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D3.2 Eco-designed product concepts for the FCH products

WP3 Establishing eco-design product concepts

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EXECUTIVE SUMMARY

In this deliverable the eco-designed FCH product concepts are presented. Concepts are defined based on the **inventory definitions** of the observed products and the eco-design **brainstorming procedure**. Based on the features of the selected FCH products and their life-cycle profiles and identified hotspots, product ideas were generated.

The **eco-design wheel** was adapted to FCH products on the component level, product structure level and product system level, and specific areas and activities were identified targeting the whole life cycle of observed FCH products.

After the basic product ideas generation for the two selected products, ideas were categorized according to the areas addressed in the eco-design wheel and according to their **expected implementation** in the industry **timewise**. Thus, short-, medium- and long-term actions were identified and described based mainly on industrial data, ongoing parallel Clean Hydrogen Partnership projects (BEST4Hy) and latest findings in the literature.

All the selected ideas were integrated into **product concepts** to fulfil the performance requirements. These concepts consider new materials and concepts, their final shape, optimization of processes, replaced or reused materials/parts, etc.

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ABBREVIATIONS

BoP	Balance of Plant
CCM	Catalyst Coated Membrane
EoL	End of Life
EU	European Union
FC	Fuel Cell
FCH	Fuel Cells and Hydrogen
GDL	Gas Diffusion Layer
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
MEA	Membrane Electrode Assembly
MOF	Metal-Organic Framework
PEEK	PolyEther Ether Ketone
PEMFC	Proton Exchange Membrane Fuel Cell
PGM	Platinum Group Metals
REE	Rare Earth Element
RES	Renewable Energy Sources
SoA	State-of-the-art
SOEC	Solid Oxide Electrolysis Cell
SOFC	Solid Oxide Fuel Cell
WP	Work Package

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INTRODUCTION

Based on previous work and a definition and preliminary sustainability evaluation of two FCH products in a previous work package, this work aims to deliver those eco-design actions within the defined systems that have the potential to be implemented in the short, medium, or long-term considering all life-cycle phases of the products. The reference FCH products are a PEMFC – polymer exchange membrane fuel cell – stack (mature technology) and a SOEC – solid oxide electrolysis cell – stack (emerging technology).

The key objective of this deliverable is to define a set of potential product concepts to improve the life-cycle profile of the selected FCH products. The eco-design methodology is applied. In the first part of the deliverable the generation of new ideas to improve the products and their categorization is addressed, followed by the generation of new product concepts incorporating the selected ideas and their screening considering general design principles and criteria.

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ECO-DESIGN

Eco-design is both a principle and an approach. It consists of integrating environmental/sustainability protection criteria over a service or a product life cycle. The main goal of eco-design is to anticipate and minimize negative environmental impacts (of manufacturing, use and end-of-life of products). Simultaneously, eco-design also keeps a product quality level according to its ideal usage. The principles can be found in ISO/TR14062 [1].

Eco-design is a "multi-step" and "multi-criteria" approach that supports a product entire life cycle in a circular economy perspective by saving and recycling at maximum the natural resources. Eco-design actions address different product levels:

Product Component Level, with selection of low-impact materials and/or reduction of material use.

Product Structure Level, with optimization of production techniques, optimization of the distribution system and reduction of impacts during the use phase.

Product System Level, with optimization of lifetime and optimization of the end-of-life system.

The basic approach for the generation and categorization of eco-design ideas for the two eGHOST case studies involved **brainstorming** sessions following the eco-design strategy wheel (Figure 1). The ideas generated based on the findings of the sustainability assessment carried out in WP2 and aligned with the eco-design wheel were verified by the expert team and industrial partners and advisors. The actions defined for the two base-case FCH products were divided into **short- (within 3 years)**, **medium- (3-10 years)** and **long- (>10 years)** term actions.

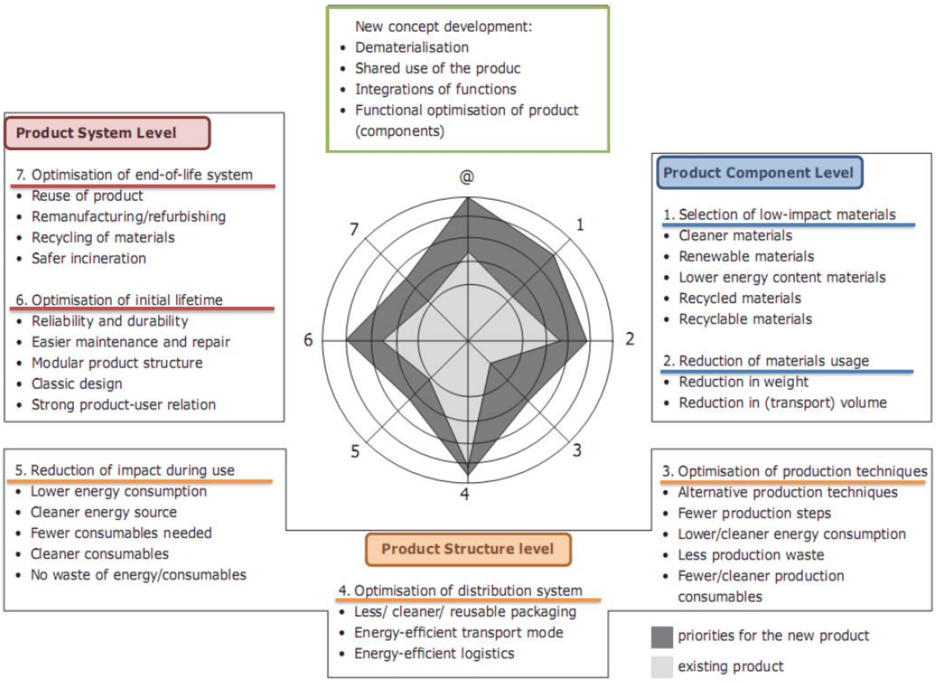

Figure 1. Eco-design strategy wheel [2]

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PEMFC STACK ECO-DESIGN ACTIONS

Two brainstorming sessions were held online on November 11th 2021 and December 16th 2021. All the partners proposed possible eco-design actions to improve the PEMFC stack design, based on the findings of the sustainability assessment carried out in WP2 of this project. The actions were proposed following the eco-design strategy wheel and were afterwards screened by the project technical experts to ensure their feasibility and to determine whether they seemed viable in the short, medium or long term. The actions proposed from these sessions are presented in Tables 1-10.

1.1 Short-term actions for the PEMFC stack

Short-term actions that were considered feasible are presented from Table 1 to Table 7 for the PEMFC stack. Based on the presented actions, an additional description is added to each table, to further describe how the actions could influence the modification of the current concept and the inventory of the PEMFC.

Table 1. Eco-design measures for the PEMFC case study (Axis 1 – Low-impact materials)

Action number	Action	Material/Component	Description of action
1.1	Recycled platinum	Platinum (MEA)	Reduce the use of virgin platinum with recycled platinum that is already available on the market and meets technical requirements (low amounts expected).
1.2	Low/Renewable-energy platinum		Reduce energy consumption and/or use of renewable energy with EU investments (e.g. offsetting programs for carbon footprint).
1.3	Aluminum	Stainless steel (external case)	Reduce the stack weight. The current external case is made of aluminum with stainless steel covers.
1.4	Reusable materials/parts	Stack/system	Reduce the overall stack impacts (i.e. end plates and housing). • Bipolar plates are very difficult to be reused; it largely depends on the use phase. • End plates, tie-rods in principle could be reused after some chemical treatment/cleaning. • Housing can be reused, after corrosion evaluation.

In the short term there are few actions foreseen to replace the current materials with low-impact ones since recycling of platinum from PEMFC stacks is still at the laboratory scale and it is not yet proven to meet all technical requirements to be implemented in the new PEMFC stack. The target is more than 75% of recycled platinum in new PEMFC stacks, which will be addressed in medium-to-long term actions as a closed-loop strategy.

Regarding the low/renewable platinum action, it is hardly foreseeable that platinum production countries will use renewable energy sources (RES) in the production process unless EU countries invest in it (e.g., through a carbon footprint offsetting program [3]).

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Table 2. Eco-design measures for the PEMFC case study (Axis 2 – Reduction of material usage)

Action number	Action	Material/Component	Description of action
2.1	Reduce the catalyst loading	Platinum (MEA)	Reduce the amount of platinum loading. Targets: lower than 0.41-0.52 mg/cm^2. Current best-case scenario is 0.22-0.25 mg/cm^2 for the new Toyota Mirai [4]. Prospective target: 0.125 mg/cm^2 or EU KPIs [5].
2.1.1	Optimize the catalyst shaping		Better utilization of Pt due to particle optimization (smaller and homogeneous size, shape, surface roughness can be tailored to increase the specific surface area of Pt particles).
2.1.2	Pt alloys		Higher mass activity of catalyst due to interaction of Pt and alloying material, which can decrease the amount of Pt. Additionally, in a catalyst particle Pt is partially substituted with alloying material, which further decreases Pt loading.
2.2	Optimize triple phase boundary	MEA	Tailor the porosity of carbon support and achieve homogeneous distribution of Pt particles on carbon support, adopt the use of highly oxygen-permeable ionomer in the catalyst layer [4].
2.3	Minimize the components thicknesses	Stack	Less material for membrane, gaskets, bipolar plates production and better system performance due to reduction of thickness and mass: • Membrane: from 15-20 µm to 8-12 µm (smaller ohmic losses). • Gas Diffusion Layer (GDL): from 150-300 µm to 90-110 µm (reduced mass transport losses). • Bipolar plates: 15-20% reduction in thickness.
2.4	Component merging		Optimal molding and welding processes to reduce bolts, clamps. Redesign of the end plates (function integration): • Replacement of the steel clampers used to compress the stack.
2.5	Use of fasteners		Replacement of tie-rods
2.6	Redesign of the end plates		Replacement of the steel clampers used to compress the stack: • Screwing the clamping bars directly on the reinforced plastics, with metallic inserts (function integration in the end-plate). Substitute the compression bars with ribs or stripes.

In action 2.1 the reduction of platinum loading is feasible, and some options are already commercially available [6]. The reduction of the loading can be achieved in two ways. Primarily, by optimizing pure Pt particles in several ways:

- Research shows small and homogeneous particles with narrow distribution in size have the potential to balance performance and durability [7].
- Different geometry and electronic states of different crystal faces of nanoparticles have different catalytic properties for the same reaction. The surface structure of metal catalyst can be obtained by controlling the shape of metal nanoparticles [8].

Secondly, Pt alloys can be used to increase the mass activity which is attributed to the lattice strain of the platinum skin surface formed by the surface dealloying and the modified electronic structure, which weakens the interaction between the atoms

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on the Pt surface and the intermediate species [7]. At the same time, the amount of Pt in the catalytic particles is reduced, which leads to lower overall Pt loading.

Component merging (action 2.4) means to merge parts at the component level with welding or soldering processes. By using those processes, we must be careful not to negatively influence the end-of-life process since the components are in this case not easy to dismantle.

Table 3. Eco-design measures for the PEMFC case study (Axis 3 – Production optimization)

Action number	Action	Material/ Component	Description of action
3.1	Low-impact impregnation/different coating technologies	MEA	Optimized, low-impact, and low-waste manufacturing processes (e.g. replace the decal process with CCM direct coating processes).
3.2	Integration of RES for the production processes	Stack	The manufacturing company should use renewable heat and electricity in the manufacturing process.
3.3	Ready-to-recycle assembly technologies		In design and manufacturing processes, enable that the PEMFC stack is dismountable, parts can be reused, materials are ready to recycle [9].
3.4	Reduce rejection rate		Improving defect detection technologies / reduce the rejection rate.
3.5	Waste minimization and management		Minimize material losses and waste during all the manufacturing phases. Recycle/recirculate the waste produced during the production.

In action 3.1 the idea is to reduce the loss of platinum in the coating process. Many manufacturers coat their membranes by themselves. The raw material they get is platinum on carbon support and then they produce the catalyst ink. There are various methods of applying the ink (e.g. bar coating, spray coating or slot die coating either sheet to sheet or roll to roll). Assembling processes and methods of applying the ink can be optimized to meet the requirements of the manufacturers, while using less energy and creating less waste. Catalyst Coated Membrane (CCM) direct coating process should be developed to replace the so called "decal" process which supposes multistep production and use of intermediate liners for anode and cathode catalytic layers.

Table 4. Eco-design measures for the PEMFC case study (Axis 4 – Distribution optimization)

Action number	Action	Description of action
4.1	Minimize the packaging	Keep the wooden packaging. Reduce the mass of packing material. **Note**: No technical specifications of the packaging available.
4.2	Use reusable and low-impact packaging	Keep the wooden packaging with reusable strategy. Use the recycled corrugated cardboard box material.

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Table 5. Eco-design measures for the PEMFC case study (Axis 5 – Low impact during use phase)

Action number	Action	Description of action
5.1	Optimize Energy Management System	Optimize the control strategy to minimize the stack energy consumption (machine strategy based on drop-control, prioritize energy hybrid structure rather than power hybrid structure in the control strategy, etc.). **Note**: recommendation for manufacturers.
5.2	Supply the fuel cell with green hydrogen	The use of green (renewable) hydrogen is recommended in the use phase. **Note**: recommendation for consumers.
5.3	Ease the stack dismantling and replacement within the system	More efficient maintenance – i.e. place the stack in the vehicles in very reachable places, simplify the fastening. **Note**: recommendation for manufacturers.

Table 6. Eco-design measures for the PEMFC case study (Axis 6 – Prolonged lifetime)

Action number	Action	Description of action
6.1	Optimize the battery-stack hybridization strategy	The hybridization strategy can influence the energy consumption (i.e. it is possible to minimize the dynamic conditions of the stack). **Note**: recommendation for manufacturers.

Table 7. Eco-design measures for the PEMFC case study (Axis 7 – End-of-life optimization)

Action number	Action	Advantages and notes
7.1	Improve the recycling of materials, especially platinum	Potential recovery of platinum and membrane. Recovery of copper in current collectors. **Note**: To include the results from the BEST4Hy project.

1.2 Medium-to-long-term actions for the PEMFC stack

Medium-to-long-term actions are those that are not foreseen to be implemented in the industry in the short term but are expected to be realized after several years from this point in time. Medium-to-long term actions are also divided into three basic groups of actions:

- Product Component Level (Table 8)
- Product Structure Level (Table 9)
- Product System Level (Table 10)

For instance, reasons behind categorization as medium/long-term actions are that some alternatives are still being tested at the laboratory scale (e.g. non-platinum catalysts, alternative ionomers) or the current lack of established supply chains for the FCH market. These actions should be therefore considered as technological milestones that the FCH sector could target soon, but that will not be available for achieving imminent sustainability improvements.

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Table 8. Medium/long-term eco-design measures at the product component level of the PEMFC stack

Axis	Action nr.	Action	Component	Description of action
1 – low-impact materials	**1.5**	Recycled platinum	Platinum (MEA)	Target is 70-80% of recycled platinum in new products as a closed-loop strategy. To establish the recycling market, a large volume of technology in the market is required.
	1.6	Non-platinum catalysts		Avoid the use of platinum. This is still at laboratory level.
	1.7	Other proton exchange materials	Ionomer (MEA)	Avoid/Reduce the use of ionomer (PFSA), improve conductivity (sulfonated PEEK, sulfonated pentablock terpolymers, MOF-polymer hybrid materials, etc.).
	1.8	Recycled ionomer		Reduce the use of virgin ionomer (PFSA).
	1.9	Carbon fiber or graphene/ epoxy resin composites	Stainless steel (Bipolar Plates)	Reduce the stack weight with material substitution that meets technical demands.
2 – reduction of material usage	**2.7**	Innovative cooling system design	Balance of plant	Reduce the overall system size/weight with less material use.
	2.8	Optimize the cell power density	Full stack	Reduce the number of cells, the number of components and the weight (i.e., in the case of a 48 kW stack, from 1.66-2.12 kW/kg to 2.46-4 kW/kg). This is done by increasing the MEA efficiency with different catalyst and ionomer choice: • 2.12 kW/kg stack needs 280 "standard MEA" to reach 48- 50 kW. • 2.46 kW/kg stack needs 280 "light weight MEA" or keep 48-50 kW with only 241 MEA. • 4 kW/kg stack needs 280 "light & efficient MEA" or keep 48-50 kW with only 149 MEA.
	2.9	Use of alternative commercial membranes	Membrane	Lower density and higher durability.

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Table 9. Medium/long-term eco-design measures at the product structure level of the PEMFC stack

Axis	Action nr.	Action	Component	Description of action
3 – production optimization	3.6	Optimize upstream manufacturing	Component level	Especially in platinum extraction/supply chain.
	3.7	Improve the stack and system modularity	Stack / overall system	Simplifies maintenance, repairs, refurbishing, and dismantling in EoL.
	3.8	Reduce the distance between component manufacturers and system assembly site	Overall system	Find the strategy (within EU) where the distances between manufacturers of components will be optimized.
	3.9	Low-activation stack	Stack/BoP	Increases the stack durability and efficiency (by optimizing the thermal management system). Decrease of hydrogen and energy consumption during activation phase using optimized catalyst.
4 – distribution optimization	4.3	Optimize packaging logistics	Component level / Overall system	Product specifications might lead to specific packaging with dedicated cleaning & washing logistics, logistic loops plus optimization [10]. **Note**: No data currently available due to lack of logistical details and established infrastructure. ***Recommendation level***
	4.4	Sustainable logistics, including storage optimization		*Logistics*: Use of renewable fuels and sustainable transport for delivery of products. *Storage*: Reduce the frequency of distribution / balanced production and optimization of costs. ***Recommendation level***
	4.5	Optimization of overall supply chain including EoL location		Avoid long distances by local (EU-based) manufacturing and recycling sites. ***Recommendation level***
5 – low impact during use phase	5.4	Running older stacks at lower loads and adding new, more efficient stacks to the system	Overall system	At lower load the efficiency of FC is higher, and lifetime is prolonged. New stacks provide additional power at higher efficiency due to technological improvements.
	5.5	Develop refurbishing technologies for FC systems failing within low-to-medium lifetime	Overall system	Especially in the case of BoP components. Within the stack, refurbishing (or even reusing) the bipolar plates could be feasible.
	5.6	Optimize the design of flow channels	Bipolar plates	Optimize fuel consumption, oxygen distribution and water balance (humidification) systems.

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Table 10. Medium/long-term eco-design measures at the product system level of the PEMFC stack

Axis	Action nr.	Action	Component	Description of action
6 – Prolonged lifetime	**6.2**	Reduce nitrogen crossover	Stack	Increases the stack durability and efficiency (by optimizing the anode purging cycles and recirculation).
	6.3	Alternative catalyst support	MEA	Replacing carbon support with another material to improve cell durability.
7 – EoL optimization	**7.2**	Establish a secondary raw materials market specific to FCH systems	Overall system	Involve manufacturers in EoL phase of their products and establish market where all entities would participate.
	7.3	Promote the creation of industrialized processes and recycling centers to collect/recycle the stacks		

1.3 Interaction between design ideas and eco-design criteria

Once technically feasible actions in the short, medium, and long term were identified, it is crucial to determine whether they interact with each other (Table 11) and up to which degree they affect the eco-design criteria (Table 12). The goal of this section is to find compatibilities and incompatibilities in order to ease a later evaluation of the most preferable actions.

The interactions among eco-design actions contained in Table 1, Table 2, Table 3, Table 4, Table 5, Table 6 and Table 7 are presented in Table 11. Medium- and long-term actions (Table 8, Table 9, Table 10) were excluded from this analysis as their implementation potential remains largely uncertain. The visual code to define such interactions is the following: "+" implies a positive interaction between actions (green box), "0" implies no interaction (white box), "-" implies a negative interaction (red box), and "+/-" implies no accurate knowledge about the nature of the eventual interaction between the two assessed actions.

The actions marked in blue in Table 11 and Table 12 were identified as general recommendations since targeted at another audience (e.g., car manufacturers) rather than directly related to the design and manufacturing of the stack, or not fully specifiable. In this sense, they are not included in the new product concepts definition.

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Table 11. Interaction among processed eco-design actions (short term)

	AXIS 1				AXIS 2								AXIS 3					AXIS 4		AXIS 5			AXIS 6	AXIS 7
	1.1	1.2	1.3	1.4	2.1	2.1.1	2.1.2	2.2	2.3	2.4	2.5	2.6	3.1	3.2	3.3	3.4	3.5	4.1	4.2	5.1	5.2	5.3	6.1	7.1
2.3	+	+	+	-	+	+	+	+		+	+	+	0	0	0	0	+	+	+	+	0	0	+	0
3.5	+	+	+	0	+	+	+	+	+	0	0	+	+	0	±	+		+	+	0	0	0	0	+
6.1	+	+	±	0	+	+	+	+	+	0	+	0	0	0	0	0	0	0	0	+	0	0		+
7.1	+	0	±	+	0	0	0	0	0	-	0	+	±	+	+	0	+	+	+	0	0	+		
1.1		0	0	0	+	+	+	±	+	-	0	0	+	0	+	0	+	0	0	0	0	0	+	+
2.1	+	+	0	0		+	+	+	+	0	0	0	0	0	0	0	+	0	0	+	0	0	+	0
2.1.1	+	+	0	0	+		+	+	+	0	0	0	0	0	0	0	+	0	0	+	0	0	+	0
1.2	0		0	0	+	+	+	+	+	-	0	0	+	0	0	0	+	0	0	0	0	0	+	0
2.1.2	+	+	0	0	+	+		±	+	0	0	0	±	0	0	0	+	0	0	+	0	0	+	0
5.1	0	0	±	0	+	+	+	+	+	0	+	0	0	0	0	0	0	0	0		+	0	+	0
2.2	±	+	0	0	+	+	±		+	0	0	0	±	0	0	0	+	0	0	+	0	0	+	0
2.6	0	0	±	±	0	0	0	0	+	+	+		0	0	+	0	+	0	0	0	0	+	0	+
3.3	+	0	0	+	0	0	0	0	0	-	+	+	+	+		±	±	0	0	0	0	±	0	+
2.5	0	0	±	±	0	0	0	0	+	-		+	0	0	+	0	0	0	0	+	0	0	+	0
3.1	+	+	0	0	0	0	±	±	0	0	0	0		+	+	0	+	0	0	0	0	0	0	±
4.1	0	0	+	0	0	0	0	0	+	0	0	0	0	0	0	0	+		+	0	0	0	0	+
4.2	0	0	+	0	0	0	0	0	+	0	0	0	0	0	0	0	+	+		0	0	0	0	+
1.3	0	0		-	0	0	0	0	+	±	±	±	0	0	0	0	+	+	+	±	0	±	±	±
3.2	0	0	0	0	0	0	0	0	0	0	0	0	+		+	0	0	0	0	0	+	0	0	+
1.4	0	0	-		0	0	0	0	-	-	±	±	0	0	+	0	0	0	0	0	0	0	0	+
2.4	-	-	±	-	0	0	0	0	+		-	+	0	0	-	0	0	0	0	0	0	-	0	-
5.2	0	0	0	0	0	0	0	0	0	0	0	0	0	+	0	0	0	0	0	+		0	0	0
5.3	0	0	±	0	0	0	0	0	0	-	0	+	0	0	±	0	0	0	0	0	0		0	+
3.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	±		+	0	0	0	0	0	0	0

Recommendation
Positive interaction/synergy
Unknown interaction
Negative interaction

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Table 12. Combination of eco-design actions and criteria

Action number	Positive	Unknown/moderate	Negative	Changes to the system	Cost	Dependency	Transport	Energy consumption	Social impacts
2.3	15	0	1	Positive	Positive	Positive	Positive	Positive	Positive
3.5	14	1	0	Unknown/moderate	Unknown/moderate	Positive	Positive	Unknown/moderate	Positive
7.1	10	3	1	Negative	Negative	Unknown/moderate	Positive	Positive	Positive
6.1	10	1	0	Negative	Negative	Negative	Positive	Positive	Positive
1.1	9	1	1	Positive	Negative	Negative	Positive	Unknown/moderate	Positive
2.1.1	9	0	0	Positive	Negative	Negative	Positive	Unknown/moderate	Positive
2.1	9	0	0	Unknown/moderate	Unknown/moderate	Unknown/moderate	Positive	Positive	Positive
2.1.2	8	2	0	Unknown/moderate	Unknown/moderate	Unknown/moderate	Positive	Positive	Positive
5.1	8	1	0	Negative	Negative	Negative	Positive	Positive	Positive
1.2	8	0	1	Positive	Negative	Unknown/moderate	Unknown/moderate	Positive	Positive
2.2	7	3	0	Unknown/moderate	Negative	Unknown/moderate	Positive	Positive	Positive
3.3	7	3	1	Negative	Negative	Negative	Positive	Unknown/moderate	Positive
2.6	7	2	0	Negative	Unknown/moderate	Unknown/moderate	Unknown/moderate	Unknown/moderate	Positive
3.1	5	3	0	Positive	Negative	Negative	Positive	Positive	Positive
2.5	5	2	1	Unknown/moderate	Unknown/moderate	Unknown/moderate	Unknown/moderate	Unknown/moderate	Unknown/moderate
4.1	5	0	0	Positive	Positive	Positive	Positive	Positive	Positive
4.2	5	0	0	Positive	Negative	Negative	Positive	Positive	Positive
1.3	4	7	1	Unknown/moderate	Unknown/moderate	Positive	Positive	Positive	Positive
3.2	4	0	0	Positive	Negative	Unknown/moderate	Unknown/moderate	Positive	Positive
1.4	2	2	3	Unknown/moderate	Negative	Positive	Unknown/moderate	Positive	Positive
2.4	2	1	7	Negative	Positive	Unknown/moderate	Unknown/moderate	Negative	Unknown/moderate
5.3	2	2	1	Unknown/moderate	Positive	Positive	Unknown/moderate	Unknown/moderate	Positive
5.2	2	0	0	Positive	Negative	Negative	Positive	Positive	Positive
3.4	1	1	0	Unknown/moderate	Unknown/moderate	Positive	Unknown/moderate	Positive	Positive

Negative effect

Unknown/moderate effect

Positive effect

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1.4 Definition of product concepts for the PEMFC stack

Based on the actions, three product concepts were defined: **realistic, optimistic,** and **disruptive**. The realistic product concept is further sub-divided into two:

Realistic short-term concept: based just on short-term actions that will be realized and implemented in the FC industry in the near future.

Realistic medium-to-long-term concept: based on short-term actions and additionally including some medium-to-long-term actions.

Optimistic product concept is the concept already under implementation by some top-end technological companies and/or developed at the laboratory scale.

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

1.4.1 Realistic product concept

Realistic product concept is divided into two as explained above: realistic at short term and realistic at medium-to-long term.

1.4.1.1 Realistic short-term concept

Short-term actions are presented in Table 1 to Table 7. Four axes of the eco-design wheel are addressed in the realistic short-term concept with a total of 10 actions:

- 2 actions from Table 1: 1.1 and 1.4.
- 4 actions from Table 2: 2.1.1, 2.1.2, 2.2 and 2.3.
- 2 actions from Table 3: 3.1 and 3.4.
- 2 actions from Table 4: 4.1 and 4.2.

In action 1.1 **recycled platinum use** is addressed. Since the commercial way of platinum recovery from PEMFC is still under development or on the laboratory scale [9], the proposed action is to use the share of recycled platinum already available on the market (from different source) that still meets technological requirements.

Action 1.4 anticipates the **reuse of the stack housing** which is completely feasible when the supply chains in all life-cycle phases are planned and controlled. In this action **the reuse of end plates** is also foreseen, but in this case a refurbishment of end plates is needed.

Actions 2.1.1 and 2.1.2 are addressing **the reduction of platinum** due to decreased platinum loading which is the consequence of: (i) better utilization of platinum due to particle optimization (smaller size, shape, tailored surface roughness to increase the surface area of particles), and (ii) the use of Pt alloyed materials which can decrease the amount of platinum itself.

Because of **optimized triple phase boundary** (action 2.2), the electrochemical reaction is improved (e.g. achieved by more homogeneous distribution of platinum particles), and the technology has higher efficiency.

Mass reduction (action 2.3) of various materials is achieved with the reduction of membrane thickness (ionomer), GDL thickness (carbon fibers) and reduction of mass of bipolar plates (carbon composites or stainless steel). In addition, it is expected that in some case the system performance (specific power) will improve due to simultaneous improvement of the component characteristic and the reduction of the mass.

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Axis 3 is addressing production optimization in eco-design. The designated actions are **optimized catalyst coating** on MEA (action 3.1), with the smallest possible material loss during the coating process. Action 3.4 addresses **the rejection rate** of components that must be minimized with improving defect-detection technologies.

In **distribution optimization** (axis 4) actions 4.1 and 4.2 are included; they address the packing material that should be sustainable (wood), reusable and recycled (recycled corrugated cardboard box).

Realistically, most FC systems are equipped with a battery pack. As a recommendation, by optimizing the integration and **battery-stack hybridization strategy** the lifetime of the system can be prolonged (**axis 6**).

1.4.1.2 Realistic medium-to-long-term concept

In the realistic medium-to-long term concept all compatible short-term actions are foreseen to be implemented plus several actions that are realistic but are not expected to be implemented by the industry in the near future.

In **axis 2** (where **material reduction** is addressed) the **increase** in **power density** is expected from 1.66 to 2.46 kW/kg due to the lower number and weight of components, alongside other technological improvements.

Unlike in the case of the short-term realistic concept, the medium-to-long-term realistic concept **axis 5** (low impact during use phase) addresses the **refurbishment strategies of FC systems**. This is especially the case for BoP components. Within the FC stack, refurbishing (or even reusing) the bipolar plates that are not too degraded/damaged could be feasible. Furthermore, by **optimizing the flow channels** design on bipolar plates, the fuel consumption, oxygen distribution and water balance (humidification) systems can be optimized, consequently reducing the impacts during the use phase (**axis 5**).

Prolonging lifetime (**axis 6**) in a medium-to-long-term prospective is achieved by alleviating nitrogen crossover. With this action the stack durability and efficiency will be increased (by optimizing the anode purging cycles and recirculation).

A schematic representation of the realistic concepts is provided in Figure 2.

1.4.2 Optimistic product concept

This concept includes all the actions foreseen in the realistic concept except when the new ones produce a better performance under the same aspect.

In **axis 1** the paramount action is to significantly **increase the use of recycled platinum (70% - 80%)** in the fuel cell catalyst (closed-loop recycling). Additionally, offsetting carbon footprint due to investments in mining process in platinum production countries (e.g. South Africa) is considered. Realistically, **refurbishment (reuse) of bipolar plates** is already possible on a very small scale. This is expected to be adopted on a larger scale throughout the FC market. Introduction of new, different ionomers or other hybrid materials should improve proton conductivity and durability, while reducing the environmental impact.

Reduction of material usage (in **axis 2**) can be done by **redesigning the systems**. Innovative cooling systems could be smaller in size, while being as efficient but bringing down the mass of the system. This and other improvements to the system would make a target of > 2.46 kW/kg power density attainable.

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In product optimization (**Axis 3**), **catalyst application techniques are expected to improve** to the point that no material (catalyst ink) is lost. Also, at the level of MEA manufacturing the **rejection rate should be close to zero**.

Introducing **smart energy management system** can reduce impacts during the use phase (**axis 5**). Various components or processes can be controlled (consumption of BoP, recirculation and purging of anode, dynamic monitoring of optimal operating point, etc.)

Prolonging the lifetime (**axis 6**) of the FC stack can also be achieved by alleviating the corrosion of catalyst support. **Alternative catalyst supports** that will replace regular high surface area carbons are expected to provide this durability.

Recent research and EoL optimization (**axis 7**) of FCH technologies raise hopes that it will be possible to attain **high closed-loop recycling ratios** for valuable materials (Pt, Co, Au, ionomer). In a worse case, these valuable materials could be used as secondary material in open-loop recycling.

1.4.3 Disruptive

To reduce the impacts of materials (**axis 1**) the recycling rates of materials should be extremely high. For platinum recovery some laboratory experiments show that more than 95% utilization is possible. Long-term industrial scale FCH recycling processes should **attain more than 95% recycling rate for platinum**. A different (but to a certain extent complementary) approach is to **develop non-PGM catalysts**, but they need to meet all technical requirements. A **high recycling rate of ionomer** would additionally lower the impact of PEMFC technology.

Reducing material usage (**axis 2**) should improve specific power substantially. The goal is to reach **4 kW/kg in a stack**.

Production optimization (**axis 3**) should foster the **use of renewable energy in production processes** and **optimize upstream manufacturing** to reduce the impacts in platinum extraction and supply. Further on, it should reduce the **rejection rate of components to zero** and create **no waste on stack level production while employing a closed-loop recycling** approach within the manufacturing company. Optimizing the **distance between the manufacturing sites of components and system assembly sites** would additionally reduce the environmental impact. **Ready-to-recycle assembly technologies** should provide modularity, while using materials with high recyclability and relying on well-established and technologically ready recycling technologies.

Axis 4 represents distribution optimization. The actions contained in this axis are presented more at a recommendation level: optimize the packaging and storage logistics, ensure sustainable logistics (e.g., renewable fuels for transport), and reduce distances on all levels of the product (i.e. production, use, and end of life).

The goal of FC technologies is to reduce the impact in the operation phase (**axis 5**) by **renewable hydrogen** [11]. Significant shift in hydrogen production methods is required to provide vast amounts of green hydrogen.

EoL optimization (**axis 7**) should also be done through consolidation of the recycling sector. Industrialized processes and recycling centers to collect and recycle the FCH products need to be established. Also, a secondary market for recycled materials from FCH products should be created.

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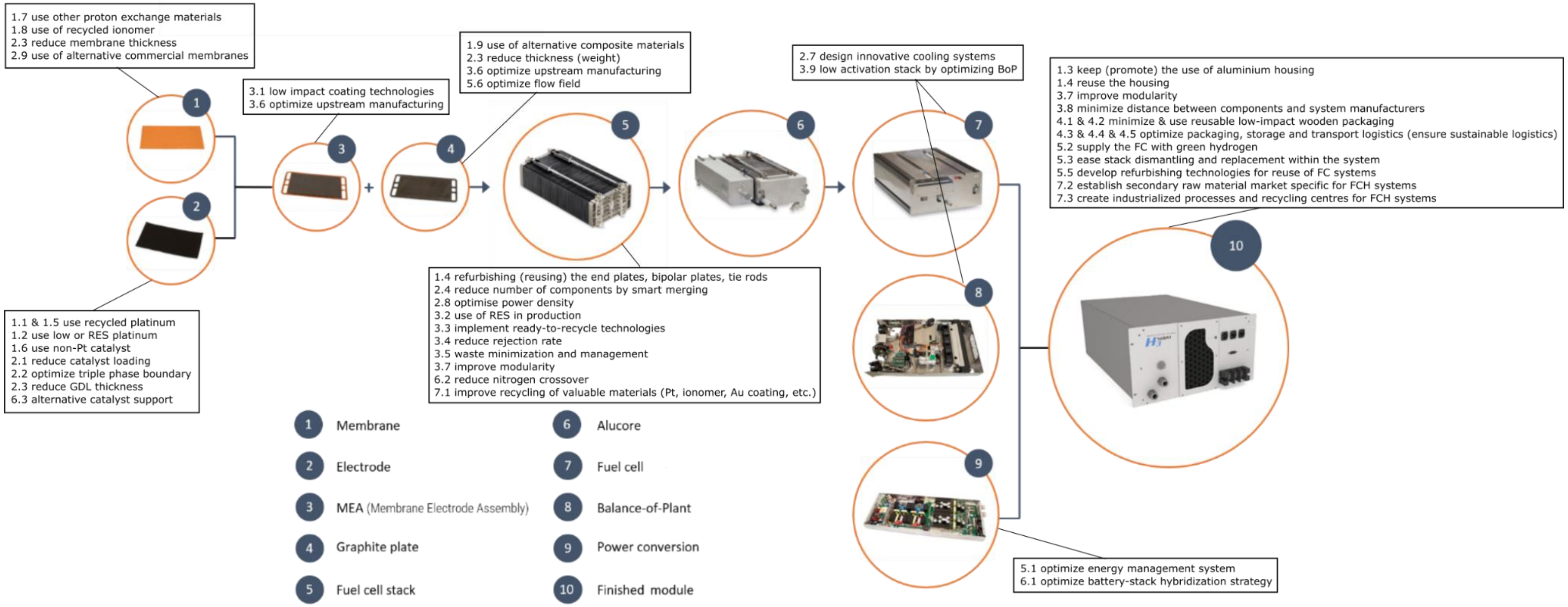

Figure 2. Schematic of the FC system and eco-design actions in developing product concepts. Original image courtesy of Advent Technologies A/S

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SOEC STACK ECO-DESIGN ACTIONS

Two brainstorming sessions were held in hybrid mode (face-to-face and online) on March 31st 2022 and April 1st 2022. For this task the connection with relevant industry partners was established and relevant technological SoA data was collected (2 online meetings: October 22 and November 22). All partners and the technical experts of the External Working Group (EWG) proposed possible eco-design actions to improve the SOEC stack design. The actions proposed in these meetings are listed in the tables below.

In general, it can be added that the SOEC technology is very similar (if not the same) to SOFC –solid oxide fuel cell– technology when it comes to the materials and components used in the stack. Therefore, with caution, this part of the study could also be used for SOFC technology or increasingly researched reversible SOFC.

2.1 Medium-term eco-design actions for the SOEC stack

The **enhanced realistic product concept** is the concept based on the medium-term actions that will be realized and implemented in the FCH industry in the near future (medium-term perspective). Actions and eco-design measures are presented in Table 13.

Table 13. Medium-term eco-design actions for the SOEC stack

Axis	Action number	Action	Material/ Component	Description of action
1	1.1	Different steel alloys	Stainless steel	Reduce the use of virgin stainless steel
	1.2	Recycled steel	Steel	Reduce the use of virgin steel
2	2.1	Optimize the end plates / frames / meshes	End plates, frames, meshes	To reduce the stainless-steel amount
	2.2	Change/optimize the cell shape and size	Cell	To reduce the amount of material employed
	2.3	Change the stack type (electrolyte supported/cathode supported)	Stack	To reduce the amount of REE materials and of nickel
3	3.1	Use less or cleaner energy	All	Especially for cell sintering, which is particularly energy consuming (reduce the time and temperature)
	3.2	Reduce the amount of chemicals/solvents in all production steps	All	E.g., use colloidal processing based on water instead of organic solvents
4	4.1	Keep the current packaging	1*	Wooden boxes with multiple uses, durable packaging. There is room for improvement, but plastic bags are still used to ship stack components. Cardboard is also used.

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5	**5.1**	Supply the system with green electricity	2*	To lower environmental impacts due to RES electricity use
	5.2	Optimize the balance of plant	2*	To reduce the overall energy consumption
	5.3	Produce low-impact steam	2*	To reduce the environmental impacts due to steam production
	5.4	Use steam from steam networks	2*	To reduce the environmental impacts due to steam production. Depends on the location → recommendation level
	5.5	Use water recirculation	2*	To reduce overall water consumption
6	**6.1**	Have harmonized standards to measure stack degradation	2*	-
	6.2	Create harmonized protocols/recommendations to start/operate the system	2*	-

1* - This recommendation relates to transport/logistics and will not be validated in next steps as transportation is not included in the methodology presented in D2.1 and D2.3.
2* - This recommendation action relates to the use phase of a product's eco-design (not subjected to further Life Cycle Assessment as only manufacturing and EoL phases are included in the methodology presented in D2.1 and D2.3).

2.2 Medium-to-long-term eco-design actions for the SOEC stack

After screening the actions within the consortium and the technical expert team from the EWG, some of the actions in Table 14 were considered difficult to be implemented in the nearby future. This is attributable to the fact that SOEC is still an emerging technology, therefore many stages of production/manufacturing are still at a laboratory scale. For the same reason, the technology supply chain and the EoL strategies are not well developed. Therefore, the eco-design actions identified in axes 3, 4 and 7 are mainly considered as long-term actions.

The **optimistic product concept** includes all relevant above-mentioned medium-term actions with additional view on possible actions which are still under development or in the early research phase or even conceptual phase.

Table 14. Medium-to-long-term eco-design actions for the SOEC stack

Axis	Action number	Action	Component	Description of action
1	**1.3**	Different doping strategy for the catalysts	Cell	To reduce the amount of REEs (especially of lanthanum and yttrium) in the stack
	1.4	Ceramic materials	Interconnects D	To reduce the amount of stainless steel in the stack
2	**2.4**	Reduce material losses	Overall stack	Target: <5%

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				E.g., by using additive manufacturing instead of subtractive manufacturing
	2.5	Utilize a different electrolyte	Electrolyte	To reduce the amount of REE materials (e.g. proton conducting electrolyte)
3	**3.3**	Optimize the surface polishing/cleaning	Cell [D]	To reduce material losses/impacts
	3.4	Use additive manufacturing instead of subtractive manufacturing	Stack	To reduce material losses
	3.5	Improve the recycling rate	Module/system	Target/base case recycling rate
4	**4.2**	Optimize logistics	1*	E.g., reduce the distance between producers and consumers
	4.3	Clean way of transportation	1*	RES based electricity vehicles, FCEV trucks
	4.4	Vertical integration	1*	E.g., in-house production. This might reduce the impacts but increase the costs
5	**5.6**	Reduce the operating temperature	2*	To reduce the overall energy consumption
	5.7	Change from sweep gas to pure oxygen	2*	Unclear whether this could reduce or increase the impacts (using pure oxygen could cause corrosion and safety issues)
6	**6.3**	Operate the system at lower temperatures	2*	To limit the stack degradation
	6.4	Improve stack modularity	2*	To optimize part load operation and limit degradation
	6.5	Redesign the BoP	BoP components	E.g., to heat up only the active area and not the structural elements such as end plates
7	**7.1**	Reuse some components after eventual remanufacturing	End plates, tie-rods	It may be possible to design some components to be reused after the first usage (e.g., increase end plates thickness to allow remanufacturing); in this case, thermal and mechanical properties need to be checked
	7.2	Recycle/recover materials	Cathode, anode	BEST4Hy project [9] (e.g., cobalt and lanthanum, through hydrometallurgical processing)

D - This action was discarded and will not be considered in further analyses.
1* - This recommendation relates to transport/logistics and will not be validated in next steps as transportation is not included in the methodology presented in D2.1 and D2.3.
2* - This recommendation action relates to the use phase of a product's eco-design (not subjected to further Life Cycle Assessment as only manufacturing and EoL phases are included in the methodology presented in D2.1 and D2.3).

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2.3 Interaction between ideas and design criteria for SOEC stack

Following the same procedure described in Section 1.3, feasible actions in the medium and long term were identified by exploring the interaction between potential actions (Table 15) as well as eco-design criteria effects (Table 16).

The interactions between eco-design actions contained in Table 13 are presented in Table 15. Medium-to-long-term actions (Table 14) were excluded from this analysis as their implementation potential remains largely uncertain. The visual code to define such interactions is the following: "+" implies a positive interaction between actions (green box), "0" implies no interaction (white box), "-" implies a negative interaction (red box), and "+/-" implies no accurate knowledge about the nature of the eventual interaction between the two assessed actions.

The actions marked in blue in Table 15 and Table 16 were identified as general recommendations since targeted at another audience rather than directly related to the design and manufacturing of the stack, or not fully specifiable.

Table 15. Interaction among medium-term eco-design actions for the SOEC stack

		AXIS 1		AXIS 2			AXIS 3		AXIS 4	AXIS 5					AXIS 6	
		1.1	1.2	2.1	2.2	2.3	3.1	3.2	4.1	5.1	5.2	5.3	5.4	5.5	6.1	6.2
AXIS 1	1.1		+	+	+	0	0	0	0	0	0	0	0	0	0	0
	1.2	+		+	+	0	0	0	0	0	0	0	0	0	0	0
AXIS 2	2.1	+	+		±	0	0	0	0	0	0	0	0	0	0	0
	2.2	+	+	±		±	0	±	0	0	±	0	0	0	0	0
	2.3	0	0	0	±		±	±	0	0	±	0	0	0	0	0
AXIS 3	3.1	0	0	0	0	±		0	0	+	+	+	+	+	0	0
	3.2	0	0	0	±	±	0		0	0	0	0	0	0	0	0
AXIS 4	4.1	0	0	0	0	0	0	0		0	0	0	0	0	0	0
AXIS 5	5.1	0	0	0	0	0	+	0	0		+	+	+	+	0	0
	5.2	0	0	0	±	±	+	0	0	+		+	+	+	0	0
	5.3	0	0	0	0	0	+	0	0	+	+		+	+	0	0
	5.4	0	0	0	0	0	+	0	0	+	+	+		+	0	0
	5.5	0	0	0	0	0	+	0	0	+	+	+	+		0	0
AXIS 6	6.1	0	0	0	0	0	0	0	0	0	0	0	0	0		+
	6.2	0	0	0	0	0	0	0	0	0	0	0	0	0	+	

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Table 16. Combination of eco-design actions and criteria for the SOEC stack

Action number				Changes to the system	Cost	Dependency	Transport	Energy consumption	Social impacts
3.1	6	1	0						
5.2	5	2	0						
5.1	5	0	0						
5.3	5	0	0						
5.4	5	0	0						
5.5	5	0	0						
2.1	3	2	0						
1.1	3	0	0						
1.2	3	0	0						
2.2	2	4	0						
3.2	1	3	0						
6.1	1	0	0						
6.2	1	0	0						
2.3	0	5	0						
1.3	0	4	0						
4.1	0	0	0						

Negative effect
Unknown/moderate eff.
Positive effect

2.4 Definition of product concepts for SOEC stack

Based on the actions for SOEC stack described above in Table 13 and Table 14 and represented in Figure 3, two product concepts for SOEC stack were defined: ***enhanced realistic product concept*** and ***optimistic product concept***.

The **enhanced realistic product concept** is the concept based on medium-term actions that will be realized and implemented in the FCH industry in the near future (medium-term perspective in next 3 to 10 years).

The **optimistic product concept** includes all relevant above-mentioned medium-term actions with additional view on possible actions still under development or in the early research phase or even conceptual phase.

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Figure 3. Schematic of the solid oxide system and eco-design actions in developing product concepts. Original image courtesy of Sunfire GmbH

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2.4.1 Enhanced realistic product concept

In the enhanced realistic product concept, all compatible medium-term actions are foreseen to be implemented plus several actions that are realistic, but are not expected to be implemented soon.

The ***enhanced realistic concept*** involves the following selection of actions listed in Table 13. Medium-term eco-design actions:

- 2 actions from 1st axis: 1.1 and 1.2.
- 3 actions from 2nd axis: 2.1, 2.2, and 2.3.
- 2 actions from 3rd axis: 3.1 and 3.2.
- 1 guideline/recommendation from 4th axis: 4.1.
- 5 guidelines/recommendations from 5th axis: from 5.1 to 5.5.
- 2 guidelines/recommendations from 6th axis: 6.1 and 6.2.

In **(axis 1) action 1.1 the reduction of virgin stainless steel** is addressed as well as **action 1.2 addressing the use of recycled steel**, thus reducing the amount of used virgin (stainless) steel. Use of secondary steel is possible, and recycling of steel is theoretically possible in high shares but in practice there are some challenges. Mainly, due to the impurities and other materials which can considerably change material properties compared to properties of virgin stainless steel alloys used in the SOEC technology. Since most used are **high chromium alloyed steels**, some alternatives could be used instead e.g. ferritic steel 441 or 444, which are not yet widespread in the FCH industry.

Reduction of material usage **(in axis 2)** can be done by redesigning or optimizing the SOEC components. The **action 2.1 addresses redesign of end plates** (e.g., thinner plates) **frames and meshes,** thus reducing the total amount of used stainless steel. **Action 2.2 focuses on SOEC cell shape and size optimization** (square vs. tubular design, increased cell size - active area, thinner layers of materials, etc.) to reduce the amount of material employed and consequently increasing the power density of the SOEC stack. As pointed out by the EWG, in the next 5 years the **power density (kW/kg) is expected to double** compared to the current state-of-the-art (SoA). **Action 2.3 addresses the change of the stack type** (e.g., electrolyte supported or cathode supported), with the aim of **reducing/replacing the amount of REE materials and nickel**. For near future targets the replacement with alternative materials is not possible, but **30% amount reduction of REE** materials is nevertheless foreseen for the enhanced realistic concept.

For the manufacturing phase two recommendation actions are foreseen within **production optimization (axis 3)**: **action 3.1 on using less or cleaner energy for SOEC production**, especially for cell sintering, which is particularly energy consuming (with the aim of reducing the time and the temperature of the process), and **action 3.2 to reduce the amount of harmful chemical/solvents** in all production steps (e.g. use colloidal processing based on water instead of organic solvents), which will be feasible in the medium term with increased production volume.

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In **distribution optimization** (**axis 4**) action 4.1 is included, which addresses the packing material, which should be sustainable (wooden boxes as currently already available packaging) and reusable (for multiple uses and durable).

Actions addressing **low impact during the use phase** (**axis 5**) of the SOEC stack are: **5.1 on the use of green electricity** during the use phase of the SOEC system, **5.2 on the optimization of the balance of plant (BoP)** (to reduce the overall system's energy consumption), **5.3 on the production of low-impact steam** (use by-product heat or "green" fuels) or **5.4 on the use of steam from steam networks** if possible (as recommendation action), and **5.5 on the implementation of the water recirculation system** to reduce the water consumption of the SOEC system.

When addressing **axis 6 (prolonged lifetime)** of the SOEC stack eco-design, SOEC testing and technical and environmental benchmarking of different SOEC systems should be harmonized. In this area the EU harmonised testing procedure for electrolysers [12] is available and some initial LCA guidelines can be found [13], while the SH2E project on FCH-specific life cycle assessment guidelines is currently in progress. In terms of stack degradation measurements and protocols for system operation, harmonized standards should be defined and used by all manufacturers in the FCH industry.

2.4.2 Optimistic product concept

In the optimistic (long-term) product concept, all compatible medium-to-long-term eco-design actions are foreseen (expected to be implemented in the FCH industry in 10 years at the earliest). This concept includes all the actions foreseen in the enhanced realistic product concept, except when the new actions produce a better performance under the same action aspect.

Seven axes of the eco-design wheel are addressed in the ***optimistic concept***, with a number of **additional actions** and **recommendations** (mainly from Table 14):

- 1 recommendation action from Table 14: 1.3.
- 2 actions from Table 13 and 2 recommendation actions from Table 14: 2.2, 2.3, 2.4 and 2.5.
- 2 actions from Table 14: 3.4 and 3.5.
- 2 recommendation actions from Table 14: 4.2 and 4.3.
- 1 recommendation action from Table 14: 5.6.
- 1 recommendation action from Table 14: 6.3.
- 2 recommendation actions from Table 14: 7.1 and 7.2.

Under **axis 1 (low-impact materials)** only one action as possible recommendation is foreseen in this concept. The catalytic layer on the anode side generally consists of lanthanum-based perovskites. Action **1.3 on a different doping strategy for the catalysts** addresses the possibility of finding alternative materials for the oxygen electrode. This action partially goes hand in hand with the proposed action 2.3, where general reduction of REE is foreseen. Based on the discussions with the EWG, the proposed action **1.4 on ceramic materials** was found to be impractical, and will be discarded in future analyses, because the ceramic interconnects are based on REE and less stable than their

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stainless-steel counterparts. Moreover, the technology for producing stainless steel interconnects is well developed, which makes them cheaper.

In this concept further **reduction of the material usage (axis 2)** is foreseen. **Action 2.2** in the optimistic product concept focuses on further optimization of the SOEC cell shape and size (decreasing the amount of material used) with the goal to **triple the SOEC power density (kW/kg)** (as suggested by the EWG) compared to the SoA (reference SOEC product). Similarly, increased amount of REE reduction is foreseen under **action 2.3** (weight reduction of REE) in the optimistic concept, namely **60% reduction of REE materials**. Regarding **action 2.4 on the reduction of material loss during the manufacturing phase**, tape casting and screen printing will probably be used for a long time, currently not many other techniques are being explored. Medium-term target involves **material losses <5%** for the overall SOEC stack production with alternative methods (e.g., by using additive manufacturing instead of subtractive manufacturing). Furthermore, action **2.5 on the utilization of a different type of electrolyte** is foreseen to reduce REE materials, as now electrolyte materials are mainly based on yttrium, cerium, scandium or gadolinium. Additional research efforts should be done in the next 10 years for alternatives.

Within the **axis 3 (production optimization)** two actions are foreseen (while action 3.3 on optimized surface polishing/cleaning is generally not needed and it will be discarded in further analyses). The first focuses on the production process: action **3.4 on the use of additive manufacturing** instead of subtractive manufacturing could consequently reduce the material losses during production of the SOEC, e.g., this could be applied to the production process of interconnects and cells. The second action focuses on **improving the recycling rate of the materials (3.5)** and their use in the production processes. Results of the undergoing BEST4Hy project [9], where recyclability of yttrium, nickel, lanthanum and cobalt is studied, could be used.

For **distribution optimization** (**axis 4**) two recommendation actions are included: **action 4.2 on the optimization of the logistic chains** (e.g., reduce the distance between producers and consumers) and **4.3 on transportation with lower life-cycle environmental impact** (e.g., “green” hydrogen or electric trucks, trains).

One of the goals of the SOEC technology is also to reduce the impact in the **operation phase (axis 5)** and energy consumption by **reducing the operating temperature (action 5.6)** under current SoA, which is between 700°C and 800℃, to around 650°C.

Action 5.6 also correlates with **action 6.3 on lower operating temperature** to **limit/lower the SOEC stack degradation** and thus **prolonging the operational lifetime (axis 6). Action 6.4 on improved modularity of stacks** can potentially increase the lifetime if certain “smart algorithms” are used for stacks/modules to run at part load –or even in short reversable (fuel cell) mode– while others work at constant load. Also, **action 6.5 on redesigning the BoP** (e.g., localized but uniform heating system) can reduce strain on components and prolong the lifetime.

EoL optimization (**axis 7**) for SOEC stack should also be done through consolidation of the recycling industry and further R&D in this field as the SOEC technology is not widely

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commercialized yet. Industrialized processes and recycling centers to collect and recycle the FCH products need to be established. Also, a secondary market for recycled materials from FCH products should be created, as SOEC stacks consist of highly valuable REE materials, which is also relevant according to the EU criticality methodology. Under axis 7, two recommendation actions are foreseen: **7.1 on the reuse of the SOEC components for remanufacturing** (due to strain at high temperatures, the reuse of components might be limited and recycling of the metal components is seen as a more viable solution), and **7.2 on the recycling/recovery of key materials** (e.g., yttrium-stabilized zirconia [YSZ], cobalt and lanthanum via hydrometallurgical processes; referring to BEST4Hy results [9]).

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CONCLUSIONS

This deliverable summarizes the procedure followed for eco-designing the reference products selected in the project: PEMFC and SOEC stacks. This procedure was based on the conventional one with the typical stages of ideas generation (including merging similar ones, studying the interactions between ideas and design criteria, and their selection and prioritization) and product concepts development. As a novelty of the eGHOST project, criticality and social aspects were taken into account in addition to environmental issues.

For the PEMFC stack, the concepts proposed were:

- Realistic short-term concept: based just on short-term actions that will be realized and implemented the near future.
- Realistic medium-to-long-term concept: based on short-term actions and additionally including some medium-to-long-term actions.
- Optimistic product concept is the concept already under implementation by some top-end technological companies and/or developed at the laboratory scale.
- Disruptive product concept includes relevant above-mentioned actions plus others that are still under development or in the early research or even conceptual phase.

In the case of SOEC stack, some production/manufacturing stages are still at a laboratory scale, reason why the supply chain and the EoL strategies are not well developed. Therefore, the product concepts proposed are:

- Enhanced realistic product concept that is based on medium-term actions (in next 3 to 10 years).
- Optimistic product concept that includes additional possible actions, which are still under development or in the early research phase or even conceptual phase.

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