eco-design
Guidelines for Hydrogen
Systems and Technologies

D2.3 Definition and evaluation of base case studies

WP2 Definition of FCH products systems

Grant No. 101007166

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EXECUTIVE SUMMARY

This deliverable is related to Work Package 2 (WP2) of the EU eGHOST project: Definition of FCH Products Systems. The key objective of WP2 is to define the two FCH systems that will be subject to eco-design within the EU eGHOST project. A second objective is to evaluate their environmental, social, and economic performances. This deliverable includes a detailed description of the two hydrogen-related products: a Proton-Exchange Membrane Fuel Cell (PEMFC) stack and a Solid Oxide Electrolysis Cell (SOEC) stack. Moreover, this deliverable presents the preliminary results of the sustainability assessment of both products. The deliverable also addresses the implementation plan of datasets from the partner project BEST4Hy, which is engaged in end-of-life (EoL) solutions on critical, strategic materials in FCH products.

For the PEMFC stack, the results from the environmental life cycle assessment (LCA) show that electricity and platinum production have the highest contribution to the environmental impacts in general. For 50,000 units produced per year, a cost of 2,288 €/stack is calculated through life cycle costing (LCC). Moreover, platinum production is found to be the main hotspot regarding to all the selected social life-cycle indicators with a negative connotation.

For the SOEC stack, the LCA results show an environmental hotspot related to the stainless steel used for mechanical assembly (frames) and electrical conductivity (interconnects, end plates). For 50,000 units produced per year, a cost of 940 €/stack is calculated through LCC. Moreover, stainless-steel production is found to be the main social hotspot, arising as the major contributor to five out of six indicators.

All these results will be used for the subsequent identification of eco-design actions effectively improving the sustainability of both products.

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ABBREVIATIONS

ABC	Activity Based Costing
AE	Accumulated Exceedance
BPP	Bipolar Plate
BoM	Bill of Materials
CCM	Catalyst Coated Membrane
CCS	Carbon Capture and Storage
CRM	Critical Raw Materials
EE	Energy Extraction
EF	Environmental Footprint
EoL	End of Life
EU	European Union
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FCH	Fuel Cells and Hydrogen
GDL	Gas Diffusion Layer
GWP	Global Warming Impact Potential
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LF	Landfill
LSCF	Lanthanum Strontium Cobalt Ferrite
LSM	Lanthanum Strontium Manganese
MEA	Membrane Electrode Assembly
moh	Medium opportunity hours
mrh	Medium risk hours
NGCC	Natural Gas Combined Cycle
PGM	Platinum Group Metals
PEMFC	Proton-Exchange Membrane Fuel Cell
PET	Polyethylene Terephthalate
PFSA	Perfluorosulfonic Acid
P-LCA	Prospective Life Cycle Assessment
S-LCA	Social Life Cycle Assessment
SOEC	Solid Oxide Electrolysis Cell
SRU	Single Repeated Unit
TRL	Technology Readiness Level
TT	Total
UN	United Nations
WP	Work Package
YSZ	Yttria Stabilized Zirconia

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REPORT

1. INTRODUCTION

The eGHOST project aims to support the whole Fuel Cells and Hydrogen (FCH) sector. Therefore, it addresses the eco-(re)design of mature products (Proton-Exchange Membrane Fuel Cell – PEMFC – stack) and those emerging with a Technology Readiness Level (TRL) around 5 (Solid Oxide Electrolysis Cell – SOEC – stack) in such a way that sustainable design criteria can be incorporated since the earliest stages of the product development. eGHOST will be the first milestone for the development of eco-design criteria in the European hydrogen sector and will go a step beyond the current state of the art in eco-design.

This deliverable is related to **Work Package 2 (WP2) of the project: Definition of FCH Products Systems**. The key objective of WP2 is to define the **two reference FCH systems (PEMFC & SOEC)** that will be subject to eco-design for the rest of the project. A second objective is **to evaluate their environmental, social, and economic performances**.

This deliverable includes **a detailed description of the two hydrogen related products**: a PEMFC stack and a SOEC stack. Moreover, this deliverable presents **the preliminary results of the following assessments** that have been methodologically described in a previous deliverable (D2.1: Assessment methodologies):

- **Conventional environmental Life Cycle Assessment** (LCA) of the PEMFC stack.
- **Prospective environmental Life Cycle Assessment** (P-LCA) of the SOEC stack.
- **Conventional and environmental Life Cycle Costing** (LCC) of the two reference FCH systems.
- **Social Life Cycle Assessment** (S-LCA) of the two reference FCH systems.

Major contributors to environmental, economic, and societal impacts are clearly identified in this deliverable in order to contribute to the definition of eco-design guidelines for the two evaluated reference FCH systems.

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2. DEFINITION OF THE REFERENCE PRODUCTS

2.1 Proton-Exchange Membrane Fuel Cell stack

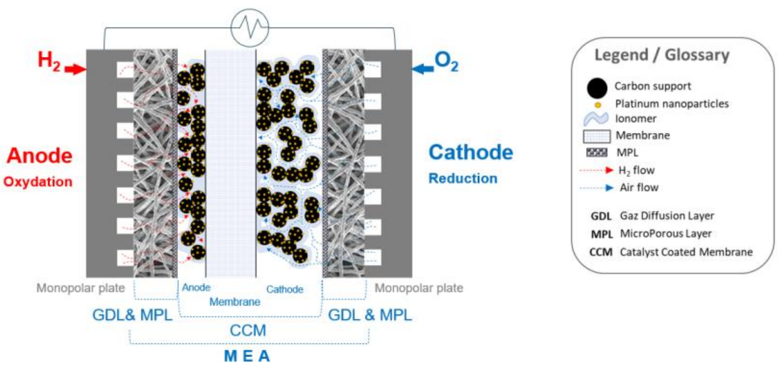
This section defines and describes a reference PEMFC stack, which is further evaluated in this document as part of the EU project eGHOST [1]. The reference product used in this project is a 48 kW_{el} PEMFC stack, which can be used in light vehicles (single or multiple stack units). The detailed product data and specifications were provided by the manufacturing company SYMBIO France to define all the material and energy flows needed to produce the reference PEMFC stack. The automotive PEMFC stack is used in a highly efficient fuel cell system, which is designed as [2]:

1. Range extender fuel cell (single PEMFC stack unit) for electric vehicles (EV) to increase the insufficient range of battery-only vehicles and to improve usage flexibility, and
2. Dual-power or full-power system for light fuel cell electric vehicles (FCEV) (as a multi-stack unit with upscaling).

The PEMFC technology definition is presented in Table 1, where main boundary conditions and limitations are summarized.

Table 1: PEMFC technology definition for LCA, S-LCA and LCC

<table>
<tr><th colspan="2">PEMFC technology definition and boundary conditions</th></tr>
<tr><td>Technical Operation Scheme</td><td>Membrane Electron Assembly (MEA) structure




</td></tr>
<tr><td>Technical Perimeter</td><td>Stack only</td></tr>
<tr><td>Life Cycle Perimeter/scope</td><td>"Cradle to gate" (manufacturing phase; EoL planned)</td></tr>
<tr><td>Size of the system</td><td>48 kW_{el}</td></tr>
<tr><td>Technology</td><td>Representative PEMFC stack design</td></tr>
<tr><td>Application</td><td>Light vehicles (FCEV)</td></tr>
<tr><td>Timeline</td><td>Current technology</td></tr>
<tr><td>BoM</td><td>Finalized by SYMBIO France</td></tr>
</table>

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The main input data used was the Bill of Materials (BoM) provided by SYMBIO France for the 48 kW_{el} PEMFC stack, shown in Table 2. Furthermore, schematic representations of the PEMFC stack design and main components are briefly shown in Figure 1 and Figure 2.

Table 2: Bill of Materials for 48 kW_{el} PEMFC stack used for base case study

Level					Designation	Quantity	Weight		Units	*Material*
1	2	3	4	5			Min	Max		
x					Platinum	/	0.41	0.52	mg/cm²	Platinum nanoparticles
	x				Platinum on carbon	/	1.03	1.29	mg/cm²	Platinum nanoparticles on carbon support
	x				Ionomer	/	0.28	0.37	mg/cm²	Perfluorosulfonic Acid (PFSA) ionomer
	P				Ink mixing	/	/	/	/	
		x			**Catalytic ink**					
		x			Membrane	1	0.4	0.5	g/MEA	Perfluorosulfonic Acid (PFSA) ionomer
		P			Catalyst ink coating	1	0.26	0.33	g/MEA	
			x		**Catalyst Coated Membrane (CCM)**	**1**				
			x		Sub-gaskets	2	3	3.5	g/MEA	PEN or PET film with thermoactive glue
			x		Gas Diffusion Layer (GDL)	2	1.76	2.7	g/MEA	Carbon fiber fabrics and carbon black with PTFE binders
			P		MEA thermal assembly	/	/	/	/	
				X	**Membrane Electrode Assembly (MEA)**	**1**				
x					Monopolar plate anode	1	0.03	0.04	kg/part	Stainless steel
x					Monopolar plate cathode	1	0.03	0.04	kg/part	Stainless steel
	P				Polar plate assembly	1				
	X				**Bipolar plate (BPP)**	**1**				
x					MEA	280	0.010	0.013	kg/part	Assembly
x					Bipolar plate (BPP)	279	0.07	0.085	kg/part	Assembly
x					End Bipolar plate anode	1	0.07	0.085	kg/part	Assembly
x					End Bipolar plate cathode	1	0.07	0.085	kg/part	Assembly
x					Gaskets	560	0.002	0.0025	kg/part	Silicone
P					Stacking					
	x				**Stack pre-Assembly**					
	x				Wet endplate	1	1.5	1.8	kg/part	Glass reinforced thermoplastic
	x				Compression bar M6	6	0.135	0.14	kg/part	Steel
	x				Current collector	2	0.45	0.5	kg/part	Copper
	x				Spring	6	0.125	0.125	kg/part	Steel + polymer coating
	x				Clamping bar	6	0.3	0.39	kg/part	Steel
	x				Gaskets	2	0.002	0.0025	kg/part	Silicone
	x				Hexagonal screws	6	0.004	0.005	kg/part	Steel
	x				Dry endplate	1	1.8	2.5	kg/part	Glass reinforced thermoplastic
		x			**48 kW_{el} PEMFC Stack Assembly**					

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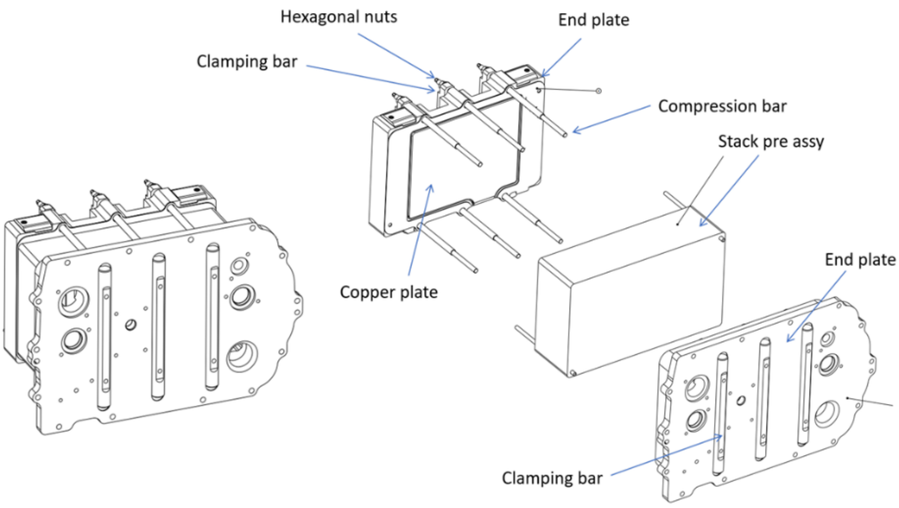

Figure 1: 48 kW PEMFC stack assembly final step during manufacturing

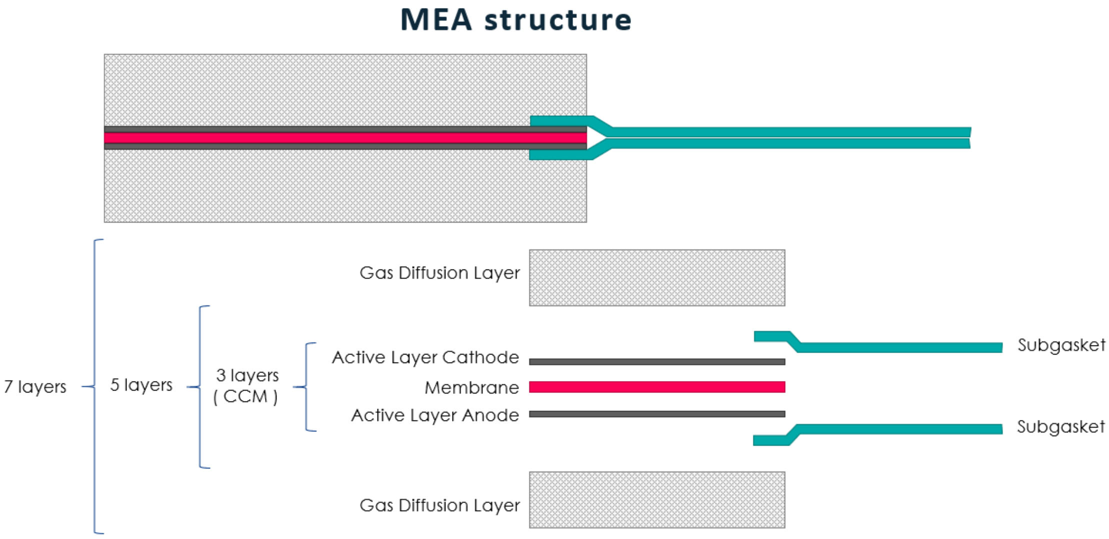

Figure 2: Membrane electrode assembly (MEA) main components

2.2 Solid Oxide Electrolysis Cell stack

This section defines and describes the 5 kW_{el} SOEC stack, which is further evaluated in this document as part of the EU project eGHOST. This is the second product assessed.

The assessed SOEC stack is defined according to projections for 2030, when this technology is supposed to reach a sufficient level of maturity to be commercially available [3]. The main parameters evolved and their corresponding values are summarized in Table 3, based on European projections [4].

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Table 3: Prospective parameters of the SOEC stack

Parameter	Value
Active area per single repeated unit (cm^2/SRU)	100
Current density (A/cm^2)	1.5
Degradation (%/1,000 h)	0.5
Lifetime (h)	80,000

Additionally, the electricity needed for stack manufacturing and stainless-steel production is considered to be generated according to the expected Spanish electricity mix for 2030 [5]. Within this mix (Figure 3) a major deployment of renewable energy sources is expected, with a renewable power percentage around 80%.

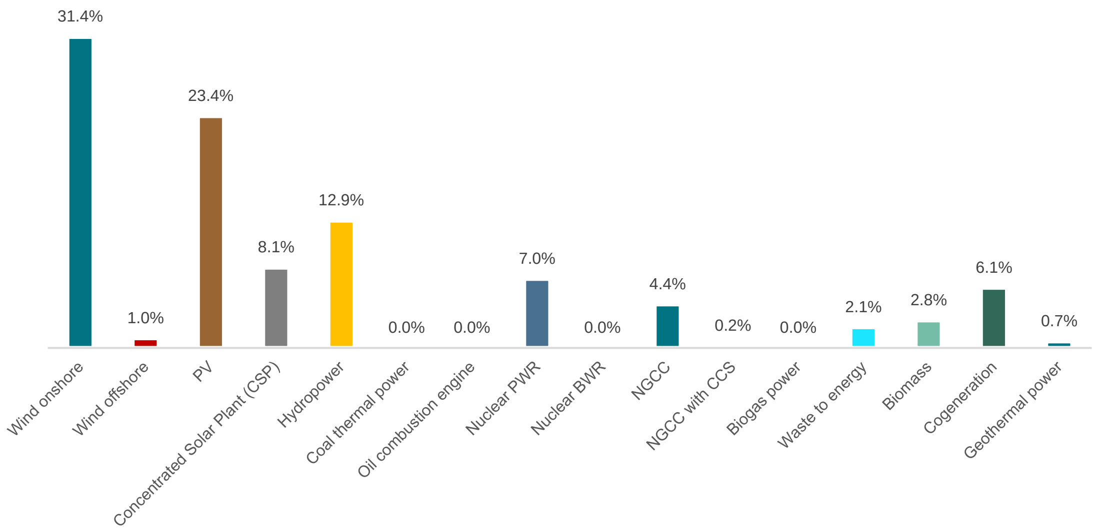

Figure 3: Electricity mix considered for 2030 (based on [5])

The evaluated SOEC stack is a planar cathode-supported one, whose **sizes have been determined considering the geometrical configuration in** [6] **and the active area set for the prospective design (100 cm²/SRU)**. A total area of 144.78 cm² per single repeated unit (SRU) is estimated, maintaining the proportion of active area constant (82.61%).

The 5 kW stack is formed by 26 SRUs. Each of them is constituted by a **cathode (hydrogen electrode), an anode (oxygen electrode), an electrolyte, one interconnect with a perovskite coating, three frames and two meshes** (one for the anode and another for the cathode). The total number of interconnects of the stack is set to 28 because of the two additional interconnects needed to assure electrical conductivity between the SRU and the end plates. Additionally, there are three layers of sealant per SRU and it is considered that the stack is furnace-brazed and kept together with eight tie rods [6]. It should be noted that the number of SRUs required to fulfil the 5 kW nominal power is

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calculated considering that **the SOEC stack will work at the thermoneutral voltage at 800 °C.** In this sense, the enthalpy of reaction at this temperature is estimated based on [7]. The electrolyte and cathode material composition is derived from the composition of the ceramic slurries used in [6]. In both cases, it involves water, a weak polyelectrolyte as dispersant and a binder. For the two tape-casting processes, the thickness of deposition is doubled because of expected losses due to the drying of the wet slurry [6]. In regard to the anode, it is divided into three different layers: (i) lanthanum strontium cobalt ferrite (LSCF) layer, (ii) contact layer, and (iii) active layer. The last two are formed by a composite material: yttria stabilized zirconia (YSZ), and lanthanum strontium manganese (LSM). The thicknesses of the three layers are 30, 10, and 5 μm, respectively. For the first one, the Sr index is set to 0.4 according to typical chemical composition for these devices [8]. Thus, densities of 6,370 kg/m^3 and 4,640 kg/m^3 are considered for LSCF [8] and YSZ/LSM [9], respectively. Similarly, the mass of the rest of the parts is calculated considering the new sizes of the stack and the density of the materials, typically stainless steel. The glass used for sealant purposes is made up of 50/50 vol% lanthanum oxide and boron-silicate glass [6]. A **summary of the materials used per stack** is presented in Table 4.

Table 4: Summary of materials of the SOEC stack

Part of the stack	Material	Mass with losses (kg)
Electrolyte	8% mol YSZ	0.015
	Binder Dow B-1000/B-1014	
	Ammonium polyacrylate	
	Water	
Cathode	8% mol YSZ	0.99
	Nickel oxide	
	Binder Dow B-1000/B-1014	
	Ammonium polyacrylate	
	Water	
Anode	LSCF	0.12
	YSZ/LSM	
	YSZ/LSM	
Interconnects/Frames	Stainless steel	11.90
	Perovskite coating	
Anode and cathode meshes	Stainless steel	4.57
Sealant	Lanthanum oxide	0.019
	Boron-silicate glass	
End plates/Tie rods	Stainless steel	12.47

Waste generated during the manufacturing processes (e.g. ceramic slurry production, tape casting, sealant application) is estimated at 20% according to [6]. Waste flows involve metal scrap and ceramic glass, which are assumed to be further recycled. A cut-off approach is followed, attributing the impacts of the recycling and the potential benefits to the future user. Wastewater arising from the ceramic slurry production and tape casting is treated in a wastewater facility.

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3. LIFE CYCLE ASSESSMENT OF THE REFERENCE PRODUCTS

GaBi software with GaBi and ecoinvent databases is used to perform LCA on the PEMFC case study, while SimaPro software with the ecoinvent database is used to perform LCA on the SOEC case study. LCA responsible partners for the two case studies were UL for the PEMFC one and IMDEA Energy for the SOEC one. Both partners use different LCA software under license for their studies. As the objective of these LCA studies is not to compare the environmental results between the case studies but to identify environmental hotspots within both case studies separately (and subsequently propose eco-design guidelines), the use of different software and databases for this evaluation is not an issue for the project.

3.1 LCA of Proton Exchange Membrane Fuel Cell stack

This chapter presents an LCA case study of the reference product, a **48 kW$_{el}$ PEMFC stack**. The LCA study is conducted with the approach presented in deliverable D2.1 "Assessment methodologies", taking into account ISO 14040 [10] and 14044 [11], ILCD guidelines [12] and FC-HyGuide [13]. A 48 kW$_{el}$ PEMFC stack is analyzed for the manufacturing phase ('cradle to gate') in this preliminary assessment, without the EoL phase. Nevertheless, when all data for the EoL phase is provided from the BEST4Hy project [14], then this analysis will be updated with EoL phase analysis and results. As disclosed in deliverable D2.1, datasets of recycled critical materials (platinum) and ionomer will be integrated into eGHOST WP4, where product concepts will be evaluated based on eco-design actions from WP3 and new established inventories built in WP4. The PEMFC stack in the manufacturing phase is modelled part by part with numerical models set up in GaBi [15].

3.1.1 Goal and the scope

The goal of this analysis is to evaluate potential environmental impacts of one 48 kW$_{el}$ PEMFC stack in the manufacturing phase using the EF 3.0 life cycle impact assessment (LCIA) method.

The **scope of the study is 'cradle to gate' excluding the use phase and, in this preliminary study, also the EoL phase**. The functional unit is **1 PEMFC stack with 48 kW electrical power** output. This preliminary study is a good starting point for pursuing the following objectives in the continuation of the study and the eGHOST project, e.g. definition of EoL strategies, best EoL strategies for critical materials, comparison of environmental impacts of the manufacturing and EoL phases, etc.

System boundary: The foreground system comprises all processes related to the production of the PEMFC stack itself. In the case of a fuel cell stack, this includes the main production processes for the main components, such as the manufacturing of the catalyst coated membrane (CCM), sub-gaskets and gas diffusion layers (GDL) which comprise the MEA. Additionally, manufacturing processes for gaskets, bipolar plates

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(BPP), current collector, screws, springs, and end plates are also included in the PEMFC stack manufacturing. The background system supports the foreground system described above and its processes. It deals with almost all material and energy flows going in and out from the foreground system. As for secondary data, the databases ecoinvent 3.7 and GaBi Professional are used for the background system.

The **physical and methodological limitations** of the LCA study are:

- **Functional unit**: 1 PEMFC stack with 48 kW electrical power output.
- Preliminary scope: from **cradle to gate (manufacturing phase)**.
- **LCI**: materials and processes provided by industry partners (SYMBIO France) and other FCH technologies manufacturers.
- LCIA method: **Environmental Footprint 3.0** (EF 3.0).
- **Software** environment: GaBi Sphera.
- Generic databases: **GaBi professional** and **ecoinvent 3.7.**

A graphical representation of the system boundaries, inputs, and outputs for the current PEMFC LCA study is shown in Figure 4.

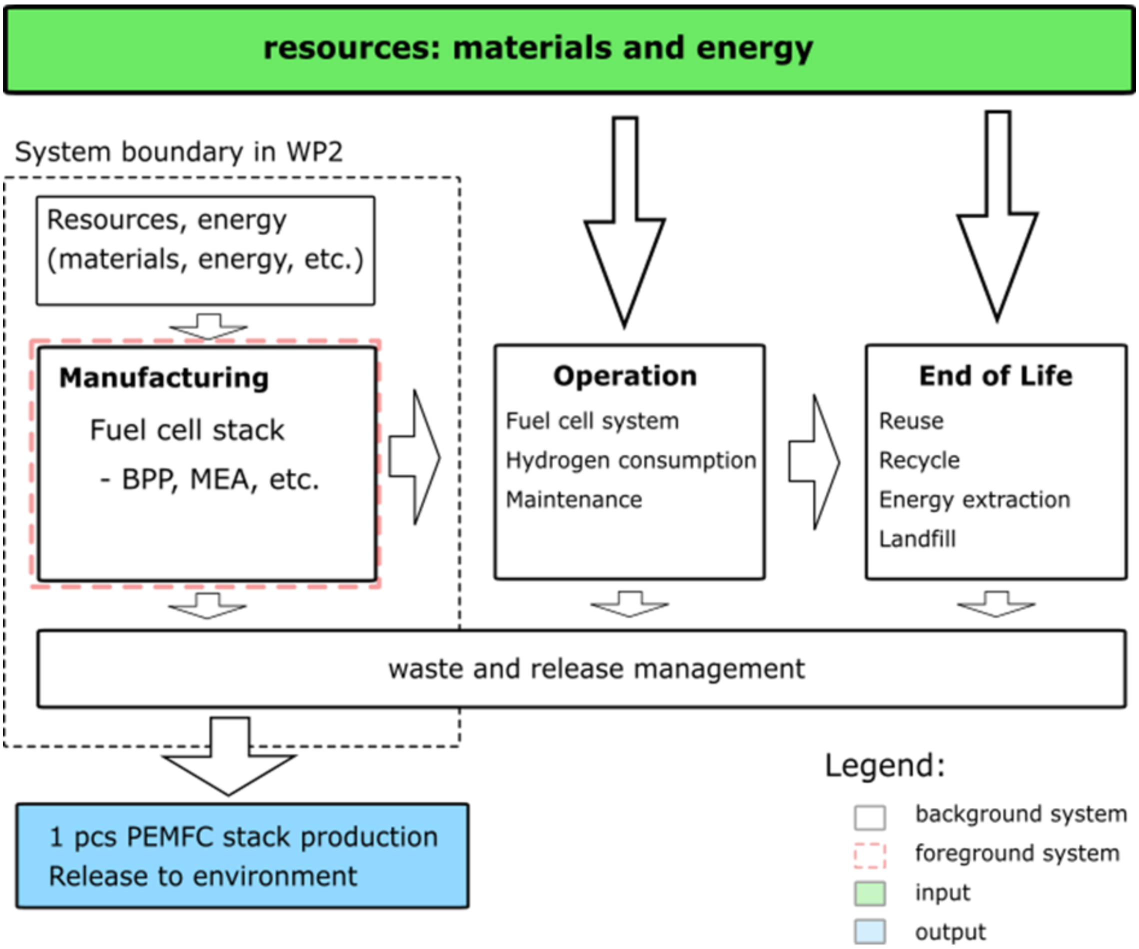

Figure 4: Inputs, outputs, and system boundary for the PEMFC stack preliminary LCA study

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The EoL phase is very important when addressing LCA and eco-design of FCH technologies. EoL will be modelled and evaluated using the common recycling approaches for conventional materials (aluminum, copper, steel, plastic, etc.), while recycled critical and rare earth materials will be integrated from the FCH 2 JU funded project BEST4Hy. In BEST4Hy, the PEMFC technology is evaluated, studied and modeled in the EoL phase to recover critical, rare-earth materials and ionomer. After applying eco-design in WP3, all actions in the EoL phase will be assessed and evaluated using LCA in eGHOST WP4.

3.1.2 Life cycle inventory analysis

In this section the methodology and steps for obtaining LCI tables are presented in terms of materials and energy use for 1 piece of the 48 kW_{el} PEMFC stack. Data is obtained from the PEMFC technology manufacturer involved in the consortium (SYMBIO France) during LCI preparation. The methodology used to create the LCI involves data collection for all the necessary materials and processes used during production for the proposed reference product. The main data for the LCI is provided in the form of the BoM presented in Table 2, which are further analyzed while all mass and energy balances needed for the LCI are properly defined. The LCI is presented in Table 5 with all the materials and energy in the final 48 kW_{el} PEMFC stack.

Table 5: Life cycle inventory of the 48 kW_{el} PEMFC stack used for the base case study

Material	Total amount	Amount per kW_{el}	Share [total w%]
Silicone	1.265 kg	26.34 g	3.6%
Stainless steel	21.623 kg	450.47 g	61.3%
Carbon cloth fibers	1.249 kg	26.02 g	3.5%
PEN or PET film with thermoactive glue	1.82 kg	37.92 g	5.2%
Platinum	0.026 kg	0.54 g	0.1%
Carbon black	0.039 kg	0.81 g	0.1%
PFSA (Nafion)	0.144 kg	3 g	0.4%
Water	0.49 kg	10.21 g	1.4%
Alcohol	0.22 kg	4.58 g	0.6%
Glass reinforced thermoplastic	3.800 kg	79.17 g	10.8%
Chromium steel	0.852 kg	17.75 g	2.4%
Copper	0.950 kg	19.79 g	2.7%
Steel product	2.820 kg	58.75 g	8.0%
Electricity	410.2 kWh	8.5 kWh	-

Based on the described methodology and intermediate iterative improvements, we obtain a well-defined LCI that is used for further analysis of the potential environmental impacts of the 48 kW_{el} PEMFC stack.

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3.1.3 Life cycle impact assessment methodology

The EF3.0 LCIA method is used to evaluate the selected environmental impact categories presented in D2.1. The selection of environmental indicators follows the guidelines of one of the main documents for LCA of FCH technologies, the HyGuide, while in recent years the European Commission supports the EF3.0 method. The EF3.0 method includes 16 environmental impact indicators, which will provide good additional insight into the environmental impacts of the production processes of the PEMFC technology, namely the PEMFC stack.

The environmental indicators used in the study are:

- **EF 3.0 Climate Change - total [kg CO_2 eq.] - GWP in HyGuide**
- **EF 3.0 Acidification [mol H^+ eq.]**
- **EF 3.0 Eutrophication, freshwater [kg P eq.]**
- **EF 3.0 Eutrophication, marine [kg N eq.]**
- **EF 3.0 Eutrophication, terrestrial [mol N eq.]**
- **EF 3.0 Resource use, fossil [MJ] - PED in HyGuide**
- **EF 3.0 Resource use, minerals and metals [kg Sb eq.] - AD in HyGuide**

It should be noted that, while the remaining indicators within the EF3.0 method (ionizing radiation, ozone depletion, particulate matter, land use, water use, etc.) could also be directly considered, this idea is discarded due to the nature of the eGHOST project. eGHOST addresses sustainability criteria belonging to the environmental, economic, and social dimensions. Hence, the implementation of multiple environmental indicators could jeopardize the identification and interpretation of sustainability-oriented design actions, and thus the formulation and prioritization of new eco-designed product concepts.

3.1.4 PEMFC results

Environmental impacts of the manufacturing phase are presented for the 48 kW_{el} PEMFC stack and separately for each component (material used) of the 48 kW_{el} PEMFC stack.

3.1.4.1 Manufacturing phase

The LCA model for one 48 kW_{el} PEMFC stack (Figure 5) consists of different materials, which are used in: **membrane, catalytic ink production, sub-gaskets, GDL and BPP production**. Also, the electricity needed for all manufacturing processes is included. Waste streams (due to inefficiency of manufacturing processes) and energy losses related to the manufacturing phase are partly included, but additional environmental impacts due to waste treatment are neglected in the preliminary assessment. The additional separate analysis related to waste streams will be analyzed more in detail later during the project.

Figure 5 shows the final LCA model of the manufacturing phase for the 48 kW_{el} PEMFC stack in the GaBi software environment with all the major mass and energy (total) flows required for the manufacturing phase. Table 6 shows the absolute values of the environmental indicators for acidification, climate change, eutrophication, and resources consumption for the 48 kW_{el} PEMFC stack manufacturing phase. For a more detailed analysis of the environmental indicators and a hotspot analysis for each

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indicator analyzed, the results for the relative contribution of electricity and materials to the total environmental impacts of the production of the 48 kW_{el} PEMFC stack are presented in Table 7.

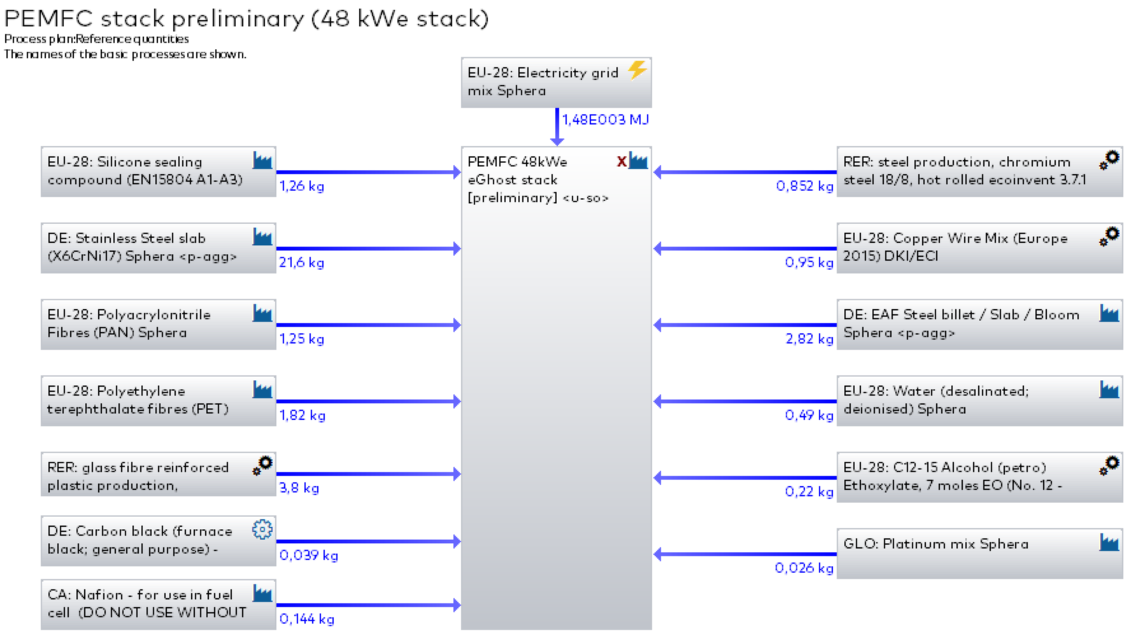

Figure 5: LCA model of 48 kW PEMFC stack manufacturing in GaBi Sphera software

From results presented in Table 6, Table 7, Figure 6 and Figure 7, we can summarize results and conclude:

- The total potential environmental impact of the 48 kW_{el} PEMFC stack manufacturing for climate change is **1,160 kg $CO_{2eq.}$**, which is equal to **24,2 kg $CO_{2eq.}$ per 1 kW_{el}.**
- Electricity, Nafion and platinum (which is a critical raw material – CRM) production have the highest contribution to the **climate change environmental indicator**, namely **platinum represents 63.5%, Nafion represents 11.9%** and **electricity represents 13.2%** of total climate change impact. The fourth most influential item in climate change is stainless steel, with 6.3 %.
- For the **resource use (minerals and metals)** environmental indicator, the highest impact comes from Pt (86.6%) followed by stainless steel (9.1%) and copper (3.6%).
- For the **acidification** environmental indicator, most of the impact comes from platinum production (94.2%), followed by stainless steel (2.8%) and electricity (1.6%).
- **Glass fiber reinforced plastic** has the highest impact contribution to **freshwater eutrophication**, with 61.0% followed by chromium steel (26.2%) and electricity (8.7%).

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- On average, for all environmental impact indicators the highest contribution to the environmental impacts of the 48 kW_{el} PEMFC stack comes from **platinum** (despite the **total mass share of Pt** in the whole PEMFC stack is only **0.1%**, see Table 5), followed by **electricity, glass fiber reinforced plastic, stainless steel and chromium steel**.

Table 6: Absolute values of environmental indicators for 48 kW_{el} PEMFC stack manufacturing

	EF 3.0 Acidification [mol H^+ eq.]	EF 3.0 Climate change - total [kg CO_2 eq.]	EF 3.0 Eutrophication, freshwater [kg P eq.]	EF 3.0 Eutrophication, marine [kg N eq.]	EF 3.0 Eutrophication, terrestrial [mol N eq.]	EF 3.0 Resource use, fossils [MJ]	EF 3.0 Resource use, mineral and metals [kg Sb eq.]
PEMFC stack preliminary (48 kW_{el} stack)	**20.8**	**1160**	**0.005**	**1.44**	**15**	**13800**	**0.052**
Electricity	3.32E-01	1.53E+02	4.41E-04	7.45E-02	7.82E-01	2.74E+03	4.13E-05
Platinum	1.96E+01	7.37E+02	6.54E-05	1.24E+00	1.36E+01	8.81E+03	4.52E-02
Nafion	1.92E-04	1.38E+02	1.36E-07	3.97E-05	4.40E-04	4.04E+02	2.77E-08
Carbon black	2.20E-04	9.48E-02	1.26E-07	1.39E-05	1.48E-04	2.52E+00	1.49E-08
Steel	2.53E-03	1.06E+00	3.39E-06	6.59E-04	7.03E-03	1.27E+01	4.02E-07
Stainless steel	5.92E-01	7.29E+01	7.90E-05	5.54E-02	6.13E-01	8.18E+02	4.75E-03
Alcohol	1.52E-03	5.49E-01	9.55E-07	2.68E-04	2.85E-03	1.56E+01	1.48E-07
Copper	3.52E-02	3.66E+00	2.09E-05	4.67E-03	5.14E-02	3.60E+01	1.88E-03
Polyacrylonitrile fibers (PAN)	1.64E-02	6.40E+00	8.68E-06	6.67E-03	6.65E-02	1.41E+02	6.36E-07
Polyethylene terephthalate fibers (PET)	7.78E-03	4.98E+00	1.85E-05	2.12E-03	2.31E-02	1.35E+02	5.96E-07
Silicone	2.82E-02	8.86E+00	1.47E-05	6.10E-03	6.60E-02	1.41E+02	1.71E-04
Water (desalinated; deionized)	1.19E-06	5.74E-04	2.98E-08	4.42E-07	3.85E-06	9.31E-03	1.40E-10
Glass fiber reinforced plastic	1.37E-01	3.35E+01	3.10E-03	4.41E-02	2.21E-01	5.24E+02	6.53E-05
Chromium steel	2.38E-02	3.78E+00	1.33E-03	4.48E-03	4.80E-02	5.15E+01	1.34E-04

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Table 7: Relative contribution of electricity and materials to the entire environmental impacts of the 48 kW_{el} PEMFC stack manufacturing

	EF 3.0 Acidification [mol H⁺ eq.]	EF 3.0 Climate change - total [kg CO_2 eq.]	EF 3.0 Eutrophication. freshwater [kg P eq.]	EF 3.0 Eutrophication. marine [kg N eq.]	EF 3.0 Eutrophication. terrestrial [mol N eq.]	EF 3.0 Resource use. fossils [MJ]	EF 3.0 Resource use. Min.&met. [kg Sb eq.]
PEMFC stack preliminary (48 kW_{el} stack)	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
Electricity	1.6%	13.2%	8.7%	5.2%	5.1%	19.9%	0.1%
Platinum	94.2%	63.5%	1.3%	86.1%	88.3%	63.8%	86.6%
Nafion	0.0%	11.9%	0.0%	0.0%	0.0%	2.9%	0.0%
Carbon black	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Steel	0.0%	0.1%	0.1%	0.0%	0.0%	0.1%	0.0%
Stainless steel	2.8%	6.3%	1.6%	3.8%	4.0%	5.9%	9.1%
Alcohol	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%
Copper	0.2%	0.3%	0.4%	0.3%	0.3%	0.3%	3.6%
Polyacrylonitrile fibers (PAN)	0.1%	0.6%	0.2%	0.5%	0.4%	1.0%	0.0%
Polyethylene terephthalate fibers (PET)	0.0%	0.4%	0.4%	0.1%	0.2%	1.0%	0.0%
Silicone	0.1%	0.8%	0.3%	0.4%	0.4%	1.0%	0.3%
Water (desalinated; deionized)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Glass fiber reinforced plastic	0.7%	2.9%	61.0%	3.1%	1.4%	3.8%	0.1%
Chromium steel	0.1%	0.3%	26.2%	0.3%	0.3%	0.4%	0.3%

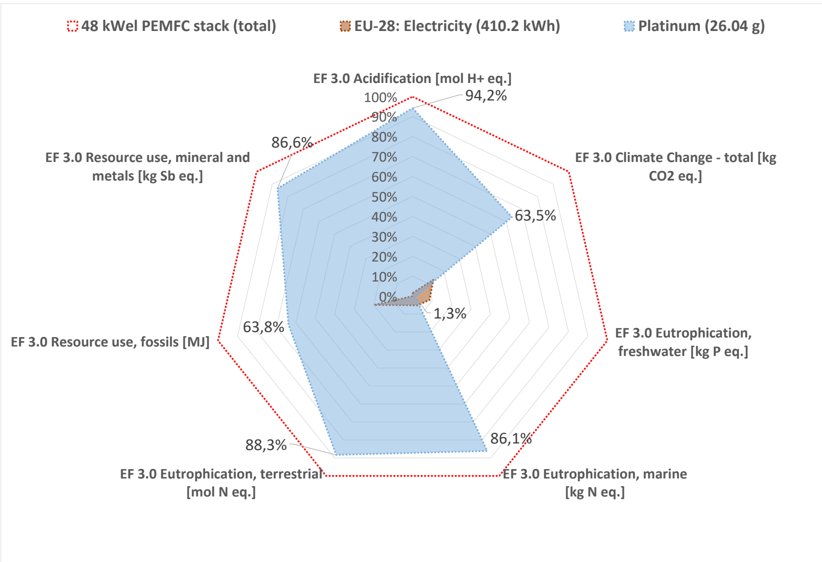

Figure 6: Pt and electricity contribution to the potential environmental impacts of the 48 kW PEMFC stack

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Figure 7: Contribution to EF 3.0 environmental impact results for manufacturing phase of 48 kW PEMFC stack

3.1.4.2 Operational phase

For FCH technologies, the operational phase generally has the greatest environmental impact, especially when grey hydrogen is used for fuel cells and fossil fuel electricity is used for electrolyzers. To evaluate the importance of the operational phase in the eco-design strategy of FCH technologies, the assessment and discussion in WP4 will be performed together with the environmental assessment of all defined product concepts in WP3.

For PEMFC technology, grey hydrogen consumption will be the baseline, and all ecodesign actions will be evaluated based on grey hydrogen consumption in the PEMFC stack. Lifetime of the stack and hydrogen consumption will be defined based on the manufacturer's data (SYMBIO France). The eco-design actions target green hydrogen consumption, efficiency improvement (based on the actions defined in WP3) and lifetime of future product concepts (based on the actions defined in WP3).

3.1.4.3 End-of-life phase

The EoL phase is critical when applying eco-design rules in each technology. Only with relevant inputs from industry and research the EoL phase can be evaluated in a proper way to give results that will show the potentials that technology has in the near-to-medium term or in the long term. In PEMFC technology, actions for eco-design will be introduced in WP3 and evaluated with LCA in WP4. Main inputs will come from the associated BEST4Hy project, and EoL will be integrated into eGHOST with:

- Recycled platinum dataset integration with primary data from the BEST4Hy project, integrated from conventional Pt recycling process (hydrometallurgical).
- Recycled platinum dataset integration with novel recycling technology from the BEST4Hy project.

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- Recycled ionomer dataset integration from recycling strategy from the BEST4Hy project.

Other actions that will be integrated into the EoL phase linked with eco-design actions that will be introduced in WP3:

- Reuse of bipolar and end plates and housing after quality assessment after the stack lifetime. Within this action the development of refurbishing technologies for reusing the bipolar plates is crucial prior to integration.
- Use reusable and recycled materials in packing of the stack prior to final distribution.

When addressing recycled Pt and recycled ionomer, the following recycling strategy will be adapted in the recycling process from the BEST4Hy project:

- The aim is to recover 80-95% of the input Pt, depending on the technology (BEST4Hy target).
- The aim is to recover more than 80% of the ionomer in solution.
- The aim is to recover/refurbish more than 90% of stainless steel from bipolar plates and other components (recovered as a whole or sent to recycling).

Environmental impacts of the product manufacturing phase will be re-evaluated using the targets of the BEST4Hy project, in which product performance of PEMFC components will be undertaken considering the following percentage of recycled content:

- 95% of Pt content from recycling will be tested in new product (BEST4Hy target).
- 70% of ionomer from recycling will be tested in new product (BEST4Hy target).

Based on the previous data, the LCA of the EoL phase performed within WP4 will be done considering:

- Closed recycling loop with the recycled fraction of Pt and ionomer in the production phase as will be available from the recycling process of one 48 kWe PEMFC stack.
- Open recycling loop in which enough recycled Pt and recycled ionomer is available to meet 95% of Pt content from recycling and 70% of ionomer from the recycling process.

3.2 LCA of Solid Oxide Electrolysis Cell stack

The methodology used for the P-LCA of the SOEC stack is detailed in the eGHOST Deliverable 2.1: Assessment methodology. The main inventory data for this evaluation are those presented in Section 2.2 of this document. The ecoinvent 3.7 database is employed for background processes, while using the software SimaPro 9 to implement the LCI and carry out the LCIA.

According to eGHOST purposes, the focus of this section is on the identification of hotspots and possible areas for improvement in terms of environmental impacts. As presented in Table 8, the results show that stainless steel is a hotspot under each of the assessed indicators, along with nickel oxide in terms of acidification.

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Table 8: Relative contribution to the 5 kW SOEC stack life-cycle impacts

	EF 3.0 Climate Change - total [kg CO_2 eq.]	EF 3.0 Acidification [mol H^+ eq.]	EF 3.0 Eutrophication, freshwater [kg P eq.]	EF 3.0 Eutrophication, marine [kg N eq.]	EF 3.0 Eutrophication, terrestrial [mol N eq.]	EF 3.0 Resource use, fossils [MJ]	EF 3.0 Resource use, mineral and metals [kg Sb eq.]
SOEC stack preliminary (5 kW stack)	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
Electricity 2030 (Spain)	12.24%	1.81%	3.76%	7.03%	6.87%	25.46%	3.81%
Wastewater	< 0.01%	< 0.01%	< 0.01%	< 0.01%	< 0.01%	< 0.01%	< 0.01%
Lanthanum oxide	1.08%	0.47%	1.01%	0.84%	0.82%	1.67%	2.29%
Borosilicate	< 0.01%	< 0.01%	< 0.01%	0.01%	0.02%	< 0.01%	0.03%
YSZ	0.86%	0.49%	1.05%	0.91%	1.07%	1.06%	1.05%
Nickel oxide	3.28%	59.59%	12.72%	8.15%	10.22%	2.85%	9.70%
Stainless steel	82.29%	37.55%	81.24%	82.88%	80.82%	68.50%	82.98%
Tape casting water	< 0.01%	< 0.01%	< 0.01%	< 0.01%	< 0.01%	< 0.01%	< 0.01%

Bearing in mind that stainless steel is the material with the highest mass rate within the stack, this reveals the importance of eco-designing the parts of the stack dedicated to mechanical assembly (frames) and electrical conductivity (interconnects, end plates). The absolute results of the LCA for the 5 kW SOEC stack are reported in Table 9.

Table 9: LCA results for the 5 kW SOEC stack

	EF 3.0 Climate change - total [kg CO_2 eq.]	EF 3.0 Acidification [mol H^+ eq.]	EF 3.0 Eutrophication, freshwater [kg P eq.]	EF 3.0 Eutrophication, marine [kg N eq.]	EF 3.0 Eutrophication, terrestrial [mol N eq.]	EF 3.0 Resource use, fossils [MJ]	EF 3.0 Resource use, minerals and metals [kg Sb eq.]
SOEC stack preliminary (5 kW stack)	154.52	2.19	0.059	0.177	1.96	1964.58	0.0058

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The contribution of electricity to the potential impacts is generally moderate in the selected indicators, which is closely linked to the consideration of the Spanish electricity mix for 2030. This consideration is found to be significant since high reductions in the assessed midpoint indicators are observed when compared with the consideration of the current Spanish electricity mix (Figure 8). Such a decrease (23-42%) is observed for every indicator, except for resource use (where a slightly increase occurs; a common trend associated with the relatively high consumption of materials in renewable energy technologies).

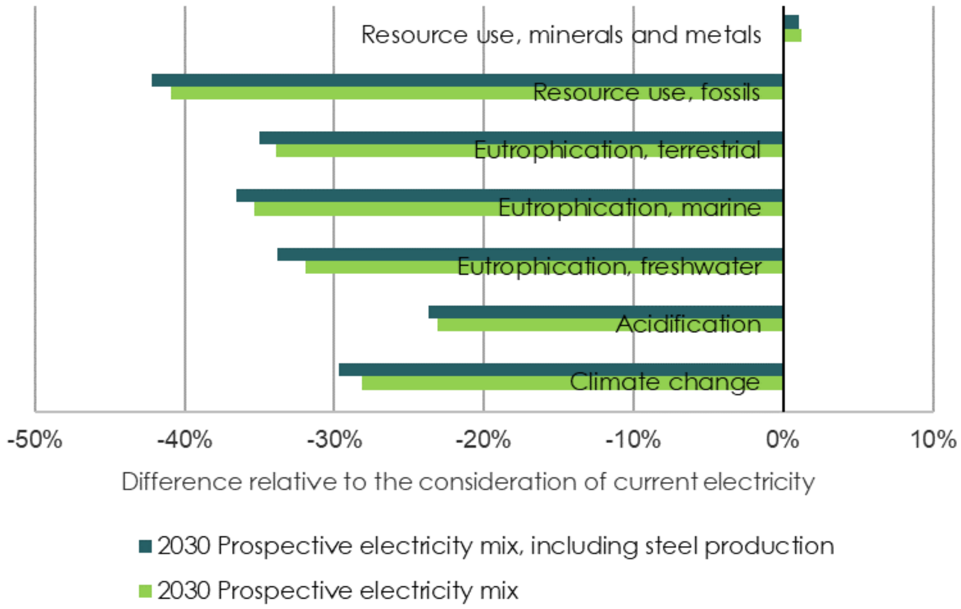

Figure 8: Influence of the consideration of prospective electricity on the LCA results of the SOEC stack

The high contribution of stainless-steel production calls for deeper research into this particular process in order to make it fully prospective. In the framework of this assessment, only the electricity needed for its production is changed to 2030. While the consideration of the prospective electricity mix slightly lowers the results, steel production could additionally benefit from a shift to alternative fuels (other than coke or natural gas) and a rise in energy efficiency.

The results also suggest that the necessary assumptions made to model the different materials and components in the LCA software are acceptable. These were made mainly for LSCF and LSM, which are found to involve a low contribution to the evaluated indicators. Moreover, the results show that the inclusion of a criticality indicator would be convenient since conventional impact indicators do not respond to the particularities the SOEC stack has in terms of CRM.

Overall, these findings show that efforts must be oriented towards increased material efficiency, the improvement of material production processes, and/or the use of alternative materials. The contribution of direct energy flows is lowered because of the prospective approach, also giving meaning to the eco-design goal of the system.

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3.2.1 Operational phase

The operational phase is expected to play a major role due to energy consumption. Its influence on the LCA results will be explored in WP4 when evaluating the eco-designed product concepts for the SOEC technology. The eco-design actions target green energy consumption, efficiency improvement (based on the actions defined in WP3) and lifetime of future product concepts (based on the actions defined in WP3).

3.2.2 End-of-life phase

In prospective SOEC technology, actions for eco-design will be defined in WP3 and assessed in WP4 with LCA. Since the BEST4Hy project addresses SOFC materials similar to those in SOEC technology, the integration of datasets from the recycling process of rare earth materials and other materials is possible. Inputs that will come from the associated BEST4Hy project regarding EoL will include:

- The use of recycled yttria stabilized zirconia (YSZ) and recycled nickel (Ni as NiO) from anode material in solid oxide technology.
- The use of recycled cobalt and recycled lanthanum from cathode material in solid oxide technology.

When addressing recycled YSZ and recycled Ni as NiO, the following recycling strategy will be adapted in the recycling process from the BEST4Hy project:

- The aim is to recover more than 80% of the input YSZ (BEST4Hy target).
- The aim is to recover more than 80% of the Ni as NiO (BEST4Hy target).

Environmental impacts of the product manufacturing phase will be re-evaluated using the targets of the BEST4Hy project, in which product performance of SOFC components will be undertaken considering the following percentage of recycled content (strategy to be adapted to SOEC technology):

- In SOFCs cells, 30% of Ni (as NiO) and 30% of YSZ from recycling will be used according to BEST4Hy targets.

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4. LIFE CYCLE COSTING OF THE REFERENCE PRODUCTS

4.1 General hypotheses and parameters for LCC

Since 2008, CEA has developed internally SOEC and PEMFC stack cost models. Both models were used to monitor the improvements of stack components in several FCH JU-funded projects like IMPALA, IMPACT, MATISSE, COBRA for PEMFC and RAMSES, AGRAL for SOEC. The figure below proposes a schematic representation of the cost model used in this deliverable for the PEMFC stack:

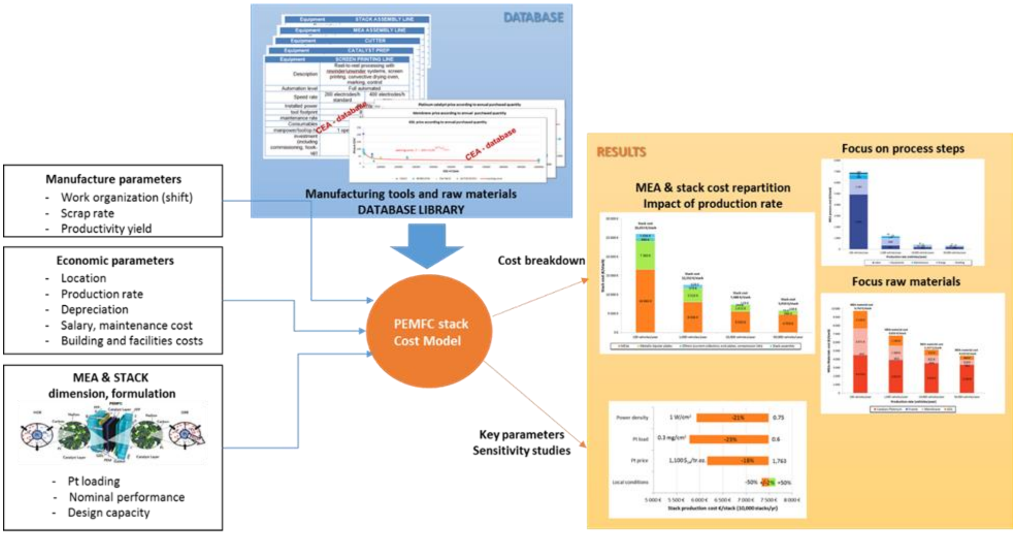

Figure 9: Schematic representation of PEMFC cost model

The model is based on the **Activity Based Costing (ABC) methodology** that decomposes the process of stack manufacturing into elementary process steps with the detailed contributions of raw materials, tool depreciation, labor, energy, consumables, maintenance and quality control. This was described more deeply in D2.1.

The following chapters present the main financial hypotheses and manufacturing parameters as well as the results of the LCC evaluation for both stacks.

4.1.1 Production process description

The annual production rate is a key parameter for LCC. It depends on the application, market size and the business cycle of the product (start-up, growth, maturity, decline). For the SOEC stack in particular, the prospective approach for the LCC requires to **analyze several production rates** in order to estimate the **scale effect on future production cost**.

For both technologies the chosen annual production rates are: 100 – 1,000 – 10,000 – 50,000 stacks/year. 100 units/yr corresponds to laboratory scale and 50,000 units/yr to a medium size plant, just before mass production. Above this value, the volume effect is

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expected to be much lower. The annual production rates involve the production of the following annual quantities:

Table 10: Quantity of active area according to stack production rates

Stacks/year	100	1,000	10,000	50,000
SOEC 5 kW active area	26 m²	260 m²	2,600 m²	13,000 m²
PEMFC 48 kW active area	561 m²	5,606 m²	56,056 m²	280,280 m²

Indeed, quotations from raw material suppliers and tool makers were done for several production rates. For intermediate production volumes, the cost model adapts automatically the process parameters to fit the new scale. The material costs corresponding to the annual purchased volume are interpolated applying the formula below, which considers both scale and learning effects (the latter based on three or more price quotes corresponding to different annual purchased quantities):

$$P_n = P_0 \times Pr^{\left(\frac{ln\left(\frac{Q_n}{Q_0}\right)}{ln2}\right)}$$

Where P_n is the price at the desired annual production quantity Q_n , given the initial quotation price P_0 at an initial quantity Q_0, and a progress ratio Pr. Pr can be derived from industry data if two sets of price quotes are provided at least.

Stack vertical manufacturing integration: in the stack cost assessment, each subcomponent of the stack is independently considered, with materials and processes costs evaluated through exhaustive cost models, supplier quotes or bibliographical data. Vertical integration is largely assumed for cell and stack assembly. Figure 10 displays a simplified view of the PEMFC stack manufacturing integration.

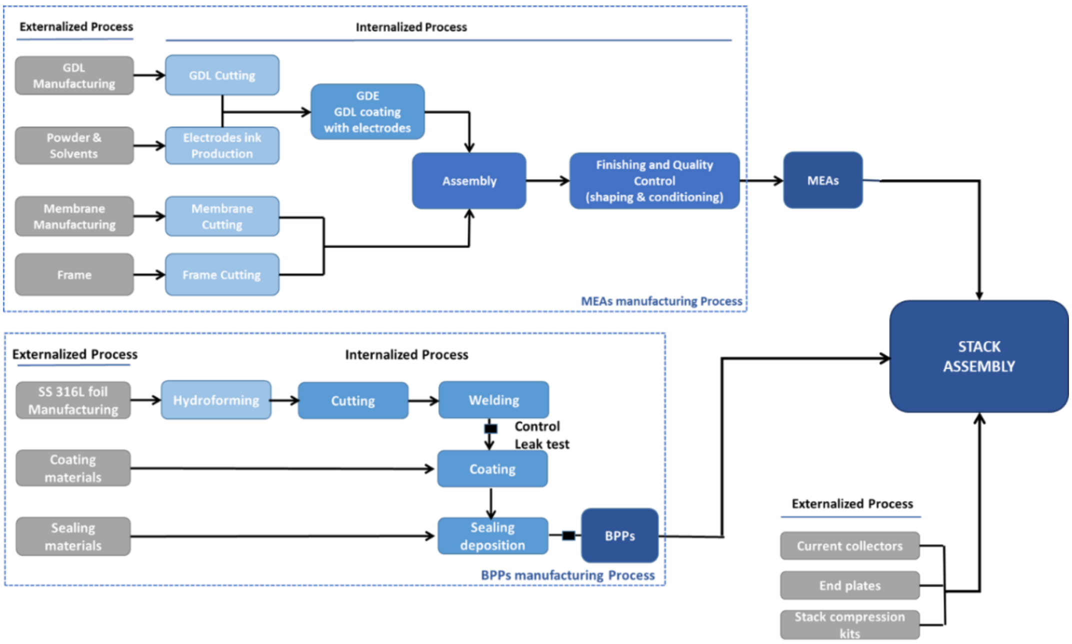

Figure 10: Vertical manufacturing integration of PEMFC stack

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4.1.2 Main process cost parameters

Process costs can be split into six main cost categories:

- Infrastructure and surface costs.
- Energy and consumables costs.
- Labor cost.
- Maintenance cost.
- Raw materials.
- Scrap rate and loss of preparation.

Some of their parameters depend on the plant location, like labor cost and energy costs. The plant is supposed to be located in Europe.

Building and facilities cost: The cost of infrastructure is evaluated taking into account the surface footprint (m^2) of each machine and multiplying by a factor of 3 to define the process building surface (m^2) and else by a factor 2 for the facilities and administrative building. It is assumed that the infrastructure cost (rental, cleaning, lightening, insurance…) of these buildings is about 200 €/m^2/year.

Energy and consumables cost: it is supposed that the manufacturing plant will mainly consume electricity. Eurostat provides electricity prices in industry for different European countries in 2019 as presented in the following table. Values depend on the annual consumption and are indicated without recoverable taxes and levies.

Table 11: Electricity price in industry excl. recoverable taxes and levies *(source: Eurostat* [16])

	20 – 500 MWh/yr	0.5– 2 GWh/yr	2 – 20 GWh/yr	20–70 GWh/yr	70 – 150 GWh/yr
Spain	99	83	65	61	53
Euro area	101	84	72	63	55

Labor cost is determined thanks to the Eurostat database. estimating in 2020 [17] the average hourly labor costs in the EU Member States, with hourly labor costs ranging between 6.5 €/h in Bulgaria and 45.8 €/h in Denmark and 23 €/h for Spain. Additionally, the number of working hours per year in the manufacturing plant has to be adjusted depending on the shift work organization (1x8, 2x8, 3x8, 5x8), as well as salary premiums for shift work.

It is assumed that the calculation of effective days per year takes into account the necessary maintenance periods (here, an assumption of 35 days per year is considered). The work organization can vary from one process step to another, especially when high time difference occurs between manufacturing steps.

Table 12: Number of effective hours per year depending on shift work organization scheme

	Number of effective days per year	Number of effective hours per year
1x8	198	1,584
2x8	198	3,168
3x8	198	4,752
5x8	330	7,920

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The salary premiums are considered as follows:

- + 6.25% salary for 2x8 work shift (morning/afternoon)
- + 13.33% salary for 3x8 work shift (morning/afternoon/night)
- + 16.32% salary for 5x8 work shift (morning/afternoon/night/weekend)

The employment of the different socio-professional categories is calculated as follows:

1. Calculation of manpower time related to equipment utilization (number of working hours for a qualified employee).
2. Implementation of time ratios: management ratio 15% time "foreman" and 2.25% (15%x15%) time "engineer".
3. Additionally, the supporting work tasks (accountability, human resources, R&D, etc.) are considered by multiplying the total salary mass by a factor 1.2.

Capital investment and depreciation: the tools prices obtained from quotes are multiplied by 1.3 to consider the installation cost. Moreover, to update quotation obtained few years ago, the index CEPCI for Chemical Engineering Plant Cost is applied.

The capital depreciation is calculated based on a depreciation time depending on the equipment type as presented in the following table:

Table 13 : Depreciation time depending on equipment type

	Depreciation time
Building	20 years
Equipment	10 years
Furniture	10 years
Tooling	5 to 10 years

Maintenance cost was systematically asked to equipment providers. In case this data is not available, the following approach is considered:

- annual maintenance cost of 4% of machine purchase price, if the machine is used continuously (3x8 or 5x8 work organizations)
- 3% of machine purchase price in the other cases (1x8, 2x8)

When the equipment is used below its nominal load, the maintenance cost is supposed to be proportional to the effective machine time (maintenance percentage is multiplied by the time ratio between effective machine time and maximal machine time). Nevertheless, it is assumed that if effective machine time is below 0.5x maximal machine time, the maintenance ratio is kept as the half of the predefined full use machine ratio.

Scrap rate and raw material loss: scrap rate was fixed according to the manufacturing scale as follows:

Table 14: Assumption on scrap rate according to manufacturing scale

Process steps	150 m²/yr.	15,000 m²/yr.
Cell manufacture	18%	4%
Stack conditioning	10%	2%

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Moreover, in the manufacturing process, the following loss of raw materials was considered: 20% on ceramic powders and chemicals, and 30% of cutting waste on metal foil and mica sheet.

Process tools: the different tool makers involved in the process line were consulted in order to define the specification of the corresponding equipment: capital cost, manpower, consumables, maintenance rate and surface footprint.

When possible, several equipment ranges were requested to cover different throughput and level of automation. This information was used to constitute the process tool database.

Raw materials database: quotations from raw material suppliers and subscription to market database on metal and rare earth (metalprices.com) enabled to build a raw material database. The cost requests were made for three or more production rates in order to establish the relationship between price and purchased volume, applying the formula described in the previous chapter.

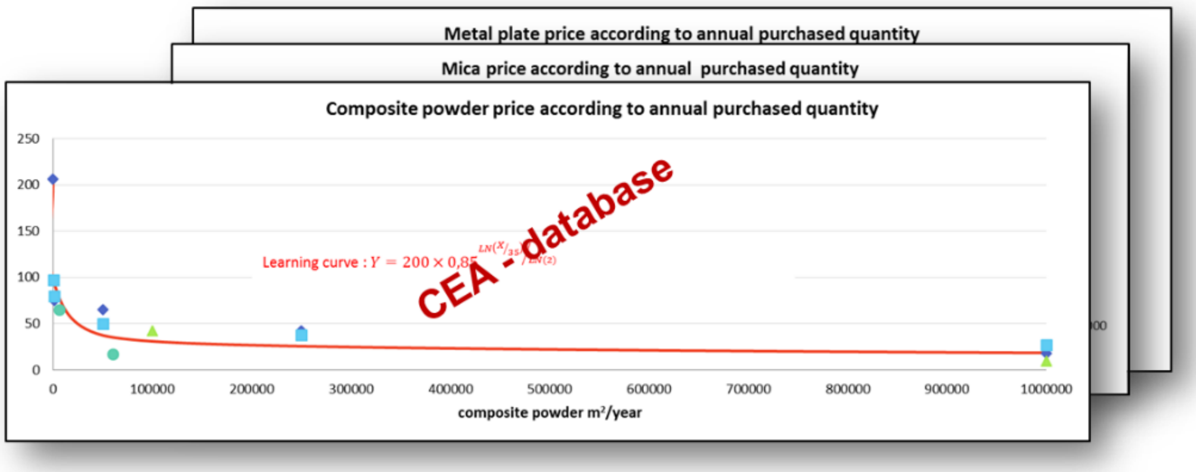

Figure 11 : Example of raw material price interpolation curves

4.2 LCC of Proton Exchange Membrane Fuel Cell stack

4.2.1 Manufacturing parameters according to production rate

The following table presents the impact of the selected production rate on process and materials data. The cost value for the MEA materials and assembly equipment are from [6], whereas platinum catalyst and metallic bipolar plate are from the CEA database.

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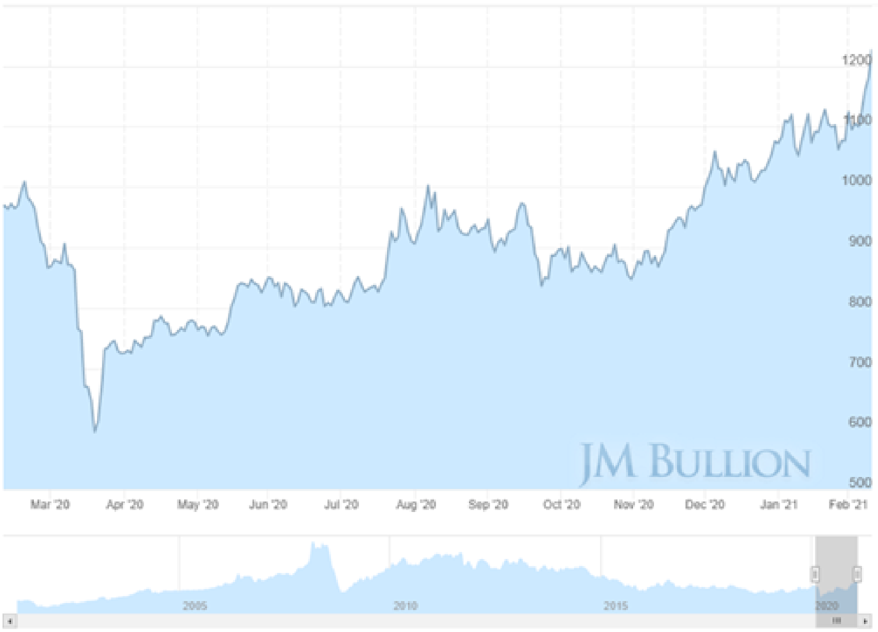
Table 15: PEMFC BoM and unit price according to quantity purchased

BoM - Bill of materials		Quantity	Unit Price (€/unit)				
			stacks/yr	100	1,000	10,000	50,000
Components	Materials	/stack	Unit \ m²/yr	560	5,600	56,000	280,000
Catalyst	PtC (46.9% Pt)	26	g Pt	57.0	50.0	45.0	42.0
	Nafion	0.018	kg	14 322	8 347	4 864	3 335
	Propanol	0.11	kg	0.9	0.8	0.7	0.6
GDL	GDL	13.96	€/m²	512.7	149.5	43.6	18.4
Membrane	Membrane	6.0	€/m²	835.7	321.4	123.6	63.4
Frame	PTFE	21.0	€/m²	1.4	1.3	1.2	1.2
BPP	Steel roll	17.36	kg	5.0	5.0	5.0	5.0
	Coating	8.4	g	0.8	0.8	0.8	0.8
Assembly equipments	End plates	1	unit/stack	101.0	46.0	41.0	32.0
	Assembly hardware current collector, clamping, compression bar	1	unit/stack	54.0	50.0	47.0	45.0

Figure 12: Platinum market price from March 2020 to February 2021 in $ per ounce [18]



Concerning the platinum catalyst value, it includes (1) the value of the precious metal (market price), which can be very volatile as illustrated in Figure 12, and (2) the mark-up cost that covers the production costs and indirect costs of the manufacturer. According to a recent discussion with suppliers, this mark-up cost corresponds to 10-20 €/g Pt depending on volume. The Pt cost on 04.06.2021 was 1,165 $/oz (33.16 €/g). Thus, the catalyst price was determined by the following formula:

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$$P_{Pt}(€/g) = 33.16 + 20 \times P_r^{\left(\frac{ln\left(\frac{Q_{Pt}}{1000}\right)}{ln2}\right)}$$

With P_r (progress ratio) of 0.9 and Q_{Pt} standing for the annual quantity of platinum. The next table presents the main characteristics of the stack plant for different scales:

Table 16: PEMFC plant characteristics according to production scale

Process	**Process scale (stacks/yr)**	**100**	**1,000**	**10,000**	**50,000**
Bill of materials		1,424 k€	5,724 k€	28,506 k€	100,938 k€
Operating shift		1x8	1x8	3x8	3x8
Cells (MEA) manufacturing process					
Catalyst preparation	**Ball milling**	1 line	2 lines	2 lines	4 lines
Layers deposition	**Screen printing**	1 tool	1 tool	4 tools	18 tools
Hot press	**Hot press**	1 tool	1 tool	5 tools	9 tools
Cutting	**Cutting**	1 tool	1 tool	1 tool	3 tools
Control	**Control (IR, leak test...)**	1 tool	1 tool	2 tools	3 tools
Bipolar plate (BPP) manufacturing process					
Metal foil preparation	**Decoiling, flattening**	1 tool	2 tools	2 lines	4 lines
Forming	**Stamping, cutting**	1 tool	1 tool	2 tools	9 tools
Welding	**Laser welding**	1 tool	7 tools	6 tools	26 tools
Coating	**Coating**	1 tool	1 tool	2 tools	13 tools
Control	**Control (IR, leak test...)**	1 tool	1 tool	1 tool	3 tools
Stack assembly					
Assembly	**Automate**	1 tool	2 tools	2 tools	10 tools
Press	**Press**	1 tool	1 tool	1 tool	2 tools
Test	**Bench**	1 tool	1 tool	1 tool	3 tools
Capital investment	**(installed equipment)**	7,856 k€	13,842 k€	24,561k€	111,750k€
Building cost		250 k€/yr	580	876	3,870
Process building surface		400 m²	1,500 m²	2,190 m²	9,445 m2
Tooling, consumables		13 k€/yr	134 k€/yr	1,340 k€/yr	6,740 k€/yr
Energy consumption		100 MWh	1,058 MWh	11,000	52,813
Maintenance cost		292 k€/yr	640 k€/yr	1,770	10,327
Manpower **Labor total operators, technicians, managers**		32 k€/yr 2 operators, 1 technician, 1 manager	512 k€/yr 5 operators, 2 technicians, 1 manager	1647 17 operators, 4 technicians, 2 managers	2320 80 operators, 12 technicians, 7 managers

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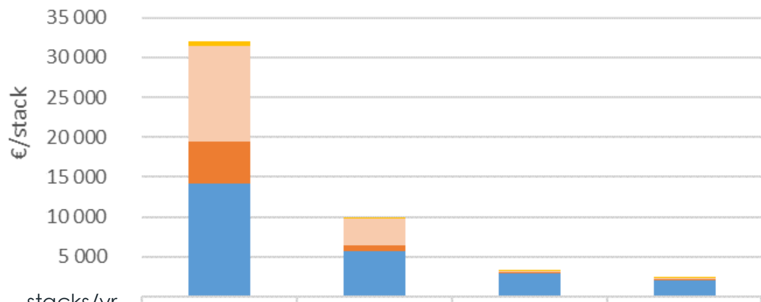
4.2.2 Manufacturing cost results

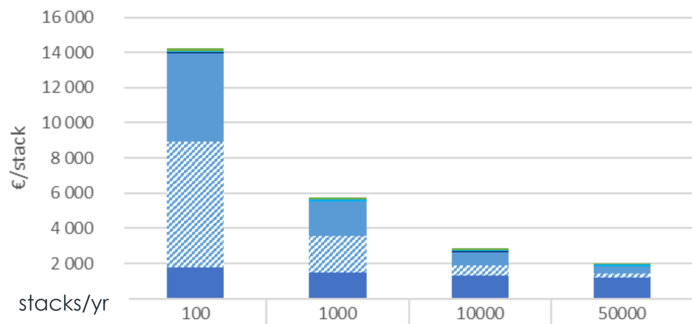
The cost assessment is held on the 48 kW PEMFC manufacturing cost for the four production scales.



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**

Figure 13: PEMFC cost distribution according to production rate

The cost of the stack is very dependent on the production rate. The transition from laboratory to industrial scale enables to divide the cost more than three times by acting on both process and material costs. For 10,000 stacks and above, the process part becomes insignificant compared to the BoM. Figure 14 details the materials cost distribution.



stacks/yr	100	1000	10000	50000
Assembly	155	96	88	77
BPP	94	94	94	94
frame	29	28	25	25
membrane	5 019	1 930	742	381
GDL	7 156	2 086	608	257
catalyst	1 785	1 490	1 293	1 185
Total	**14,238**	**5,724**	**2,851**	**2,019**

Figure 14: PEMFC BOM cost distribution according to production rate

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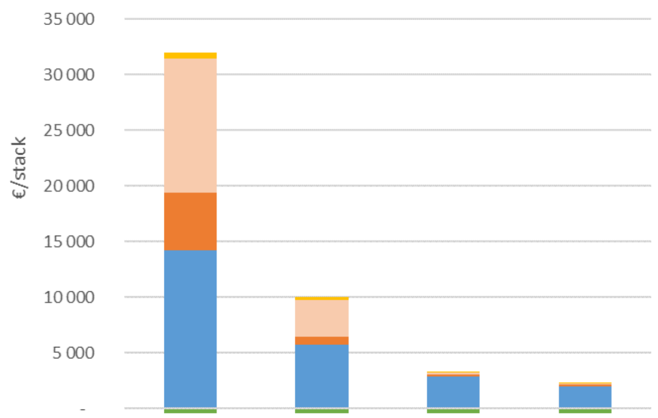
At low production rates, GDL and membrane are the key drivers, however their prices decrease rapidly with the economy of scale and, above 10,000 stacks per year, the Pt catalyst becomes the main driver with more than half of the material contribution.

4.2.3 Decommissioning and recycling credit

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 stack life. It could be possible as well to recover metal bipolar plates or Nafion ionomer but the cost-effectiveness remains unclear. Concerning platinum, we do not know yet what would be the financial paradigm. Nevertheless, several analyses of platinum recycling have already been conducted [19], [20]. 90% of the initial Pt load should be recovered. The cost of recycling has to be considered as well as the cost of the supply chain of the salvage. Based on current practice, the salvage expects to be paid by the recycler about 70%-75% of the total value of recycled platinum, with the remaining Pt value going to the recycler as payment for the recycling process. Finally, due to platinum market price volatility, it is unlikely that the Pt price will be exactly the same at system purchase as it is 10 years later at the time of recycling. For purposes of the baseline LCC, the price of platinum is held constant at the purchase price used for the catalyst within a new vehicle (50 €/g). In our reference stack, the Pt quantity in the 48 kW PEMFC stack is 26.8 gr. The recycling credit would be: 26.8 x 0.9 x 0.7 x 50 = 844 €/stack. Considering the 10 years lifetime of a vehicle and a discount rate of 8% (usual for innovative processes), the discounted value of the recycled platinum is: 844 €/stack x $(1+0.08)^{-9}$ = 422 €. Figure 15 presents the corresponding PEMFC LCC results.



stacks/yr	100	1000	10000	50000
Pt recycling	- 422	- 422	- 422	- 422
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

Bill of materials, MEA process, BPP process, Assembly process, Pt recycling

Figure 15: LCC results for one 48 kW PEMFC stack according to production scale (including Pt recycling)

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4.3 LCC of Solid Oxide Electrolysis Cell stack

4.3.1 Manufacturing parameters according to production rate

The following table presents the impact of the selected production rate on process and materials data.

Table 17: SOEC BoM and unit prices according to quantity purchased

BoM – Bill of Materials		Quantity without losses	Unit Price (source: [6])				
		LCI	stacks/yr	100	1,000	10,000	50,000
		/SOEC stack	Unit \ m²/yr	26	260	2,600	13,000
Electrolyte	Yttria-stabilized zirconia 8% mol (8YSZ)	0.007	kg	63.80	44.96	31.68	24.81
	Binder Dow B-1000/B-1014	0.003	kg	7.41	4.32	2.52	1.73
	Dispersant ammonium polyacrylate	0.0001	kg	7.93	4.62	2.70	1.85
	Water	0.002	kg	0.18	0.11	0.06	0.04
Anode LSCF layer	Lanthanum Strontium Cobalt Ferrite	0.072	kg	201.20	141.78	99.91	78.23
Anode contact layer	YSZ/LSM	0.017	kg	172.48	121.55	85.65	67.07
Anode active layer	YSZ/LSM	0.009	kg	172.48	121.55	85.65	67.07
Cathode	Yttria-stabilized zirconia 8% mol (8YSZ)	0.215	kg	6380	44.96	31.68	24.81
	Nickel oxide (NiO)	0.306	kg	60.76	42.82	30.17	23.63
	Binder Dow B-1000/B-1014	0.199	kg	7.41	4.32	2.52	1.73
	Dispersant ammonium polyacrylate	0.008	kg	7.93	4.62	2.70	1.85
	Water	0.099	kg	0.18	0.11	0.06	0.04
Interconnects	Ferritic stainless-steel SS-441	1.477	kg	3.11	1.81	1.06	0.72
Frames	Ferritic stainless-steel SS-441	8.410	kg	3.11	1.81	1.06	0.72
Perovskite coating	Perovskite coating	0.028	kg	410.53	289.29	203.86	159.62
Anode mesh	Ferritic stainless steel	1.502	kg	208.07	146.62	103.32	80.90
Cathode mesh	Ferritic stainless steel	2.308	kg	208.07	146.62	103.32	80.90
Sealant	Lanthanum oxide	0.012	kg	162.64	114.61	80.76	63.24
	Borosilicate glass	0.016	kg	10.51	6.13	3.57	2.45
End plates	Stainless steel Hastelloy X	7.585	kg	34.22	24.11	16.99	13.31

The cost value for the SOEC materials are from [6]. The next table presents the main characteristics of the stack plant for different scales:

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Table 18: SOEC plant characteristics according to production scale

Process	Process steps	100 stacks/yr	1,000 stacks/yr	10,000 stacks/yr	50,000 stacks/yr
Bill of materials		137 989 €	967 641 €	6 791 171 €	26 522 571 €
Operating shift		1x8	1x8	3x8	3x8
Cells manufacturing process					
Slurries preparation	**Ball milling**	1 line	2 lines	4 lines	4 lines
Cathode support	**Tape casting, cutting**	1 tool	1 tool	1 tool	1 tool
Layers deposition	**Screen printing**	1 tool	1 tool	2 tools	4 tools
Sintering	**Sintering**	1 tool	1 tool	3 tools	9 tools
Control	**Control (IR, leak test...)**	1 tool	1 tool	1 tool	3 tools
Stack assembly					
Interconnect	**Punch**	1 tool	1 tool	2 tools	6 tools
Interconnect	**Coating**	1 tool	1 tool	1 tool	3 tools
Interconnect	**Heat treatment**	1 tool	1 tool	1 tool	3 tools
Interconnect	**Laser welding**	1 tool	1 tool	2 tools	6 tools
Mesh	**Laser cutting**	1 tool	1 tool	4 tools	6 tools
End plates					
Conditioning	**Sintering**	1 tool	7 tools	62 tools	310 tools
Capital investment	**Installed equipment**	3,420 k€	6,070 k€	11,000 k€	46,200 k€
Building cost		55 k€/yr	84 k€/yr	360 k€/yr	1,626
Process building surface		300 m²	420 m²	1000 m²	4000 m²
Tooling, consumables		10 k€/yr	70 k€/yr	200 k€/yr	500 k€/yr
Energy consumption		83 MWh/yr	769 MWh/yr	6,700 MWh/yr	33,400 MWh/yr
Maintenance cost		170 k€/yr	379 k€/yr	670 k€/yr	2,838 k€/yr
Manpower **Labor total operators, technicians, managers per shift**		115 k€/yr 2 operators, 1 technician, 1 manager	821 k€/yr 8 operators, 5 technicians, 1 manager	2,000 k€/yr 28 operators, 12 technicians, 2 managers	5,650 k€/yr 60 operators, 20 technicians, 3 managers

4.3.2 Manufacturing cost results and LCC

The production cost assessment is held on the 5 kW_{gross} SOEC for four production scales. The cost of the stack is very dependent on the production rate. The transition from laboratory to industrial scale could enable to divide the cost almost by five acting on both process and material costs. For 10,000 stacks and above the economy of scale effect becomes much lower and the bill of materials plays a bigger part. Figure 17 details the materials cost distribution. For any production rate, interconnects including meshes remain the key drivers.

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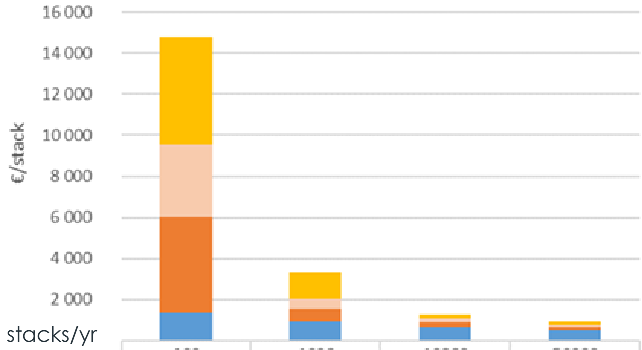
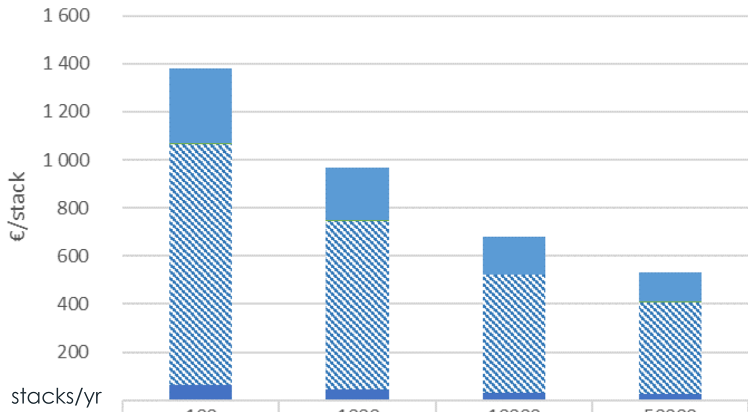


stacks/yr	100	1000	10000	50000
Conditioning	5 222	1 258	234	172
Interconnect & assembly	3 538	497	152	112
Cells	4 637	598	241	126
Bill of materials	1 380	968	679	530
TT (€/stack)	**14,777**	**3,321**	**1,302**	**940**

Figure 16: SOEC cost distribution according to production rate



stacks/yr	100	1000	10000	50000
end plates	311	219	155	121
sealant	2	2	1	1
interconnects	1 002	702	492	384
cells	64	45	32	25
TT (€/stack)	**1,380**	**968**	**679**	**530**

Figure 17: SOEC BoM cost distribution according to production rate

Concerning the end of life of the SOEC stack, material recyclability needs to be demonstrated as well as its cost-effectiveness. Then, at this stage, only the production step of the SOEC stack is taken into account in the LCC.

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4.4 Environmental LCC for Proton Exchange Membrane Fuel Cell stack

The environmental LCC carried out in this work is based on the Environmental Prices methodology as explained in eGHOST Deliverable 2.1. The results of this evaluation aim at translating the LCA results into monetary values. In this case, the external costs are calculated for climate change, as well as for marine and freshwater eutrophication. These costs have to be interpreted as the loss of welfare society could experience due to an additional unit of environmental impact in the selected impact indicators.

The environmental price of the 48 kW PEMFC stack is 70.14 €$_{2015}$, with the climate change category contributing the most (Table 19).

Table 19: External costs of the PEMFC stack

Impact category	Environmental price	Unit	LCA result	External cost (€$_{2015}$)
Climate change	0.0566	€/kg CO_2 eq	1,160	65.66
Freshwater eutrophication	1.86	€/kg P eq	0.005	$9.30 \cdot 10^{-3}$
Marine eutrophication	3.11	€/kg N eq	1.44	4.48
Total				**70.14**

4.5 Environmental LCC for Solid Oxide Electrolysis Cell stack

The environmental price of the 5 kW SOEC stack is 9.41 €$_{2015}$, with the climate change category contributing the most (Table 20).

Table 20: External costs of the SOEC stack

Impact category	Environmental price	Unit	LCA result	External cost (€$_{2015}$)
Climate change	0.0566	€/kg CO_2 eq	154.522	8.75
Freshwater eutrophication	1.86	€/kg P eq	0.0588	0.11
Marine eutrophication	3.11	€/kg N eq	0.177	0.55
Total				**9.41**

4.6 Eco-efficiency assessment of the reference products

The eco-efficiency assessment of both FCH products (with an annual production of 10,000 stacks) is carried out using climate change as the environmental life-cycle indicator. In this sense, a high quotient refers to a high economic value (numerator; inverse of the total production cost without externalities) and a low climate change

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impact (denominator). A high score is therefore interpreted as a good compromise between the economic and environmental spheres.

The analysis yields a result of 5.27 · 10^{-6} ($€_{2015}$/stack · kg CO_2 eq/stack)$^{-1}$ for the 5 kW SOEC stack, and 2.81 · 10^{-7} ($€_{2015}$/stack · kg CO_2 eq/stack)$^{-1}$ for the 48 kW PEMFC. These eco-efficiency scores serve as starting points in the eGHOST project to benchmark future options that will be proposed under the eco-design framework of the project.

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5. SOCIAL LCA OF THE REFERENCE PRODUCTS

5.1 Proton Exchange Membrane Fuel Cell stack

An S-LCA is carried out for the 48 kW PEMFC stack, following the methodological choices detailed in eGHOST Deliverables 2.1 and 2.2. The focus of the analysis is on the identification of social hotspots.

In order to define the supply chain of the PEMFC stack, the materials and components provided in the conventional inventory are categorized as follows:

- **Components:** MEA, bipolar/end plates, gaskets, connectors, and current collectors.

- **Materials:** platinum, PFSA, polyethylene terephthalate (PET), thermoactive glue, carbonaceous compounds, stainless steel, glass-reinforced thermoplastic, and silicone.

The BoM is categorized according to the previous components/materials based on data availability on economic flows of commodities in databases such as UN Comtrade and Eurostat. Figure 18 shows the rearranged inventory along with the identification of the manufacturing countries involved in the resultant supply chain of the PEMFC stack [21]. Monetary values are expressed in 2015 United States dollars and are consistent with those in the LCC section for an annual production of 10,000 stacks. Values in Figure 18 refer to one PEMFC stack.

The S-LCA results in terms of process contribution to the selected social indicators are shown in Figure 19 (the label "Rest" embeds all processes with a contribution below 3% to every indicator). **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. 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 [22]. The production of carbonaceous compounds in China arises as the main contributor to economic development (the only positive social indicator assessed). In general, materials production plants are found to be more relevant than the other manufacturing plants (i.e. those linked to the main product and its components); in this regard, only bipolar and end plates manufacturing accounts for a significant share in five of the indicators, mainly because of their mass relevance in the stack. 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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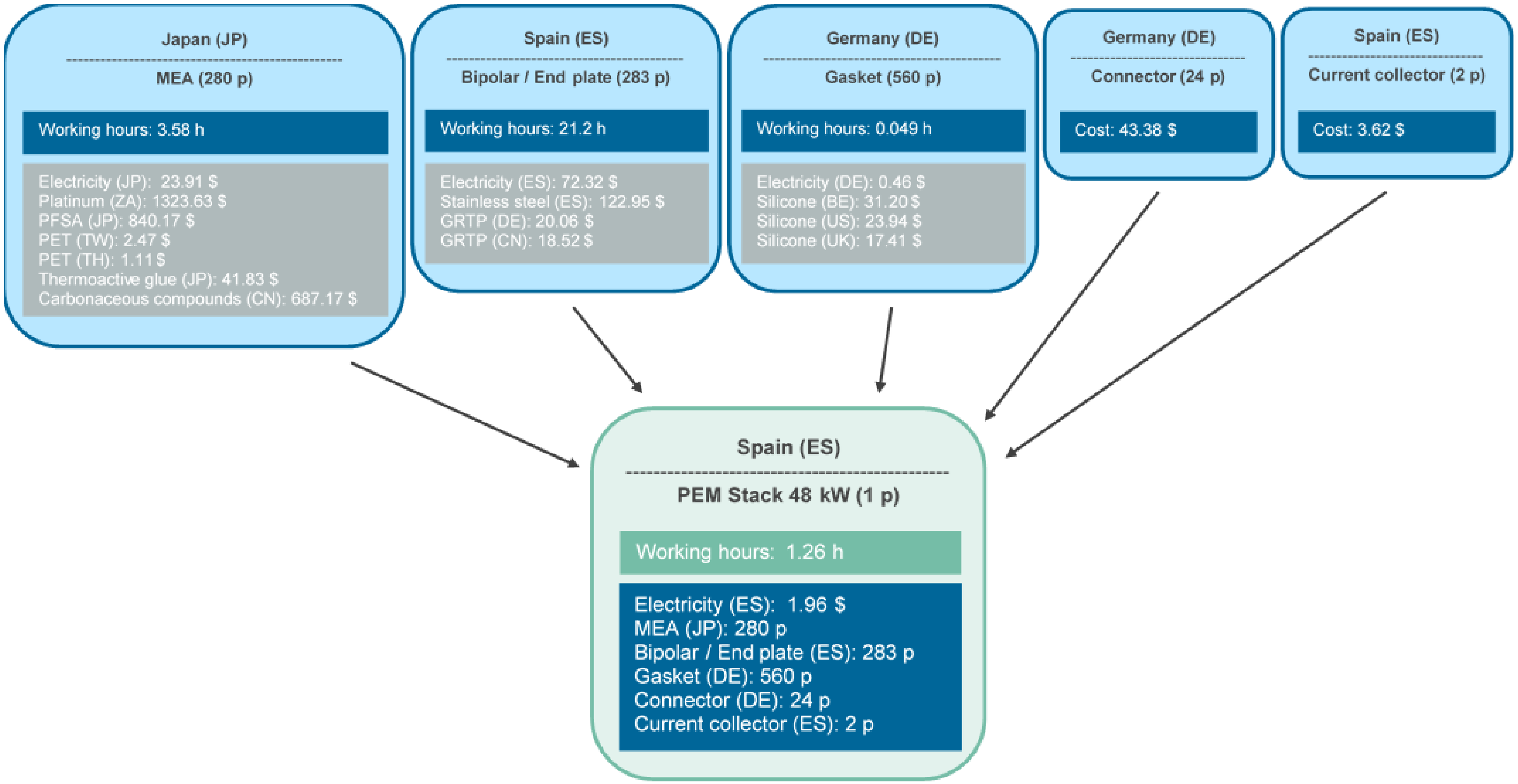

Figure 18: Supply-chain inventory of the 48 kW PEMFC stack

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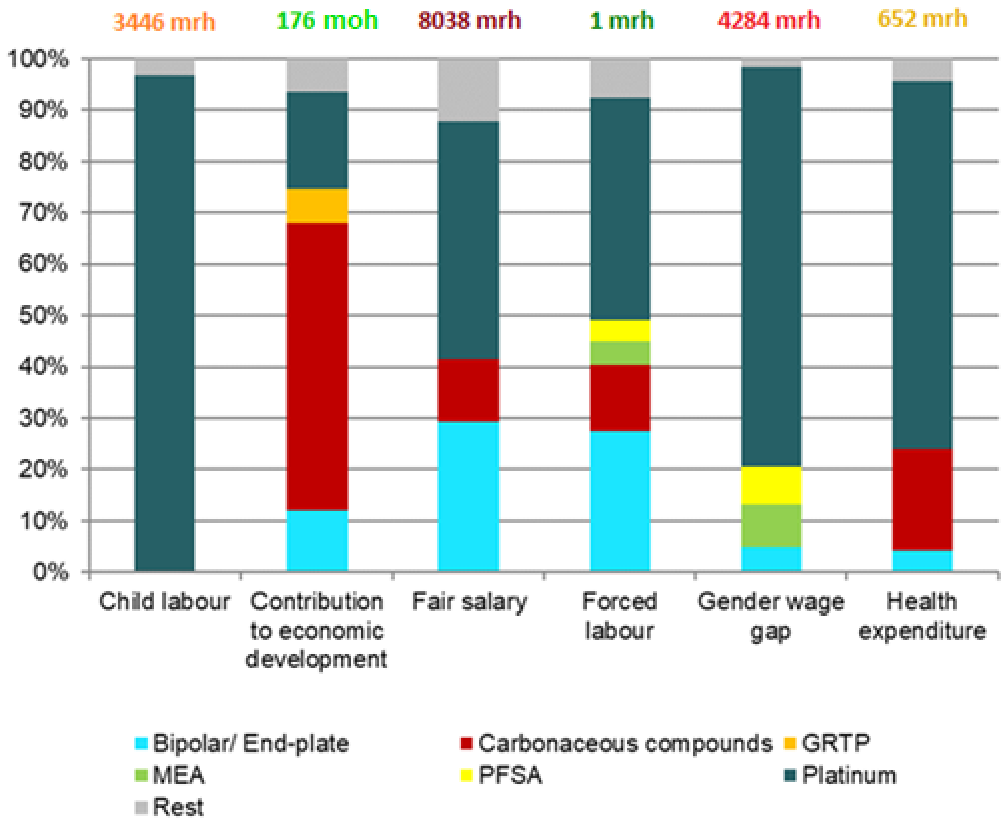

Figure 19: Contribution to the potential social impacts for the 48 kW PEMFC stack

5.2 Solid Oxide Electrolysis Cell stack

An S-LCA study is also carried out for the 5 kW SOEC stack, again following the methodological choices detailed in eGHOST Deliverables 2.1 and 2.2 and focusing on the identification of social hotspots. In order to define the supply chain of the SOEC stack, the materials and components provided in the conventional inventory are categorized as follows:

- **Components:** cermet preparations, nickel-based catalyst, frames & plates, anode & cathode meshes, sealant, and connectors.

- **Materials:** zirconium dioxide, cobalt oxide, yttria, iron oxide, strontium oxide, manganese oxide, nickel oxide, perovskite, stainless steel, boron oxide, silicates, and lanthanum oxide.

This categorization takes into account data availability on economic flows of commodities in databases such as UN Comtrade and Eurostat. Figure 20 shows the rearranged inventory along with the identification of the manufacturing countries involved in the resultant supply chain of the SOEC stack [21]. Monetary values are

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expressed in 2015 United States dollars and are consistent with those in the LCC section for an annual production of 10,000 stacks. Values in Figure 20 refer to one SOEC stack.

The SLCA results in terms of process contribution to the selected social indicators are shown in Figure 21 (the label "Rest" embeds all processes with a contribution below 5% to every indicator). Values in Figure 21 refer to one SOEC stack. **Stainless-steel production in Spain is found to be the main social hotspot**, arising as the major contributor to 5 out of 6 indicators. This is mainly due to the high economic flow associated with the stainless steel as a consequence of its high mass rate in the SOEC stack. In general, the materials production plants account for a higher share than the components manufacturing plants, although the potential social impacts are found to be more distributed across tiers than in the PEMFC stack case study. The plants linked to SOEC stack manufacturing (assembly and testing), cermet preparations and nickel-based catalyst account for a significant share in at least 5 out of 6 indicators. The indicator "child labor" shows an impact distribution that significantly differs from that observed in the other indicators; under this indicator, materials produced –at least partially– in China (zirconium dioxide, iron oxide, and lanthanum oxide) arise as the most relevant contributors. Finally, the social risks associated with energy flows play a minor role, which is linked to the countries involved for these flows.

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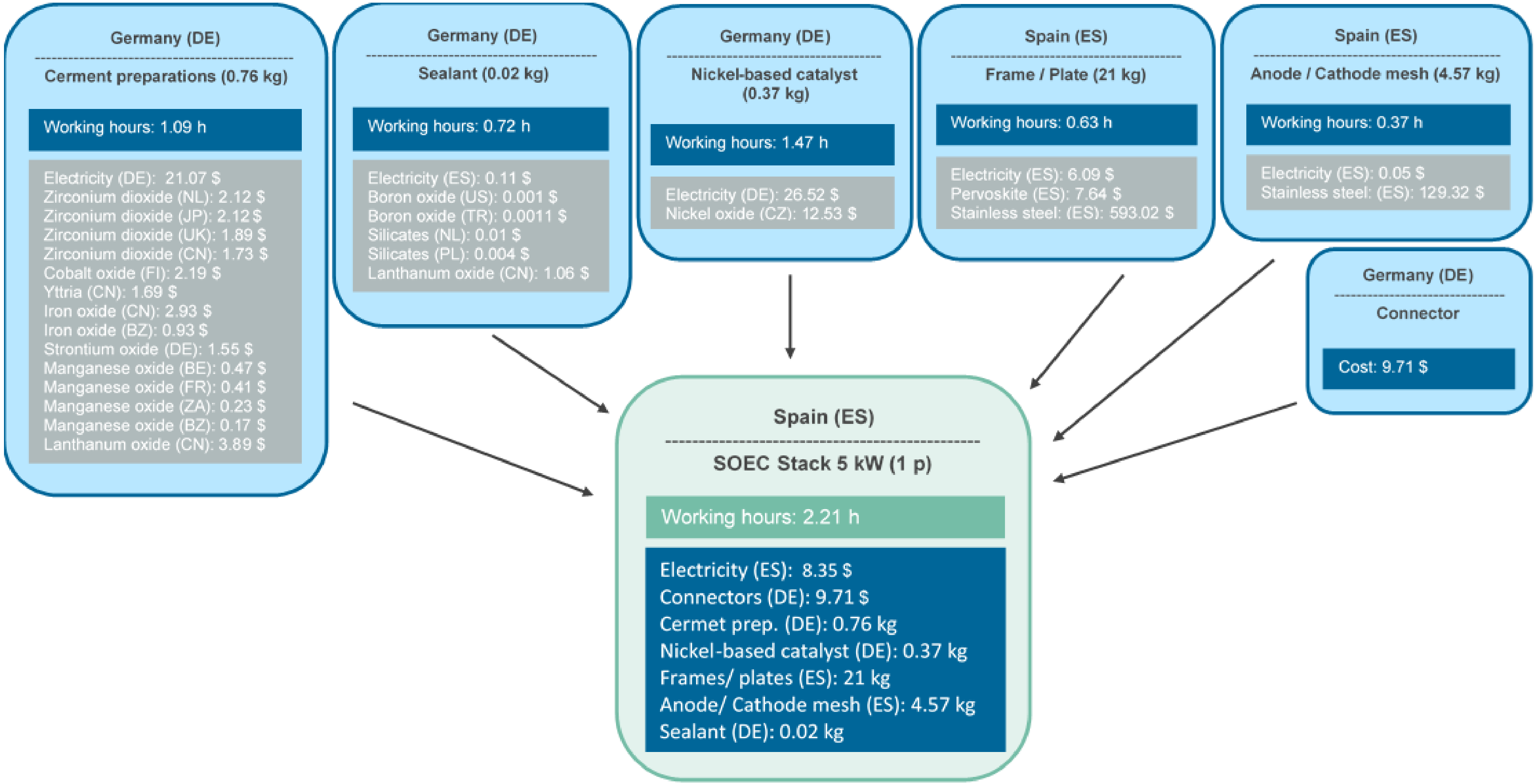

Figure 20: Supply-chain inventory of the 5 kW SOEC stack

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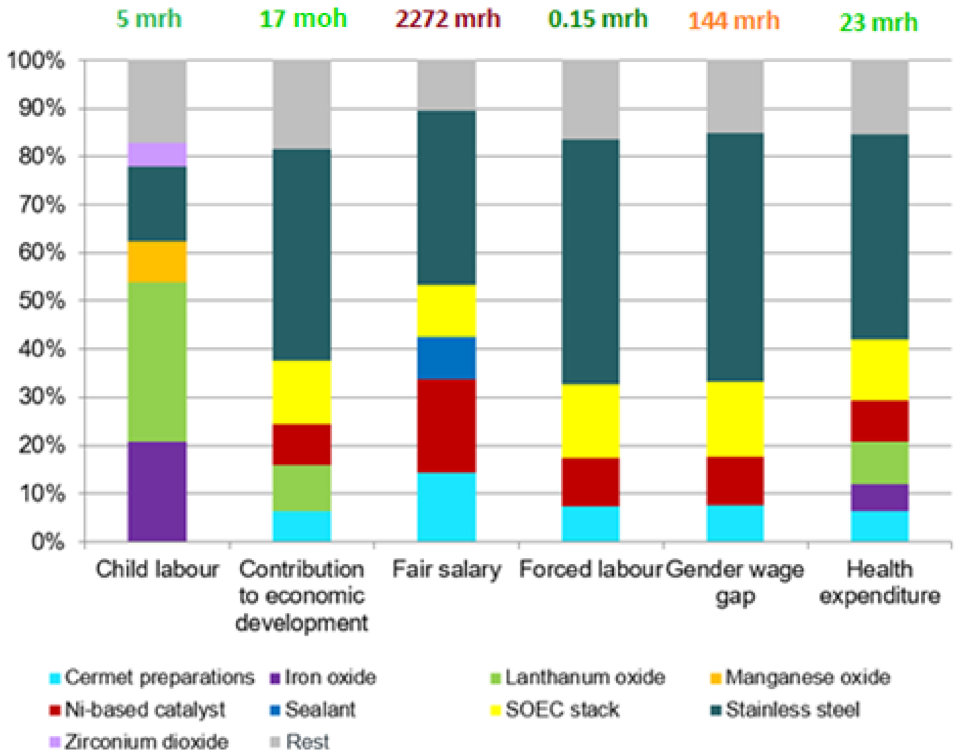

Figure 21: Contribution to the potential social impacts for the 5 kW SOEC stack

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CONCLUSIONS

A key objective of this deliverable was to define the two FCH systems (PEMFC & SOEC) that will be subject to eco-design for the eGHOST project. A second objective was **to evaluate their environmental, social and economic performances**. Below, a summary of the main results and conclusions related to these objectives is presented:

- **Definition of the reference products (PEMFC stack & SOEC stack)**

PEMFC stack: The first reference product described in this deliverable and subject to sustainability assessment is a 48 kW_{el} PEMFC stack. The detailed product data and specifications for assessment were provided by SYMBIO France to define all the material and energy flows needed to produce the reference PEMFC stack.

SOEC stack: The second reference product is a 5 kW_{el} SOEC stack, defined according to projections for 2030, when this technology is supposed to reach a sufficient level of maturity to be commercially available. The evaluated eGHOST SOEC stack is a planar cathode-supported one with a total area of 144.78 cm^2 per single repeated unit (SRU) (26 SRUs in total).

- **LCA results for both products (PEMFC stack & SOEC stack)**

PEMFC stack: The total environmental impact of the 48 kW_{el} PEMFC stack manufacturing for climate change is 1,160 kg CO_2 eq., which is equal to 24.2 kg CO2 eq. per kWel. Electricity, Nafion and platinum production have the highest contribution to the climate change environmental indicator. Platinum represents 63.5%, Nafion represents 11.9% and electricity represents 13.2% of the total climate change impact. The fourth most influential item in climate change is stainless steel, with 6.3 %. In the case of the resource use (minerals and metals) environmental indicator, the highest impact comes from Pt (86.6%) followed by stainless steel (9.1%) and copper (3.6%). In general, for the set of selected environmental impact indicators, the highest contribution to the environmental impact of the 48 kW_{el} PEMFC stack comes from platinum, despite its low mass (only 0.1% in the PEMFC stack), followed by electricity, glass fiber reinforced plastic, stainless steel and chromium steel.

SOEC stack: The environmental impact for the SOEC stack for climate change is 154.52 kg CO_2 eq. LCA results on SOEC stack show that stainless steel is a hotspot under each of the assessed indicators, along with nickel oxide in terms of acidification. Bearing in mind that stainless steel is the material with the highest mass rate within the stack, this reveals the importance of eco-designing the parts of the stack dedicated to mechanical assembly (frames) and electrical conductivity (interconnects, end plates). The consideration of a prospective electricity mix for Spain in 2030 significantly affects the results.

- **LCC results for both products (PEMFC stack & SOEC stack)**

PEMFC stack: For the PEMFC stack (48 kW), the cost is very dependent on the production rate. The transition from laboratory to industrial scale could enable to divide the cost more than three times acting on both process and material costs. For 50,000 units produced per year, a cost of 2,288 €/stack has been calculated. The environmental price

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of the 48 kW PEMFC stack is 70.14 $€_{2015}$, with the climate change category contributing the most.

SOEC stack: For the SOEC stack (5 kW), the cost is also very dependent on the production rate. The transition from laboratory to industrial scale could enable to divide the cost almost by five acting on both process and material costs. For 50,000 units produced per year, a cost of 940 €/stack has been calculated. The environmental price of the 5 kW SOEC stack is 9.41 $€_{2015}$, with the climate change category contributing the most.

- **Social LCA results for both products (PEMFC stack & SOEC stack)**

PEMFC stack**:** 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. The social risks associated with energy flows are found to be negligible.

SOEC stack: Stainless-steel production in Spain is found to be the main social hotspot, arising as the major contributor to 5 out of 6 indicators. The social risks associated with energy flows play a minor role, which is linked to the countries involved for these flows.

The sustainability assessment presented in this deliverable will be consolidated during the project. In particular, as it is presented in this document, the EoL models for both products will be completed and added to these results as the project develops. Finally, these results will be used to feed eGHOST WP3 to define a set of potential product concepts to improve the life-cycle sustainability profile of the selected FCH products.

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