New technologies and strategies for fuel
cells and Hydrogen Technologies in the
phase of recycling and dismantling

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D2.5 Study on needs and challenges in the phase of recycling and dismantling

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Executive Summary

This document, which is presented as deliverable 2.5 ‘Study on needs and challenges in the phase of recycling and dismantling’, is part of HyTechCycling project, and set the basis for future developments that are going to be needed in the recycling of FCH technologies.

Taking into account since the designing phase, where this document proposes the use of eco-design and circular economy, a brief guide that shows the tendency to follow in the future is presented. Moreover, an analysis of the different materials that compounds FCH technologies is made, looking for overcoming milestones and needs such materials toxicity or the capacity to recycling and dismantling FCH technologies.

This document analyses the general needs from recycling obtained in previous documents of this project, such the development of recycling technologies to recover the maximum amount and type of materials, or promoting the use of treated waste of FCH technologies by manufacturer companies. The technologies available nowadays to recycle these materials and their needs are also listed in this document.

Subsequently, this document shows briefly the normative frame, looking for specific regulation affects to FCH technologies and the administrative processes to overcome in the EU frame. Finally, other needs and challenges are presented, such a split of the recycling responsibilities between customer and supplier, or a proposal of a sustainable business model based on the recycling and dismantling of FCH technologies.

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Abbreviations

AWE	Alkaline Water Electrolyser
BoP	Balance of Plant
EcoM2	Eco-design Maturity Model
ELV	End-of Life Vehicles
EoL	End of Life
ERP	Extended Responsibility of Producer
FC	Fuel Cell
FCH	Fuel Cell and Hydrogen
NPMCs	non-precious metal catalysts
PDP	Product Development Process
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PEMWE	Polymer Electrolyte Membrane Water Electrolyser
PGM	Platinum Group Metals
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RoHS	Restriction of Hazardous Substances
SETIS	Strategic Energy Technology Plan
SME	Short and Medium Enterprise
SOFC	Solid Oxide Fuel Cell
SPE	Solid Polymer Electrolyte
WEEE	Waste Electrical and Electronic Equipment

1. Introduction

This document shows the needs and challenges that must be overcome in order to boost Fuel Cell and Hydrogen (FCH) technologies within the markets that exist in Europe. These challenges and needs are focused from a vision of recycling and dismantling, that is, from the end of life of products.

Within the previous work of the HyTechCycling project, limitations or barriers have been detected for a major penetration of these technologies. These impediments have been carefully analyzed and needs and challenges of the FHC technologies have been established and must be overcome. All these elements will serve as a basis for further developments within the project and achieve the initially set objectives.

For a better identification and understanding of needs and challenges the different facets of the end of life of the products have been structured in three large study groups. These groups are the materials that make up the equipment, the existing recycling technologies and the legal aspects that govern FCH technologies in Europe.

The choice of one material instead of another can carry great differences even going so far as one technology imposes itself on another. In a clear example could be choose a catalyst that requires more energy to operate but its obtaining process is very simple and is more abundant in the earth's crust. This factor of availability of materials is in addition to other factors such as the hazard of materials or the cost of the same. These factors have made it possible to identify the challenges faced by these technologies.

Existing recycling techniques were also studied to see which of them were most likely to be used for FCH systems and to determine what is needed to take advantage of those processes. These recycling technologies are associated with a number of legal, economic and environmental constraints therefore are taken into account in order to establish the challenges to be met.

The existing regulation is another group that has been analyzed in the course of the project to be able to adapt correctly, find solutions and propose improvements in European regulations. Within this document, the needs and challenges faced by FCH equipments have been identified once the product has reached the end of its life.

Finally, other challenges and needs have been established that may be more transverse or could not be collected in the other groups. These needs have been identified throughout the project and thanks to the previous experiences of the partners of HyTechCycling.

All these needs and challenges identified will support later documents giving a clear basis where future work will be carried.

2. Materials for FCH technologies

During the development of the project, HyTechCycling has identified the main materials that integrate the hydrogen technologies which are studied in this project, i.e. PEMFC, SOFC, PEMWE and AWE. These materials have some characteristics and requirements to operate properly. The selection of materials is done in the design phase and has consequences until the end of life of products.

Materials that are part of FCH technologies can be hazardous to people and environment. That is why one of the first needs to be achieved is the minimization or elimination of any material that can cause damage to them.

Another factor that affects the selection and use of materials is their availability and the risk that exists in their supply. One of the challenges evolving this type of technology is to promote the use of materials whose supply is guaranteed and is very difficult to exhaust. At this point it is shown that recycling centres have the opportunity to become key producers for the supply of key materials for equipment manufacturers by recycling materials and components from waste equipments. This factor and previous one are explained in the following point, special materials.

These needs and challenges on the materials must be taken into account since the moment of the design of the products since all these materials are an integral part of the effects they have at their end of life. It is a challenge to select products and materials from the first moment, the design phase of equipments, consider its end of their use and recycling phase. This selection is a holistic strategy that allows the production companies to facilitate the recovery of all those critical materials for the manufacture of new products. These strategies that minimize environmental impact are known as eco-design of the products.

Finally, it is important to highlight the road map that the European Commission has designed through the development of a strategic plan for the implementation of carbon-free technologies collected on Strategic Energy Technology Plan (SETIS) [1]. This roadmap establishes the material needs that it believes must be met in order to achieve optimal market penetration. It also establishes the main challenges that must be addressed not only from the stage of production and use of equipment but also to the end of life of the equipment.

2.1 Special materials

The most commonly used materials for FCH technologies were listed in the *D2.1 Assessment of critical materials and components in FCH technologies* [2]. These materials differ significantly among the different equipments studied in this project (PEMFC, SOFC, PEMWE and AWE). The materials' lists are included in Annex A.

In order to detect the importance of all materials, these were analyzed under three different categories. The first category, hazardousness, collect the toxicological information of materials studied, classifying them as hazardous and non-hazardous for humans. Another factor that categorized the materials was the cost, valuing them in high, medium and low. The risk in the supply of materials together with their importance in the EU market gives rise to the third category, called criticality. A high value in this category indicates that the material is very important within the Community market and can present a lack of supply [3].

Figure 1 collects the materials of each FCH technology classified according to each of the three mentioned categories. All needs and challenges of the materials have been detected by analyzing the results that categorise all those materials.

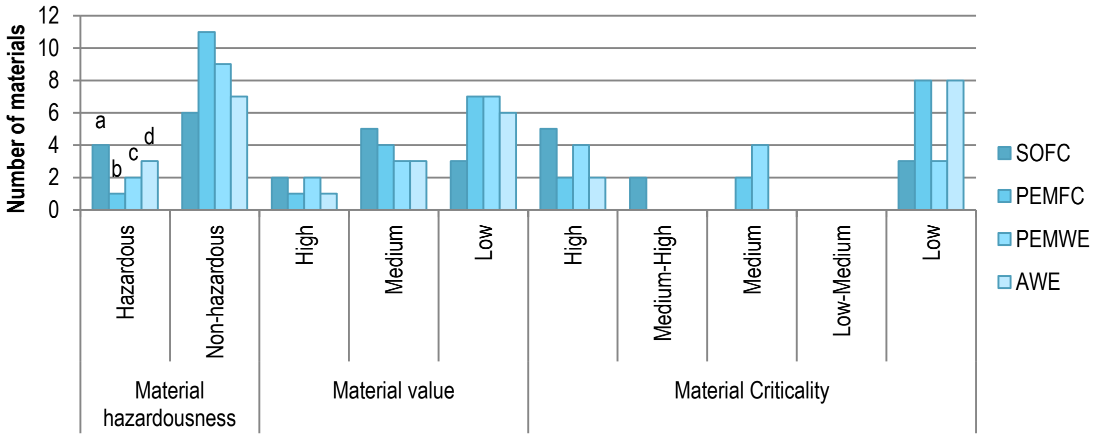

Figure 1. List of materials classified according material categories [2]. [a] **Carcinogen cat. 1, irritant, harmful;** [b] **Corrosive;** [c] **Irritant, harmful, toxic, carcinogen;** [d] **Corrosive, carcinogen.**

It is sought that is needed to use materials that do not generate any risk to the health of users. In many cases replacement of hazardous materials represent a need due to serious risk, but in other cases this task is considered a challenge since the risk is less critical. In general the risks presented in the materials studied are carcinogenic, irritant, toxicity, corrosibility or irritability, among others. These harmful effects can temporarily or permanently damage parts or organs of people and even be cause of death due to high exposition. A clear example can be found in AWE, where the membrane is usually formed by asbestos. Asbestos is carcinogen, category I [4], being the risk to health is the highest. This is why new materials with similar performance, such as Zirfon®, are being used, but with lower health risks.

Of all the technologies analyzed, in the SOFC there are 4 hazardous materials for health detected, mainly compounds of Ni and La, which are used as electrodes due to their resistance in the environment in which operate. The next equipment in number of hazardous substances is the AWE, which uses asbestos, Ni and KOH, as membrane, electrode and electrolyte respectively. These materials are considered carcinogenic and corrosive, so it should seek solutions for their replacement and in some cases, like asbestos, legal bans are added for their use and commercialization.

PEM equipments (PEMFC and PEMWE) are the technology that employs the least amount of hazardous materials. Ru, Ir and H_3PO_4 are used as part of the exchange membrane and at the electrodes and can cause irritation, corrosion and cancer.

As noted, hazardous materials are usually confined within the equipment, so the risks to the users are minimal. However, during assembly, disassembly and recycling stages, where the materials are exposed, there is a significant risk. And that is why although throughout the life of the equipment it is necessary to take precautions; it must be extreme in the stages where the risk of contact is important, as mentioned previously.

Analyzing the costs of the materials it is observed that those that reach higher values are the precious metals, the PGM and their alloys. In many cases the amount of them used is very small in the fuel cells and electrolysers, which reduces their impact on the total cost of the equipment. In these cases the need to find a substitute is low, but if the amount of expensive material is high, as in SOFCs with the interconnectors [1], a solution is required that results in a reduction of the cost of the equipment.

According to the European Commission [3], the materials used in FCH technologies must be of low criticality (*Frugal materials*) as they facilitate the development of markets and the implementation of equipments because of selection of easy to find materials instead of scarce materials. Again the SOFC is the technology that has the highest number of elements against it, with five of them at the most critical level and two more with a medium high level. In order to improve the implementation of this technology, these materials must be replaced by less risky ones. However, and like the previous variable, the proportion of these materials in the final products have a direct impact into the contamination generated.

With all these variables exposed, the end of life of the systems must take into account hazardousness of materials used to avoid causing harm to both people and environment. The recovery of materials should focus on those whose criticality is medium or high, due to the fact that these materials implies a high impact on the market and / or the need for it, being able to reuse them easily. If they are economically analyzed the most attractive materials for recycling are those that have a high value. On the other hand it is necessary to subtract the cost that requires recovering them. A high recycling cost can make the recovery of a certain material economically unfeasible.

Finally, the amount of materials that form each equipment affects all variables analyzed, requiring an individualized analysis of the conditions they might have at the time of recovery and recycling.

2.2 New strategies (Eco-design)

Ecodesign is defined as a holistic environmental management approach that integrates environmental issues into product development and related processes. It is known that the environmental impacts of any product arise throughout the entire life cycle of the material / product, from the extraction of the raw materials to the final disposal. Most of these impacts are defined from the early stages of Product Development Processes (PDPs).

For this reason, the best opportunity to reduce the environmental impacts of a product / service throughout its life cycle takes place in the design phase as shown in Figure 2. It shows the possibilities for improvement as represented as capability to influence in the emissions generated [5]. In the development stages of the product, Idea and Design, there are very few emissions while in EoL there are located main of associated emissions, but it is in the stage of development of the idea and product where the emissions can be more influenced than in other steps.

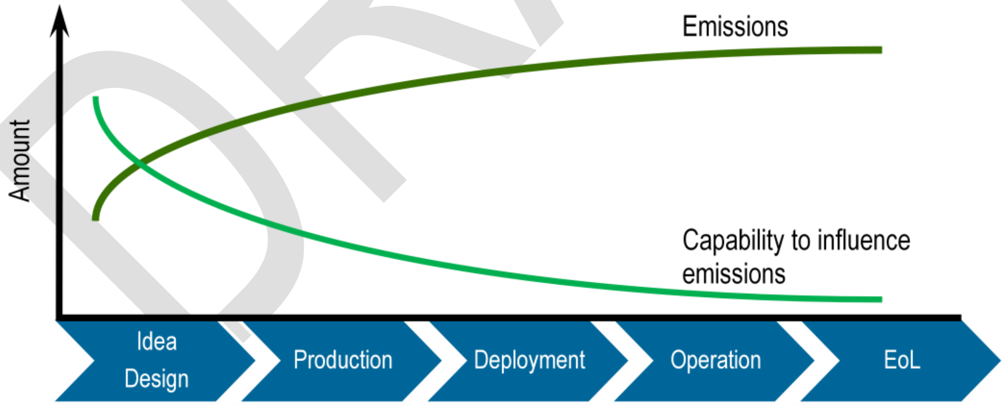

Figure 2. Distribution of environmental impacts of a product [5].

In order to minimize the impacts, including those associated with EoL, a development strategy or model must be developed from the outset to obtain products or equipment with the least possible environmental footprint. The implementation of new design models requires the proper systematization of ecodesign practices in the PDP, which is an important concern to reach higher levels of reduction of environmental impacts.

The eco-design maturity model (EcoM2) [6] is taken as the main theoretical framework on which the ecodesign process is structured. This model has been selected for its maturity in the management of the ecological design. It establishes a procedure of the best practices of ecological design in a feasible and organized application method, and therefore it supports the companies in the process of implementation and continuous improvement of ecodesign [7].

To overcome a partial and unstructured consideration of eco-design practices and achieve a formalized, monitored and controlled approach to product development, companies must define and use process-oriented indicators to ensure performance and to act in its improvement towards higher maturity levels in ecodesign [6]. Process-oriented indicators are defined as a mechanism for knowing the state of the product development process itself, regardless of the type and number of products under development.

Based on the EcoM2, have been developed a set of process-oriented performance indicators to measure the performance of the possibility of implementing eco-design through the use of eco-design management practices [8]. These indicators are collected in Annex B. This model covers all stages of the products, with indicators for each of them.

There are specific indicators for the EoL to be able to control and verify that there are tools and strategies for when the equipment life expires. *The first indicator that is found is the definition of the mechanisms for the reverse logistics*[1] and the EoL of the products. This indicator encourages companies to think from the design phase about the end of life of the equipments and which steps should be taken with rejected products.

The following indicators are focus on the information given to users, explaining how they could act during the use and end-of-life stages to minimize environmental impacts. For this purpose, recommendations should be made and communicated to users. This process requires the knowledge of feasible recycling processes for FCH.

Finally, the proper operation of all the recycling measures developed during the design stage must be verified. The information collected should help to improve reverse logistics and recycling procedures.

In all these indicators is highly recommended to the manufacturers that work together with recycling centres to know the latest information about recycling procedures and to monitor information about recycling FCH technologies.

2.3 SETIS Roadmap specifications

It is important to note that effective and sustainable use of available resources is essential to develop energy systems technologies. Processes related to recycling are an important element both in the manufacturing processes and at the end of the product life, as well as during the design operation [10].

SETIS [1] has identified several routes for main technologies to reduce energy carbon emissions. In this section only FCH technologies have been exposed for future developments. Only related elements to HyTechCycling are showed here, i.e. PEMFC, SOFC, PEMWE and AWE.

2.3.1 PEMFC

The two main elements in the development of this technology have been the catalysts and the polymer that works as electrolyte. Most studies identify both elements as the most critical components of a complete fuel cell system. However, the cost impact of these elements is not the same, while the noble metal catalyst (mainly platinum) is expected to account for approximately 30 – 50 % of the cost of a PEMFC, the polymer membrane represents only 4 % of the final system cost.

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[1] Reverse logistics is the process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal [9].

In fuel cells the membrane has typically a thickness less than 100 µm, meaning that if 15 million of fuel cell vehicles are manufactured each year, less than 30 000 tons of membrane should be produced annually worldwide.

Recycling of the polymer membranes of the fuel cell does not seem feasible because of the relatively low amount on each cell and the reduced quality of the recycled polymer. On the other hand, the recycling of Platinum Group Metal (PGM) is established in the industrial mass scale. So recycling PGM of fuel cells is not a technical problem, but rather a challenge with regard to the collection of exhausted PEMFCs. A highly efficient logistics chain is needed to collect used PEMFCs and recycle PGMs.

The technological developments focused on the polymer membrane of this technology are:

- The use of shorter side groups to strengthen the attractions between chains of neighbouring macromolecules and thus allow a higher density of sulphonic acid groups with sufficient mechanical properties;
- The manufacture of composite membranes in which proton conducting inorganic materials such as heteropolyacids or stratified zirconium phosphates can actively contribute to the overall conductivity at high temperatures
- The incorporation of water retention additives such as nanoscale oxides

In the field of catalysts, efforts should be focused on:

- The exploration of non-noble metal catalysts that cost much less, but still needs to improve their characteristics under PEMFC operating conditions
- Reduction of the Pt catalyst load, while maintaining high performance. Among catalysts there are two routes, the first of which is to substitute the Pt for another less expensive precious metal, such as ruthenium or palladium. The second is to use non-precious metal catalysts (NPMCs) such as cobalt-polypyrrole-carbon compounds.

Another element of PEMFCs that may gain importance in the recycling stages of fuel cells are bipolar plates. Of them you can find different versions that vary from one another for their composition and assembly, such as:

- Graphite composite: It is the main type of bipolar plate, but there is a constant search for better composites with a maximized electrical conductivity. One of the proposed strategies is to incorporate advanced materials such as multi-walled carbon nanotubes, multiple walls and single carbon walls, carbon fibres, expanded graphite and combinations thereof.
- Uncoated metals: Various types of metals and alloys are currently being tested and evaluated to develop bipolar plates which have the combined characteristics of graphite and metals: high corrosion resistance, non-permeability to reactive gases, etc. Candidates such as stainless steel, aluminium, titanium and nickel have been tested and used as bipolar plaques.
- Coated Metals: Metal bipolar plates can be coated with protective coating to prevent corrosion. The coatings must be conductive and adhere to the base metal without exposing the substrate to corrosive media. Two types of coatings (carbon-based and metal-based) have been investigated. Carbon-based coatings include graphite, conductive polymer, diamond-like carbon, and self-assembled organic monopolymers. Noble metals, metal nitrides and metal carbides are some of the metal based coatings.

The material specification objectives in different time horizons presented in this report are defined by estimating the performance requirements for the introduction of different technologies into the market [1] (see

Table 1).

Table 1. PEMFC specifications [1].

Characteristic	2010 Status	2020-30 Target	ultimate goal
PEMFC stack (operating conditions)			
Peak stack temperature (°C)	90	120	150
Operating pressure (atm)	2	1.5	1.2
PEMFC electrolyte			
Hydrogen crossover (mA/cm^2)	> 2	< 0.5	0,1
Operating temperature range (°C)	-20 to 90	-30 to 120	-40 to 150
Proton conductivity (S/cm) at -20 °C + 20 °C + 90 °C + 120 °C + 150 °C	0.01 0.07 0.1 -- --	0.05 0.1 0.2 0.1 --	0.1 0.15 0.3 0.2 0.1
Cost (€/m^2)	200	100	10
Durability with cycling (h)	2 000	5 000	5 000
PEMFC catalyst			
Pt total content (g/kW)	0.5	<0.1	<0.02
Pt total loading (mg/cm^2)	0.4	<0.1	<0.05
cost (€/kW)	26,0	6	3
Mass activity, A/mgPt at 900 mV (iR free)	0.14	0.4	0.6
specific activity, µA/mgPt at 900 mV (iR free)	500	900	1 500
Durability with cycling (hours)	2 000	5 000	5 000
ECSA loss (%)	< 30	< 10	< 5
PEMFC bipolar plates			
H_2 permeation flux (Ncm^3/s/cm^2)	$1 – 2·10^{-6}$	$< 1·10^{-7}$	$< 1·10^{-7}$

Finally, it is possible to summarize in a non-exhaustive way those applications where the different elements that make up a PEMFC can be reused because of the operating characteristics of the systems. When a PEMFC reaches its end of life the various elements, membrane, catalysts, metals, can be reused directly, or with some specific treatments, in the recycling stage. This allows a market between recycling centers and producing companies favouring the development of the collection of equipment and its recycling. In some markets, it has already been shown that it is more feasible to purchase raw materials from recycled products than from any other source [11]. For this reason below are some applications that can take advantage of materials or components of PEMFC to encourage their revalorization and recycling.

Polymer membranes (Nafion) are also used in:

- Chlor-Alkali Reactors
- Drying or humidifying gas
- Production of fine chemicals acting as catalysts
- Water electrolysis
- Electrolytic regeneration of exhausted chrome solutions
- Sensors.

Platinum group metals are used in a wide variety of industries:

- Autocatalysis (platinum, palladium and rhodium)
- Industrial use (i.e. production of nitric acid based on platinum, in the glass and oil industry, palladium on hydrocracking).

Carbon products find applications in areas such as industry - steel and aluminium production, glassmaking, aerospace, nuclear power and electronics. Graphite products are used in applications such as brake linings, castings, lubricants and batteries.

Approximately two-thirds of all titanium metal is used in aircraft engines and frames. The petrochemical and chemical industry uses titanium in heat exchangers and reactors. The automotive industry uses titanium in the frame and components such as connecting rods, valves and suspension springs.

There are synergies between the membrane electrode assemblies and the battery manufacturing with respect to the coating processes.

2.3.2 SOFC

A SOFC cell can be considered to consist of 3 types of materials based on metals, ceramics and glass. The materials of the components are shown in the Figure 3. It can also be seen that the amount of metal components is much higher (≈ 12 kg / kW) than the glass and ceramic components (≈ 0.8 kg / kW), the former representing 94 % of the mass of the fuel cell.

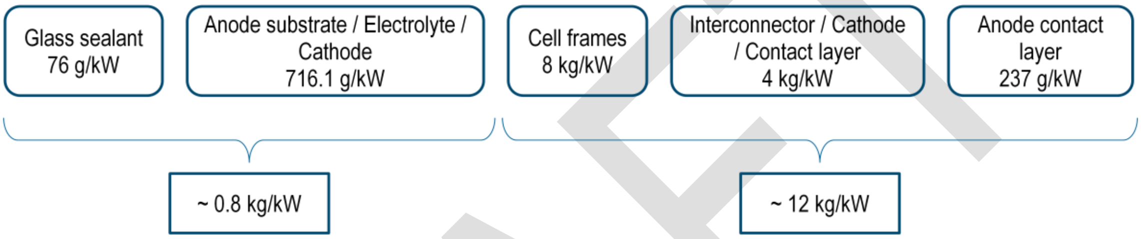

Figure 3. Different components of SOFC stacks and their relative proportions [1].

The need to use rare earth elements in alloys can lead to complications since the production of most of them is in one country. The rare earth elements (La, Ce, Gd) and Scandium used in electrodes and electrolytes are of strategic importance. Ni is heavily employed, but its processing creates health risks. The other elements used in the stack and in the interconnections are highly available or require less amounts compared to other applications that dominate the consumption. Primary sources, supply chains and the economy are well established.

According to *Strategic energy technology plan* [1] SOFC technology requires some material research and development on basic development and its applications. Here are listed research topics for SOFC:

Basic research:

Electrolyte:

(I) Materials based on apatite,
(II) Development of thin films

Anode:

(I) Nanometric scale investigations ("segregation of impurities");
(II) Electrochemical kinetics;
(III) Electrode modelling models: modelled electrodes;
(IV) Ni-free ceramic anodes (Sr-titanate based materials).

Cathode:

(I) Alternative cathodic materials: Nickelates (Ln_2NiO_4), SOFC600: Pr_2NiO_4, $0.130\ \Omega\cdot\mathrm{cm}$ compound with ceria;

(II) Electrochemical processes, oxygen exchange kinetics;
(III) Investigations at nanoscale ("segregation of impurities").

Applied research

Electrolytes:

(I) Fluorite-based electrolytes: zirconia stabilized with yttria-scandia, with other modifications to increase conductivity at around 600 °C;
(II) Barrier layer development in ASC with cobalt and ferrite cathodes, durability and cell performance.

Anode:

(I) Tolerance to the presence of impurities and less processed fuels (Sulfur, C:H:O ratios, redox cycles), fuel flexibility;
(II) internal reformed;
(III) Mechanisms of poisoning;
(IV) Degradation mechanisms, accelerated tests;
(V) Development of new cellular concepts: supported metal cells, increased production, durability;
(VI) Complete ceramic cells: integration of ceramic materials into large-scale SOFC cells;
(VII) Increased electrocatalytic activity

Cathode:

(I) Increase durability, development of low temperature cathode materials and integration into cells;
(II) Mechanisms of degradation, accelerated testing;
(III) Increased electrocatalytic activity

Interconnections

(I) Corrosion resistance: adaptation of the composition;
(II) Protective coatings to prevent corrosion.

Seals:

(I) Adapt the compositions of glass and ceramic glass to adapt them to the thermo-mechanical requirements (load cycle);
(II) Cell level related to materials;
(III) Accelerated test routines;
(IV) Thermomechanical properties of components and cells;
(V) Advanced diagnosis;
(VI) Technique of thin film SOFCs (micro SOFC) and prototype development.

The material specification objectives in different time horizons presented in this report are defined by estimating the performance requirements for the introduction of different technologies into the market

Table 2. SOFC specifications [1].

Property	State of art	Target 2020-2030	Ultimate goal
Operating temperature (°C)	800 – 950	600 – 700	550 – 700
Operating pressure (bar)	1	1 – 4	1 – 4

Property	State of art	Target 2020-2030	Ultimate goal
Fuel	NG	NG, Biomass	Fuel NG, Biomass Fuel
Area specific resistance ($\Omega \cdot cm^2$)	0.3 – 0.6	0.2 – 0.3	0.1 – 0.3
DC efficiency (%) POx ref. SR 2:1 ref.	35 % 50 %	40-50 % 65 %	direct –internal 90 %
CHP efficiency Gas (LHV)	85 – 90 %	90 – 95 %	>95 %
Load cycles	1 000	80 000	best practice
StartUp time (h)	5 – 12	1 – 6	best practice
StartUp /Shut down cycles	<10	100	best practice
Cell voltage degradation (at 1 A/cm^2)	> 0.5 %/1 000 h	< 0.5 %/1 000 h	0.2 %/1 000h
Durability (h)	15 000	50 000	75 000
Sulphur tolerance (ppm)	< 10	< 10	n.a.
Costs (€/kW)	< 4 000	1 000 5 000 (for mCHP)	90 % materials cost

As was done in the previous section it is wanted to make a compilation of other applications that have the potential to take advantage of the elements of SOFC. High temperature fuel cell technology has synergies with high temperature electrolysis and fuel processing (cell materials and catalysts, respectively). SOFC materials with good conductivity of oxygen, proton or mixed ions can also be used on high temperature sensor solid state membranes, gas separation, carbon containing fuel processing and CO_2 concentrators.

2.3.3 PEMWE

The development of PEM water electrolysis is not a market-driven process. Private companies are active in the field but business is restricted to niche markets (meteorology, gas chromatography, etc.) or to the supply of prototypes for demonstration purposes. Electrolytic hydrogen from water cannot compete with hydrogen from methane in terms of energy costs. Regarding PGM catalysts and Solid Polymer Electrolyte (SPE), PEM water electrolysis is in competition with PEM fuel cell technology. Also, PEM water electrolysis is using PGM as electrocatalysts that growing automotive markets in emerging countries will require PGM for use in catalytic converters (car industry) which will be a serious competitor.

The main challenges for PEM water electrolysis are to identify and synthesize alternative materials with performances similar to those used today. Another challenge is to increase the efficiency and durability of new materials and the development and optimization of large systems (industrial electrolysers are limited to a low capacity range <10 Nm^3 H_2 / hour). This technology still cannot compete with alkaline technology due to prohibitive non-energy costs. Currently, elementary research activities focus on:

(I) Research on noble metal-free catalysts (also applied research);
(II) Research on alternative SPE
(III) Reduction of platinum charges at the anode by developing carriers of stable catalysts or new alloys, for example Ru / Ir and an inert oxide (tin, titanium, etc.).

In applied research:

(I) Reduction of platinum charges at the cathode using carbon carriers and / or specific printing methods such as screen printing.
(II) Surface treatment of titanium bipolar plates and current collectors to reduce contact resistance.

A provisional roadmap for enhancement PEM electrolysers is provided in Table 3.

Table 3. PEMWE specifications [1].

Property	State of art	Target 2020-2030	Ultimate goal
Operating current density (A/cm^2)	0 – 1	0 – 2	0 – 5
Operating temperature (°C)	50 – 80	80 – 120	100 – 150
Operating pressure (bar)	1 – 50	1 – 350	1 – 700
Enthalpic efficiency with PGM catalysts	80 % at 1 A/cm^2	80 % at 2 A/cm^2	80 % at 4 A/cm^2
Enthalpic efficiency with non-PGM catal.	30 – 40 % at 1 A/cm^2	60 % at 1 A/cm^2	60 % at 1 A/cm^2
SPE Voltage drop (mV at 1 A/cm^2)	150	100	67
SPE ionic conductivity (S/cm at 80 °C)	0.17	0.20	0.30
SPE gas permeability to H_2 ($cm^2/s{\cdot}Pa$) (80 °C, full humidity)	10^{-11}	10^{-9}	10^{-9}
Cathodic PGM (Pt) content (mg/cm2)	1.0 – 0.5	0.5 – 0.05	< 0.05
Anodic PGM (Ir, Ru) contents (mg/cm^2)	1.0 – 2.0	0.5 – 0.1	< 0.1
Durability (h)	10^4	$10^4 – 5{\cdot}10^4$	> 10^5
Production capacity of electrolysis units	1 kg/hour (≈ 10 Nm^3/hour)	> 10 kg/hour (≈ 100 Nm^3/hour)	> 100 kg/hour (≈ 1 000 Nm^3/hour)
Energy (kWh/kg H_2 at 80 °C, 1 $A{\cdot}cm^{-2}$)	56	< 50	48
Non-energy cost (€/kg H_2)	5	2	1

The materials and processes that are used in the electrolysis by PEM are very similar to those that occur in the PEMFC, so reuse is very similar in both cases. PEM technology can also be used in sister technologies such as hydrogen purification or electrochemical hydrogen compression.

2.3.4 AWE

The Strategic energy technology plan [1] has identified no limitation regarding resources or material scarcity. Electrolysis of industrial alkaline water is a mature technology. But from the point of view of the process, some improvements can still be implemented.

The main research efforts are focused on the development of advanced diaphragms with adapted electrodes / catalysts and intermittent operation for coupling with renewable electricity sources. The challenges relate to system life and maintenance costs are summarized in Table 4 with other parameters that have to be improved. One option of interest would be to use fluoropolymer conductive hydroxyl ions that allow the use of economical catalysts.

Table 4. Alkaline water electrolysis specifications [1]

Property	State of art	Target 2020-2030	Ultimate goal
Operating current density (A/cm^2)	0.2 – 0.5	0.1 – 1	0 – 2
Operating temperature (°C)	Ambient – 120	Ambient – 150	Ambient – >150

Operating pressure (bars)	1 – 200	1 – 350	1 – 700
Durability (h)	10^5	> 10^5	> 10^5
Cyclability	Poor	Improved	High
Production capacity of electrolysis units	Up to 50 kg/h (≈ 500 Nm^3/h)	> 100 kg/h (≈ 1 000 Nm^3/h)	> 1000 kg/h (≈ 10 000 Nm^3/h)
Non-energy cost (€/kg H_2)	5	2	1

3. Existing recycling technologies for FCH

Report *D2.2 Existing end-of-life technologies applicable to FCH products* [12] presented an exhaustive analysis of recycling technologies available to obtain different elements and materials at FCH technologies EoL. Those technologies are available to process equipments and extract parts to be reused, recycled, landfilled or incinerated. Following are identified all barriers that affect the implementation of the recycling technologies.

Magnetic separation is a process of waste treatment in recycling companies through which the ferromagnetic materials can be removed from the rest of waste. For this treatment of materials it is necessary that the residues get a small size to be easily extracted, while it must be as large as possible to facilitate their later treatment. The smaller they are the easiest to separate, but the more complicated it is to classify them. This technology is a common process in recycling centres where magnetic materials are separated from other types of waste, like urban waste, so their integration into the FCH technologies does not require any specific pre-processing or other treatment.

The use of Foucault electromagnetic currents is known as **Eddy current separation**. This separation mechanism of materials with magnetic properties permits to separate and classify the materials according to their behaviour against magnetic fields. For a correct separation the materials require a smaller particle size than in the magnetic separation. As seen above, this particle size has a direct impact in any later step. Recycling centres often use equipment that takes advantage of Foucault's streams to separate other waste types, which it means an easy integration with FCH technology waste.

There is a technology less extended than the previous ones for the separation of materials called **densimetric table** but in this case takes advantage of different materials' densities to obtain an optimal separation. This separation is carried out by means of a vibrating table and a fluid, air or water, which permits to separate the residues. Moreover, for effective separation of the materials it is necessary that they are very finely divided. A disadvantage of this technology is the transfer of potentially harmful substances to water, which requires further treatment of contamination in water.

Flotation is a technique that allows materials to be separated by densities. For this, the waste must be finely ground and poured into water or other liquid, collecting the materials as they float, precipitate or remain suspended. This technique is an economically expensive process as it requires, among other costs, water treatment systems to eliminate dissolved and suspended contaminants.

When materials with relatively low melting points are available they can be joined by **thermal processing**. This technique is common in plastic waste treatment companies to obtain useful materials in manufacturing companies. The main impediment for this technology is to obtain compositions that are more or less stable and / or homogeneous in order to take advantage of them. As these techniques are common their integration with FCH technologies residues is not complicated although require a critical step of correct separation.

The **mechanical processing** of waste involves a large number of techniques and processes by which materials are separated from each other, crushed and classified. Depending on later recycling stages and the applications to be addressed, the processes can be nearly mechanized and automated; therefore the costs of this type of processing can vary enormously.

One technology that is being implemented recently in recycling centres is the **optical processing** of waste. For the moment it is an expensive technology that allows separating the residues finely by colour, limiting its application to certain materials.

Waste **incineration** is a technology in which combustible materials, like most plastics, are completely oxidized. This technique allows eliminating combustible materials of those that are not, like minerals and metals. The processes that are carried out are usually exothermic so that it can take advantage of thermal energy in other processes; this is known as energetic valorisation of waste. As a final result the combustible materials are transformed into gases such as CO_2 and CO but can also be found SO_2 and organic compounds, all of them with different environmental impacts. This causes this technology to be an expensive process due to the requirements of eliminating pollutants from the exhaust gases and auxiliary fuel consumption to keep the incinerator always running. It is also important to mention that all the emissions have caused the appearance of quite restrictive legislation on this technology.

A similar technology to the previous one is the **pyrolysis**, by means of which plastic materials can be separated of other materials. This process uses a lower amount of oxygen in the reaction, without generating as many exhaust gases as incineration process. In spite of this, the technical, economic and legislative limitations are practically the same as those of incineration.

The **hydrometallurgical** and **pyro-hydrometallurgical processes** obtain as final result the precious metals and PGM of treated wastes. These materials have high prices, so their recovery is economically attractive although to be feasible recycling companies must assume large volumes of waste, with all waste generated in Europe there are less than five recycling companies in Europe that works with those technologies.

The **reuse of ceramic waste** is a technology for the direct use of this type of material. The separation of the ceramics from other materials is feasible however nowadays there is no market for the recycling of ceramic materials since the separation of the different types of ceramics is a very expensive process. Due to this difficulty the ceramic materials are deposited in landfills.

Mineral wool incineration is a process similar to waste incineration while it needs higher combustion temperatures to be effective. Reaching the necessary temperatures is an expensive process so the solution that the recycling centres perform is to associate with other industries, such as cement manufacturers which have furnaces with enough temperature. Most of the recycling companies are not able to associate or assume the costs of this process so the most used solution is the discharge of mineral wool waste.

As a summary in Table 5 are listed all those limitations that have identified and can affect to every known recycling technology. They are expressed as economic barrier, where a high cost to implement and maintain this technology represent a barrier; and as legal barrier, a restrictive legal framework limits use of recycling process that means a legal barrier.

Table 5. Barriers for recycling technologies.

	Economic barrier	Legal barrier
Magnetic separation	No	No
Eddy current separation	No	No
Densimetric table	Yes	No
Flotation	Yes	Yes
Thermal processing	No	No
Mechanical processing	No	No
Optical processing	Yes	No

	Economic barrier	Legal barrier
Incineration processing (energetic valorisation)	No	Yes
Pyrolysis	No	Yes
Hydrometallurgical processes	Yes	Yes
Pyro-hydrometallurgical processes	Yes	Yes
Re-use of ceramic waste	Yes	No
Incineration of mineral wool	Yes	Yes

Once recycling technologies have been listed there are needs and challenges to implement those technologies to FCH equipment's EoL. From a general point of view needs for all recycling technologies are:

- To develop specific protocols or mechanisms for the recycling of FCH technologies, adapted to the materials that compose it and to the later uses made of recycled materials.
- To ensure that the processes employed are economically attractive to all agents involved in the life of products in order to facilitate the implementation of FCH technologies and their EoL.
- To adapt technologies to legal requirements.
- To reduce the environmental impact of recycling processes, reducing the impact of FCH technologies throughout their lives.

Moreover, all those technologies showed in this point have challenges that can be integrated into them for a better treatment of materials:

- To develop recycling technologies to recover the maximum amount and type of materials.
- To find processes in which recovered materials prevent the recovery of another, such as the recovery of Pt through the pyro-hydrometallurgical process.
- To promote the use of treated waste of FCH technologies by manufacturer companies so that recycling processes can be useful and a flow can be generated between these companies and the recycling centres.
- Establish mechanisms, and promote them, so that end users of FCH technologies can send waste equipment to recycling centres.

4. Regulations and policies – legal and administrative processes

Report *D2.3 Regulatory framework analysis and barriers identification* [13] exposed all EU legislation identifying legal barriers for FCH technologies development, use and EoL. This document exposed all legislation acts that have influence over different FCH technologies sub elements and it comparison with similar technologies like batteries and electronic equipments. To achieve an effective and controlled development of FCH technologies, all barriers must be overcome.

Main legislative acts are: Eco Design Directive [14], which has to be considered in the whole FCHs system design but also in the materials selection both FC stack and BoP components; REACH Regulation [15], which has to be considered in stack and BoP materials selection; RoHS Directive [16], which is specific for material selection in power control systems; WEEE Directive [17], related to electric and electronic parts in a fuel cell system; Landfill directive [18], referred to limitations and procedures to dispose waste; Hazardous waste Directive [19], which has to be used for FC stacks and BoP components with hazardous materials; Batteries Directive [20], specific for EoL batteries installed in a FCH system; and ELV Directive [21], used for fuel cell electric vehicles.

Once the different procedures have been analyzed, it has been seen that there is no legislation entirely focused on hydrogen technologies, so that one of the needs that must be solved is the creation of a legislative framework. Without this framework the development of FCH technologies must be based on laws that are sometimes not intended for the specific situation of fuel cells or electrolysers. An example that can be found is the recycling targets found in the WEEE Directive, which can be applied to FCH technologies since there are similar components.

Since commercial equipment is developed certain specific chemical compounds are required. In many cases these materials are supplied by SMEs that cannot comply with the administrative requirements established in the REACH regulation, which hinders or prevents the commercialization of any necessary resources. As a consequence of this can trend to an increase in the final product cost and an impediment in their commercial development. Getting chemicals registered in the REACH regulation is a challenge that must be solved in order to take advantage of the materials needed to manufacture FCH equipment.

The materials used in any FCH equipment need to comply with the RoHS directive to eliminate hazardous materials and avoid damaging people.

As it has been seen in previous points, the design is the stage where more can be influenced for the emissions and residues generated in the other stages. That is why it is considered a necessity to establish the mechanisms and procedures for an efficient design, as found in the Eco-Design Directive.

FCHs manufacturers and developers are required to implement and provide evidence of eco-design. However, the Eco-design Directive does not mention FCH technologies explicitly, but it applies to all energy products.

In order to show the environmental benefits of FCH technologies, the limitations of hazardous waste and Landfill Directives must be taken into account and again in the design phase of the equipment. Companies must take these directives into consideration by facilitating the treatment of waste, so it is a necessity that from the first moment the companies become involved and take into consideration the end of life of products.

Once the equipment is located for use, various regulations must be applied, but at present for large FCH equipment there is no regulation to control the electrical and electronic waste generated. Therefore it is a challenge that this, and other applications, meets the requirements of the WEEE directive.

5. Other needs and challenges

The basic rules governing the market for recycled materials and products do not differ much from those in other markets for goods and services. The products have to be competitive, that is to say that they are of quality, reasonably priced and every day more innovative. The recycling market still faces a strong deficit, the demand for these products, i.e. the problem is not to recycle but to consume recycled. In the supply side a first obstacle can be found, generally related to aspects of product quality. Other times it is not the quality but the quality image, which is damaged by the association of product and waste.

Keramitsoglou and Tsagarakis [22] demonstrate that recycling behaviour and action are influenced by factors like financial incentives, information and infrastructure rather than beliefs, behaviour and skills when people have to make choice on practical issues of recycling implementation. They have detected that for recycling without prior information and experience in recycling it is preferred more flexible and voluntary systems than mandatory ones feeling. At later stages, financial incentives could be applied to enhance the effectiveness of an existing drop-off system.

The processes of recycling are, therefore, a complex process that depends not only on legal or technical factors, but there are variables that can encourage or discourage the recycling and recovery of equipment and materials at the end of its life cycle of FCH systems. Each recycling system must face its own challenges and difficulties, but it can always learn from other strategies for the development of effective recycling processes [23]. In the following subsections are collected some of the challenges and solutions that have been found in the development of recycling processes.

5.1 Establishment of Extended Responsibility of Producer (ERP) system for recyclable resources with a small-generation scale and potential environmental risk

For markets where waste generation is small-scale, as the case of fuel cells if compared to other more developed markets such as the vehicles case [24], the recycling system is mostly informal and less developed; however, when recyclable resources are potentially dangerous to the environment and human health, have a high critically value or are expensive materials, this informal system will bring with it several problems. Recycling electronic waste is a typical example: instead of using environmentally-friendly recovery technologies, the current preferred recycling approach uses traditional methods such as incineration and acid treatment, despite the serious environmental impacts of these practices and the high risks to workers' health [25].

It is also considered in many cases the illegal dumping of unrecoverable waste, and therefore worthless, generated during the recycling process. Illegal dumping is economically advantageous when all given waste cannot be recycled, and inadequate treatment practices are adopted when environmental-friendly treatment is too expensive and when the responsibility for recycling a particular waste is not well distributed within the current system.

As in other recycling markets, the most practical method is redistributing responsibility for recycling and recovery. The ERP system can be the best practical means for improving these problematic recycling systems and avoiding the aforementioned problems. Producers must take responsibility for recycling their goods after the life cycle, either by direct recycling of their own waste or by subsidizing the resource recycling system.

5.2 Tax incentives to balance recycled resources recovered as raw materials.

To promote the use of recyclable resources as raw materials, it is important to look the problem from FCHs manufacturers' point of view. This part of the business is able to use as raw materials recyclable resources or raw materials obtained from mining companies directly. In both cases, taxes associated to materials purchasing are the same, not creating any economical incentive, avoiding the use of recycling resources. However one of the reasons that can be argued to not establish two types of differentiated taxes is the necessary invoice of the sellers for the buyers of waste to obtain, thus permitting to establish a recycled origin of the raw materials. Although recycling companies may request a special invoice for this type of recycling, the additional administrative costs for identification, accounting and potential tax evasion have been obstacles to a real exemption [23].

Due to the high recovery value and the recovery scale, the tax burden is very sensitive for recycling, to promote this type of resource recycling, more practical tax incentives must be introduced to rectify this inequality within the system, and thus benefit from the tremendous energy saving by recycling resources instead of stimulating virgin ore extraction processes. However, as raw material producers can use mining and recycling sources, a reliable and accurate system is needed to calculate the detailed volume of each source.

5.3 Regulation of the collection system.

Today, the main player of the collection system is the individual unsupervised collection business, as this artificial recycling mode is more practical for the collection of recyclable resources on a small scale. However, the logistics of all these systems are difficult to develop due to economic and regulatory factors. Therefore it is important to develop models of collection of the equipments once they have reached their end of life [26].

Firstly, an important effort has to be made, creating a recycling philosophy where users and recycling companies are connected. One the one hand, as Keramitsoglou and Tsagarakis regards [22], an easy way to recycle has to be created, settling specific and clear identification to dispose FCH technologies. Important is also the customer receive clear information of the environmental issues caused by an incorrect landfill of the components. This information should be given to the customer as soon as the FCH is purchased.

On the other hand, recycling centers should create continuously new campaigns, giving information to the new costumers and regarding it to the old ones. To accomplish this task, the recycling company has to introduce a strong marketing department able to cover adapt its strategy to big and small size customers, being a way to increase its incomes has a result of its own activity.

Once the customer is aware of the importance of the recycling process, the regulation of the collection system should follow a structure able to cover from the FCH technologies´ collection to the final landfilling of the unit. This structure may be formed by a collection system, where a logistics company collect the FCH technologies after receive information of its status. Relying on the size of the FCH technologies, a different methodology of transport has to be followed to transport FCH technologies when it is needed to a special recycling plant. For small FCH technologies it is possible to storage in an intermediate warehouse or creating street bins and wait until a big amount of waste is ready to be recycled and transport it in big trucks. Big size FCH technologies may need an individual transport.

The recycling company has to separate different components and decide how to proceed with them. If a component is waste, the recycling company has to manage a proper transport to the landfill, being interesting avoid long distances by landfilling it near the recycling plant. On the other hand, if the material is recycled, recycling company should storage them, looking for the cheapest way to transport them to the raw materials producers by a similar system of the collection one.

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Annex A. List of equipments composition

Table 6 List of common material assessment for SOFC [3], [27]–[30].

	Component	Material	Material hazardousness	Material value	Material Criticality	Current recycling and dismantling technology
Solid Oxide Fuel Cells (SOFC)	Electrolyte	Yttria-stabilised zirconia	Non-hazardous	Medium	High	[12, Ch. 7.4]
	Anode	Nickel-based oxide doped with YSZ	Hazardous (Cat. 1 carcinogen)	Medium	High	[12, Ch. 7.3.1.2]
		Nickel	Hazardous (Cat. 1 carcinogen)	Medium	High	[12, Ch. 7.3.1.2]
	Cathode	Strontium-doped lanthanum manganite	Hazardous (Irritant)	Medium	High	[12, Ch. 7.4]
	Interconnect	Doped lanthanum chromate	Hazardous (Irritant, harmful)	Medium	Medium-High	[12, Ch. 7.4]
		Inert metals/alloys	Non-hazardous	High	Medium-High	[12, Ch. 7.3]
	Sealant	Glass/Glass-ceramic	Non-hazardous	Low	Low	[12, Ch. 7.4]
		Mineral	Non-hazardous	Low	Low	[12, Ch. 7]
		Precious metals	Non-hazardous	High	High	[12, Ch. 7.3]
	Substrate	Ceramic	Non-hazardous	Low	Low	[12, Ch. 7.4]

Table 7. List of common material assessment for PEMFC [3], [27]–[30]

Polymer Electrolyte Membrane Fuel Cell (PEMFC)	**Component**	**Material**	**Material classification**	**Material value**	**Material Criticality**	**Current recycling and dismantling technology**
	Electrolyte	Perfluorosulphonic acid (PFSA)	Non-hazardous	Medium	Medium	[12, Ch. 7.2]
		Sulfonated polyether ether ketone (s-PEEK)	Non-hazardous	Medium	Low	[12, Ch. 7.2]
		polystyrene sulfonic acid (PSSA)	Non-hazardous	Low	Medium	[12, Ch. 7.2]
		polybenzimidazole (PBI) doped with H_3PO_4 *	Hazardous (corrosive)	Medium	Low	[12, Ch. 7.2]
	Anode and Cathode - GDL	Carbon cloth or paper treated with hydrophobic agent	Non-hazardous	Low	Low	[12, Ch. 7]
		Metallic mesh or cloth (e.g. stainless steel)	Non-hazardous	Low	Low	[12, Ch. 7.1]
	Anode and Cathode - Catalyst layer	Platinum or Pt-alloys	Non-hazardous	High	High	[12, Ch. 7.3.1.1]
		Catalyst support (carbon, metal oxides, carbides, etc.)	Non-hazardous	Medium	Low	[12, Ch. 7.3.2.1]
	Interconnect	Graphite or graphite composites	Non-hazardous	Low	High	[12, Ch. 7]
		Stainless steel	Non-hazardous	Low	Low	[12, Ch. 7.1]
	Sealant	Thermoplastic	Non-hazardous	Low	Low	[12, Ch. 7.2]
		Elastomer	Non-hazardous	Low	Low	[12, Ch. 7.2]

* used only in HT PEMFC

Table 8. List of common material assessment for PEMWE [3], [27]–[30]

Polymer Electrolyte Membrane Water Electrolyser (PEMWE)	**Component**	**Material**	**Material classification**	**Material value**	**Material Criticality**	**Current recycling and dismantling technology**
	Electrolyte	Perfluorosulphonic acid (PFSA)	Non-hazardous	Medium	Medium	[12, Ch. 7.2]
		Sulfonated polyether ether ketone (s-PEEK)	Non-hazardous	Medium	Low	[12, Ch. 7.2]
	Catalyst layer - Cathode	Pt or Pt-alloys	Non-hazardous	High	High	[12, Ch. 7.3.1.1]
	Catalyst layer-Anode	Iridium and Ir-alloys	Hazardous (irritant, harmful)	High	High	[12, Ch. 7.3]
		Ruthenium and Ru-alloys	Hazardous (toxic, carcinogen)	Medium	High	[12, Ch. 7.3]
	Anode and Cathode - GDL	Thermally sintered Ti	Non-hazardous	Low	Medium	[12, Ch. 7.3]
		Ti or stainless steel mesh	Non-hazardous	Low	Medium	[12, Ch. 7.3]
		Graphite or graphite composites (only possible on cathode side)	Non-hazardous	Low	High	[12, Ch. 7]
	Interconnect	Coated titanium or Ti-alloys	Non-hazardous	Low	Medium	[12, Ch. 7.3]
	Sealant	Thermoplastic	Non-hazardous	Low	Low	[12, Ch. 7.2]
		Elastomer	Non-hazardous	Low	Low	[12, Ch. 7.2]

Table 9. List of common material assessment for AWE [3], [27]–[30]

	Component	Material	Material classification	Material value	Material Criticality	Current recycling and dismantling technology
Alkaline Water Electrolyser (AWE)	Electrolyte	Potassium Hydroxide	Hazardous (corrosive)	Medium	Low	[12, Ch. 7]
	Anode	Precious metals	Non-hazardous	High	High	[12, Ch. 7.3]
		Plastic	Non-hazardous	Low	Low	[12, Ch. 7.2]
	Cathode	Raney-Nickel	Hazardous (carcinogen)	Medium	High	[12, Ch. 7.3.1.2]
		Plastic	Non-hazardous	Low	Low	[12, Ch. 7.2]
	Interconnect	Plastic	Non-hazardous	Low	Low	[12, Ch. 7.2]
	Sealant	Thermoplastic	Non-hazardous	Low	Low	[12, Ch. 7.2]
		Elastomer	Non-hazardous	Low	Low	[12, Ch. 7.2]
	Diaphragm (membrane)	Asbestos	Hazardous (carcinogen)	Low	Low	[12, Ch. 7]
		Polymers	Non-hazardous	Medium	Low	[12, Ch. 7.2]

Table 10. List of common material assessment for BoP.

BoP components	Main materials
Blower or compressor	Metals, plastics
Humidification membrane	Metals, plastics, polymers
Pumps	Metals, Teflon®, rubbers, plastics
Regulators	Metals, plastics, rubbers
Printed circuit boards (PCBs)	Metals, plastics, semiconductors, precious metals
Power conditioning system	Metals, plastics, semiconductors, precious metals
Deionising filter	Metals, plastics, resins
Pipes	Metals, plastics, rubbers
Valves	Metals, plastics, nylon, Teflon®
Gaskets (piping system)	Paper, plastics, rubbers
Thermal insulation system	Mineral wool, fibreglass
Heat exchangers	Metals
Sensors	Plastics, precious metals, semiconductors, glass
Water condensers	Stainless steel

Annex B. Ecodesing indicators

Table 11. List of process-related performance indicators [8].

#	Ecodesign management practices	Proposed process-related performance indicators	Suggested units
1	Examine the relevant internal and external drivers for the development of products with a better environmental performance	1. Number of examined internal/external drivers for ecodesign	Number of drivers examined
2	Assess technological and market trends (including new customer requirements) related to ecodesign	2. Rate of market trends (%) related to ecodesign	Percentage of market trends (in relation to the total number of trends)
		3. Rate of technology trends (%) related to ecodesign	Percentage of technology trends (in relation to the total number of trends)
		4. Rate of customer demands (%) related to ecodesign	Percentage of customer demands (in relation to the total number of trends)
3	Ensure alignment among strategic and operational dimensions concerning environmental issues in product development	5. Product development alignment with business strategy concerning environmental issues	Dimensionless (qualitative/scale)
		6. Alignment with corporate strategy and core competence concerning environmental issues	Dimensionless (qualitative/scale)
4	Clearly define the goals to improve environmental performance of the products under development	7. Rate of environmental goals (%)	Percentage of environmental goals (in relation to the total number of goals)
		8. Ambition level of environmental goals	Dimensionless (qualitative/scale)
		9. Feasibility of environmental goals	Dimensionless (qualitative/scale)
5	Include the environmental goals into the product target specifications	10. Rate of environmental requirements (%) in product target specifications	Percentage of environmental requirements (in relation to the total number of requirements)
		11. Integration level of environmental requirements into traditional product requirements	Dimensionless (qualitative/scale)
6	Integrate the environmental dimension in the strategic decision making process jointly with the traditional aspects	12. Rate of strategic decisions (%) made considering environmental dimension	Percentage of decisions considering environmental dimensions (in relation to the total number of decisions)
		13. Rate of decisions (%) changed due to environmental concern	Percentage of changed decisions (in relation to the total number of decisions)
7	Establish product-related vision, strategy and environmental roadmaps in the strategic level at the company	14. Number of environmental issues in strategic roadmaps	Number of issues
		15. Integration level between environmental issues and product-related vision	Dimensionless (qualitative/scale)
8	Strategically consider the product environmental performance in the company portfolio management	16. Number of products with enhanced environmental performance in the portfolio	Number of products
		17. Number of discontinued products due to environmental concerns	Number of products
		18. Revenue from products with enhanced environmental performance	Monetary units

Table 11. List of process-related performance indicators [8].

#	Ecodesign management practices	Proposed process-related performance indicators	Suggested units
10	Incorporate product-related environmental goals into the technological strategy	19. Rate of environmental goals (%) considered in technological strategy	Percentage of environmental goals (in relation to the total number of goals)
		20. Expected environmental improvements due to new technologies	Dimensionless (qualitative/scale) or Number of improvement or Types of improvement
		21. Rate of new technologies (%) with environmental gains	Percentage of new technologies with environmental gains (in relation to the total number of new technologies)
11	Identify customers' and stakeholders' requirements and priorities concerning the environmental performance of products	22. Integration level of environmental issues into marketing methods and tools (e.g. focus groups, interviews, surveys etc.)	Dimensionless (qualitative/scale)
		23. Number of initiatives targeted at actively creating market demands regarding environmental performance of products	Number of initiatives
		24. Number of initiatives targeted at identifying other stakeholders' requirements (e.g. communities, shareholders, suppliers, government etc.)	Number of initiatives
13	Identify and/or develop new technologies that can contribute to improve the environmental performance of the developed products	25. Breadth of implementation of environmental-oriented technologies in the product portfolio	Dimensionless (qualitative/scale)
		26. Comparative environmental gains of new technologies vs. incumbent technologies	Dimensionless (qualitative/scale) or Number of environmental gains
		27. Rate of research and development projects (%) with environmental-oriented technology	Percentage of environmental- oriented technological R&D projects (in relation to the total number of R&D projects)
		28. Investment rate (%) in environmental- oriented technology research and development projects	Percentage of monetary units invested in environmental-oriented technological R&D projects (in relation to the total number of R&D projects)
		29. Rate of environmental-oriented implemented technologies (%)	Percentage of technologies with environmental focus (in relation to the total number of technologies)
14	Perform functionality analysis to determine requirements for a product and find new ways to deliver the functions with a better environmental performance	30. Rate of sustainability-oriented solutions (%)	Percentage of sustainability- oriented solutions (in relation to the total number of solutions)
15	Improve the interaction between product and service developments in order to explore the potential to offer solutions with a better environmental performance	31. Rate of products (%) with service offerings enabling an increased environmental performance	Percentage of products with service offering that enables superior environmental performance (in relation to the total number of products)
		32. Revenue from product-service integrated offerings with superior environmental performance	Monetary units
		33. Number of new environmental-oriented business	Number of new opportunities

Table 11. List of process-related performance indicators [8].

#	Ecodesign management practices	Proposed process-related performance indicators	Suggested units
		model opportunities identified due to product-service integrated offerings	
16	Define a strategic roadmap for the development and implementation of new technologies that allows a better environmental performance over the product life cycle	34. Rate of environmentally-oriented technology 2 (%) in the roadmap	Percentage of environmental- oriented technologies (in relation to the total number of technologies in the roadmap)
		35. Investment rate (%) in environmentally- oriented technology research and development projects	Percentage of monetary units invested in environmental-oriented technology R&D projects (in relation to the total amount invested on R&D projects)
		36. Rate of environmentally-oriented implemented technologies (%)	Percentage of environmental- oriented technologies that were implemented (in relation to the total number of implemented technologies)
17	Evaluate the environmental performance of technologies	37. Rate of technologies (%) with impact assessment	Percentage of technologies with impact assessment (in relation to the total number of technologies)
18	Consider the environmental performance as one selection criterion for the product concept and design options	38. Rate of new environmentally-oriented concepts3 (%)	Percentage of new environmental-oriented concepts (in relation to the total number of concepts)
19	Evaluate the environmental performance of products during the product development process	39. Rate of products (%) with evaluation of environmental performance in the early stages of product development process	Percentage of products with evaluation of environmental performance in the early stages (in relation to the total number of products under development)
		40. Rate of products (%) with evaluation of environmental performance in the late stages of product development process	Percentage of products with evaluation of environmental performance in the late stages (in relation to the total number of products under development)
		41. Rate of products (%) using the results of environmental evaluation during decision-making in the product development process	Percentage of products with evaluation of environmental performance with results used for decision-making in product development (in relation to the total number of products under development)
20	Establish priorities on the environmental impacts to be minimized over the entire life cycle of the product	42. Rate of products (%) with established priorities of environmental impacts to be minimized over the entire life cycle	Percentage of products with establish priorities for environmental impacts (in relation to the total number of products)
21	Consider the trade-offs among the environmental requirements and the traditional requirements of a product (such as quality and cost)	43. Rate of products (%) with prioritized environmental requirements in the trade-off analysis	Percentage of products with prioritized environmental requirements in trade-off analysis (in relation to the total number of products)
22	Identify the ecodesign guidelines that can be applied in product design in order to increase the environmental performance of the product under development	44. Alignment level between ecodesign guidelines and the product's environmental targets	Dimensionless (qualitative/scale)
23	Develop and/or customize environmental product-related guidelines to support product development	45. Customization level of ecodesign guidelines	Dimensionless (qualitative/scale)
24	Incorporate the environmental	46. Rate of suppliers (%)	Percentage of suppliers identified,

Table 11. List of process-related performance indicators [8].

#	Ecodesign management practices	Proposed process-related performance indicators	Suggested units
	aspects in the identification, qualification and management of suppliers	identified, qualified and managed based on their environmental performance	qualified and managed based on environmental performance (in relation to the total number of suppliers)
		47. Rate of relationships (%) terminated due to low or non-compliant environmental performance	Percentage of relationships/contracts terminated due to low or non-compliant environmental performance (in relation to the total number of terminated relationships/contracts **or** the total number of relationships/contracts)
		48. Rate of new suppliers (%) identified and selected due to their superior product-related environmental performance	Percentage of new suppliers identified and selected due to environmental performance (in relation to the total number of new suppliers)
		49. Coverage of environmental aspects (%) in the identification, qualification and management of suppliers	Dimensionless (qualitative/scale)
25	Consider and involve the total value chain for improving the environmental performance of products	50. Degree of value chain partners' involvement in improving the environmental performance of products	Dimensionless (qualitative/scale)
		51. Rate of downstream/upstream value chain partners (%) involved in the improvement of environmental performance of products	Percentage of partners involved in improving environmental performance of products (in relation to the total number of partners)
26	Establish cooperation programs and joint goals with suppliers and partners aiming to improve the environmental performance of products	52. Number of cooperation programs focused on environmental performance improvement in collaboration with value chain partners	Number of programs
		53. Number of joint goals in the value chain focused on environmental performance improvement	Number of joint goals
27	Develop a "green" incentive scheme for the ecodesign implementation and management	54. Coverage of environmental-related incentives linked to ecodesign implementation and management across hierarchical levels	Dimensionless (qualitative/scale)
28	Select and/or develop new manufacturing and assembly processes with better environmental performance	55. Integration level of environmental considerations in designing new manufacturing and assembly processes	Dimensionless (qualitative/scale)
		56. Integration level of environmental considerations in the selection of new manufacturing and assembly processes	Dimensionless (qualitative/scale)
		57. Rate of new manufacturing and assembly processes (%) with increased environmental performance	Percentage of new manufacturing/assembly processes with increased environmental performance (in relation to the total number of new manufacturing/assembly processes selected or developed)

Table 11. List of process-related performance indicators [8].

#	Ecodesign management practices	Proposed process-related performance indicators	Suggested units
		58. Investment rate (%) in new manufacturing and assembly processes with increased environmental performance	Percentage of monetary units invested in new manufacturing/assembly processes with a view to increasing environmental performance (in relation to the total amount invested in new manufacturing/assembly processes)
29	Optimize the existing production processes in order to improve the environmental performance of products during manufacturing	59. Enhancement of environmental performance of manufacturing processes over time	Dimensionless (qualitative/scale)
		60. Rate of actions/initiatives/programs (%) towards enhancing environmental performance of manufacturing processes	Percentage of actions/initiatives/programs with environmental focus for manufacturing processes (in relation to the total number of action/initiatives/programs targeted at improving manufacturing processes)
		61. Investment in enhancing environmental performance of manufacturing processes	Monetary units
30	Develop the technical support processes (e.g. maintenance, change of spare parts, etc.) aiming to improve the environmental performance of the product over its entire life cycle	62. Rate of products (%) in the portfolio with extended lifetime due to environmental-related technical support processes	Percentage of products with extended lifetime due to technical support processes (in relation to the total number of products in the portfolio)
		63. Rate of products (%) in the portfolio with increased operational efficiency due to environmental-related technical support processes	Percentage of products with increased efficiency due to technical support processes (in relation to the total number of products in the portfolio)
31	Define the end-of-life and reverse logistics strategies to be addressed during product development in order to improve the environmental performance of the product in the end-of-life phase	64. Rate of products (%) in the portfolio with defined end-of-life and reverse logistics strategies	Percentage of products with defined end-of-life and reverse logistics (in relation to the total number of products in the portfolio)
32	Improve the environmental performance of packaging and distribution during the product development and related processes	65. Rate of products (%) with environmentally-enhanced packaging/distribution	Percentage of products with environmentally-enhanced packaging/distribution (in relation to the total number of products in the portfolio)
33	Elaborate and communicate recommendations to consumers on how to improve the environmental performance of the product during the use and end-of-life phases	66. Rate of products (%) with environmental recommendations to consumers regarding use and end-of-life	Percentage of products environmental recommendations to consumers regarding use and end- of-life (in relation to the total number of products in the portfolio)
		67. Relevance of the information provided to consumers regarding the product's use and end-of-life	Dimensionless (qualitative/scale)
34	Communicate the environmental performance and benefits as part of the total value proposition of the product, exploring the green marketing opportunities	68. Rate of products (%) with eco-label	Percentage of products with eco- label (in relation to the total number of products in the portfolio)
35	Monitor the product environmental performance during use and end-of-life phases of the life cycle	69. Rate of products (%) monitored during use and end-of-life phases	Percentage of products monitored during use and end-of-life (in relation to the total number of products the company has)

Table 11. List of process-related performance indicators [8].

#	Ecodesign management practices	Proposed process-related performance indicators	Suggested units
36	Communicate to customer and stakeholders the improvements on the product environmental performance and consequent economic gains	70. Degree to which product-related environmental information is shared with stakeholders	Dimensionless (qualitative/scale)
		71. Rate of stakeholders (%) informed about the total amount of economic gains related to ecodesign	Percentage of stakeholders informed about economic gains (in relation to the total number of stakeholders)
37	Supply the product development process with information related to the environmental performance of materials, processes and components in the whole product life cycle phases	72. Rate of consideration of information (%) collected during life cycle in new product development projects	Dimensionless (qualitative/scale) or Percentage of the amount of environmental information considered as input for new development projects in relation to the total amount of environmental information collected during life cycle
38	Define and measure performance indicators for the environmental performance of stakeholders such as suppliers, after sales, service providers, recyclers, etc.	73. Coverage of performance indicators for different stakeholders	Dimensionless (qualitative/scale)
39	Structure a systematic procedure to gather ecodesign- related knowledge	74. Concentration level of ecodesign-related knowledge across functions	Dimensionless (qualitative/scale)
		75. Investment in ecodesign-related knowledge management	Monetary units
40	Perform internal and external benchmarking of the environmental performance of products and/or ecodesign best practices	76. Rate of products (%) benchmarked for environmental performance	Percentage of products benchmarked for environmental performance (in relation to the total number of benchmarked products)
		77. Coverage of environmental-oriented criteria used in benchmarking analysis	Dimensionless (qualitative/scale)
42	Deploy and maintain an environmental policy and/or strategy in the product level	78. Rate of product-related strategies (%) based on environmental policy and/or strategy	Percentage of product-related strategies based on environmental policy/strategy (in relation to the total number of product-related strategies)
43	Establish a prioritized program for the implementation and management of ecodesign	79. Rate of investment (%) in the ecodesign program	Percentage of monetary units invested in the ecodesign program (in relation to the total investment in monetary units)
		80. Coverage of environmental issues of ecodesign program	Dimensionless (qualitative/scale)
		81. Rate of business units (%) involved in the ecodesign program	Percentage of business units involved in ecodesign (in relation to the total number of business units)
		82. Rate of functional areas (%) involved in the ecodesign program	Percentage of functional areas involved in ecodesign (in relation to the total number of functional areas)
44	Clearly define the product- related environmental goals for the whole company	83. Rate of product families (%) with clearly defined environmental goals	Percentage of product families with defined goals (in relation to the total number of product families)
45	Increase consciousness and awareness of the company in regards to the application opportunities and benefits of ecodesign	84. Level of employee awareness regarding opportunities and benefits of ecodesign application across functions	Dimensionless (qualitative/scale)
		85. Number of initiatives targeted at promoting opportunities and	Number of initiatives

Table 11. List of process-related performance indicators [8].

#	Ecodesign management practices	Proposed process-related performance indicators	Suggested units
		benefits of ecodesign application in the company	
46	Ensure commitment, support and resources to conduct the activities related to ecodesign	86. Amount of resources available related to ecodesign	Monetary units **or** number of people
		87. Number of higher executives with ecodesign performance related to their pay bonuses	Number of higher executives
		88. Rate of employees (%) with ecodesign performance related to pay bonuses per functional area	Percentage of employees with ecodesign performance related to pay bonuses (in relation to the total number of employees in the functional area)
		89. Rate of employees (%) with ecodesign performance related to pay bonuses per business unit	Percentage of employees with ecodesign performance related to pay bonuses (in relation to the total number of employees in the business unit)
47	Deploy the responsibilities and authorities among people of different areas and hierarchical levels	90. Number of functional areas with responsibilities and authorities over ecodesign implementation	Number of functional areas
		91. Number of hierarchical levels with responsibilities and authorities over ecodesign implementation	Number of hierarchical levels
49	Provide ecodesign-related training for the employees involved in the product development and related processes	92. Rate of employees (%) trained in ecodesign-related topics	Percentage of employees trained in ecodesign-related topics (in relation to the total number of employees **or** the total number of employees working on ecodesign)
		93. Level of employees' knowledge regarding ecodesign-related topics	Dimensionless (qualitative/scale)
		94. Rate of acquired knowledge (%) shared among other employees	Dimensionless (qualitative/scale)
		95. Level of access to ecodesign knowledge base by employees	Dimensionless (qualitative/scale)
50	Make environmental considerations a part of the daily routine of the employees involved with product development	96. Integration level of ecodesign into employees' daily activities	Dimensionless (qualitative/scale)
51	Integrate ecodesign into the product development and related processes standards and procedures	97. Maturity level of ecodesign implementation and management	Dimensionless (qualitative/scale)
		98. Integration level of ecodesign into product development standards and procedures	Dimensionless (qualitative/scale)
52	Conduct management reviews to evaluate the effectiveness of the environmental issues consideration in the product development and related processes	99. Frequency of ecodesign management reviews	Reviews per unit of time (e.g. month, quarter, year etc.)
		100. Effectiveness of corrective actions taken after ecodesign management reviews	Dimensionless (qualitative/scale)
53	Select and customize ecodesign methods and tools according to the company's needs	101. Integration level of ecodesign methods and tools into the product development process	Dimensionless (qualitative/scale)

Table 11. List of process-related performance indicators [8].

#	Ecodesign management practices	Proposed process-related performance indicators	Suggested units
		102. Integration level of environmental issues into existing methods and tools	Dimensionless (qualitative/scale)
		103. Coverage of ecodesign methods and tool across the product development process	Dimensionless (qualitative/scale)
		104. Number of employees properly trained or capable of using ecodesign methods, tools and outputs	Number of employees
54	Formulate, update and monitor mandatory rules (internal standards) and/or product requirements in order to comply with environmental product-related legislations and/or regulations	105. Comprehensiveness of product-related environmental legislation requirements	Dimensionless (qualitative/scale)
		106. Compliance level with product-related environmental legislation requirements	Dimensionless (qualitative/scale)
55	Effectively integrate product-related environmental goals into the corporate strategy	107. Integration level of environmental goals into the corporate strategy	Dimensionless (qualitative/scale)
56	Select the relevant people from functions across the company to be involved in the ecodesign activities	108. Number of people per function engaged in ecodesign activities	Number of people
57	Implement the Life Cycle Thinking into the product development and related processes	109. Integration level of Life Cycle Thinking into the product development and related processes	Dimensionless (qualitative/scale)
60	Check the environmental performance of products during the gates (phase assessments)	110. Rate of projects (%) with checked environmental targets during the phase assessments	Percentage of projects with checked environmental targets (in relation to the total number of projects)
61	Define and measure environmental performance indicators for product improvement	111. Coverage of performance indicators for different product development stages	Dimensionless (qualitative/scale)
		112. Level of alignment between performance indicators and the decisions taken in product development	Dimensionless (qualitative/scale)
62	Define and measure performance indicators for the 5 of the ecodesign program	113. Coverage of performance indicators for different projects in the ecodesign program	Dimensionless (qualitative/scale)
		114. Level of alignment between the performance indicators and the decisions taken in the ecodesign program	Dimensionless (qualitative/scale)