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eco-design
Guidelines for Hydrogen
Systems and Technologies

D5.2 Eco-design guidelines for SOE

WP5 Formulation of eco-design guidelines

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EXECUTIVE SUMMARY

Electrolysis is currently a promising method of hydrogen production from water due to high efficiency of conversion and relatively low required energy input. Solid Oxide Electrolysis Cells (SOEC) technology is in fact solid oxide fuel cells (SOFCs) operating in reverse mode. It produces hydrogen and oxygen with steam water splitting and with the application of an external electrical energy source. Pure hydrogen in gaseous form is therefore obtained in the process of high-temperature electrolysis (HTE) at about 800°C. **SOEC technology can be seen as a promising technique for decarbonized hydrogen production** compared to current production techniques. However SOEC technologies are less mature and are for example also strongly dependent in specific strategic minerals and metals resources (lanthanum, yttrium, nickel, strontium…). **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 Solid Oxide Electrolysis Cells (SOEC) technology**.

This document integrates **a synthesis of the main results of the project regarding environmental, cost and social impacts evaluation of SOEC technology** as well as **eco-design recommendations and products concepts for sustainability impacts improvements** all along the different life cycle phases of SOEC systems (materials extraction, system manufacturing, operation and end of life).
Among relevant eco-design recommendations for SOEC developed in the context of this project, we can find the following ones:

- *Reduce the mass of steel components in the stack, module and system (optimize the design), reduce thickness;*
- *Optimize the cells shape and size to reduce the amount of critical materials employed;*
- *Select water-based solvent instead of organic solvents in production steps;*
- *Supply the system with renewable electricity to lower environmental impacts in use;*
- *Develop harmonized standards to measure and limit stack degradation;*
- *Develop recycling streams and processes for SOEC 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 SOEC value chain actors to reach more sustainable solutions for the development of future SOEC systems.

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ABBREVIATIONS

BoP	Balance of Plant
CRM	Critical Raw Materials
EoL	End of Life
FCH	Fuel Cell and Hydrogen
HMS	Hydrogen Management System
HTE	High Temperature Electrolysis
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
PEMFC	Proton Exchange Membrane Fuel Cell
SLCA	Social Life Cycle Assessment
SOE	Solid Oxide Electrolyzer
SOEC	Solid Oxide Electrolysis Cells
SOFC	Solid Oxide Fuel Cells

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1. OBJECTIVES & CONTEXT OF THESE GUIDELINES

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

Eco-design 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 or a system of products.** Simultaneously, eco-design also keeps a product quality level according to its intended use. The principles can be found in the standard ISO/TR14006 [2].

Eco-design approaches have been developed initially, to focus and improve the environmental aspect 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 electrolyzers 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 environmental or social challenges can be highlighted for these technologies identified for clean energy transition. Among them, we can cite their needs in

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specific strategic 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 to operate these systems: 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 impact of end of life management*) 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 European industrial leadership. This will boost the path towards a well-established hydrogen economy that has to be based on sustainable Fuel Cell and Hydrogen (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 includes the development of **specific eco-design guidelines for two FCH products: Proton Exchange Membrane Fuel Cells (PEMFC) and Solid Oxyde Electrolyzers (SOE)**, which serve as seed for the (re)design of other FCH products.

This document refers to the eco-design guidelines for the SOE 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 with 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 aims at 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 Solid Oxide Electrolyzers** and would like to understand where environmental, social and economic challenges occur along the value chain of their products and identify actions to improve these challenges.

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 Solid Oxide Electrolysis Cells (SOEC) technology to improve its sustainability.

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2. TECHNICAL DESCRIPTION OF SOE TECHNOLOGY

2.1 Operation of a SOEC cell

Solid oxide electrolysis cells (SOECs) are in fact solid oxide fuel cells (SOFCs) operating in reverse mode, that is, they produce hydrogen and oxygen in the process of water splitting and under application of external electrical energy source. The specific feature of this variation of electrolysis is that pure hydrogen in gaseous form is obtained in the process of high-temperature electrolysis (HTE). In this configuration of SOEC, water is being introduced in form of steam.

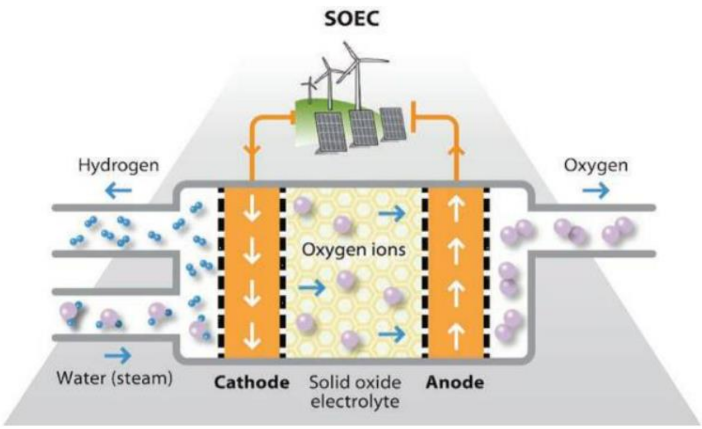

Figure 2. Principle of operation of a solid-oxide electrolytic cell

The graphical representation of SOEC principle of operation is demonstrated on the Figure 2. Stream of hot steam is fed into the porous cathode. After voltage is applied the water particles are directed to the cathode-electrolyte interface and are being reduced to H_2 and oxygen ions. Next, hydrogen in gaseous form diffuses back through the cathode and is collected at the surface of that cathode to later serve as hydrogen fuel. On the other hand, the oxygen ions are conducted through the electrolyte. Electrolyte used for this process is a dense solution to prevent steam and hydrogen diffusion, preventing the recombination into water. In other words, the electrolyte provides the separation of the products of reduction and oxidation. The electrolyte used for this technology is a solid ceramic material: non-porous metal oxides of zirconium and yttrium $ZrO_2 - Y_2O_3$. The materials used in SOECs, due to their relative scarcity leads to high unit prices of zirconia and yttria, which contributes to generally higher prices of the technology. This rises another issue, namely the availability of resources, which makes the technology commercialization and industrial-scale development more challenging.

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2.2 Description of SOEC systems

For the production of hydrogen at adequate power levels, it is necessary to use a large number of electrolysis cells. These cells are generally connected in series to form the elementary object called a "stack", which can have different designs depending on the manufacturer and application. These stacks have the functions of distributing and collecting the different gases, ensuring electrical conductivity between the cells, and a good level of sealing between the layers and with the outside of the stack.

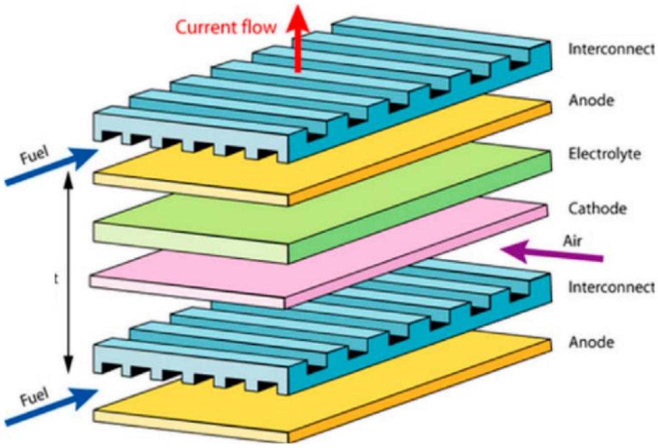

Figure 3: Schematic representation of a SOEC stack layers

To ensure all these functions, these stacks are generally composed of interconnectors, thermal plates, contact layers allowing the passage of gases, and components allowing the sealing of the stack. The interconnection plates are usually made of ferritic stainless steel metal plates. Their role consists of ensuring the electrical connection between two adjacent cells, then constituting a sealing physical barrier between anode and cathode compartments to ensure the separation of oxygen and hydrogen, and to ensure the distribution and collection of combustible and oxidizing gases. This distribution can be, depending on the manufacturer and application, in co-flow, counter-flow or cross-flow. Sealing is ensured by seals, which for high temperature electrolyzers are often made of glass, glass-ceramic composites or mica. End plates generally made of steel complete this assembly to provide mechanical support to the cell stack. The contact layers on each side of the cells must be good electrical conductors and allow the passage of the gas. These contact layers can be used in the form of grids, pores, channels, etc.

All the materials of the stack components must be chosen carefully so that they can have good electrical, thermal, and mechanical properties and can endure thermal cycling stresses without damaging the assembly. Temperature of operation of such systems is about 800°C. In a full SOEC system we generally need several stacks to achieve the desired hydrogen production rate. These stacks can be grouped into modules that are inserted into a full hydrogen system which includes gas distribution pipes, and auxiliaries such as steam generator or recovery, heat exchangers, condensers, electrical supply, heat management elements, etc. Figure 4 illustrates the complete life cycle of a generic SOE system.

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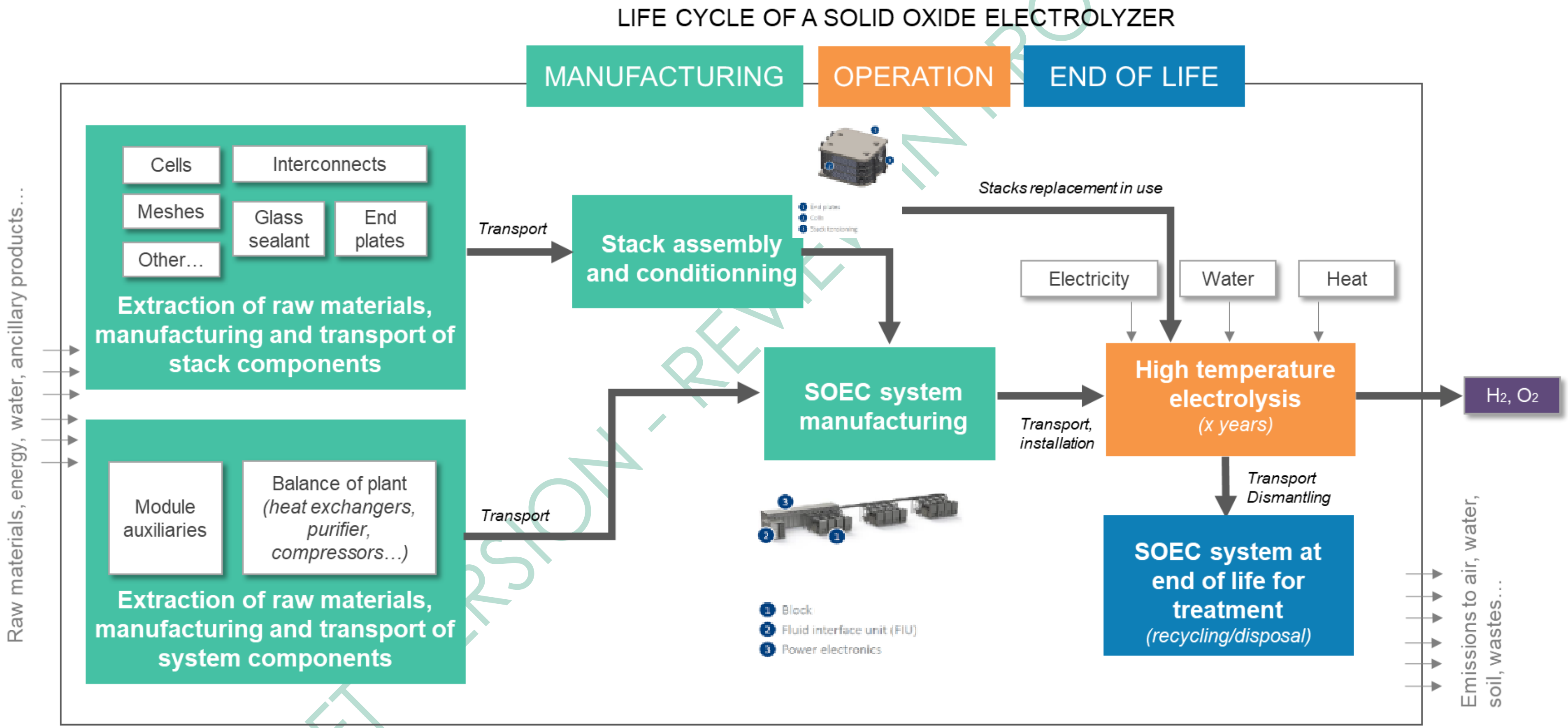

Figure 4: Simplified representation of the life cycle of a high temperature electrolyzer system

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3. ENVIRONMENTAL, COSTS AND SOCIAL CHALLENGES OF SOEC TECHNOLOGY

In the framework of the eGHOST project, a sustainability assessment of generic SOEC technology has been realized. It includes assessment of environmental, economic and social impacts of a standardized SOEC stack with $5kW_{el}$. This assessment is a prospective assessment according to 2030 projection of electricity mix for stack manufacturing in Spain [6]. The perimeter of analysis is focused **on the manufacturing phase of the stack and end-of-life (EoL) phase**. Operation phase was not taken into account in the first project evaluation, but literature data were taken into account to identify the share of environmental impact of the operation phase compared to the manufacturing phase for SOEC technology. The goal and scope as well as the hypotheses and perimeter taken for this study are presented in eGHOST deliverable 2.3 [6].

Table 1: Environmental impacts categories selected within the eGHOST project for environmental impact evaluation of SOEC technology

EF IMPACT CATEGORY	INDICATOR	UNIT
CLIMATE CHANGE	Global Warming Impact Potential (GWP)	kg CO_2 eq
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 social impact evaluation, workers on the SOEC 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*

The detailed results as well as hypotheses of environmental, social and economic assessment of the $5kW_e$ SOEC stack are presented in deliverable 2.3 and have been adjusted in deliverable 4.2 of the eGHOST project (public documents)[6,5]. The following paragraphs present a summary of these results with the main identified challenges for the SOE technology on the three sustainability pillars.

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3.1 Environmental challenges for SOEC technology

3.1.1 Environmental Life Cycle Assessment

Operation phase has not been taken into consideration in the eGHOST sustainability evaluation. However, it is important to notice that several studies **present the operation phase of SOEC technology as the most impacting life cycle phase on the majority of environmental impacts**, due to electricity consumption during operation for electrolysis (> 80% of contribution to the majority of environmental impacts) [7,8,9]. The impacts during the operation phase **are strongly dependent of the electricity mix used in operation**, therefore it is important to take this criteria into consideration when decisions regarding location of electrolyzer installation and type of electricity used to operate the system are made. **The improvement of cells performance in use and the increase of cells current density** could support reduction of climate change on the global life cycle of SOEC technology by up to 20% [7]. Optimization of water use and steam sources could support also impacts reduction of the operation phase of SOEC technologies. Furthermore, in operation, the durability of stacks remains a major issue, with lifespans of less than 5 years often requiring several replacements over the life of the system. To reduce the impact of stack replacement, design and operating conditions favoring durability should be preferred, as dismantlability so that cells can be replaced while allowing certain sub-components, such as terminal plates, to be reused.

In the eGHOST evaluation, for the manufacturing phase of the SOEC stack, **the stainless steel used is a major challenge in terms of environmental impacts** and represents the main contributor for the Climate change impact [kgCO_2 eq.] of the SOEC technology (82%) (see Table 2).

Table 2: relative contribution of material and energy to the eGHOST 5kW SOEC stack environmental life-cycle impacts [6]

	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%

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For other environmental impacts such as eutrophication, and resource use we can observe the same contribution for stainless steel material (between 80% and 83%). Bearing in mind that stainless steel is the material with the highest mass within the SOEC stack, this reveals the importance of eco-designing the parts of the stack dedicated to mechanical assembly (frames) and electrical conductivity (interconnects and end plates). Moreover, **nickel oxide materials are responsible of the major contribution of impact on acidification** mainly due to SO_2 emissions from roasting nickel ores. Reduction of nickel use in future stacks design will allow some impact reduction on acidification for the stack.

Concerning **electricity use for manufacturing the stack, it represents also a high contribution of the environmental impacts** of the stack (for example 12% of the impact of climate change and 25.5% of the impact on fossils resources use, according to eGHOST study D2.3). Among electricity use for stack production, **cells sintering is the most impacting process step in terms of energy consumption**. Indeed, the cell is made up of several layers of ceramic with different composition and porosity, requiring several stages of deposition and sintering between 800 and 1400°C for several hours under different atmospheres, in pass-through furnaces. Co-sintering should be favored in order to reduce the number of stages, as well as optimization of the energy and gases consumption of the furnaces. Optimization of this production step is therefore a lever to improve global environmental performances of the stack manufacturing.

The absolute results of the LCA performed in the LCA are presented in the following table.

Table 3: LCA eGHOST results for the 5kW SOEC stack [5]

Impact category	5kWel SOEC stack
	Score
Acidification [mol H^+-eq]	1.45E+00
Climate change [kg CO_2-eq]	1.34E+02
Energy resources: non-renewable [MJ_{ncv}]	2.25E+03
Eutrophication: freshwater [kg P-eq]	4.43E-02
Eutrophication: marine [kg N-eq]	1.68E-01
Eutrophication: terrestrial [mol N-eq]	1.50E+00
Material resources: metals/minerals [kg Sb-eq]	5.00E-03

3.1.2 Material criticality of SOE 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 [10].

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34 CRMs 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), 87 individual raw materials in total.

2023 Critical Raw Materials (*new CRMs in italics)*			
aluminium/bauxite	coking coal	lithium	phosphorus
antimony	*feldspar*	LREE	scandium
arsenic	fluorspar	magnesium	silicon metal
baryte	gallium	*manganese*	strontium
beryllium	germanium	natural graphite	tantalum
bismuth	hafnium	niobium	titanium metal
boron/borate	*helium*	PGM	tungsten
cobalt	HREE	phosphate rock	vanadium
		*copper**	*nickel**

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

Figure 5: 2023 CRM list for European Commission

Figure 5 shows the 34 CRMs 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) [11]. 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 as they are raw materials important for technologies that support the twin green and digital transition and defense and aerospace objectives for Europe.

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

- ***Cobalt*** *(in the oxygen electrode for cell manufacturing and possibly for the protective coating for the interconnect)*
- ***Lanthanum (LREE)*** *(in the oxygen electrode for cell manufacturing)*
- ***Yttrium (HREE)*** *(in YSZ material for cell manufacturing)*
- ***Strontium*** *(in the oxygen electrode for cell manufacturing)*
- ***Nickel*** *(NiO for the hydrogen electrode for the cell manufacturing and Nickel as contact material in single repeat units (SRU) manufacturing)*
- ***Manganese (in particular for protective coatings)***

The International Energy Agency identified that rapid growth of hydrogen as an energy carrier underpins major growth in demand for nickel and zirconium for electrolyzers. **The primary mineral demands of SOECs are nickel (estimated around 150-200 kg per MW by IEA), zirconium (estimated around 40 kg per MW by IEA), lanthanum (estimated around 20 kg per MW by IEA) and yttrium (less than 5 kg per MW).** Each of these quantities are expected to be reduced by 50% thanks to better design in the next decade, with the objective to drop nickel content below 10 kg per MW in 15 years [12]. These quantities can be adjusted downwards in line with the higher efficiencies of SOECs and according to new architectures and innovative technical improvements.

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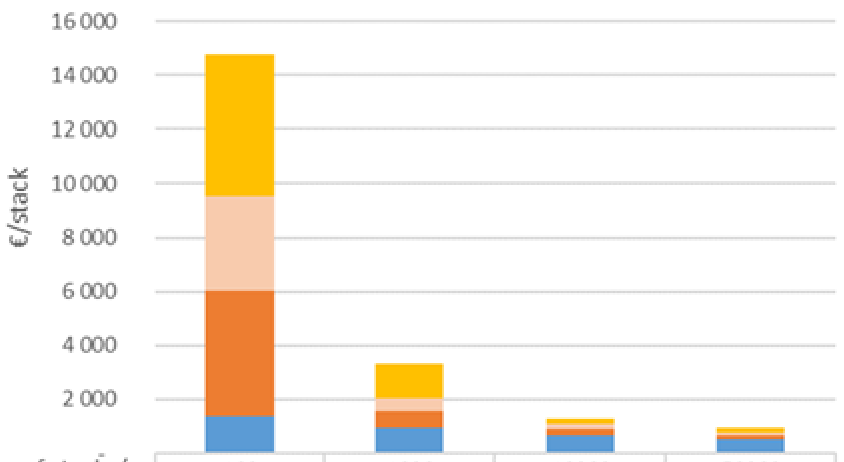
3.1.3 Costs challenges for SOEC technology

According to the eGHOST study, SOEC stack costs are **strongly dependent of the production rate of the stack**. The transition from laboratory to industrial scale allows to divide the cost by sixteen (from 15 k€ per stack at laboratory scale to 940 € per stack at industrial scale). For a production rate of 50 000 stacks per year, **the bill of materials to manufacture the stack represents 56% of the total cost of the stack**. In the BoM, interconnects materials, including meshes represent 72% of the cost. Eco-design actions that could reduce the use of these materials (new geometries, thinner components or change of material) could reduce the global cost of the stack. In addition, cells materials represent only 5% of the total cost of materials needed for stack manufacturing according to the study realized in the project. This is mainly due to the small mass of the cells compared to other materials needed for stack manufacturing.

Finally, the conditioning step and assembly step for stack manufacturing represent 30% of the total cost of the stack considering the production rate of 50 000 stacks/year. At lab scale (100 stacks/year) these steps represent 59% of the total cost of the stack. Figure 6 represents the distribution of the costs calculated in eGHOST for SOE stack manufacturing, at different production rate.



number of 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**

Bill of materials Cells Interconnect & assembly Conditioning

Figure 6: Distribution of costs for SOE stack manufacturing at different production rate (from 100 stacks/yr to 50 000 stacks/yr) [6]

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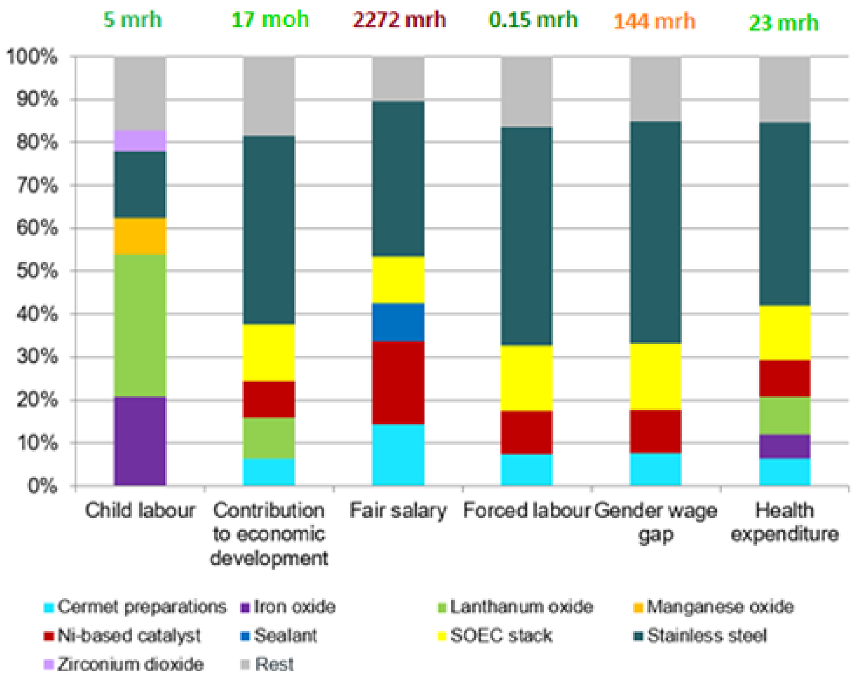
3.1.4 Social challenges for SOEC technology

A Social Life Cycle Assessment (SLCA) study was also carried out in eGHOST project for the 5 kW_{el} SOEC stack, again following the methodological choices detailed in eGHOST deliverables 2.1 and 2.2 [13,14] and focusing on the identification of social hotspots of the manufacturing value chain of the stack. 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 mesh, 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 has been made taking into account data availability on economic flows of commodities in databases such as UN Comtrade and Eurostat [15,16].



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

Figure 7: Contribution to the potential social impacts for the 5 kW eGHOST SOEC stack [6]

[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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Stainless-steel production in Spain is found to be the main social hotspot, arising as the major contributor to 5 out of 6 social indicators (Figure 7). This is mainly due to the high economic flow associated with the stainless steel and its high mass rate in the SOEC stack. In general, the materials production plants account for a higher share than the components manufacturing plants. 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 labour" 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 important contributors. Finally, the social risks associated with energy flows play a minor role, which is linked to the countries involved for these flows which represent low social risks. Indeed, SLCA results are really linked to the country of origin of components manufacturing or materials extraction on the value chain. The social impacts calculated depends on the processes that occur in the countries with higher risks of given social impact than other steps that are carried out in countries will lower risks.

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4. SOE ECO-DESIGN GUIDELINES

The basic approach for the generation of eGHOST eco-design guidelines for the SOEC case-study involved the setting up of brainstorming sessions with the eGHOST consortium members and technical experts of the SOE technology from the eGHOST external working group. Three brainstorming sessions were organized (face-to-face and hybrid modes) with the objective of generating new eco-design ideas for SOE stacks and systems development, reducing environmental, economic and social impacts of the technology. During these brainstorming sessions, the eco-design wheel strategies [17] were used to produce eco-design ideas among partners and technical experts according to the different life cycle phases of the SOEC stack, and to the 8 eco-design axes of the eco-design wheel (Figure 8):

Product component level:

1. *Selection of low-impact materials,*
2. *Reduction of intensity of use of materials,*

Product structure level:

3. *Optimization of manufacturing techniques,*
4. *Optimization of distribution process,*
5. *Reduction of impact during use,*

Product system level:

6. *Optimization of product lifetime,*
7. *Optimization of end of life*
8. *New concept developments*

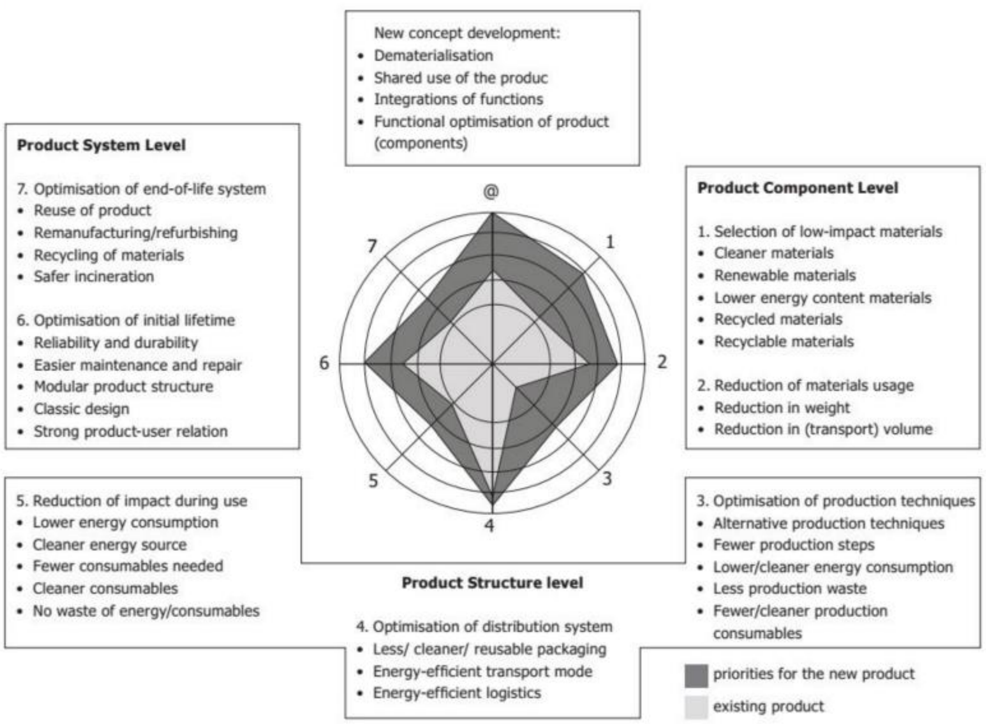

Figure 8: The eco-design strategy wheel [17]

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The most relevant eco-design guidelines 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 [18].

Based on this work, the guidelines issued from D3.2 were refined by SOE experts and completed with more precise design recommendations; SOE new eco-designed concepts were assessed in terms of sustainability performance.

The final SOE eco-design guidelines that you will find in this document are structured in 6 different sections which represent different life cycle stages of the SOE 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 SOE. 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 9).

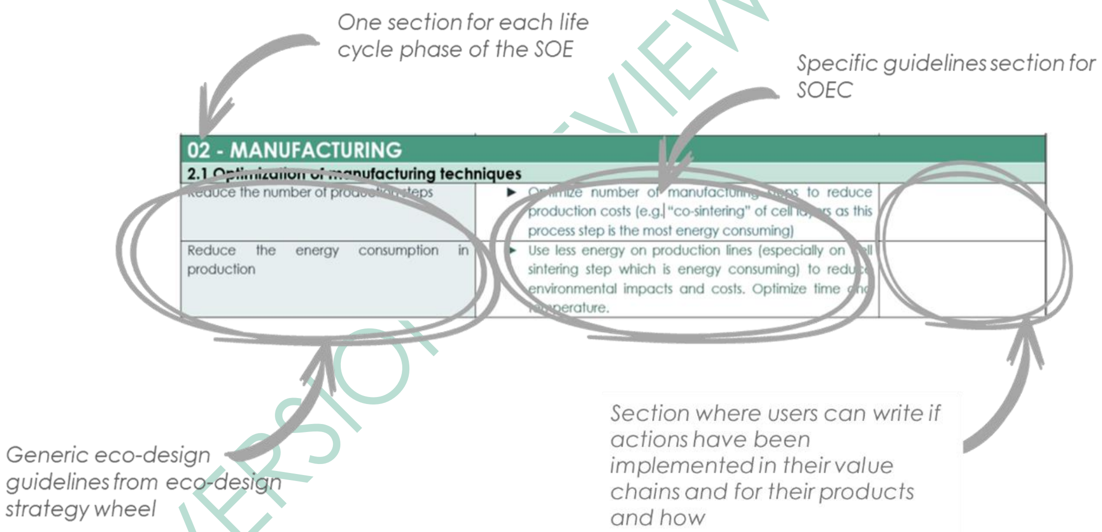

Figure 9: Description of the guidelines structure

The final eGHOST eco-design guidelines for SOE technology are presented in Table 4 below.

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Table 4: Eco-design guidelines for SOEC technology per life cycle phase

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

01 - MATERIALS		
1.1 Selection of low impact materials		
Selection of clean materials	► Choose materials with low energy content for stack manufacturing *(use environmental databases for materials selection database)* with equivalent or better performance ► Choose materials with low toxicity for human health and environment for stack manufacturing (*use environmental databases for materials selection)* with equivalent or better performance	
Selection of renewable and sustainable materials	► Use innovative doping strategy for the catalysts on cells to reduce the amount of rare earth elements (REE) in the stack ► Reduce the use of nickel in stack components to prevent environmental impacts in material extraction steps, such as acidification	
Selection of materials with low energy content	► Integrate innovation in the choice of electrolyte materials to reduce the amount of rare earth elements materials	
Integration of recycled materials	► Use recycled steel for components manufacturing in the stacks, modules, systems	
Integration of recyclable materials	► Make architecture of the stack easy to disassemble for recyclability without compromising the sealing of the stack (especially: improve the reusability of end plates which represent an important part of the weight and metal content of the stack and environmental, social and economic impacts)	

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1.2 Reduction of intensity of use of materials		
Reduction of the diversity of materials	► Utilize innovative material for electrolyte, anode and cathode to reduce the amount of rare earth elements as well as critical material	
Reduction of the mass of materials	► Reduce the mass of steel components in the stack, module and system (optimize the design), reduce thickness ► Optimized the compression technology in order to reduce the surface and thickness of the terminal plates, (e.g. using the solutions of the PEMFC stacks: compression by traps with welded belts). ► Optimize the cells shape and size to reduce the amount of materials employed in particular the surfaces that are not part of the active area, like the distribution zone. ► Change the cell architecture/type (electrolyte supported vs cathode supported) to reduce the amount of rare earth elements materials and reduce the amount of nickel employed while maintaining equivalent performances of the cells	
Reduction of the volume of materials/components		
02 - MANUFACTURING		
2.1 Optimization of manufacturing techniques		
Reduce the number of production steps	► Optimize number of manufacturing steps to reduce production costs (e.g. "co-sintering" of cell layers as this process step is the most energy consuming) ► Merge the final conditioning step of the stack, one of the most energy consuming and expensive step with the commissioning step on production site	
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. Optimize time and temperature. ► Use cleaner or renewable energy on production lines (especially on cell sintering step which is energy consuming) ► Revalorize thermal losses in production steps to reduce environmental impacts and costs	

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	► Revalorize H_2 produced during the final conditioning test to produce electricity or heat	
Limit and reduce production wastes	► Integrate internal recycling loops for production wastes as much as possible (for steel in priority, then for rare earth elements and critical materials) to reduce environmental impacts and costs ► Optimize production techniques to reduce material losses (e.g. important use of materials conditioned in coil and involving important quantity of offcuts: work with suppliers to provide the good width to reduce losses – work on a recycling process to reinject these offcuts in production.)	
Reduce consumables in production and use clean consumables	► Reduce/optimize the amount of chemicals and solvents used in all production steps ► Select water-based solvent instead of organic solvents in production steps (colloidal processing based on water instead of organic solvents)	
03- TRANSPORT		
3.1 Optimization of distribution process		
Use transportation mode with high energy efficiency	► Use as clean as possible ways of transportation for logistic	
Optimize the logistic for manufacturing, installation and maintenance	► Facilitate local supply chains for materials and components	

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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. to heat up only active materials and not structural elements such as the end plates) ► Reduce operating temperature of the system, to reduce energy consumption and increase stack durability ► Optimize cell performance ► Use H_2 management system (HMS) to optimize the system in term of performance and durability according to the demand. ► Find good compromise between performance and durability (part of the HMS function)	
Use clean energy and consumable sources for operation	► Supply the system with renewable electricity to lower environmental impacts in use ► Produce low impact steam to run the system (use steam from steam networks)	
Use less consumables and materials for operation	► Use water recirculation to reduce overall water consumption (in particular the condensate of H_2 purification step.)	
4.2 Optimization of product lifetime		
Improve the reliability and durability of the system	► Develop harmonized protocols/recommendations to start/operate the system ► Reduce operating temperature of the system, to limit stack degradation, while maintaining good contacts within the stack. The optimization of temperatures with the hot box inside the different zones of the stacks could limit stack degradation. ► Reduce cell degradation	
Ensure easy maintenance and repair	► Make cells replacement feasible in the stack	
Provide a modular structure for the system	► Improve stack modularity to optimize part load operation and limit degradation	
Standardize reparation and maintenance procedures	► Develop harmonized standards to measure stack degradation	

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05 - END OF LIFE		
Integrate possibility of reuse of components, products	► Develop processes and protocols to facilitate the reuse/remanufacturing of steel components (end plates, interconnects, module and BoP components) – in particular offcuts	
Possibility for remanufacturing / refurbishing of the components	► Develop automated and industrialized processes for efficient stack dismantling (mechanical disassembly techniques) ► Today components of the stacks are glued using glass seal that makes mechanical dismantling very difficult. Find new technique of sealing without compromising gas proofness and stack performance (e.g. inclusion of the stack in a box) ► Design for modularity and disassembly at end of life	
Possibility of recycling	► Develop recycling streams and processes for SOEC 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. ► Reuse of terminal plates developed in "material part" ► Use existing recycling streams for steel recovery ► Improve the recyclability of steels ► Improve the total recycling rate of SOEC systems ► Find other application for the stack with less stringent requirements than H2 production. Since the stack can be reversible according to its design, Fuel cell mode could offer a second life. This should take into consideration the problems that can encounter stack at end of life like leaks or contacts problems.	
Safe incineration if no possibility for recycling	► *Ensure safe incineration of the components if recycling is not possible*	
06 – NEW CONCEPTS DEVELOPMENTS		
	► *Add functionalities to end plates like thermal management system, to justify its size and weight*	

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5. ECO-DESIGN PRODUCT CONCEPTS FROM EGHOST

Based on eco-design guidelines presented, some eco-designed SOEC stacks concepts and blueprints were developed by eGHOST consortium. Main actions implemented in realistic and optimistic design for SOE stacks concepts are linked to material optimization, material changes and integration of recycled material as input for manufacturing the different components of the stack. These concepts are presented in the section below.

5.1 Description of eGHOST eco-designed products concepts

The different eco-designed concepts are represented in the figures below [Fig.10-12]. The figures present three concepts considered for the SOEC stack including the base case, realistic case and optimistic case. Especially thicknesses of the different layers are lower in the optimistic case compared to the realistic case.

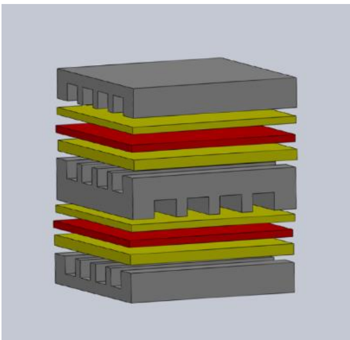

Figure 10 SOEC Base Case

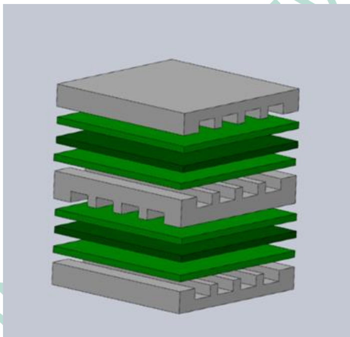

Figure 11 SOEC Realistic Case

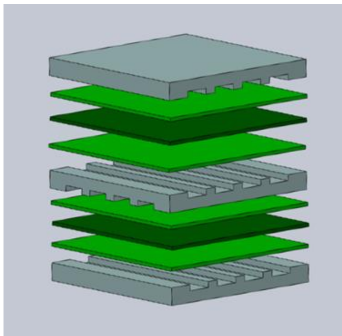

Figure 12: SOEC Optimistic Case

The blueprints have been presented in the way reflecting the reduction of the use of raw materials and implementation of recycled materials. This has been done by varying the grey tone starting from the darkest in the base case with no optimization, and applying the lightest grey tone in the optimistic case variant, where the component composes mostly of recycled materials and the use of raw materials has been significantly reduced.

The use of renewable materials and limited critical raw materials (CRM) use in both electrodes (anode and cathode) and electrolyte is depicted using different shades of green, where a more intense color indicates a higher proportion of recycled materials and a reduced reliance on CRM.

With the implementation of the eco-design actions, the thickness of the layers is decreasing representing therefore the reduction of the mass of those components due to the implementation of eco-design recommendations allowing for the stack optimization, implementation of non-CRM materials and overall, more compact design.

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Some of the medium-term and medium-to-long-term eco-design actions proposed and gathered in the Figure 11 and 12 and applied to SOEC stack correspond to the realistic and optimistic case respectively.

In the Base Case [Figure 10] the end plates/interconnection (dark gray) are made of virgin steel with no material reduction. The electrodes, both anode and cathode, (yellow) with the default thickness, represent the components manufactured using the typical materials and with the use of CRM. The electrolyte (red) of default thickness is made of typical CRM. No optimization has been represented in this variant being a reference case.

Figure 11 represents the realistic case of SOEC stack blueprint with the medium-term eco-design actions implemented, including reduction of the virgin steel (grey) used for the stack endplates and interconnectors, as well as the reduction of its mass (reduced thickness of the layer). Moreover, the implementation of some renewable materials and reduction of the use of CRM for the manufacturing of electrodes (light green) and electrolyte (dark green) has been represented in the figure. A visible reduction in the thickness of the electrolyte and both anode and cathode corresponds to the reduction of the mass of the materials implemented for the manufacturing process of those components resulting from the stack optimization and implementation of innovatory, renewable materials.

The optimistic case corresponding to the implementation of medium-and-long-term eco-design actions has been represented in the Figure 12. In this case a significant reduction in the use of virgin steel in the endplates and interconnectors can be observed (light green color) as well as the implementation of significant shares of non-CRM materials of renewable origin implemented for the production of electrodes and the electrolyte (intense light and dark green color respectively). A significant layer thickness reduction can be seen compared to the base case and optimistic case where the eco-design actions have been implemented to lower extent than the optimistic case.

5.2 Sustainability benchmarking of eGHOST eco-designed product concepts

In eGHOST project, life cycle inventories (LCI) have been developed for eco-designed SOEC stacks product concepts, defined on base case LCI and eco-design actions implemented for realistic and optimistic case studies (Table 5). These life cycle inventories have been developed mainly based on eco-design actions related to material use optimization and thickness reduction of the different layers of the stacks. They were used for a sustainability evaluation of eco-design concepts for the environmental, economic and social impacts assessment. Detailed results of this assessment are presented in deliverable 4.2 [5] of the project. A summary of this prospective sustainability assessment on SOEC stacks concepts is presented in the section below.

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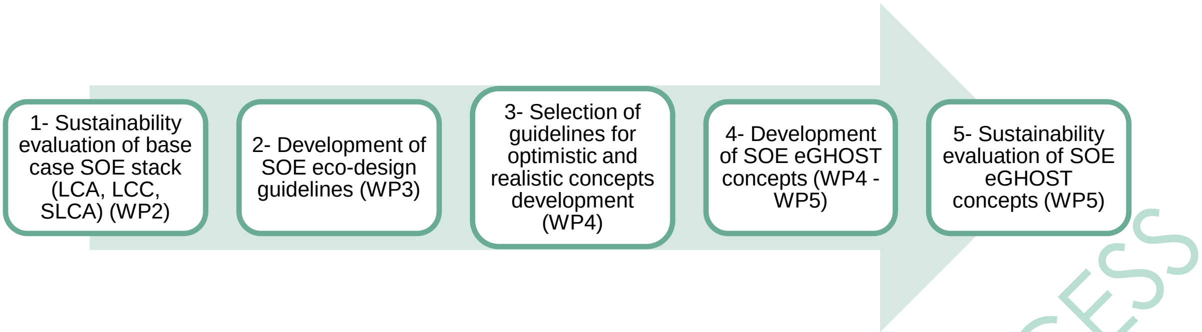

Figure 13: Process of eGHOST product concepts developments and sustainability characterization

Table 5: Manufacturing phase life cycle inventory for SOEC base case and product concepts

Component	Material	Base	Realis-tic	Optimis-tic
Electrolyte	8% mol YSZ [g]	8.7	4.0	2.5
/auxilliaries	Binder Dow B-1000 [g]	3.8	1.8	1.1
/auxilliaries	Ammonium polyacrylate[1] [g]	1.5	0.1	0.04
/auxilliaries	Water[1] [g]	2.1	1.0	0.6
Cathode	8% mol YSZ [g]	258	119	73
	Nickel oxide [g]	368	1174	110
/auxilliaries	Binder Dow B-1000[1] [g]	239	113	71
/auxilliaries	Ammonium polyacrylate [g]	10	4.7	3.0
/auxilliaries	Water [g]	119	56	36
Anode	LSCF [g]	86	36	528
	YSZ/LSM [g]	21	8,2	3007
	YSZ/LSM [g]	10	4.1	10
Interconnects/Frames	Stainless steel [g]	11864	5599	3535
	Perovskite coating [g]	33	16	10
Anode and cathode mesh	Stainless steel [g]	4572	2158	1362
Sealant	Lanthanum oxide [g]	14	4.8	2.0
	Boron-silicate glass [g]	4.7	2.2	1.4
End plates/Tie rods	Stainless steel [g]	12468	5239	3308
TOTAL mass SOEC stack [g]		**29709**	**13364**	**8430**

1 - Binder Dow B-1000, ammonium polyacrylate, and water are not included in the stack and therefore, do not contribute to the total SOEC stack mass. They are included in the LCI because they are needed in the manufacturing phase of the stack.

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 hypotheses as the environmental assessment of base case.

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Realistic eGHOST eco-design concept environmental impacts are **representing between 30% and 33% of the impacts** compared to the base case**, while optimistic concept impacts are between 12% and 19% of the base case** (Figure 14), depending on the indicators we are looking on. **The highest reduction for optimistic concept was found at *Energy resources: non-renewable* indicator.** This finding is driven by the consideration of a **100% renewable electricity sourcing at the manufacturing plants** as eco-design action implemented. On the other indicators, the mass reduction of the different materials led to a harmonized environmental impacts reduction between all the indicators. The detail of hypotheses taken for this comparative LCA is presented in eGHOST deliverable 4.2 [5].

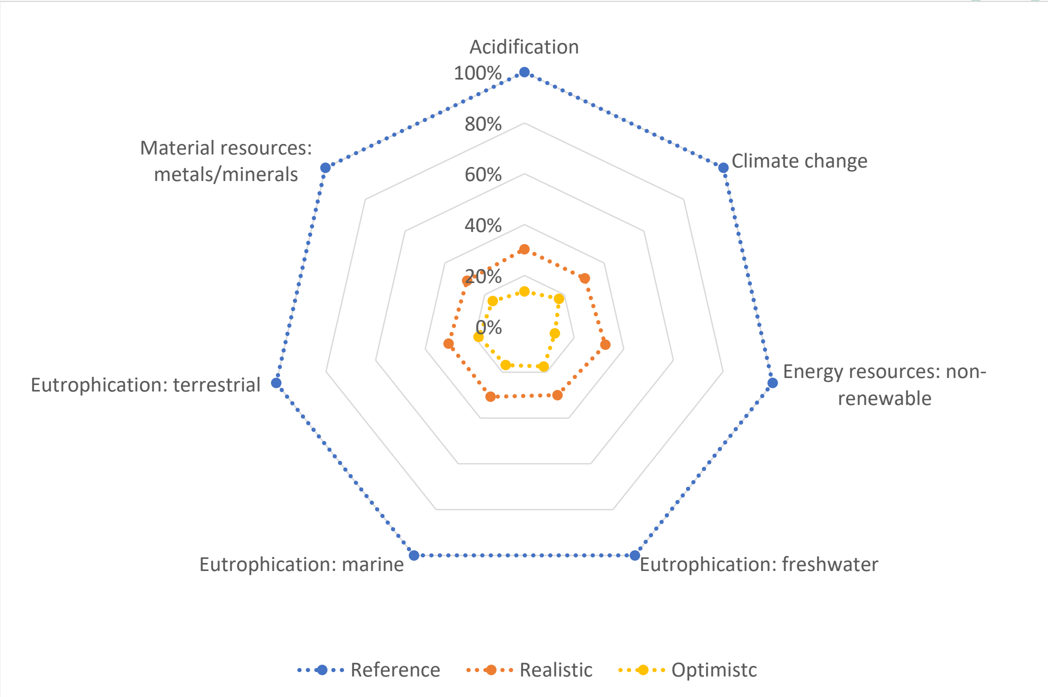

Figure 14: Relative comparison of environmental impact indicators of the SOEC stack product concepts compared to the base case

5.2.2 Cost assessment (LCC) summary of eGHOST product concepts

The contribution of the SOEC stack BoM to the total cost was found to decrease with each product concept, being the phase that accounts for the highest cost share in base case but the lowest in realistic and optimistic product concept. A production rate of 10 000 stacks/yr was considered for this evaluation. In this regard, **optimistic concept achieves a 76% reduction of total BoM cost, while only achieving an 18% reduction in manufacturing cost** (Table 6). These results are driven by the nature of the implemented eco-design actions, which mostly focus on reducing the material intensity of the SOEC stack alternatives (cf. LCIs of product concepts). More details regarding these results and hypotheses taken for this cost assessment are presented in eGHOST deliverable 4.2 [5].

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Table 6: Cost breakdown of the SOEC stack product concepts (10 000 production scale) [5]

Indicator	Realistic concept	Optimistic concept
	Impact variation compared to base case	*Impact variation compared to best case*
Total cost [%]	-41%	-50%
BoM [%]	-62%	-76%
Manufacturing [%]	-14%	-18%

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

Figure 15 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. Realistic concept impacts are between 33% and 37% of improvements compared to the base case, while optimistic concept impacts are between 14% and 22% according to the different indicators. **The impact category with the highest reduction in both product concepts was found to be child labor**. Materials sourced from China (YSZ and lanthanum oxide) account likewise for relevant contributions, especially to the child labor category. A reduction in the use of these materials lead to a high decrease of the impact on this indicator. More details regarding these results and hypotheses taken for this social impact assessment are presented in eGHOST deliverable 4.2 [5].

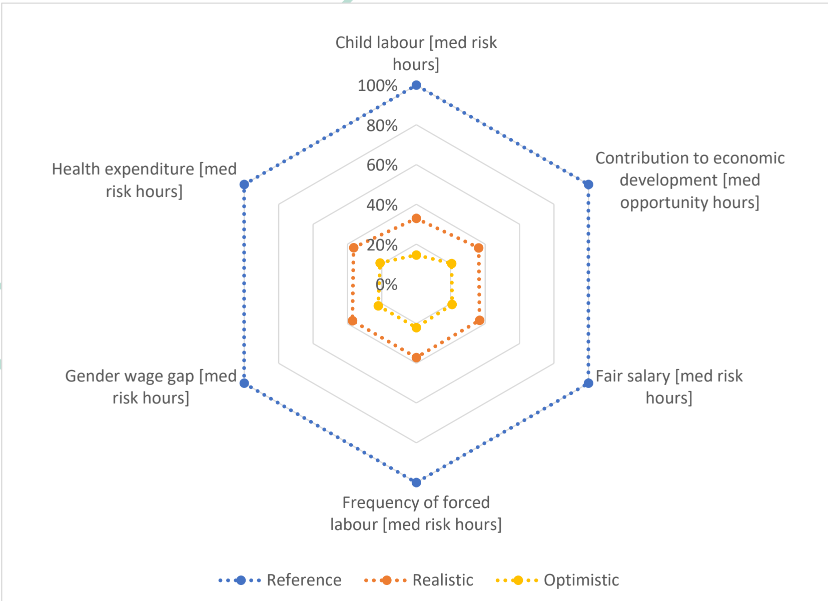

Figure 15: Relative comparison of social impact indicators of the SOEC stack product concepts in comparison to the base case

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CONCLUSIONS

This deliverable refers **to the eco-design guidelines for the SOE technology developed in the framework of the eGHOST project**. It 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 SOEC stacks for sustainability impacts improvements, which have been evaluated.

According to eGHOST sustainability assessment on SOE technology as well as on literature review, the operation phase of the electrolyzers is the most impacting phase in terms of environmental impacts before the manufacturing phase and end of life. Therefore, the choice of electricity mix used for operation and water use optimization are two key eco-design considerations for limiting the environmental impact of SOE systems across their life cycle.

For the manufacturing phase of the stack, steel is a major challenge in terms of environmental impacts and represents the main contributor for the carbon impact of the SOEC technology. Other materials such as nickel oxide contributes to most of the impacts on acidification indicators whereas materials sourced in China (such as zirconium dioxide, iron oxide, and lanthanum oxide) can represent significant contribution on social impacts categories such as child labor. The total cost of stack manufacturing strongly depends on the production scale. At industrial scale, the bill of materials (BoM) accounts for 56% of the total stack cost. Conversely, at lab scale, the manufacturing and assembly processes contribute the most to the stack cost.

In this report, with the implementation of some eco-design actions presented in the SOE eco-design guidelines, we can see that a reduction in the use of materials for stack productions can lead to significant environmental, cost and social improvements of the technology (section 5).

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 SOE 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 chain actors who develop Solid Oxide Electrolyzers and would like to understand where environmental, social and economic challenges might occur along the value chain of their products and identify potential actions to tackle those challenges**.
The different guidelines presented in this document can be seen as a framework to reach more sustainable solutions for the development of future SOE systems in the industry.

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