (e.g. South Africa) is considered.

Refurbishment (reuse) of bipolar plates is increased until 66%.

Introduction of new, different ionomers (as recycled ionomer) or other hybrid materials should improve proton conductivity and durability, while reducing the environmental impact.

The **reduction of material usage** is also optimized, compared to the base case, for platinum (- 75%), ionomer (-70%), BPP (-50%), endplates (-40%) and other mechanical parts (- 30 to 40 %).

The **rejection rate is considered close to zero**.

Recent research and EoL optimization of FCH technologies raise hopes that it will be possible to attain **high closed-loop recycling ratios** for valuable materials (Pt, Co, Au, ionomer). In a worse case, these valuable materials could be used as secondary material in open-loop recycling.

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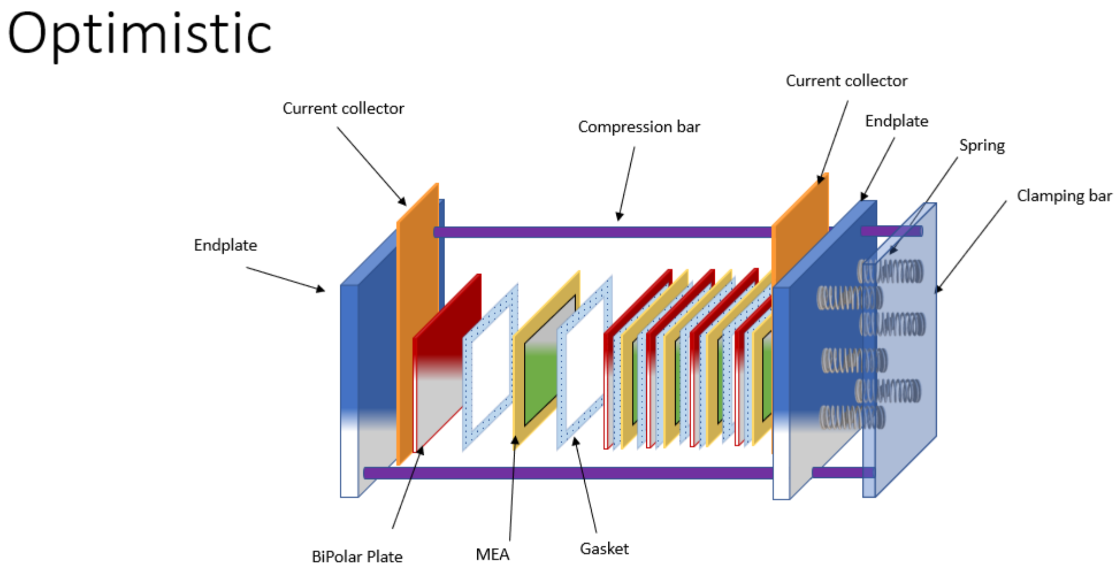

Figure 18 - Representation of the optimistic eco-design concept

5.1.4 Disruptive product concept

The Disruptive product concept includes relevant above-mentioned actions plus others that are still under development or in the early research or even conceptual phase.

To reduce the impacts of materials the recycling rates of materials should be extremely high. For platinum recovery some laboratory experiments show that more than 95% utilization is possible. Long-term industrial scale FCH recycling processes should allow to consider **more than 95% recycled platinum** in the stack.

A different approach is to **develop non-PGM catalysts**, but they need to meet all technical requirements.

A **high recycling rate of ionomer (95%)** would additionally lower the impact of PEMFC technology.

Production optimization should foster the **use of renewable energy in production processes** and **optimize upstream manufacturing** to reduce the impacts in platinum extraction and supply. Further on, it should reduce the **rejection rate of components to zero** and create **no waste on stack level production while employing a closed-loop recycling** approach within the manufacturing company.

Ready-to-recycle assembly technologies should provide modularity, while using materials with high recyclability and relying on well-established and technologically ready recycling technologies.

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Disruptive

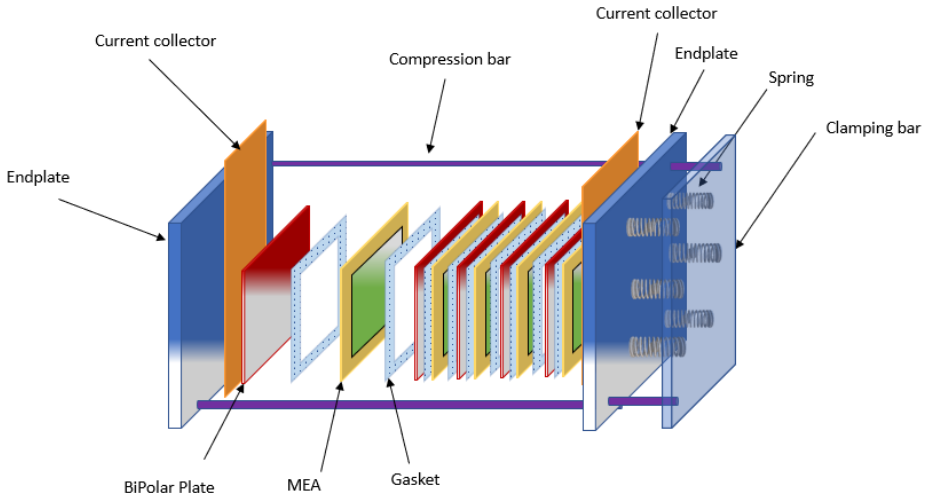

Figure 19 - Representation of the disruptive eco-design concept

5.2 Sustainability benchmarking of eGHOST eco-designed product concepts

5.2.1 Environmental assessment (LCA) summary of eGHOST product concepts

The environmental assessment of eGHOST products concepts have been realized with the same scope and hypothesis than the environmental assessment of base case.

Environmental life cycle assessment shows clear improvement in environmental performance of product concepts after eco-design actions were applied (Figure 20). In the case of the PEMFC stack there is a significant reduction of environmental impacts from base to disruptive case with additional identified reduction potential due to avoided environmental impacts. These avoided impacts are the result of materials not used in the close-loop recycling but available for open-loop recycling and for the use in open market in other technologies.

With implementation of eco-design actions, we can achieve great reductions in environmental impact indicators. With exception of eutrophication – freshwater, all environmental impact indicators are lower for realistic short-term concept by 31% - 60%, for realistic medium/long term concept by 66% - 51%, for optimistic concept by 90% - 73%, and for disruptive concept by 97% - 83%. Eutrophication – freshwater is lower by 52% in disruptive product concept.

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Eutrophication – freshwater is the only environmental indicator which is increased with introduction of eco-designed product concepts. The realistic short-term product concept has higher environmental impact (for 19%), due to the platinum recycling process. This impact is coming from the Hydrometallurgical process used in the recycling of Platinum and particularly the ammonium chloride production. In all other environmental impact indicators of eco-designed product concepts we can see a reduction of impacts.

The detail of the hypothesis taken for this comparative LCA is presented in eGHOST deliverable 4.2 [5].

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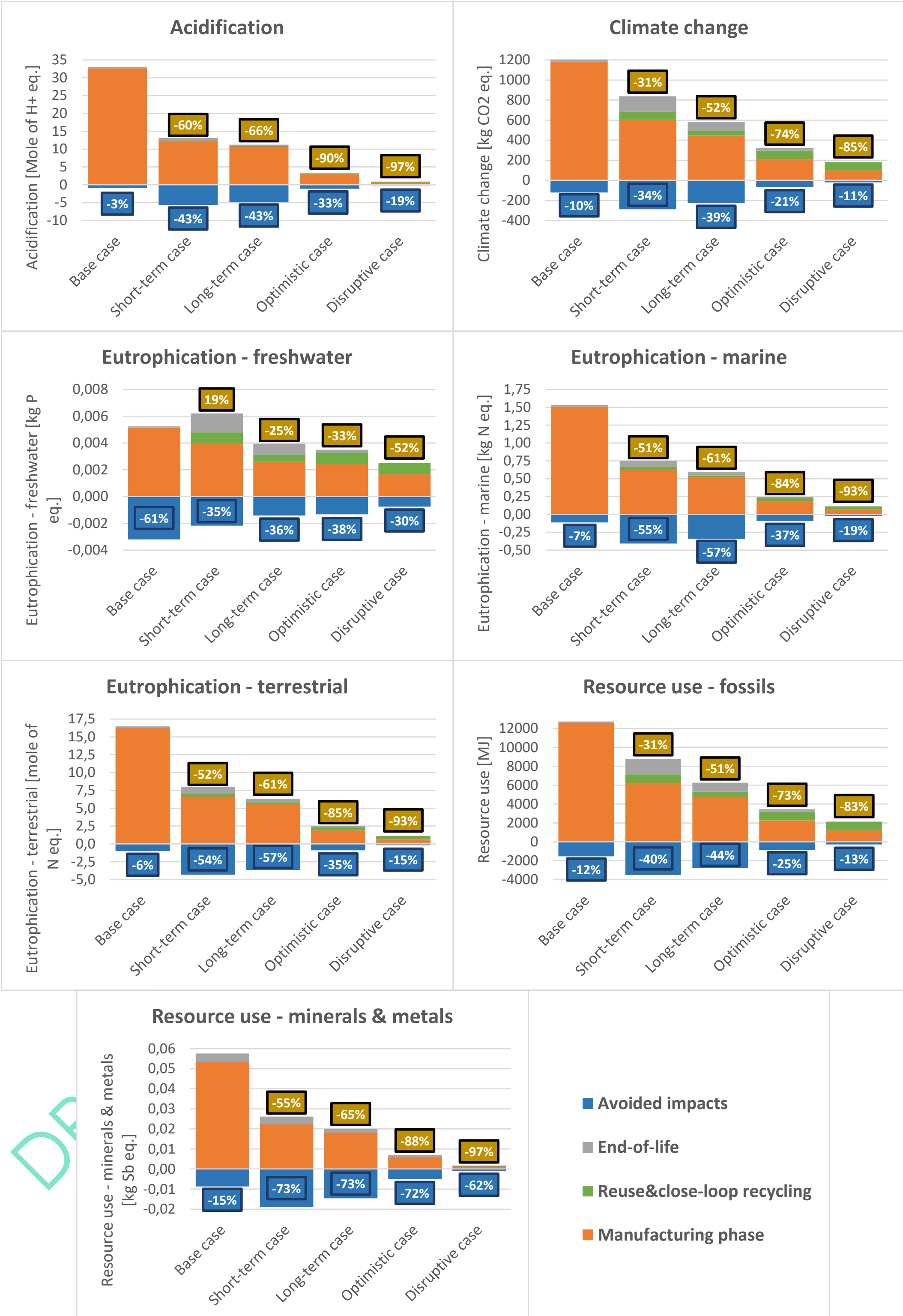

Figure 20 - Environmental LCA results for the comparison of the 4 different eco-design concepts *[5]*

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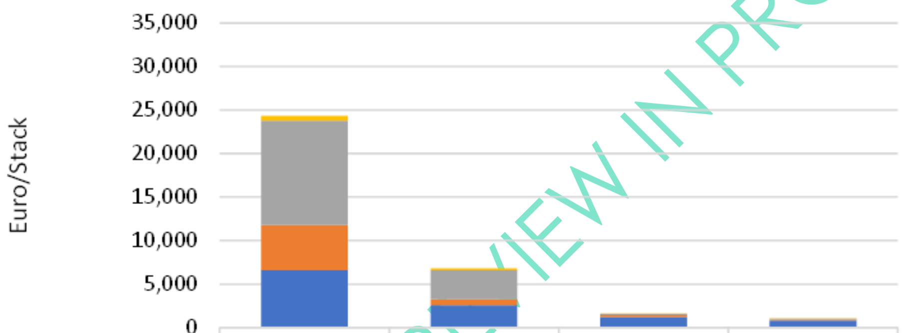
5.2.2 Cost assessment (LCC) summary of eGHOST product concepts

For each product concepts and base case, LCC is performed at different production scales. Furthermore, the costs are breakdown into assembly process, BPP (bipolar plates) process, MEA (membrane electrode assembly) process and BoM (bill of materials).

From the LCC results of the base case, it has been seen that production scale increase (from 100 to 50000 stack/year) causes a significant cost decrease. We can notice the same trend for eco-design concepts (Figure 21).



	100	1000	10000	50000
Assembly Process	578	223	35	35
BPP Process	12000	3356	149	101
MEA Process	5180	681	223	133
BoM	6,596	2,571	1,187	785
Total	24,354	6,831	1,594	1,054

Figure 21 - LCC results of the PEMFC stack optimistic product concept *[5]*

Moreover, significant reductions are achieved with eco-design product concepts, for a same production scale, due to the reduction of materials (BoM line). The cost of realistic short-term concept is by 28% lower than the base case, the realistic medium/long-term concept by 37%, the optimistic concept by 49%, and the disruptive concept by 52% than the base case.

Indeed, the eco-design concepts evaluate actions mainly based on weight and quantity reduction of materials than on process optimization.

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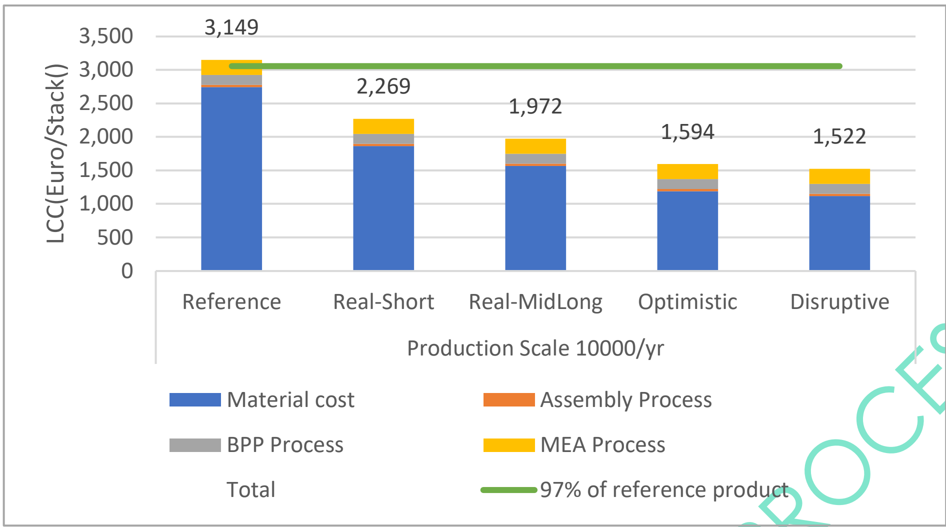

Figure 22 - LCC reduction at production scale 10000 stacks/year *[5]*

5.2.3 Social Life Cycle Assessment (SLCA) summary of eGHOST product concepts

Figure 23 shows the relative results of the product concepts benchmarked against the base case. It can be observed that **the social impacts reductions of the product concepts are almost the same for each social impact indicators**, meaning that the implementation of eco-design actions has a similar effect on most of the indicators.

Social impacts are reduced with each eco-designed product concept as is also visible on diagram in **Erreur ! Source du renvoi introuvable.**, where social impacts of product concepts are presented relative to the base case. The biggest reductions are achieved for child labor indicator, for realistic short-term concept by 64%, for realistic medium/long-term concept by 68%, for optimistic concept by 92%, and for disruptive concept by 98%. The lowest reductions are achieved for fair salary and frequency of forced labor indicators, for realistic short-term concept by 36% (fair salary 37%), for realistic medium/long-term concept by 43% (fair salary 44%), for optimistic concept by 56%, and for disruptive concept by 61%.

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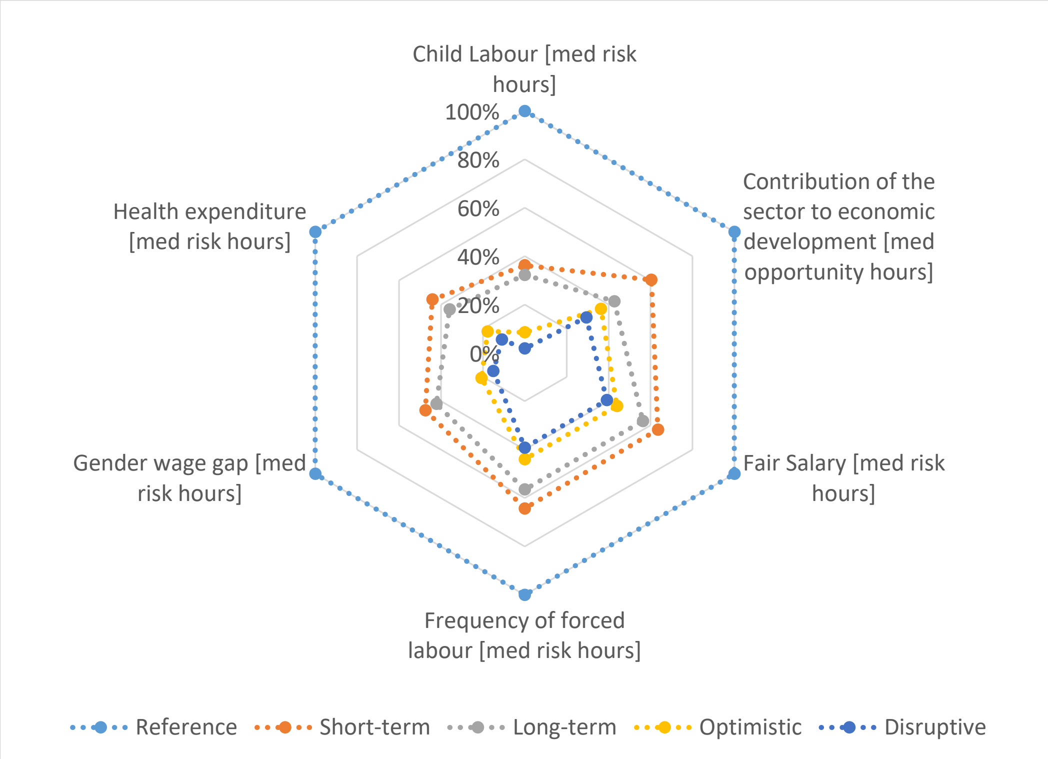

Figure 23 - Relative comparison of social indicators of the PEMFC stack product concepts in comparison to the base case *[5]*

5.3 Effects on the supply chain:

5.3.1 The issue of Platinum:

- The reduction of the rate of Platinum in the cells is the main lever that FC manufacturer have in the redesign to limit the impacts. It can be achieved using different ways : reduce the Pt loading, use Pt alloys, Optimize Pt particles in the catalyst, increase the cell power density.
  However, we have to be cautious because the Platinum content strongly depends on the use case (car, truck, bus, offroad vehicles) and influences the durability.

- The increase of the rate of recycled platinum in catalyst is not an easy issue. Two different aspects can influence this action:

  - The global open-loop recycling contributes around 28% of the total supply of platinum. Recycling is achieved through a complex, global web of companies, processes and material flows arranged to maximize the efficiency of PGM recovery from a variety of sources,

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mainly autocatalyst and jewelry. Using state-of-the art recycling technologies, over 95% of the PGM content of spent automotive catalysts (and other PGM-containing materials) can be repeatedly recovered. Some catalyst suppliers are already announcing between 75 and 95% of recycled platinum but this is data for today and when the volume of FCH products will increase, we can not be sure that this rate could be guaranteed. Increasing the rate of recycled platinum used by suppliers in the long term will need to work with suppliers to set up certificates to get official data. Maybe they can be proposed in the framework of the Critical Material Act.

  - The recycling of Platinum in close-loop could also reach a rate of 95% recycling efficiency. However, lots of steps are still needed to set up a full recycling chain and make the recycling of Fuel Cells effective: collection of the vehicles, dismantling of the FCS from the vehicle, dismantling of the system to get the MEA and optimize to recover some parts for use, separate the different components of the MEA, recycle catalyst and membrane.

- The optimization of the use of Platinum working that allow to deliver a more important quantity of kWh with the same amount of Platinum or to increase durability and allow to have a longer lifetime.

5.3.2 The issue of PFSA (Per- and polyfluoroalkyl substances):

The PFSA are targeted by REACH regulation as substances of Very High Concern [15]. Restriction of use have been proposed to minimize their release in the environment [16].

Some suppliers are starting to propose fluor-free membranes for the cells manufacturing. However, it is important to notice that it can't be a simple substitution. The fluor-free membrane has not exactly the same properties than fluor membranes. Even if they can fit the characteristics needed for MEA manufacture, the redesign and development of the Fuel Cell with new membrane could take more than 10 years.

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CONCLUSIONS

This deliverable refers **to the eco-design guidelines for the PEMFC technology developed in the framework of the eGHOST project** and integrates a synthesis of the main results of the project regarding environmental, cost and social impacts evaluation of this technology as well as design recommendations and potential products concepts for PEMFC stacks for sustainability impacts improvements.

The eco-design guidelines presented in section 4 of this document are issued from the work performed in the framework of eGHOST on sustainability assessment on generic PEMFC stack technology that have characterized potential sustainability issues and performances and from brainstorming sessions with different hydrogen actors and eGHOST consortium. **These guidelines can be used as line of thoughts for hydrogen value chains actors that are developing PEMFC and would like to understand where occur environmental, social and economic challenges along the value chain of their products and identify potential actions to improve these challenges**.

The different guidelines presented in this document can be seen as a first framework to reach more sustainable solutions for the development of future PEMFC systems in the industry.

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