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Sustainable SoluTions FOR recycling of end-of-life Hydrogen technologies

Deliverable D5.1

Environmental profile of existing EoL technologies and effects in the scope of circular economy in manufacturing phase

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Clean Hydrogen Partnership

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4	28.06.2023	**UL:** Rok Stropnik, Mitja Mori, Andrej Lotrič, Jure Gramc	Final public deliverable

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Abbreviations

BoM	Bill of Materials
BPP	Bipolar Plate
CCM	Catalyst Coated Membrane
CRMs	Critical raw materials
EE	Energy Extraction
EoL	End-of-Life
FCH	Fuel Cells and Hydrogen technologies
FCs	Fuel Cells
HMT	Hydrometallurgical Process
HRD	Hensel Recycling Deutschland
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometry
IPA	Internationally Platinum Association
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LF	Landfill
LSC	Lanthanum Strontium Cobaltite
LSC64	Lanthanum Strontium-doped Cobaltite ($La_{0.6}Sr_{0.4}CoO_3$)
MEA	Membrane Electrode Assembly
PEMFC	Proton Exchange Membrane Fuel Cell
Pt	Platinum
REC	Recycling
SOCs	Solid Oxide Cells
SOECs	Solid Oxide Electrolysis Cells
SOFCs	Solid Oxide Fuel Cells
SS	Stainless steel
WP	Work Package
YSZ	Yttrium Stabilized Zirconium
8YSZ, 3YSZ	mixture of 8%/3% mol Y2O3 stabilized zirconia

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1. Executive Summary

Within the Work Package 5 (WP5), which is under the leadership of University of Ljubljana (UL) with collaboration of all BEST4Hy EU project partners, the first Deliverable (D5.1), focuses on *Environmental profile of Existing EoL technologies and effects evaluated with LCA methodology in the scope of circular economy in the manufacturing phase of Fuel Cell and Hydrogen (FCH) technologies*, thus presenting the results of the first part of the BEST4Hy project with important work done and interaction between WP5 and WP1, WP2, WP3.

In the following document, case studies for observed technologies (PEMFC and SOFC stack) are presented in the manufacturing, and the end of life (EoL) phase with environmental profile evaluation of recycling/recovery processes for each technology defined as ''Existing technologies'' within the BEST4Hy project.

This deliverable includes a detailed description of the two Fuel cell and Hydrogen (FCH) reference products: a Proton Exchange Membrane Fuel Cell (PEMFC) stack and a Solid Oxide Fuel Cell (SOFC) stack provided by BEST4Hy industry partners.

The key objective of D5.1 is to conduct an environmental life cycle assessment (E-LCA) of reference products: PEMFC and SOFC stack, to define and quantify the impact of existing recycling/recovery processes, targeting critical raw materials (CRM) within reference products. These processes focus on Pt recycling from aged PEMFC stacks and, for the SOFC case, the focus is on recovery of the yttria-stabilized zirconia (YSZ) and Nickel oxide (NiO) – anode, which were identified as Existing recycling/recovery processes within BEST4Hy project. Furthermore, detailed analysis of Existing recycling/recovery processes is presented as complete Life Cycle inventories (LCI) datasets, which were developed for Pt, YSZ and NiO recovery from aged cells. A second objective of this D5.1 report is to evaluate the environmental profile of recovered material via the above processes and their impact on manufacturing phase within a circular economy approach (open and close-loop recycling).

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2. Introduction and methodological approach

BEST4Hy project is in part a continuation of the work of previous HytechCycling EU project [1], [2]. To assess the environmental profile of Existing recycling/recovery technologies and effects in manufacturing phase of Fuel Cell and Hydrogen (FCH) technologies, case studies of observed technologies within the BEST4Hy project have been set up to present realistic results regarding their environmental impacts. The methodological approach used in this D5.1 "Environmental profile of existing EoL technologies and effects in the scope of circular economy in the manufacturing phase" is based on standardized Life Cycle Assessment (LCA) methodology, taking into account ISO 14040 [3] and 14044 [4] standards, International Reference Life Cycle Data (ILCD) [5] system guidelines and guidance documents for performing LCA on FCH technologies by FC-HyGuide [6], [7]. LCA includes four main phases: **i) goal and scope**, **ii) life cycle inventory (LCI) analysis**, **iii) life cycle impact assessment (LCIA)**, and **iv) interpretation of the results.** In this study – which was defined within BEST4Hy EU project – two reference products in the field of Fuel Cell and Hydrogen (FCH) technologies were analyzed: **i)** a **Proton Exchange Membrane Fuel Cell (PEMFC)** stack with a **rated electrical power of 55 kW** and **ii)** a **Solid Oxide Electrolyte Fuel Cell (SOFC)** stack with a **rated electrical power of 3 kW**. Reference products under evaluation are shown in Figure 1 for PEMFC stack provided by ElringKlinger AG – EKPO [8] industry partner and Figure 2 for SOFC stack provided by Elcogen AS [8] industry partner.

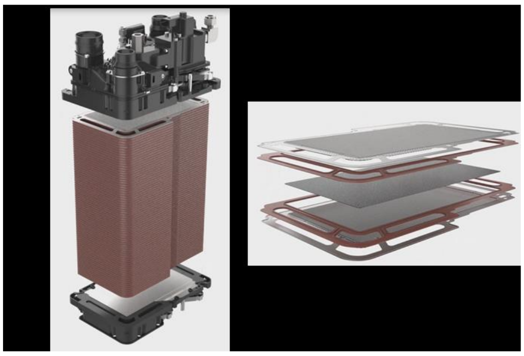

Figure 1: Reference 55 kW_{el} PEMFC stack for LCA analysis

Figure 2: Reference 3 kW_{el} SOFC stack for LCA analysis

2.1 Goal and Scope of the LCA study

The main goal of this environmental LCA study is to evaluate the environmental impacts of two reference FCH products (PEMFC stack and SOFC stack) with the effect of Existing End-of-Life (EoL) (i.e. recycling and recovery) processes for targeted critical raw materials (platinum (Pt) for PEMFC; yttria-stabilized zirconia (YSZ) and Nickel oxide (NiO) for SOFC) on environmental profile of these two reference FCH products. Both reference FCH products in this LCA study will be analysed for **manufacturing phase with EoL phase for Existing EoL processes for critical targeted materials within BEST4Hy project**. **Operation phase will not be included** in this environmental LCA analysis. System boundaries within the analysis are:

- **foreground system**, which comprises all processes related to the manufacturing phase of the PEMFC and SOFC stack itself gathered from the Bill of Materials (BoM) and processes provided by Industry partners involved in BEST4Hy. In the case of a PEMFC stack, this includes the main manufacturing processes of materials needed for manufacturing of the Catalyst Coated Membrane (CCM), Membrane Electrode Assembly (MEA), Bipolar plates (BPP), stack pre-assembly and final stack assembly. In the case of a fuel cell system, which is not included in this study, the foreground would also include the manufacturing of the Balance of Plant (BoP) and the start-up of the whole PEMFC system in a certain application.
- **background system** supports the foreground system and its processes. It includes almost all material and energy flows going to and coming from the foreground system (e.g., for the electricity supply, it includes the extraction of resources, production and distribution of the electricity generated and used in analysed foreground system). In this study, **secondary data** for the background system **from existing high-quality life cycle inventory (LCI) databases** (**Ecoinvent 3.7 and GaBi Professional** (Sphera) have been used.

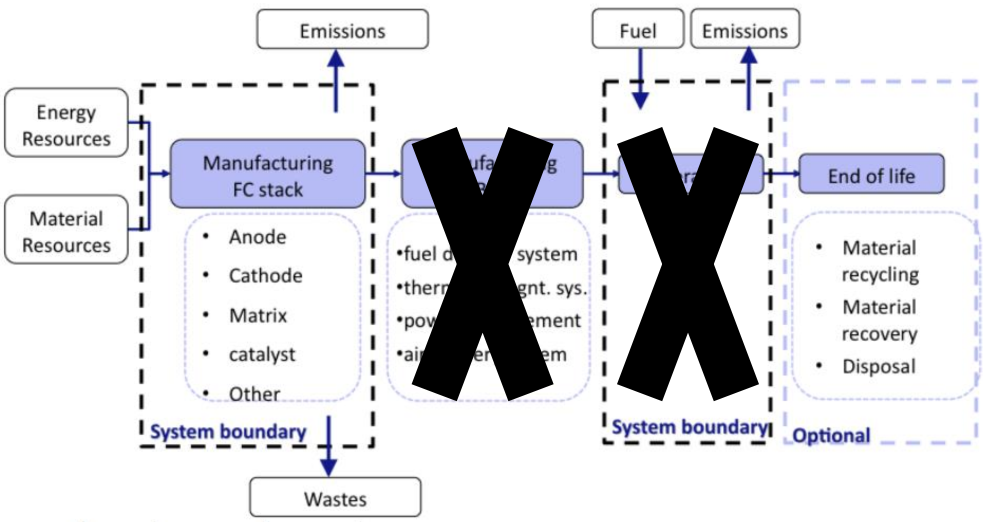

Figure 3: System boundaries and phases included for LCA analysis [6].

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2.1.1 PEMFC case

The ***functional unit*** for the PEMFC case will be ***one PEMFC stack with 55 kW electrical power output***. The reference flow for the LCA study is **one unit of a 55 kW PEMFC stack**.

The **physical and methodological boundaries** of the PEMFC LCA study are:

- Functional unit: one **PEMFC stack** with **55 kW electrical power** output.
- Scope: From ''**cradle to grave''** (manufacturing and EoL phase for Pt recycling) **with exclusion of the use phase.**
- Life Cycle Inventory (LCI): **materials (BoM) and processes** used are provided by **industry partners within the BEST4Hy project** and other FCH technology manufacturers.
- Life Cycle Impact Assessment (LCIA) Method: **Environmental footprint 3.0** (EF 3.0).
- Software environment used for LCA modelling: **GaBi Sphera software**.
- Generic databases used: Gabi professional[9] and Ecoinvent 3.7 [10].

2.1.2 SOFC case

The ***functional unit*** for SOFC case will be ***one SOFC stack with 3 kW electrical power output***. The reference flow for LCA study is **one unit of a 3 kW SOFC stack**.

The **physical and methodological boundaries** of the SOFC LCA study are:

- Functional unit: one **SOFC stack** with **3 kW electrical power** output.
- Scope: From ''**cradle to grave''** (manufacturing and EoL phase for YSZ and NiO recovery) **with exclusion of use phase.**
- Life Cycle Inventory (LCI): **materials (BoM) and processes** used are provided by **industry partners within BEST4Hy project** and other FCH technologies manufacturers.
- Life Cycle Impact Assessment (LCIA): **Environmental footprint 3.0** (EF 3.0).
- Software environment used for LCA modelling: GaBi Sphera software [11].
- Generic databases used: Gabi professional and Ecoinvent 3.7 [10].

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2.2 LCA methodology approach in End-of-Life phase

As the focus of this deliverable is to evaluate the environmental profile of reference FCH technologies within the scope of circular economy, an understanding of the End-of-Life (EoL) phase based on current EoL technologies is key. For FCH in the EoL phase, there are several possible strategies. Typically, the first phase of EoL is manual disassembly of the entire system, after which different EoL strategies can be applied to specific parts and materials:

- ***Reuse (RU) -*** Reusing of parts is usually very unlikely since after many years of operation many parts are damaged, or technologies meanwhile improved so much that "old" parts are not useful anymore. But some other parts, such as housing, could be reused.
- ***Recycling (REC) –*** Recycling will be analyzed for reference FCH cases where is possible to extract secondary material that can be used in some cases instead of virgin material (close-loop REC), in other cases they could be used in other products/industries (open-loop REC). The focus in EoL will be on key and critical raw materials, which were identified for each reference product (PEMFC – Pt, Ionomer and for SOFC – YSZ, NiO, LSC), with developed Existing and Novel EoL processes within the BEST4Hy project for recovery.
- ***Energy extraction (EE) –*** Energy extraction is a thermal treatment process in which credits are gained in the form of electricity and/or heat. Electricity can be used in the same process and modeled as a back loop, with electricity input reduced according to electricity extracted from EE.
- ***Landfill (LF) -*** Landfilling is used in the case of all materials where there is no recycling and energy extraction possible. Landfilling is also the process used in the case when no data regarding EoL process is available.

For each technology, the starting point of EoL strategy planning starts with a life cycle inventory (LCI) table, where all materials are listed with their masses. As stated at the beginning, initially the whole system is submitted to manual dismantling; after that, different EoL processes are applied. After the recycling process, there can be two main strategies:

i. **Reducing the mass input of virgin material in the manufacturing phase** – with this measure, the manufacturing phase might/should have lower environmental impacts due to fewer virgin materials, but additional impact will come from EoL phase processes (**close-loop REC**).
ii. **Preparing secondary materials for other applications/manufacturing products**, that are not usable in manufacturing of observed technologies but are usable in other products/industry. In this case the EoL phase environmental impacts are included, but with exclusion of environmental impact of production for other products with produced secondary material (**open-loop REC**).

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Steps used in the LCA analysis of EoL phase:

1) Manual dismantling of the reference FCH product.
2) Define EoL processes for targeted critical material (Pt, YSZ, NiO and LSC)
3) Calculate environmental profile of observed existing/novel BEST4Hy EoL processes.
4) Post process results and adapt (reduce) input masses of virgin materials in manufacturing phase of reference FCH products.
5) Subtract impacts of preparing secondary materials already destined to other uses from total impacts of the EoL phase.

In addition, the aim is to use an additional indicator for recovered materials, namely the Circular Footprint Formula (CFF) indicator for both FCH reference cases in the EoL phase, if sufficient data are available at the end of the BEST4Hy project to calculate the CFF as part of the BEST4Hy project results. The next chapter defines and describes life cycle inventories (LCI) of specific processes and scenarios for the EoL phase for each FCH reference product under which the LCA methodology was conducted and the environmental profile of BEST4Hy's existing EoL technologies was analyzed with impacts in the context of the circular economy.

2.3 Life Cycle Inventory (LCI) analysis

In this chapter, detailed Life Cycle Inventory (LCI) analysis is performed for PEMFC and SOFC stack manufacturing phase and EoL phase. In the manufacturing phase, detailed materials list for each component are provided, based on the Bill of Materials (BoM) from the industry partners. In the EoL phase, LCI analysis will focus on developing novel LCI for existing laboratory scale recovery processes for key/critical raw materials, within the scope of BEST4Hy project: i) Pt recycling from used PEMFC MEA and for ii) YSZ and NiO recovery from used SOFC cells. Additional EoL scenarios for each reference case with proposed EoL strategies are presented and described.

2.3.1 PEMFC case

This section describes the methodology and steps used to create LCI tables related to material and energy flows for one unit of the reference 55 kW_{el} PEMFC stack. Data were obtained from the PEMFC technology manufacturer in the BEST4Hy consortium (EKPO [12]). The method for preparing the LCI was to collect data for all necessary materials and processes used in the production of the proposed reference product. The main data for the LCI was provided in the form of a BoM, which was further analysed. Using this input, all mass and energy balances required for the LCI were properly defined for the manufacturing phase.

In the second part of this section, Pt recycling via existing path (existing EoL in BEST4Hy) is defined and presented through three main steps: Manual disassembly of MEA, Hydrometallurgical treatment (HMT) of CCM, and Pt/C catalyst powder synthesis. For PEMFC technology BEST4Hy concentrates on Platinum (high material value and high criticality [13]) and Ionomer (PFSA, medium material value but also medium criticality [13])

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and aims to recover the following percentage from the materials at INPUT (representing the 100%):

- 80-95% for Pt and
- >80% for ionomer in solution (some technologies allow the recovery of the full membrane)

Ionomer recycling will be analysed in future results as part of BEST4Hy's new EoL technologies when all required recovery processes have been developed by BEST4Hy project partners, so in this Deliverable only the Pt recycling via current Existing technology (Hydrometallurgical Process) will be evaluated from aged (used) MEA (2.3.1.2) and evaluate the impact of recovered Pt used for manufacturing phase of reference PEMFC product.

2.3.1.1 Manufacturing phase

The LCI for manufacturing phase is presented in Table 1, which was built based on a BoM gathered from the industry partner EKPO for the manufacturing of the 55 kW_{el} PEMFC stack.

Table 1: Input materials (LCI) for reference PEMFC stack manufacturing per kW_{el}

Component	Material	Unit	Value	Used LCA Database
MEA (CCM)	Carbon black	g		DE: Carbon black Sphera
	Pt	g	21.16	GLO: Platinum mix Sphera
	Ionomer	g		CA: Nafion - for use in fuel cell ts
MEA (GDL)	Carbon fibres	g	14.96	EU-28: Carbon fiber -
Gaskets	Silicone	g	43.56	EU-28: Silicone sealing compound (EN15804) Sphera
BPP, Endplates, Rods, Nuts	Stainless steel	g	325.85	EU-28: Stainless steel white hot rolled coil (316) Eurofer
BPP	Gold	g	0.10	GLO: Gold (primary) Sphera
Endplates (anode, cathode)	Glass fibres reinforced plastic	g	27.33	PPS (40% glass fibre) production <LC>
Endplates (anode, cathode)	Chromium steel 18/8	g	6.66	RER: steel production, chromium steel 18/8, hot rolled ecoinvent 3.7.1
Current collector	Copper	g	3.66	EU-28: Copper sheet (A1-A3) Sphera
Other	Electronics, controls	g	1.17	RER: electronics production, control units ecoinvent 3.7.1
Processes (energy)	Electricity [13], [14]	kWh	8.55	EU-28: Electricity grid mix Sphera
Mass of the 55 kW_{el} PEMFC stack		**kg**	**23.5**	

Based on LCI, the LCA model (see Figure 4) for the manufacturing phase was built in GaBi Sphera software for each component of the reference 55 kW_{el} PEMFC stack. Considering the manufacturing phase, the LCA model is built in such a way that all subsystems are modelled separately and can be easily modified/updated according to the specific technology standards of the PEMFC stack manufacturers. Waste streams and energy losses associated with the manufacturing phase are not included in this report, but additional analysis (if data became available) will be added as the BEST4HY project progresses.

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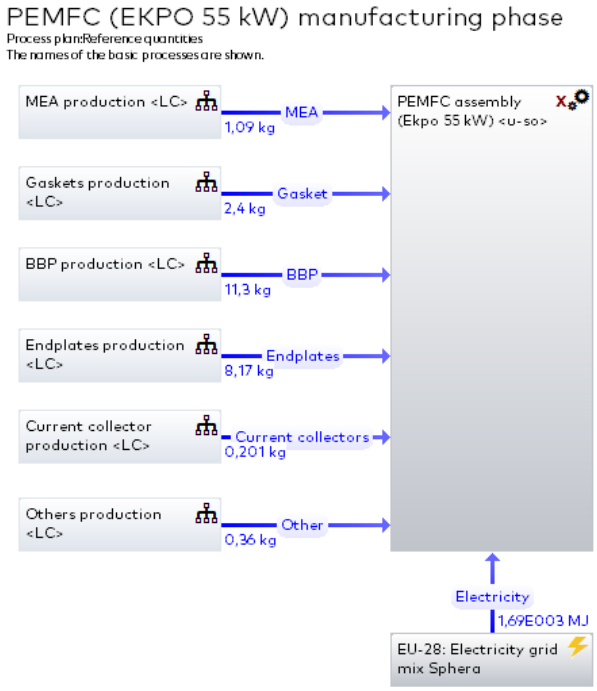

Figure 4 LCA model for manufacturing phase of reference 55 kW PEMFC stack

2.3.1.2 Pt recovery based on existing recycling technology

The EoL phase is very important in the circular economy to avoid the exclusive use of virgin materials through recycling processes (plastics, steel, non-ferrous metals, etc.), to avoid the production of new parts by reusing undamaged parts of the system, and to recover energy from non-recyclable materials with high calorific value (e.g. plastics).

Related to the objective of this report within BEST4Hy project, the main critical material is platinum (Pt) and within current/existing EoL technology, platinum recycling (Pt REC) will be analysed as the main EoL process. Pt REC used in this study is based on readaptation of existing methods applied for the PEMFC stack recycling based on a Hydrometallurgical Process (HMT) for Pt salt recovery for re-manufacturing of PEMFC catalyst coated membrane (CCM) from Pt/C catalyst obtained by synthesis. This readaptation is to reach TRL5 within the BEST4Hy project, with data collected for this report during the development of the processes at TRL3 (lab scale). Existing Pt REC processes are detailed in BEST4Hy previous deliverables, ***D1.1 Lab Scale Optimization Results on the 3 PEMFC Recycling Technologies Report***, ***D1.2 Technical report on adaptation of existing technology (hydrometallurgical process) for PEMFC material recovery: results and design and D2.1 Report on the catalyst synthesis at lab scale and quality testing of the recycled material***, compiled by WP1 and WP2 BEST4Hy partners, Hensel Recycling Deutschland (HRD), IDO-LAB and CEA.

Used PEMFC stacks are first disassembled manually: removal of tie rods, cables and housings (mainly stainless steel), removal of end plates, splitting of layers, removal of sealants and MEAs. Three main steps (processes) were then performed (see Figure 5), which were described in detail, analysed, and used to create a new LCI for the existing Pt REC. Figure 5 shows the workflow for the creation of the LCI and the process flow with the

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main input and output materials for the recovery of 1 g Pt as Pt/C catalyst (2.5 g Pt/C), which could be used for the fabrication of a new PEMFC CCM with recycled Pt/C catalyst.

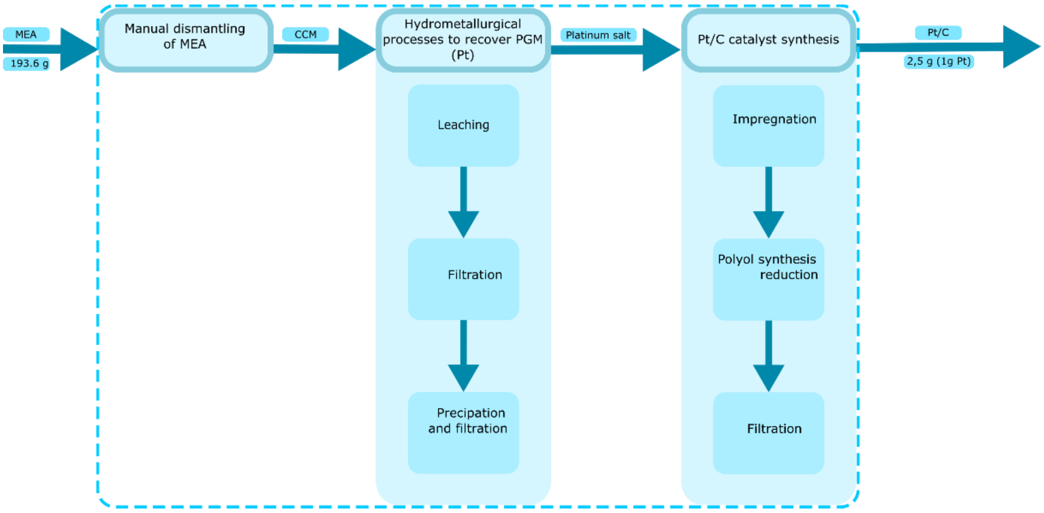

Figure 5 Existing PEMFC EoL – Pt recovery workflow

The LCI for existing Pt REC was prepared according to three main steps:

1) MEA disassembly process (led by HRD),
2) Hydrometallurgical process to recover Pt salt (led by IDO-LAB) and
3) Pt/C synthesis with polyol reduction synthesis (led by CEA).

The first main step is manual disassembling of MEA (5th hybrid method by HRD): BPPs are disassembled by hand, rubber gaskets are cut off with a professional lever cutter. GDLs are “stripped” by hand and the remaining CCMs are shredded with a standard paper shredder. In Figure 6, mass and energy balances for MEA disassembling step are presented.

1 st	***MEA disassembling***				
Description					
	Input (materials)	g		g	**output (Wastes, energy..)**
Main input	MEA (with gaskets)	14,40		9,90	Gaskets, subgasket
				3,40	GDL
			Manual disassembling + Cutting machine + Delamination+ Shredding	0,00	.....
				0,00	
	Energy			0,00	
	Electricity (kWh) (cutting machine)	0,18			**Main output**
	Electricity (kWh) (shredder)	0,125		1,10	CCM
	Heat (kWh)	0,00			

Figure 6: MEA disassembly step with energy and mass balances.

After MEA disassembly, the CCMs are used in the second main step, which is the HMT process to recover Pt (in form of Pt salt - $(NH_4)_2PtCl_6$). HMT consists of a first phase, a leaching process with aqua regia; after leaching, a filtration process removes the ionomer and carbon particles from the Pt-containing solution, and in this step the Pt concentration is also quantified by ICP-OES. The third phase is precipitation of the Pt-containing solution with ammonium chloride (NH_4Cl) to precipitate Pt as Pt salt ($(NH_4)_2PtCl_6$), which is then filtered and recovered in solid form as the final product of the HMT process. In Figure 7 mass and energy balances for lab scale (i.e. TRL3) HMT process are presented.

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The average efficiency (yield) of Pt recovery for the HMT process determined on a laboratory scale is 93.6% (CCM to Pt salt), which is in line with BEST4Hy expected objective for the technology developed.

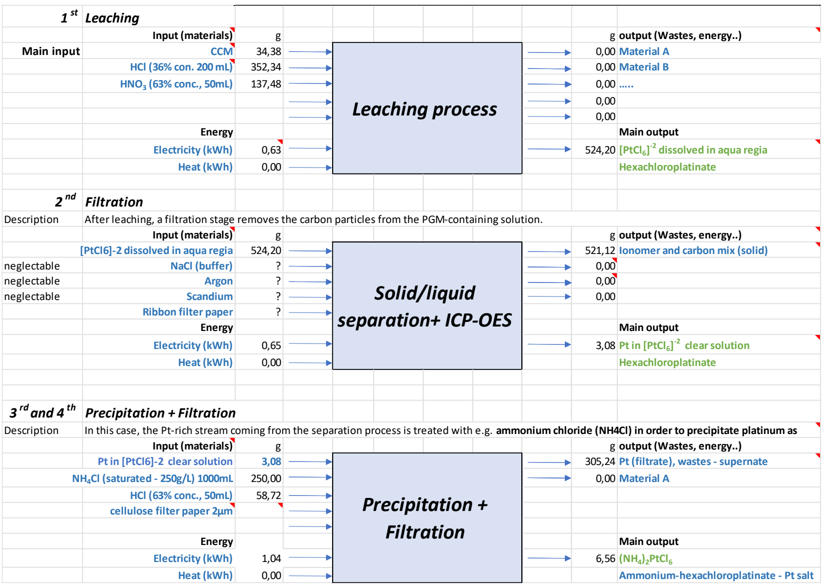

Figure 7: Hydrometallurgical treatment steps with energy and mass balances.

The final main step for the existing Pt REC is Pt/C catalyst synthesis with polyol reduction, where the main input material is Pt salt, and the final product is Pt/C catalyst powder with recycled (secondary) Pt. The Pt/C catalyst synthesis consists of the impregnation step, reduction step and three times filtration, which are shown in Figure 8.

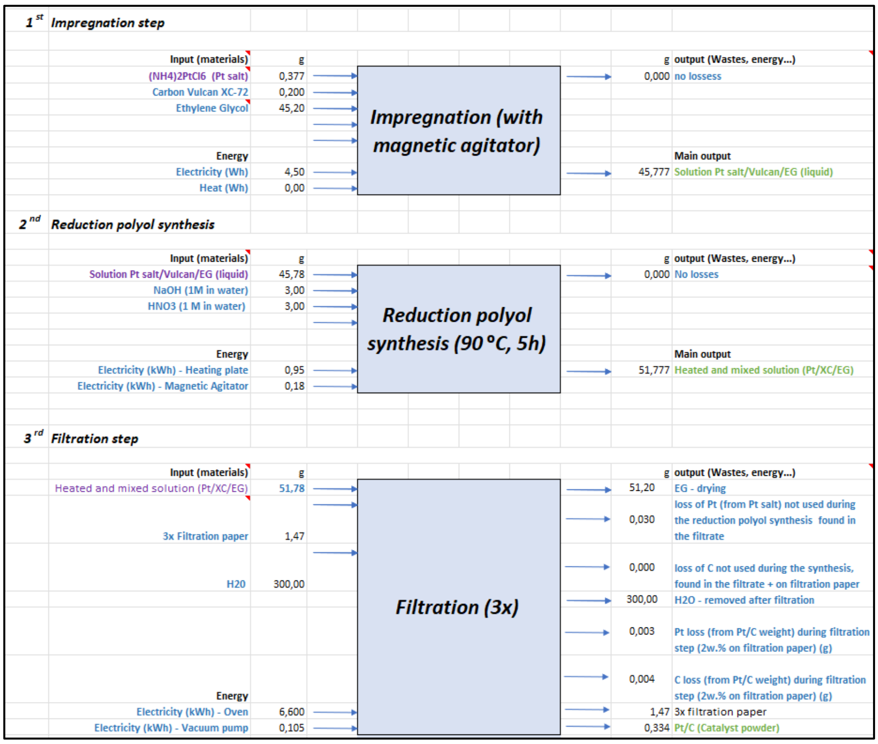

Figure 8: Pt/C catalyst synthesis steps with energy and mass balances.

Figure 8 shows the mass and energy balances for Pt/C catalyst synthesis with polyol reduction. The average Pt/C synthesis efficiency with 40 wt% targeted Pt mass in Pt/C used in the analysis is 91.2% (the Pt yield is 80.6%, which is in line with the expectations of project BEST4Hy).

Table 2: Life cycle inventory for BEST4Hy Existing Pt REC

	Inputs	Quantity	Unit	Used database
MEA dismantling	MEA (with gaskets)	193.6	g	see Table 1
	Electricity	1.86	kWh	DE: Electricity grid mix Sphera
	Outputs			
	Gaskets	133.1	g	see Table 1
	GDL	45.71	g	see Table 1
	CCM	**14.79**	**g**	
Hydrometallurgical processes to recover Pt	**Inputs**			
	CCM	**14.79**	**g**	
	HCl	151.56	g	DE: Hydrochloric acid Sphera
	HNO_3	59.14	g	DE: Nitric acid Sphera
	Electricity	1.00	kWh	DE: Electricity grid mix Sphera
	NH_4Cl	107.54	g	GLO: NH_4Cl production ecoinvent 3.7.1
	HCl	25.26	g	DE: Hydrochloric acid Sphera
	Outputs			
	Carbon powder	224.17	g	
	Pt filtrate	120.01	g	
	Pt Salt ($(NH_4)_2PtCl_6$)	**2.82**	**g**	
Pt/C catalyst synthesis - from Pt salt	**Inputs**			
	Pt Salt ($(NH_4)_2PtCl_6$)	**2.82**	**g**	
	Carbon Vulcan	1.50	g	DE: Carbon black Sphera
	Ethylene Glycol	338.32	g	EU-28: Ethylene glycol PlasticsEurope
	Electricity	92.33	kWh	FR: Electricity grid mix Sphera
	NaOH	22.45	g	RER: Sodium hydroxide mix Sphera
	HNO_3	22.45	g	DE: Nitric acid (60%) Sphera
	Filtration Paper	11.0	g	/
	Water	2245.5	g	
	Output (wastes)	2641.8	g	
	Main output			
	Pt/C	**2.5**	**g**	
	Carbon support	1.5	g	
	Platinum (secondary)	**1**	**g**	

Based on all energy and mass balances (LCI from Table 2) for all steps in Existing EoL for Pt REC presented above, the LCA model (see Figure 9) for manufacturing phase was built in the GaBi Sphera software. The main input in the model is aged MEA and output of the Existing EoL Pt REC is 2.5 g of Pt/C (1 g of recycled Pt). The cumulative Pt recovery efficiency based on the lab scale Existing EoL Pt REC from aged MEA (EKPO) to 1g of recycled Pt in the Pt/C catalyst is 65.2% (according to the CCM Active area and declared Pt loading by CCM manufacturer).

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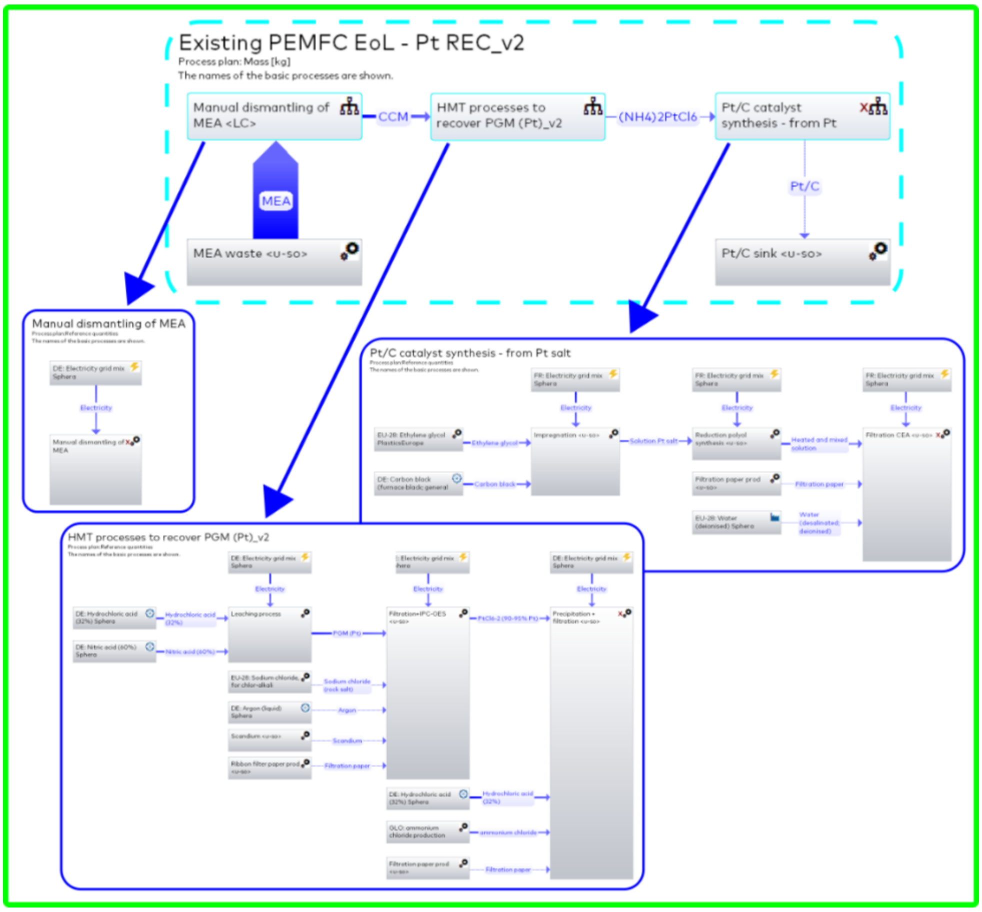

Figure 9: LCA model for Existing EoL for Pt recycling.

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2.3.1.3 Manufacturing phase with Pt recycling scenarios

Within platinum recycling (Pt REC) scenarios, which have been analyzed in this chapter, the focus is on recovering of specific critical materials within reference FCH technology.

The objective of D5.1 is to evaluate the environmental profile of the BEST4Hy Existing Pt REC so that in the PEMFC case, Pt recycling will be the focus of the closed-loop and open-loop EoL phases. In this recycling scenario, the use of recycled Pt as an input material for the manufacturing phase of a 55 kW PEMFC stack is considered to assess the environmental impact of the Pt REC processes in terms of the circular economy. The two Pt REC scenarios are:

- ***Strong close-loop Pt REC****:* This scenario includes a closed loop Pt recycling according to the existing Pt REC under the BEST4Hy project with the current Pt recovery efficiency at laboratory scale, which is 65.2% Pt recovered from aged PEMFC MEA. In this scenario, **65.2% recycled Pt** (existing BEST4Hy Pt REC) and **34.8% virgin Pt** are used to produce the new 55 kWel PEMFC reference stack.
- ***Semi close-loop Pt REC****:* This scenario includes the **Key Performance Indicator (KPI-2) for recycling Pt (target for 2024: 95% of** secondary Pt [14]), which is mentioned in the *"Strategic Research and Innovation Agenda 2021 - 2027" of the Clean Hydrogen Joint Undertaking* and is also one of the targets of the BEST4Hy project (95% of recycled Pt should be used to produce the new PEMFC stacks). In this scenario, **95% recycled Pt** (existing BEST4Hy Pt REC) and **5% virgin Pt** will be used to produce the new 55 kW_{el} PEMFC stack.

Other materials from PEMFC stack in EoL phase analysis within D5.1 are not considered, so only the impact of Pt recovery effect on manufacturing phase is presented.

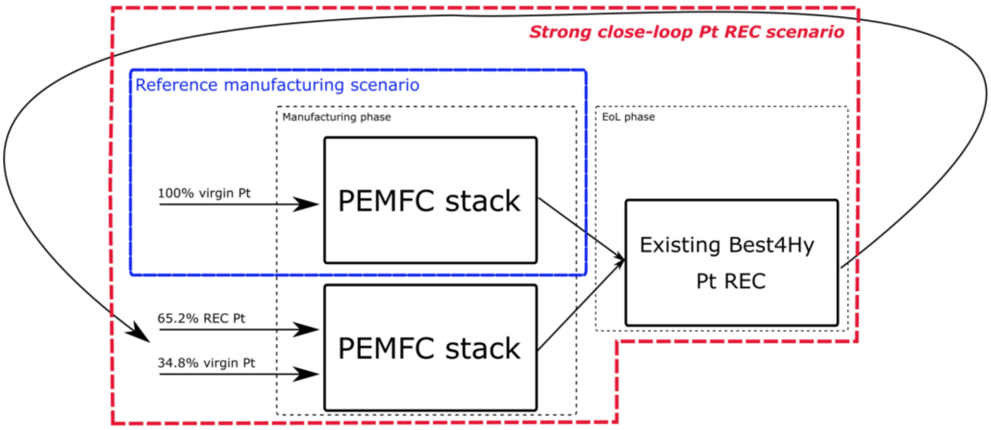

Figure 10: PEMFC strong close-loop Pt REC scenario.

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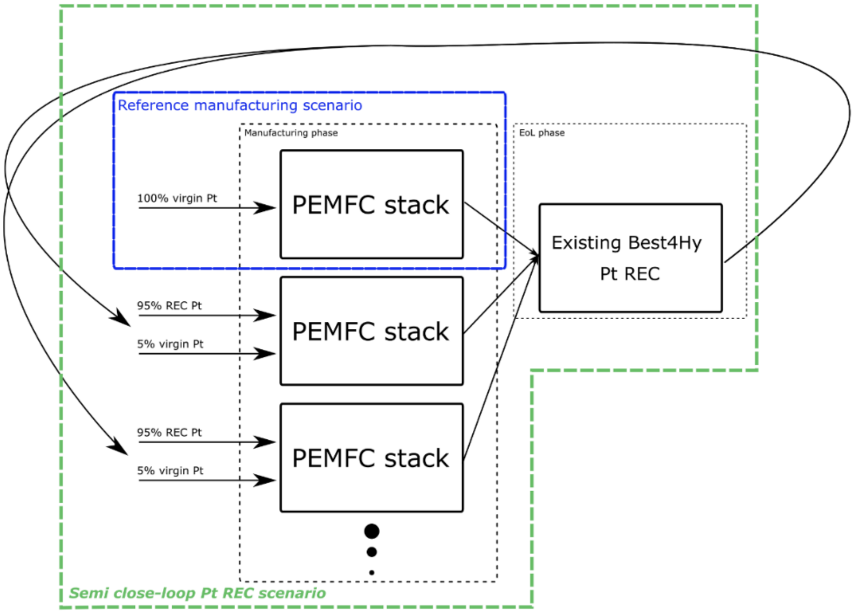

Figure 11: PEMFC semi close-loop Pt REC scenario.

2.3.2 SOFC case

This section describes the methodology and steps used to generate life cycle inventory (LCI) tables for material and energy flows for a 3 kW_{el} SOFC reference stack. Data were obtained from the SOFC technology manufacturer in the BEST4Hy consortium (Elcogen [8]) to create the LCI for the manufacturing phase. The main data for the LCI were provided in the form of the BoM, which was further analysed, and all mass and energy balances required for the LCI were properly defined for the manufacturing phase of the 3 kW_{el} SOFC stack.

In the second part of this section, yttria-stabilized zirconia (YSZ) and Nickel oxide (NiO) existing (BEST4Hy definition) recovery processes from EoL SOFC are analysed; finally, recovery of YSZ and NiO in the manufacturing of new SOFC is described in the third part of this section. Additional recovery process of NI-YSZ from scrap cells (which are results of waste flow during manufacturing phase of new SOFC cells) in the EoL phase was also analysed. In parallel to the PEMFC case, the SOFC material recovery processes developed within BEST4Hy project are to reach TRL5, while the data for this analysis were gathered from TRL3 (lab scale) processes. This means that small quantities are recovered, with processes, that are not optimised, and further limitations imposed by the availability of in-scale/dedicated equipment (e.g. calcination oven).

Since SOFC EoL processes and technology is still in its development phase (low TRL levels) and recycling processes and procedures are on lab. scale, the recovered materials have at this point higher impact on overall environmental results. These results will be essential to guide the TRL5 future development and highlight the activities with the larger impact.

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2.3.2.1 Manufacturing phase

The LCI for manufacturing phase is presented in Table 3, which was built based on BoM gathered from BEST4Hy Industry partner Elcogen for the manufacturing of a 3 kW_{el} SOFC stack. The main challenge in SOFC technology for the manufacturing phase is the **lack of generic LCI data** [20], [21], [22] so there are **still no available LCI databases for specific materials** in SOFC technology such as: yttria-stabilized zirconia (3YSZ, 8YSZ), gadolinium-doped ceria (20% GDC), strontium-doped lanthanum cobaltite (LSC64 - $La_{0.6}Sr_{0.4}CoO_3$), for which a simplified LCA models from basic materials/chemicals with additional input from BEST4Hy partners and literature data [13], [23] were made.

Table 3: LCI for manufacturing phase of the 3 kW_{el} SOFC stack

Component	Material	Unit	Mass (Avg.)	Used database
Anode support	NiO powder	g	1309	GLO, Nickel
Anode support	3YSZ	g	1309	RER, Yttria-stabilised zirconia
Anode contact	NiO powder	g	59.5	GLO, Nickel
Anode electrode	NiO powder	g	59.5	GLO, Nickel
Anode electrode	8YSZ	g	59.5	RER, Yttria-stabilised zirconia
Electrolyte	8YSZ	g	59.5	RER, Yttria-stabilised zirconia
Diffusion-layer barrier paste	Cerium gadolinium oxide	g	14.88	Cerium(IV) oxide-gadolinium doped
Cathode electrode paste	LSC64	g	89.25	Lanthanum Strontium Cobalt Ferrite
Cathode contact paste	LSC64	g	41.65	Lanthanum Strontium Cobalt Ferrite
Monopolar plate anode	Stainless steel	g	8775	Stainless steel Quarto plate (316)
Monopolar plate cathode	Stainless steel	g	8775	Stainless steel Quarto plate (316)
Cathode bipolar plate coating	MnxCoxO4	g	585	NA, Excluded
Top endplate	Stainless steel	g	3500	Stainless steel Quarto plate (316)
Current collector	Stainless steel	g	300	Stainless steel Quarto plate (316)
Bottom endplate	Stainless steel	g	3500	Stainless steel Quarto plate (316)
Springs	Steel	g	400	DE, EAF Steel billet/Slab/Bloom
Screws	Steel	g	600	DE: EAF Steel billet/Slab/Bloom
Fuel cell frame	Stainless steel	g	2500	Stainless steel Quarto plate (316)
Gaskets	Glass-ceramic, Phyllosilicates	g	6000	EU-28: Glass ceramic production
Energy (Man. processes)	Electricity	MJ	148.45	EU-28: Electricity grid mix Sphera

For YSZ the LCI and LCA model were made according to the literature [15], [16]. Furthermore, instead of NiO production Ni was used and instead of LSC64 the Lanthanum Strontium Cobalt Ferrite (LCSF) was used as substitute material for manufacturing phase. Energy needed for manufacturing process of each component was used from literature [17]–[19]. An example of the LCA model for 3YSZ production phase is presented in Figure 12.

Based on LCI (see Figure 4), the LCA model of the reference 3 kW_{el} SOFC stack for manufacturing phase was built in GaBi Sphera software presented in Figure 13, with all the main mass and energy (total) flows required for the manufacturing phase of a 3kW_{el} SOFC stack according to industry partner data Elcogen.

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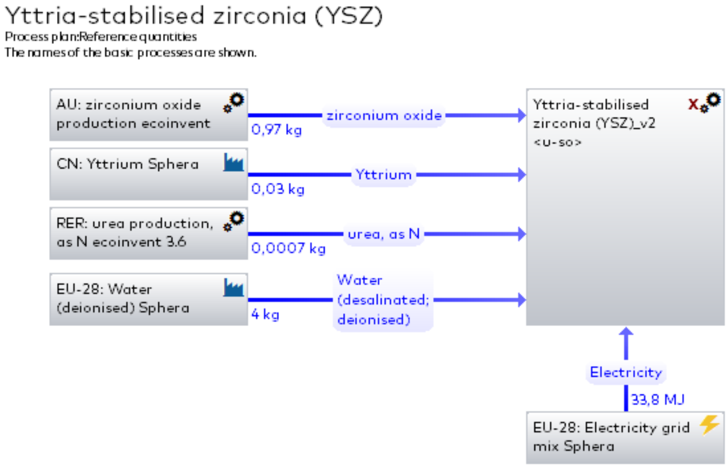

Figure 12 LCA model used for yttria-stabilized zirconia (3YSZ)

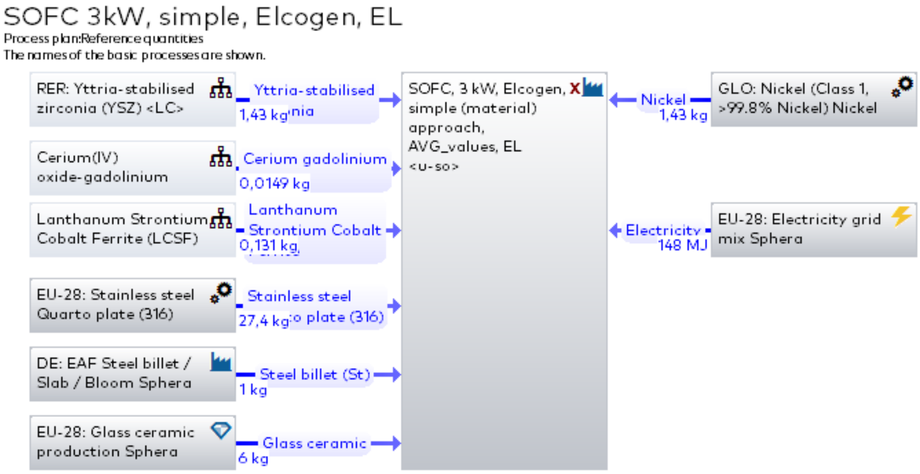

Figure 13 LCA model for manufacturing phase of the 3kW$_{el}$ SOFC stack

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2.3.2.2 Recovered materials based on existing EoL technology

Related to the objectives of BEST4Hy project, the focus of the EoL analysis is YSZ and NiO material within ''current/existing'' EoL recovery process from aged SOFC cells. Additionally, the recovery of SOFC scrap cells (NiO-YSZ powder) generated during SOFC manufacturing as waste from the Elcogen production process was also analysed. Hydrothermally-assisted (HT) recovery of yttria - stabilized zirconia (YSZ) processes (EoL) were developed in BEST4Hy project and detailed analysis with results was also published by partner Politecnico di Torino (POLITO, WP3) [24]. After HT recovery of YSZ the second phase the NiO recovery begins, also developed by POLITO (see Figure 14 below).

Existing BEST4Hy recovery technology for SOFC is described also in BEST4Hy deliverable ***D3.1 Technical report on adaptation and combination of two existing recovery technologies for SOFC,*** compiled by WP3 BEST4Hy partners: POLITO and Elcogen.

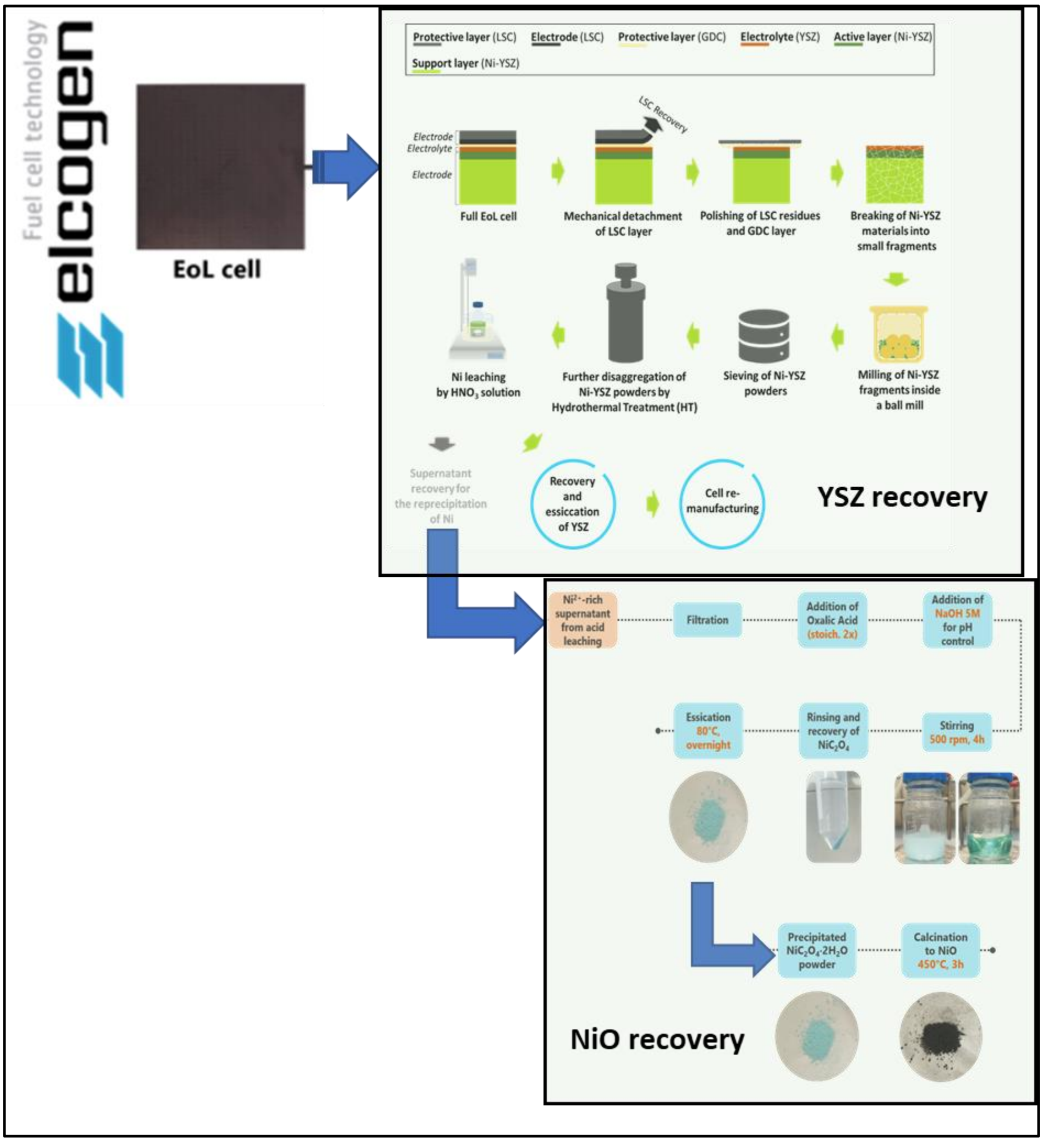

Figure 14 Existing SOFC EoL – YSZ and NiO recovery processes workflow

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SOFC EoL cells are first subjected to the LSC cathode detachment (step 1), then the anode components are milled and sieved below 25 µm (step 2), disaggregated by HT (step 3) and subsequently subjected to acid-leaching (step 4) to separate YSZ powder and nickel in the form of Ni^{2+} ions in the acidic leaching solution. YSZ materials obtained through this route are then recovered (step 5) and Ni is precipitated in the form of precursors (step 6).

Table 4: LCI table for 1g of YSZ recovery from aged SOFC cell (lab. scale)

Material /energy flow	Quantity	Unit	Used database
Inputs			
EoL SOFC cell	**2.50**	**g**	
Electricity	2.65	kWh	EU-28: Electricity grid mix Sphera
Water	205.81	g	EU-28: Water Sphera
HNO_3	24.23	g	DE: Nitric acid Sphera
Outputs			
Ni2+rich supernatant dissolved in HNO3	0.85	g	
YSZ	**1.00**	**g**	
sealant removal losses	0.24	g	
losses after cathode detachment	0.12	g	
losses after polishing	0.12	g	
Ni-YSZ losses	0.14	g	

Table 5: LCI table for 1g of NiO recovery from aged SOFC cell (lab. scale)

Material /energy flow	Quantity	Unit	Used database
Inputs			
EoL SOFC cell	**5.06**	**g**	
Electricity (all steps)	6.36	kWh	EU-28: Electricity grid mix Sphera
HNO_3	48.96	g	DE: Nitric acid Sphera
NaOH	9.61	g	EU-28: Sodium hydroxide mix Sphera
Outputs			
NiO	**1.00**	**g**	
YSZ	**2.02**	**g**	
sealant removal losses	0.48	g	
losses after cathode detachment	0.24	g	
losses after polishing	0.24	g	
Ni and YSZ loss	0.29	g	

After that, Ni2+ rich supernatant dissolved in HNO_3 is filtered (step 7) and precipitation process with Oxalic Acid and NaOH is made with stirring (step 8); after that, rinsing, recovery and drying (step 9) is done to obtain NiC_2O4*H_2O precipitated powder. The last step is calcination (step 10) to NiO. In Table 4 LCI table for reference output of 1g of the recovered YSZ is presented and in

Table 5 the LCI for reference output of 1g NiO is presented for laboratory scale EoL models. Workflow for existing SOFC EoL for YSZ and NiO recovery is presented on Figure 15 with main input mass flows and reference output - 1g of NiO.

The recovery efficiency (yield) of YSZ material from SOFC anode EoL is about 98% with respect to SOFC EoL cell input mass (100% input) and for Ni is about 83.5% for the first part (YSZ recovery) and the second part (NiO recovery) is approximately 46%.

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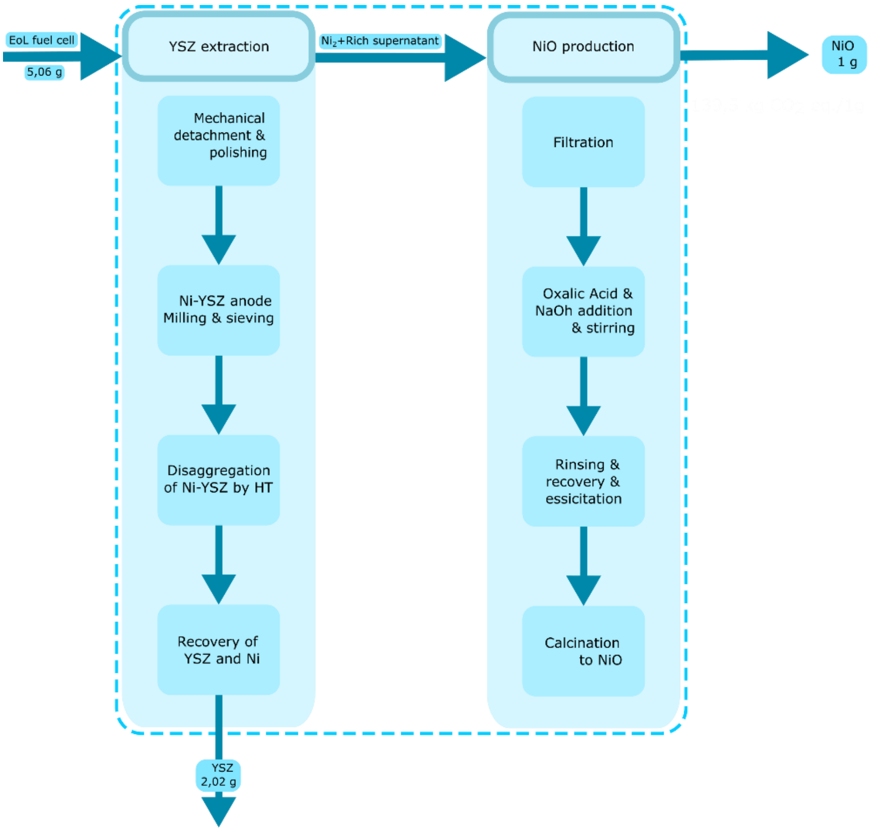

Figure 15 Existing SOFC EoL – YSZ and NiO main mass flows

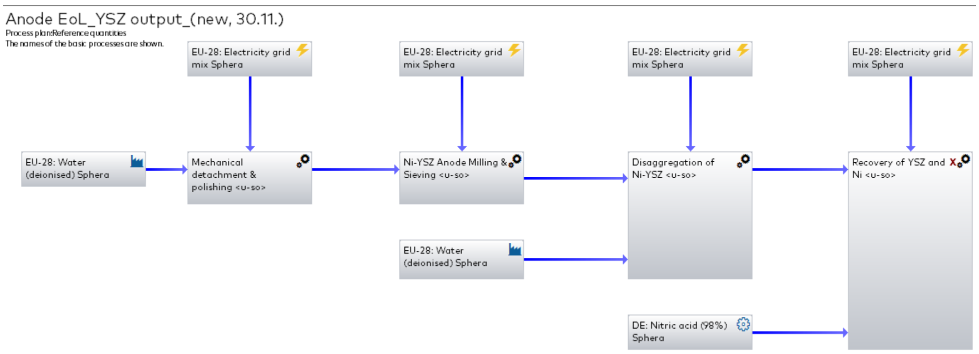

Figure 16 LCA model for YSZ recovery from aged SOFC anode

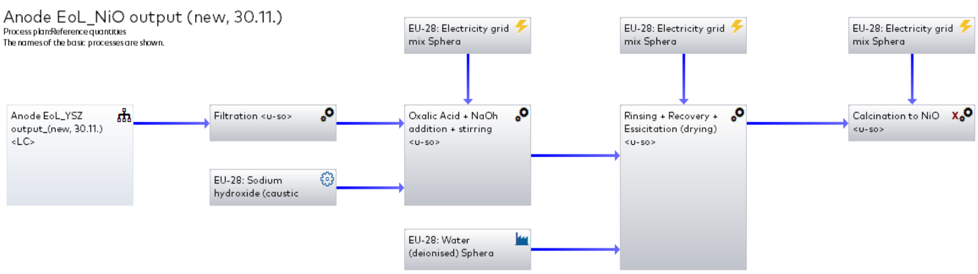

Figure 17 LCA model for NiO recovery from aged SOFC anode

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In addition, the analysis of the LCA study also considers the impact of recycling SOFC scrap cells in the EoL phase. The ***recycling of SOFC scrap cells (NiO-YSZ powder) generated during SOFC manufacturing*** is waste from the Elcogen production process.

The EoL process for scrap cells is a simple EoL process that involves mechanical crushing (milling) of SOFC scrap cells and sieving of the obtained powders, which must meet certain acceptance criteria (≤25 μm). The composite powder can be used directly for SOFC cell production without any further steps or processes (see Figure 21). At first three milling/sieving consecutive steps (see Figure 18) were applied for the scrap cells in order to maximize the amount of recovered powder with the appropriate specification in term of average particle size and specific surface area. However, due to the ratio of energy consumption vs obtained mass of the suitable powder, **only the first step allowed to recover a satisfactory amount of powder** (the second and third steps provided negligible amounts) and it is evaluated in this LCA study. **After the first milling step (10 hours of milling) and following sieving, 30 wt% (3.3 g) of suitable composite powder was obtained.** All mass and energy balances for the SOFC scrap cell EoL **(first step)** are shown in Figure 19.

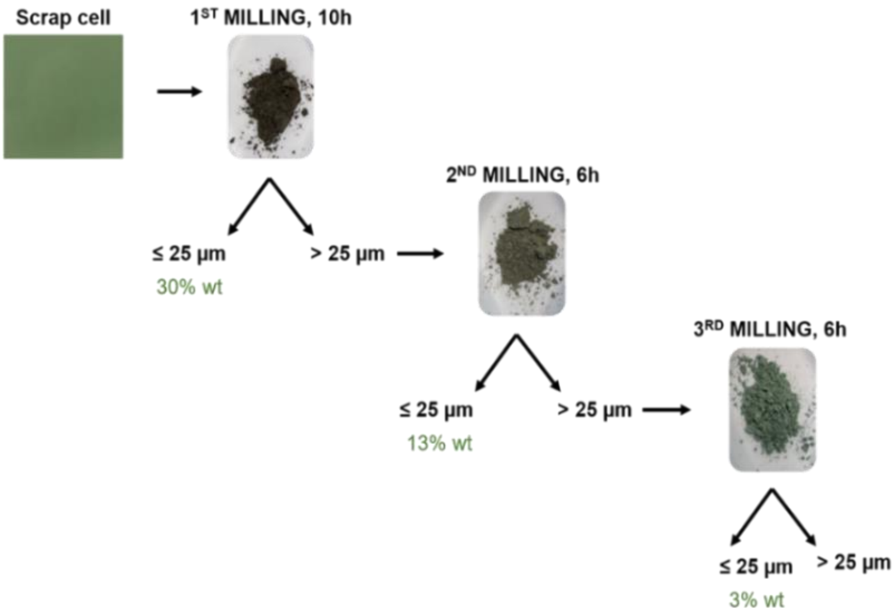

Figure 18 SOFC scrap cells EoL milling and sieving steps

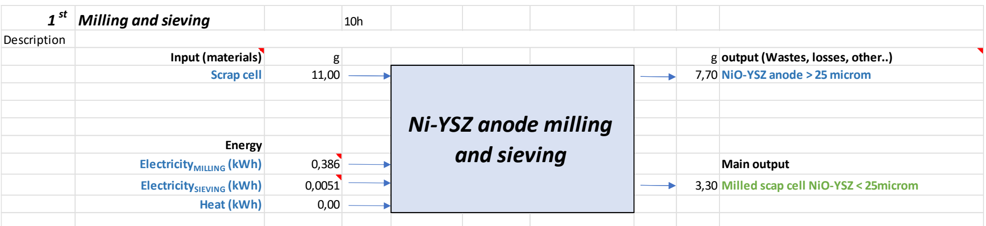

Figure 19 SOFC scrap cells EoL mass and energy balance for first step

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2.3.2.3 Manufacturing phase with recovered anode critical materials

For SOFC technology, BEST4Hy focuses on **YSZ** (medium material value and high criticality [13]) and **nickel** (NiO, hazardous, medium value, high criticality [13]) **on the anode side**, and **lanthanum and cobalt** (hazardous, medium value, high criticality [13]) on the cathode side, and aims to recover the following percentage in terms of new materials used (equivalent to 100%):

- >80% for YSZ and
- >80% Ni as NiO

In D5.1, the objective is to evaluate the environmental profile of BEST4Hy YSZ and NiO recovery (which is the focus of this LCA study for SOFC), thus the EoL phase in D5.1 focus on these two materials. Lanthanum and cobalt recovered from the cathode material will be analysed in future results as part of BEST4Hy's novel EoL technologies once all required recovery processes have been developed by BEST4Hy project partners.

Scenarios for SOFC in EoL phase for Ni and YSZ recovery considered in this study are:

- ***Close-loop (BEST4Hy)***: This scenario includes the CRM recycling performance indicator (KPI-1 [14]) mentioned in the Clean Hydrogen Joint Undertaking "Strategic Research and Innovation Agenda 2021 - 2027" (target for 2024: 30% secondary CRM [14]), which is also one of the targets of the BEST4Hy project - 30% of Ni (as NiO) and YSZ on the anode side should be used from the recycling process, based on the recovery of YSZ and NiO at laboratory scale. In this scenario, **30% of the recycled YSZ and NiO** (existing SOFC, anode side) is used with **70% virgin YSZ and NiO** to produce the reference 3 kWel SOFC stack.

- ***Semi close-loop (scrap cell REC)***: This scenario involves the recovery of SOFC scrap cells, a waste stream from the SOFC stack manufacturing process. The amount of scrap cells/waste stream should be reduced to 5% (105% gross material input) for the SOFC cell manufacturing process in the future (medium-term eco-design target of eGHOST EU project [25] for the manufacturing process of solid oxide cells). In this scenario, **5% NiO-YSZ from recovered scrap cells** and **95% virgin materials** are used to manufacture the new 3 kWel SOFC reference stack.

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2.4 Life cycle impact assessment (LCIA) methodology

The Environmental Footprint 3.0 (EF3.0) Life Cycle Impact Assessment (LCIA) method is used in this study, to assess environmental impact of reference FCH cases. Although EF3.0 is not commonly used for FCH technologies, the European Commission has proposed PEF (Product Environmental Footprint) and OEF (Organisation Environmental Footprint) as a common method for measuring environmental performance [26]. The overall purpose of PEF information is to enable the reduction of the environmental impact of goods and services, considering the activities in the supply chain (from raw material extraction to production, use, and waste disposal) [27].

The selection of environmental indicators follows the guidelines of one of the main documents for LCA of FCH technologies, the HyGuide [6], while the European Commission and the Joint Research Centre (JRC) have supported the EF3.0 methodology quite intensively in recent years. For this reason, the same LCIA methodology is also used in this document (D5.1) and in the ongoing EU project eGHOST [25].

The EF3.0 method includes 16 environmental impact indicators that could also provide good additional insight into the environmental impact of reference PEMFC and SOFC stack. The environmental indicators that we will discuss and analyse in this LCA study are presented in Table 6. They are chosen based on the literature reviewed [28], [29] and the recommendations of HyGuide [6].

Table 6: Environmental Footprint 3.0 impact categories used in LCA study

EF 3.0 impact category	Indicator	Unit	Recommended default LCIA method
Climate change	Global Warming Impact Potential (GWP)	kg CO_2 eq.	Baseline model of 100 years of the IPCC (based on IPCC 2013)
Acidification	Accumulated Exceedance (AE)	mol H+ eq.	Accumulated Exceedance
Eutrophication, Terrestrial	Accumulated Exceedance (AE)	mol N eq.	Accumulated Exceedance
Eutrophication, aquatic freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq.	EUTREND model as implemented in ReCiPe
Eutrophication, aquatic marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq.	EUTREND model as implemented in ReCiPe
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq.	CML
Resource use, energy carriers	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	CML

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3. Results and discussion

In this chapter results of the environmental LCA study are presented for both reference FCH technologies, included in the BEST4Hy project in the following order:

1) In the first part, the environmental impacts of the manufacturing phase are presented for reference 55 kW_{el} PEMFC stack and 3 kW_{el} SOFC stack,
2) then, in the second part, the environmental profile of existing BEST4Hy EoL processes are evaluated and presented,
3) and finally, the EoL phase is evaluated for targeted critical materials with effects in the manufacturing phase.

3.1 LCA results for PEMFC case

3.1.1 Manufacturing phase

In this section environmental impacts of the manufacturing phase are presented for the 55 kW_{el} PEMFC stack. Results are presented for the PEMFC stack manufacturing phase, with separate contributions to environmental impact for each component: Bipolar plates (BPP), Current Collectors (CC), Endplates, Gaskets, MEA and other. Also, electricity consumption for all manufacturing processes is included in the analysis.

Table 7: Absolute values of environmental indicators for 55 kW_{el} PEMFC stack manufacturing phase

	EF 3.0 Acidification [Mole of H+ eq.]	EF 3.0 Climate Change [kg CO_2 eq.]	EF 3.0 Eutrophication, freshwater [kg P eq.]	EF 3.0 Eutrophication, marine [kg N eq.]	EF 3.0 Eutrophication, terrestrial [Mole of N eq.]	EF 3.0 Resource use, fossils [MJ]	EF 3.0 Resource use, minerals and metals [kg Sb eq.]
Total PEMFC	2.63E+01	1.55E+03	5.00E-03	2.12E+00	2.33E+01	1.85E+04	4.48E-01
BPP	1.62E+00	2.20E+02	5.13E-04	4.29E-01	4.77E+00	2.65E+03	3.89E-01
Stainless steel	2.71E-01	3.66E+01	4.49E-05	3.57E-02	3.87E-01	4.74E+02	2.56E-03
Gold	1.35E+00	1.84E+02	4.68E-04	3.94E-01	4.38E+00	2.18E+03	3.86E-01
CC	1.46E-02	9.21E-01	1.56E-06	8.17E-04	8.52E-03	9.81E+00	6.53E-04
Endplates	2.16E-01	2.87E+01	6.07E-04	2.90E-02	3.16E-01	4.07E+02	2.40E-03
Endplate anode	1.18E-01	1.59E+01	3.06E-04	1.58E-02	1.73E-01	2.30E+02	1.28E-03
Endplate cathode	9.80E-02	1.28E+01	3.01E-04	1.32E-02	1.44E-01	1.78E+02	1.12E-03
Gaskets	5.32E-02	1.67E+01	3.00E-05	1.17E-02	1.26E-01	2.75E+02	3.22E-04
MEA	2.40E+01	1.12E+03	9.76E-05	1.57E+00	1.72E+01	1.19E+04	5.49E-02
Pt/C	2.40E+01	9.30E+02	8.64E-05	1.56E+00	1.71E+01	1.12E+04	5.49E-02
Nafion	2.49E-04	1.79E+02	1.76E-07	5.15E-05	5.71E-04	5.25E+02	3.59E-08
GDL	2.47E-02	1.10E+01	1.10E-05	1.04E-02	1.06E-01	2.13E+02	1.25E-06
Other total	2.32E-02	3.33E+00	3.18E-03	4.28E-03	4.66E-02	4.96E+01	9.26E-04
Nuts	3.92E-04	5.30E-02	6.51E-08	5.17E-05	5.61E-04	6.87E-01	3.71E-06
Rods	6.67E-03	9.01E-01	1.11E-06	8.79E-04	9.53E-03	1.17E+01	6.30E-05
Sensors	1.62E-02	2.38E+00	3.18E-03	3.34E-03	3.65E-02	3.72E+01	8.59E-04
Electricity	3.24E-01	1.55E+02	5.66E-04	7.75E-02	8.10E-01	3.19E+03	2.35E-05

Results are presented in Table 7, where the absolute values of EF3.0 environmental indicators are shown for acidification, climate change, eutrophication, and resources consumption applied to the 55 kW_{el} PEMFC stack manufacturing phase. Additionally, for a more detailed analysis, the relative contribution of each PEMFC stack components is shown in Table 8 with a hotspot identification (red color represents high, yellow medium and green low impact).

Table 8: Relative contribution of electricity consumption and components (materials) to the entire environmental impact of the 55 kW_{el} PEMFC stack manufacturing

	EF 3.0 Acidification [Mole of H+ eq.]	EF 3.0 Climate Change [kg CO_2 eq.]	EF 3.0 Eutrophication, freshwater [kg P eq.]	EF 3.0 Eutrophication, marine [kg N eq.]	EF 3.0 Eutrophication, terrestrial [Mole of N eq.]	EF 3.0 Resource use, fossils [MJ]	EF 3.0 Resource use, mineral and metals [kg Sb eq.]
PEMFC total	**26.27 (100%)**	**1546 (100%)**	**0.005 (100%)**	**2.124 (100%)**	**23.26 (100%)**	**18486 (100%)**	**0.448 (100%)**
BBP	6.2%	14.3%	10.3%	20.2%	20.5%	14.4%	86.8%
SS	1.0%	2.4%	0.9%	1.7%	1.7%	2.6%	0.6%
Gold	5.1%	11.9%	9.4%	18.5%	18.8%	11.8%	86.2%
CC	0.1%	0.1%	0.0%	0.0%	0.0%	0.1%	0.1%
Endplates	0.8%	1.9%	12.1%	1.4%	1.4%	2.2%	0.5%
Endplate anode	0.4%	1.0%	6.1%	0.7%	0.7%	1.2%	0.3%
Endplate cathode	0.4%	0.8%	6.0%	0.6%	0.6%	1.0%	0.3%
Gaskets	0.2%	1.1%	0.6%	0.5%	0.5%	1.5%	0.1%
MEA	91.4%	72.5%	2.0%	74.0%	73.9%	64.4%	12.3%
Pt/C	91.3%	60.2%	1.7%	73.5%	73.4%	60.4%	12.3%
Nafion	0.0%	11.6%	0.0%	0.0%	0.0%	2.8%	0.0%
GDL	0.1%	0.7%	0.2%	0.5%	0.5%	1.2%	0.0%
Other	0.1%	0.2%	63.7%	0.2%	0.2%	0.3%	0.2%
Nuts	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Rods	0.0%	0.1%	0.0%	0.0%	0.0%	0.1%	0.0%
Sensors	0.1%	0.2%	63.7%	0.2%	0.2%	0.2%	0.2%
Electricity	1.2%	10.0%	11.3%	3.6%	3.5%	17.3%	0.0%

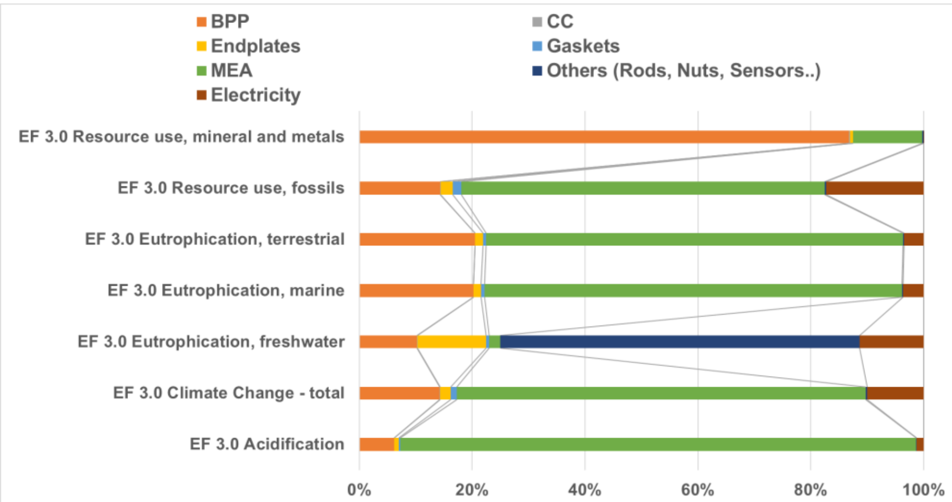

Figure 20 The main components and electricity contribution to the total environmental impact of the 55 kW_{el} PEMFC stack

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From results presented in Table 7, Table 8 and Figure 20, the summary and conclusions of the results for the manufacturing phase of the 55 kW_{el} PEMFC stack are:

- The total environmental impact for climate change indicator of the 55 kW_{el} PEMFC stack manufacturing is 1.545 kg CO_2eq. which is equal to 28.1 kgCO_2eq. per 1 kW_{el}.
- On average, for all analysed environmental impact indicators, the highest contribution to the environmental impacts of the 55 kW_{el} PEMFC stack comes from **MEA (5 out of 7)**, more precisely, from **Pt** which is the main hotspot for manufacturing phase (despite very low total mass share of Pt in the whole PEMFC stack (Table 1)), followed by **BPP** (mainly due to gold coating) and **electricity consumption**.
- MEA (Pt - which is a CRM in PEMFC) production has the highest contribution to the **climate change environmental indicator**, namely **MEA represents 72.5 %** (Pt/C - 60.2%, ionomer (Nafion) - 11.6%), BPP represents 14.3% (gold coating 11.9%) and electricity represents 10 % of total climate change impact.
- For the Resource use mineral and metals environmental indicator the highest impact comes from gold BPP coating (86.2 %) followed by Pt/C (12.3%).
- For the **Acidification environmental indicator** most of the impact comes from **Pt/C production (91.4%)** followed by **gold BPP coating (5.1%)**, electricity (1.4%) and stainless steel used for BPP (1.0%).
- Other PEMFC stack components and materials, more specifically **electronics and sensors** have the highest impact contribution to **freshwater eutrophication with 63.7%** followed by Endplates 12.1% (due to glass fibers reinforced plastic, which have high impact on freshwater eutrophication potential).

These results and assessment confirm the need for the PEMFC to work on reducing the use of virgin Pt and on increasing its permanence in the economic cycle through low impact recycling.

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3.1.2 Environmental profile of Pt recycling

In this chapter, the environmental profile of **the existing BEST4Hy EoL process at TRL3 for platinum recycling (Pt REC) from aged MEA** is evaluated for each EoL process for Pt recovery based on three main steps in the EoL phase: i) *Manual disassembly of MEA*, ii) *HMT process*, and iii) *Pt/C synthesis*. All mass and energy flows for each step are presented in Chapter 2.3.1.2. The main objective of this chapter is to **evaluate the environmental profile of existing laboratory scale Pt REC** and to identify the main hotspots. These hotspots might derive from the constraints implicit in the scale of the processes developed, from lack of suitable scale equipment to batch processing and small quantities dealt with. This analysis is in any case very useful to guide further development of the processes towards higher TRLs.

Table 9 shows the results in terms of total environmental impact of existing Pt REC in absolute values for each environmental indicator per 1 g of recovered Pt, based on the existing laboratory scale (TRL3) in BEST4Hy platinum recovery EoL processes. In addition, Table 9 includes the identification of hotspots for each subprocess with material and electricity consumption in a colored table (red represents high impact, yellow represents medium impact, and green represents low impact). From results presented in Table 9, and Figure 21, the summary and conclusions for existing BEST4Hy EoL Pt REC process (TRL3) are:

- The **highest contribution** to environmental impact of the existing Pt REC comes from the **Pt/C catalyst synthesis** with 68.1% on average for all impact indicators, followed by HMT process (20.4%) and MEA dismantling (6.3%) with the lowest contribution to total environmental impact, as expected.
- **Pt/C synthesis process has 5 out of 7 highest environmental indicators**, except for Eutrophication (freshwater) and Resources use (minerals and metals) indicators for which the main impacts come from HMT process, more exactly from ammonium chloride production used for precipitation and filtration step. Ammonium chloride production is overall the main hotspot for HMT process.
- The main hotspot for high environmental impact of **Pt/C catalyst synthesis is electricity** (FR grid mix) consumed for **filtration and drying step** (to obtain dry catalyst powder), whose share in the overall impact on environmental indicators is from 17.6% for Eutrophication, freshwater to 82.2% for Resources use, fossil.
- The total climate change indicator is **6.22 kg CO_2eq. per 1g of recovered Pt**, of which 11 % comes from MEA disassembly (DE electricity grid mix), 10.5 % from the HMT process, and 78.5 % from Pt/C catalyst synthesis. Similar relative contributions for main steps are also Acidification and Eutrophication (terrestrial) impact indicator.

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Table 9: Environmental impact indicator results of Pt REC EoL process per 1g of recovered Pt with relative contribution of each step of the existing BEST4Hy Pt REC EoL

	EF 3.0 Acidification [Mole of H+ eq.]	EF 3.0 Climate Change [kg CO_2 eq.]	EF 3.0 Eutrophication, freshwater [kg P eq.]	EF 3.0 Eutrophication, Marine [kg N eq.]	EF 3.0 Eutrophication, Terrestrial [Mole of N eq.]	EF 3.0 Resource use, Fossils [MJ]	EF 3.0 Resource use, mineral and metals [kg Sb eq.]
Total (Existing Pt REC)	**0.0144 (100%)**	**6.22 (100%)**	**1E-04 (100%)**	**0.0056 (100%)**	**0.043 (100%)**	**512 (100%)**	**5.4E-06 (100%)**
Total MEA disassembly	**7.1%**	**11.0%**	**3.5%**	**5.9%**	**8.1%**	**1.8%**	**2.3%**
DE: Electricity (Disassembly)	7.1%	11.0%	3.5%	5.9%	8.1%	1.8%	2.3%
Total HMT process	**12.3%**	**10.5%**	**58.8%**	**27.9%**	**11.1%**	**1.8%**	**61.2%**
DE: Electricity (Leaching)	1.0%	1.6%	0.5%	0.9%	1.2%	0.3%	0.3%
DE: Hydrochloric acid (Leaching)	0.6%	0.7%	0.2%	0.5%	0.7%	0.1%	0.1%
DE: Nitric acid (Leaching)	0.2%	0.4%	0.0%	0.4%	0.4%	0.1%	0.1%
DE: Electricity (Separation/Filtration)	1.1%	1.7%	0.5%	0.9%	1.2%	0.3%	0.3%
DE: Electricity (Precipitation + Filtration)	1.7%	2.7%	0.8%	1.4%	2.0%	0.4%	0.6%
DE: HCl (Precipitation + Filtration)	0.1%	0.1%	0.0%	0.1%	0.1%	0.0%	0.0%
GLO: NH_4Cl (Precipitation + Filtration)	7.6%	3.4%	56.7%	23.7%	5.5%	0.6%	59.7%
Total Pt/C synthesis	**80.6%**	**78.5%**	**37.7%**	**66.2%**	**80.8%**	**96.4%**	**36.5%**
DE: Carbon black (Impregnation)	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
EU-28: Ethylene glycol (Impregnation)	7.1%	7.2%	5.6%	4.1%	5.9%	2.4%	0.1%
FR: Electricity (Impregnation)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
FR: Electricity (Reduction Polyol synthesis)	8.8%	8.6%	2.5%	7.0%	9.0%	11.5%	2.9%
GLO: Ammonium chloride (Reduction polyol synthesis)	1.6%	0.7%	11.8%	4.9%	1.2%	0.1%	12.5%
RER: Sodium hydroxide (Reduction polyol synthesis)	0.2%	0.2%	0.1%	0.2%	0.3%	0.1%	0.0%
FR: Electricity (Filtration + drying)	62.8%	61.7%	17.6%	49.9%	64.4%	82.2%	21.0%

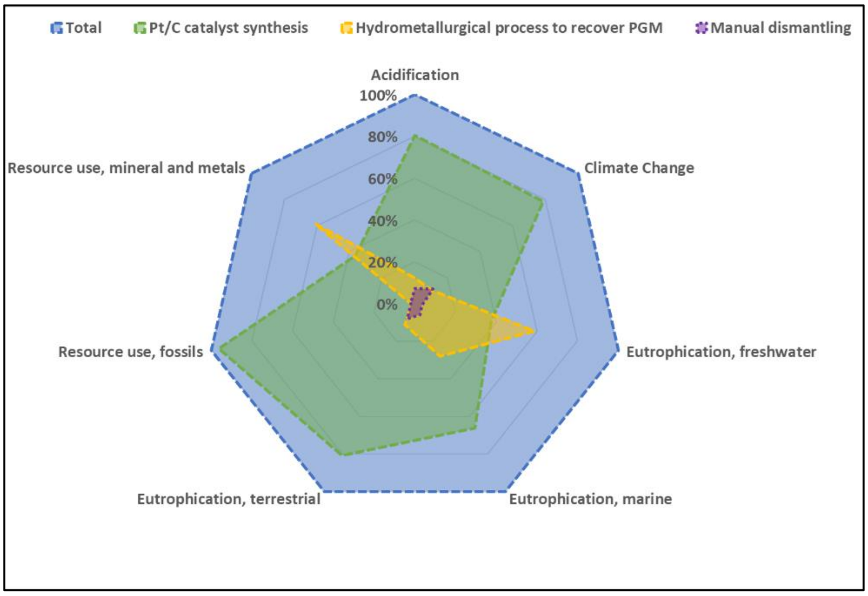

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Figure 21 The main Pt recycling EoL steps contribution to the total environmental profile of the existing BEST4Hy Pt recycling

To benchmark BEST4Hy existing Pt REC, a comparison of the environmental indicator climate change [kg CO_2 eq.] for 1g of Pt obtained by different routes was done. For virgin Pt, the two most used LCI databases (Ecoinvent and Gabi professional) were used to compare the climate change environmental impact for production of virgin Pt. In addition, virgin Pt used in automotive catalysts provided by International Platinum Association (IPA [30]), was also included and compared with other routes for Pt. It must be stressed that the above data are derived from fully industrialised process, hence the comparison is purely indicative given that the BEST4Hy processes are only lab scale. From the results can be seen that the existing laboratory scale BEST4Hy Pt REC shows quite promising results regarding climate change indicator.

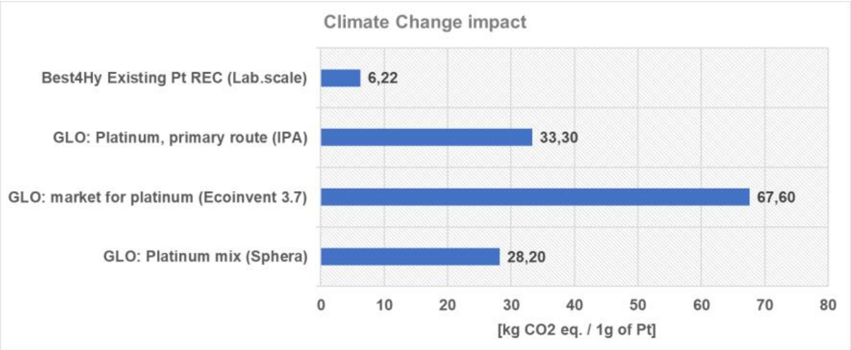

Figure 22 Comparison of climate change impacts for different Pt routes and databases

Nevertheless, the existing lab-scale Pt REC process (TRL3) has 6.22 $kgCO_2eq.$ per 1 g of obtained secondary Pt, which represents 81% lower climate change impact compared to virgin Pt (IPA), which has 33.3 $kgCO_2eq.$ per 1 g of Pt. Based on environmental profile of existing laboratory scale Pt REC process, the upscaling of the EoL processes (also beyond BEST4Hy project, which will achieve TRL5) should pursue lower energy and material consumption, and where possible guaranteed green electricity source for this EoL processes.

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3.1.3 Pt recycling effects on manufacturing phase

This chapter evaluates the impact of the recycling of the materials recovered through the existing BEST4Hy processes on the manufacturing phase in the context of the circular economy. In addition to the data presented in 2.3.1.2 and 2.3.1.3, it must be remarked that the focus is only on Pt as the most important critical material in PEMFC stacks identified previous projects and in the BEST4Hy project. In the manufacturing phase of the reference PEMFC stack with recycled Pt, the following two scenarios are considered:

i) Strong close-loop Pt REC (65.2% REC Pt, 34.8% virgin Pt - Figure 23) and

ii) Semi close-loop Pt REC (95% REC Pt, 5% virgin Pt).

Avoided environmental impacts in manufacturing phase comes from secondary Pt (with included EoL phase impacts), which substitutes virgin Pt.

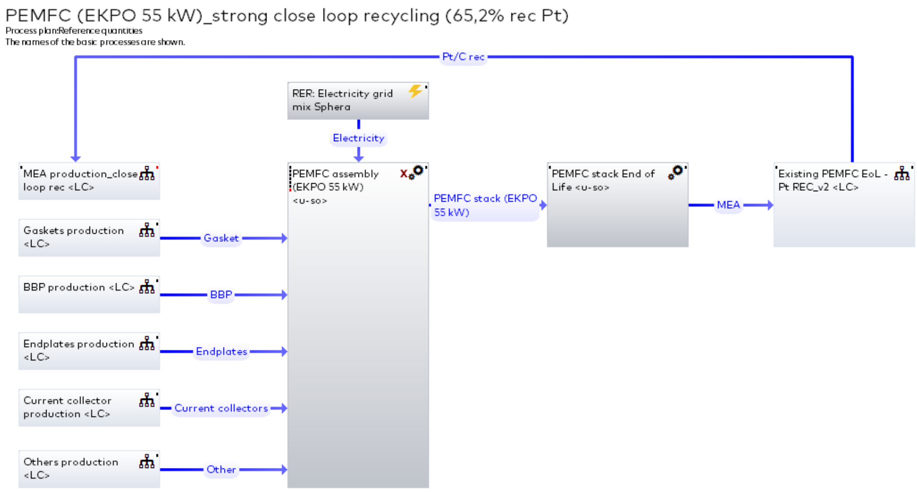

Figure 23: Strong close-loop LCA model for existing Pt recycling.

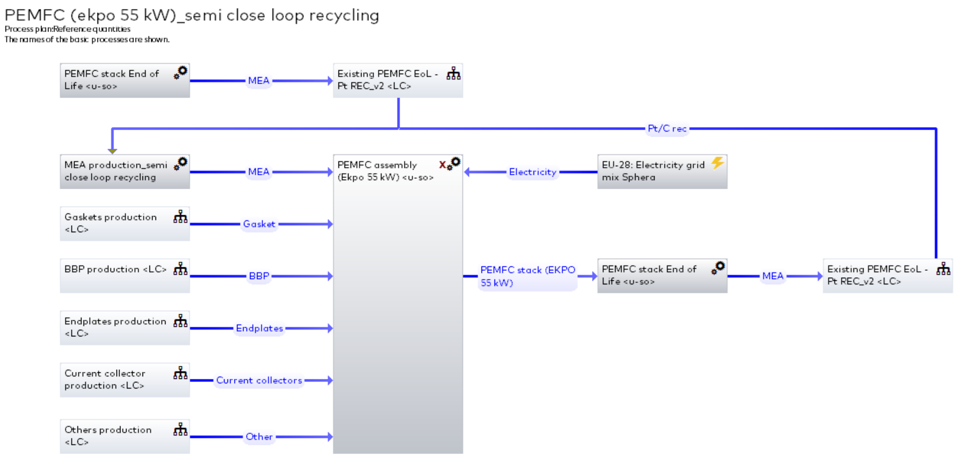

Figure 24: Semi close-loop LCA model for existing Pt recycling.

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Results for all environmental impact indicators are presented in Table 10, where absolute values are shown for the reference manufacturing phase and for each EoL scenario (Manufacturing phase + EoL phase (two Pt REC EoL scenarios)). These results are based on the TRL3 recovery processes hence some of the evaluations are a direct consequence of the limitations highlighted before. In Figure 25 the effect of EoL scenarios as described in the previous chapters is presented. After the manufacturing phase of the reference PEMFC stack case, the value of environmental indicators is set to 100 % as reference. Each EoL scenario is then normalized and compared to the reference manufacturing case presented for each environmental impact indicator.

Table 10: Total absolute values for environmental impact indicators of the 55 kW PEMFC stack manufacturing phase compared with three Pt recycling EoL scenarios

	Reference Man. PEMFC case	**Strong close-loop Pt REC**	**Semi close-loop Pt REC**
EF 3.0 Acidification [Mole of H+ eq.]	26.27	10.69	3.89
EF 3.0 Climate Change - total [kg CO_2 eq.]	1546	1056	844
EF 3.0 Eutrophication, freshwater [kg P eq.]	0.0050	0.0072	0.0083
EF 3.0 Eutrophication, marine [kg N eq.]	2.12	1.21	0.81
EF 3.0 Eutrophication, terrestrial [Mole of N eq.]	23.26	12.83	8.29
EF 3.0 Resource use, fossils [MJ]	18486	21397	22878
EF 3.0 Resource use, mineral and metals [kg Sb eq.]	0.45	0.41	0.40

From results presented in Table 10, Figure 25 and Figure 26 the summary and conclusions for environmental effects of EoL phase scenarios in the scope of circular economy in manufacturing phase of PEMFC stack are:

- The average environmental impact reduction for **strong close-loop** Pt REC for all environmental impact indicators is **18.1 %** and for **Semi close-loop** Pt REC the reduction is **25.6 %**.
- The highest reduction of environmental impact indicator is in case of Acidification, where the reduction for strong close-loop Pt REC is 59.3 % and for semi close-loop Pt REC is 85.2%.
- On the other hand, there are **increase in environmental impact** in the case of **Eutrophication (freshwater)** and **Resource use (fossil)** for both scenarios**.** The main impact for Eutrophication (freshwater) comes from **ammonium chloride production (NH_4Cl)** used for **precipitation step (HMT process)** and for Resource use (fossil) comes from **FR electricity grid mix** used for **filtration/drying of the Pt/C powder.**
- For the **climate change indicator**, the **31.7% reduction** is achieved for **strong close-loop** Pt REC, which corresponds to a reduction of **490 kg$CO_{2eq.}$ per one reference PEMFC stack**. For **semi close-loop** Pt REC a 45.4 % reduction could be achieved which corresponds to a reduction of **702 kg$CO_{2eq.}$ per one reference PEMFC stack**.

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- The climate change indicator, which is the most used in official EU documents, is for the reference PEMFC case 28.1 $kgCO_{2eq.}/kW_{el}$, for strong close-loop Pt REC is 19.2 $kgCO_{2eq.}/kW_{el}$ and for semi close-loop Pt REC is 15.3 $kgCO_{2eq.}/kW_{el}$.

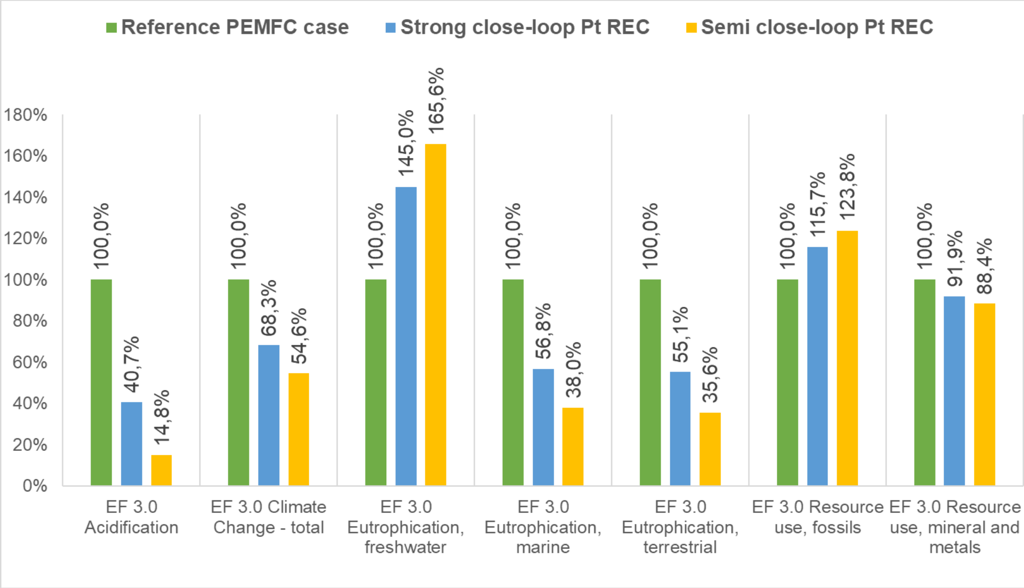

Figure 25: The relative effect and comparison of existing BEST4Hy EoL technologies (Pt REC) with different EoL scenarios for the manufacturing phase of 55 kW PEMFC stack.

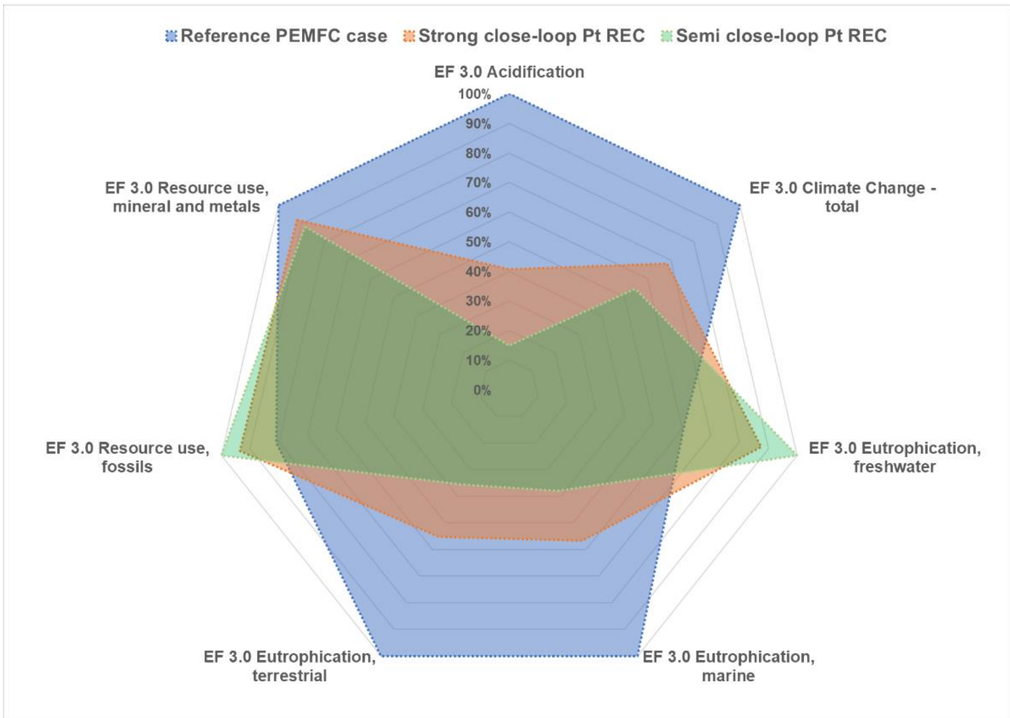

Figure 26: The relative comparison of different EoL scenarios (Pt recycling) effect on manufacturing phase of 55 kW PEMFC stack

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3.2 LCA results for SOFC case

3.2.1 Manufacturing phase

In this section environmental impacts of the manufacturing phase are presented for the reference 3 kW_{el} SOFC stack, with the limitations presented in 2.3.2. Results are presented for SOFC stack manufacturing phase, with separate contribution to environmental impact for each component: Anode (support layer, active layer and contact), Electrolyte, Barrier layer, Cathode, BPP, Endplates, Current Collectors (CC), Gaskets, Fuel cell frame, Other (springs, screws) and energy in the form of electricity used for production processes.

Results are presented in Table 11, where the absolute values of EF3.0 environmental indicators are shown for acidification, climate change, eutrophication, and resources use for 3 kW_{el} SOFC stack manufacturing phase. Additionally, for a more detailed analysis the relative contribution of each SOFC stack component is shown as a hotspot identification (red color represents high, yellow medium and green low impact to the total environmental impact indicator.).

Table 11: Absolute values of environmental indicators for 3 kWel SOFC stack manufacturing phase with relative contribution of each component/energy to total environmental impact

	EF 3.0 Acidification [Mole of H+ eq.]	**EF 3.0 Climate Change [kg CO_2 eq.]**	**EF 3.0 Eutrophication, freshwater [kg P eq.]**	**EF 3.0 Eutrophication, marine [kg N eq.]**	**EF 3.0 Eutrophication, terrestrial [Mole of N eq.]**	**EF 3.0 Resource use, fossils [MJ]**	**EF 3.0 Resource use, mineral and metals [kg Sb eq.]**
3 kWel SOFC stack total	**3.11 (100%)**	**146 (100%)**	**0.00397 (100%)**	**0.152 (100%)**	**1.57 (100%)**	**2090 (100%)**	**0.0047 (100%)**
Anode	66.7%	20.5%	65.2%	19.2%	19.5%	22.1%	6.3%
Anode support layer	61.2%	19.1%	62.3%	17.9%	18.2%	20.6%	5.9%
NiO	59.5%	11.6%	0.9%	11.5%	11.7%	12.4%	3.6%
YSZ	1.6%	7.6%	61.4%	6.4%	6.5%	8.2%	2.3%
Anode active layer	2.8%	0.9%	2.8%	0.8%	0.8%	0.9%	0.3%
NiO	2.7%	0.5%	0.0%	0.5%	0.5%	0.6%	0.2%
YSZ	0.1%	0.3%	2.8%	0.3%	0.3%	0.4%	0.1%
Anode contact	2.7%	0.5%	0.0%	0.5%	0.5%	0.6%	0.2%
Electrolyte (YSZ)	0.1%	0.3%	2.8%	0.3%	0.3%	0.4%	0.1%
Protective/barrier-layer (Cerium gadolinium oxide)	0.1%	0.2%	0.0%	0.2%	0.2%	0.2%	0.0%
Cathode (LCSF)	0.3%	0.7%	2.9%	0.8%	0.7%	0.7%	0.4%
BPP (SS)	18.9%	35.9%	1.5%	32.9%	35.6%	32.9%	53.4%
Endplates (SS)	7.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Current collectors (SS)	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Gaskets	2.5%	11.5%	25.7%	23.2%	18.8%	12.0%	10.0%
Fuel cell frame (SS)	2.7%	5.1%	0.2%	4.7%	5.1%	4.7%	7.6%
Other (springs, screws)	0.0%	0.3%	0.0%	0.2%	0.2%	0.2%	0.0%
Electricity (EU-28)	1.1%	10.5%	1.1%	4.9%	5.0%	13.2%	0.1%

From results presented in Table 11 and Figure 27 the summary and conclusions for environmental impact of the 3 kW_{el} SOFC stack manufacturing phase are:

- On average, for all analysed environmental impact indicators the highest contribution to the total environmental impacts of the 3 kW_{el} SOFC stack comes

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from **BPP** (5 out of 7), mainly due to the **high mass of stainless steel** (46.3% total mass share) and **anode (**2 out of 7**)**, due to the **anode support layer** (Ni-YSZ), followed by **gaskets** and **electricity consumption.**

- The total value for **climate change indicator** of the 3 kW_{el} SOFC stack manufacturing phase is **146 kg CO_2eq.,** which is equal to **48.66 $kgCO_2$eq. per 1 kW_{el}.** The highest contribution is from **bipolar plates (BPP)** representing 35.9%, followed by anode (20.5%), gaskets (11.5%) and electricity (10.5%).
- For the **Acidification** environmental indicator, the highest impact comes from **anode (66.7%)**, more precisely **NiO in anode support layer** contributing the most with 59.5%, follows **BPP with 18.9%** and **endplates with 7.5%.**
- For the Resource use, the highest share of the impact comes from BPP (53.4% for minerals and metals and 32.9% for fossils) followed by anode, gaskets and electricity.
- For **Eutrophication, freshwater** environmental indicator the highest impact comes from **anode (65.2%)**, more precisely **YSZ in anode support layer** contributing the most with 61.4%, Following **gaskets with 25.7%**. For the **Eutrophication, marine and terrestrial** environmental indicators the highest contribution comes from **BPP**, following **gaskets, anode** and FC frame with similar contribution as electricity.

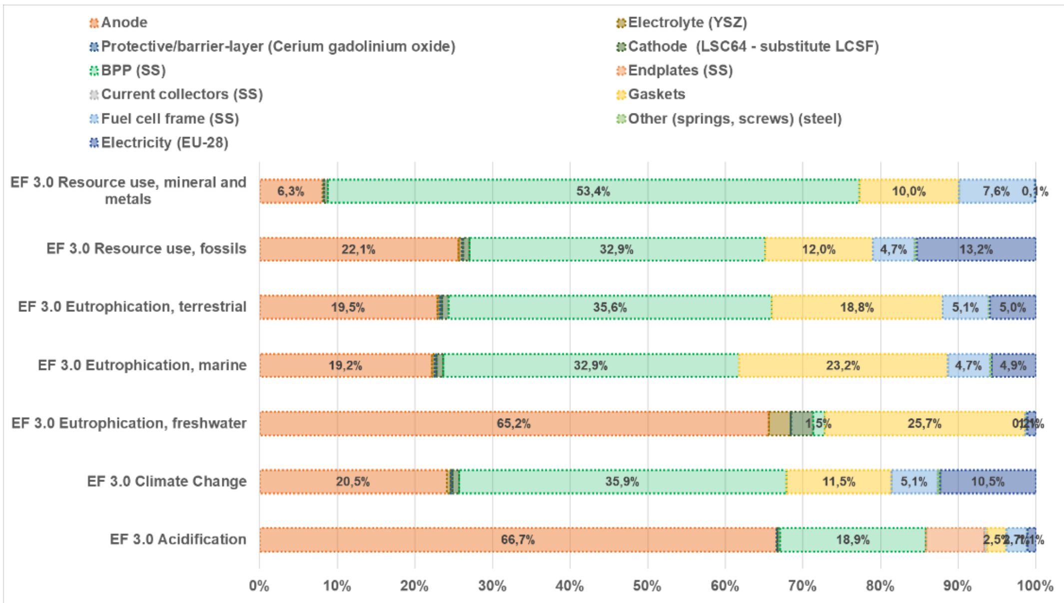

Figure 27: The relative contribution of each SOFC stack component and electricity to the total environmental impact of 3kW$_{el}$ SOFC stack

The environmental impact results presented for the manufacturing phase of the SOFC reference stack are based on an approximate (estimated) LCI datasets for virgin materials (explained in chapter 2.3.2), for which no general or detailed LCI datasets are available, so further development and updates on LCI datasets are needed in the future.

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3.2.2 Environmental profile of recovered materials

In this chapter, the environmental profile of existing BEST4Hy EoL technologies for SOFC technology, focused on YSZ and NiO recycling from aged SOFC cells, was evaluated for each recycling/recovery process in the EoL phase. The main steps and processes have been described in detail in chapter 2.3.2.2 of this document. The main objective of this chapter is to evaluate the environmental profile of the lab scale EoL processes for the recovery of YSZ and NiO materials, and to identify their main hotspots, bearing in mind the limitations deriving from the scale of the processes as explained above.

Table 12 shows the results for the total environmental impact of the TRL3 EoL phase for recovering YSZ from aged SOFC cells in absolute values for each environmental indicator per 1 g of recovered YSZ based on BEST4Hy developed EoL processes by POLITO [24]. In addition, hotspot identifications for each EoL subprocess with material and electricity consumption are included in a colored table in Table 12 (red for high impact, yellow for medium impact, and green for low impact). The same approach for analyzing the environmental profile of the EoL phase was used for NiO recovery, with YSZ (2.02 g) recovered in the first step for every 1 g of NiO. The results for the total environmental impact per 1 g of NiO recovered from aged SOFC cells are shown in Table 13, where the absolute total values for all environmental impact indicators used in this LCA study with hotspot analysis of each EoL sub-process are presented.

Table 12: Environmental impact indicator results for 1g of recovered YSZ from aged SOFC cell with relative contribution of each EoL phase step

	EF 3.0 Acidification [Mole of H+ eq.]	EF 3.0 Climate Change [kg CO_2 eq.]	EF 3.0 Eutrophication, freshwater [kg P eq.]	EF 3.0 Eutrophication, marine [kg N eq.]	EF 3.0 Eutrophication, terrestrial [Mole of N eq.]	EF 3.0 Resource use, fossils [MJ]	EF 3.0 Resource use, mineral and metals [kg Sb eq.]
Total YSZ (1g)	**0.00185 (100%)**	**0.894 (100%)**	**3.23E-06 (100%)**	**4.57E-04 (100%)**	**4.7E-03 (100%)**	**18.23 (100%)**	**1.38E-07 (100%)**
Mechanical detachment (total)	0.8%	0.8%	1.0%	0.7%	0.8%	0.8%	0.7%
EU-28: Water (deionised) (Mechanical detachment)	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%
EU-28: Electricity grid mix (Mechanical detachment)	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%
Milling & Sieving (total)	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%
EU-28: Electricity grid mix (Milling & Sieving)	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%
Disaggregation (total)	74.8%	74.3%	75.2%	72.5%	73.8%	74.9%	72.6%
EU-28: Water (deionised) (Disaggregation)	0.0%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%
EU-28: Electricity grid mix (Disaggregation)	74.8%	74.2%	74.9%	72.5%	73.8%	74.9%	72.6%
Recovery (total)	22.8%	23.4%	22.2%	25.2%	23.9%	22.7%	25.1%
EU-28: Electricity grid mix (Recovery)	21.4%	21.3%	21.5%	20.8%	21.2%	21.5%	20.8%
DE: Nitric acid (Recovery)	1.4%	2.1%	0.7%	4.4%	2.7%	1.2%	4.3%

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Table 13: Environmental impact indicator results for 1g of recovered NiO with relative contribution of each EoL phase step

	EF 3.0 Acidification [Mole of H+ eq.]	EF 3.0 Climate Change [kg CO_2 eq.]	EF 3.0 Eutrophication, freshwater [kg P eq.]	EF 3.0 Eutrophication, marine [kg N eq.]	EF 3.0 Eutrophication, terrestrial [Mole of N eq.]	EF 3.0 Resource use, fossils [MJ]	EF 3.0 Resource use, mineral and metals [kg Sb eq.]
Total NiO (1g)	**0.00443 (100%)**	**2.134 (100%)**	**7.8E-06 (100%)**	**0.00109 (100%)**	**0.0112 (100%)**	**43.56 (100%)**	**3.3E-07 (100%)**
YSZ (2.02g) - total	84.1%	84.3%	83.2%	84.4%	84.2%	84.2%	84.7%
Mechanical Detachment (total)	0.6%	0.6%	0.8%	0.6%	0.6%	0.6%	0.6%
EU-28: Water (deionised) (Mechanical detachment)	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%
EU-28: Electricity grid mix (Mechanical detachment)	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%
Milling & Sieving (total)	1.4%	1.4%	1.4%	1.3%	1.4%	1.4%	1.3%
EU-28: Electricity grid mix (Milling & Sieving)	1.4%	1.4%	1.4%	1.3%	1.4%	1.4%	1.3%
Disaggregation (total)	62.9%	62.6%	62.5%	61.2%	62.1%	63.1%	61.5%
EU-28: Water (deionised) (Disaggregation)	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%
EU-28: Electricity grid mix (Disaggregation)	62.9%	62.6%	62.3%	61.2%	62.1%	63.1%	61.5%
Recovery (total)	19.2%	19.7%	18.5%	21.3%	20.1%	19.1%	21.2%
EU-28: Electricity grid mix (Recovery)	18.0%	18.0%	17.9%	17.6%	17.8%	18.1%	17.6%
DE: Nitric acid (98%) (Recovery)	1.2%	1.7%	0.6%	3.7%	2.3%	1.0%	3.6%
NaOH addition +stirring (total)	15.7%	15.5%	15.5%	15.3%	15.6%	15.6%	15.1%
EU-28: Sodium hydroxide (NaOH addition + stirring)	15.3%	15.2%	15.1%	14.8%	15.1%	15.3%	14.9%
EU-28: Electricity grid mix (NaOH addition + stirring)	0.4%	0.4%	0.4%	0.5%	0.5%	0.3%	0.2%
Rinsing, Recovery, Drying (total)	0.1%	0.1%	1.2%	0.2%	0.2%	0.1%	0.1%
EU-28: Electricity grid mix (Rinsing, Recovery, Drying)	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
EU-28: Water (deionised) (Rinsing, Recovery, Drying)	0.1%	0.1%	1.2%	0.1%	0.1%	0.1%	0.1%
Calcination (total)	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
EU-28: Electricity grid mix (Calcination)	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%

From the results presented in Table 12 and Table 13, the following conclusions can be drawn for the TRL3 BEST4Hy EoL technologies to recover YSZ and NiO from aged SOFC cells:

- For YSZ and NiO EoL processes the highest impact comes from **electricity** used for **disaggregation of Ni-YSZ with hydrothermal treatment**.
- The highest contribution (main hotspot) to the total environmental impact of **YSZ recovery** comes from the **disaggregation of Ni-YSZ with hydrothermal treatment** (electricity) with an average **74% for all impact indicators**, followed by the **recovery process (23.6%)** and mechanical separation of LSC layer (0.8%) with the lowest contribution to the total environmental impact of YSZ recovery.
- For **NiO recovery**, the **first part** (YSZ recovery) accounts **for 84.2%** of all environmental impact indicators on average, followed by NaOH addition with

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stirring, which accounts for 15.5% of the total environmental impact indicators on average of NiO recovery.

- The total **climate change indicator** value is **0.894 kg CO_2eq. per 1g of recovered YSZ**, for which 74.3% comes from disaggregation step, 23.4% from recovery step, 1.6% from milling and sieving step, while mechanical detachment represents only 0.8% of total climate change indicator. Similar relative contributions for main YSZ recovery steps are also for other environmental impact indicators.
- The total **climate change indicator** value is **2.134 kg CO_2eq. per 1g of recovered NiO**, for which 62.6% comes from disaggregation step, 19.7% from recovery step and 15.5% from NaOH addition step of total climate change indicator. Similar relative contributions for NiO recovery main steps are also for other environmental impact indicators.

Comparison of the results of **recovered YSZ, NiO versus virgin YSZ, NiO** is not possible at this stage of development because this **EoL process was developed at laboratory scale for the recovery of 1 g of recovered material (YSZ and NiO)** and additionally the LCI datasets for virgin REE, CRM used for SOFC technology are **not complete and should be updated**. Scaling up to TRL5 of the recovery process is currently being investigated as part of the BEST4Hy project.

In addition, Table 14 presents the results for the environmental profile of the laboratory scale scrap cell EoL (first milling/sieving step).

Table 14: Environmental results for 1g of recovered Ni-YSZ from scrap SOFC cells

	1st step
Acidification [Mole of H+ eq.]	3.17E-04
Climate Change - total [kg CO_2 eq.]	1.46E-01
Eutrophication, freshwater [kg P eq.]	4.21E-07
Eutrophication, marine [kg N eq.]	7.10E-05
Eutrophication, terrestrial [Mole of N eq.]	7.45E-04
Resource use, fossils [MJ]	2.62E+00
Resource use, mineral and metals [kg Sb eq.]	3.94E-08

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3.2.3 Recovered anode materials effect on manufacturing phase

This chapter presents the scenarios of recycling YSZ and NiO from aged SOFC cells and scrap cells with BEST4Hy processes into new cells according to a circular economy approach. In addition to the information presented in Sections 2.3.2.2 and 2.3.2.3, the following comments and limitations are:

- The focus of this LCA study is **only on the anode side** of the SOFC stack for the recovery of YSZ and NiO (TRL3) identified in the BEST4Hy project.
- In the EoL phase, only the impact of recycled YSZ or NiO vs. virgin is considered for the close-loop scenario (BEST4Hy target **- 30% recycled YSZ and NiO with 70% of virgin YSZ and NiO**).
- For the second scenario, the semi-close-loop scenario (scrap cell REC), only the EoL of scrap cells is considered, i.e., 5% NiO-YSZ from recovered scrap cells and 95% from virgin materials.

No EoL scenarios in the context of the circular economy are analysed for the SOFC stack at this stage of development (TRL3). BEST4Hy project partners are seeking better LCI datasets for virgin materials and evaluating hotspots of EoL processes at TRL3 level for scale-up to TRL5. As it turned out during the BEST4Hy project, the detailed life cycle inventories (LCI) are not available for virgin materials used for SOFC production (REE, CRM), which are also at industrial scale (high TRL), so these reasons mainly contribute to the lack of environmental impact analysis of recovered materials (YSZ, NiO) in the context of the circular economy at this stage of development. The main conclusion for SOFC EoL at this stage is that laboratory scale EoL processes for recovery of NiO and YSZ should be updated, and further research and development should be conducted.

BEST4Hy project partners are planning further updates and developments:

- EoL processes for YSZ and NiO recovery with capabilities for upscaling SOFC anode EoL processes (higher TRL levels and EoL process optimization) and
- LCI datasets for new material production (REE, CRM) with focus on YSZ, NiO and LSC.

Based on further BEST4Hy updates and results, an update of this D5.1 will be done by the end of the BEST4Hy project.

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4. Conclusions

The main objective of D5.1 was to perform an environmental LCA study for two FCH technologies considered in the EU BEST4Hy project, namely a 55 kW_{el} PEMFC stack and a 3 kW_{el} SOFC stack. For these two cases, the environmental profile for the manufacturing phase was calculated, which serves as a basis for further analysis of existing EoL technologies in the context of the circular economy.

In addition, the environmental profile of existing EoL processes was defined for platinum recycling (Pt REC) in the context of PEMFC technology. There are no existing EoL processes for SOFC technology, but as defined in the BEST4Hy project, two material recovery processes were also included in this deliverable, namely yttria-stabilised zirconia (YSZ) and nickel oxide (NiO) recovered from the aged anode side of the SOFC cell. In addition, Ni-YSZ recovery from SOFC scrap cells was also analysed. All processes are being developed at TRL5 by the BEST4Hy project partners which contributed through numerous iterations, meetings, and updates to create a new life cycle inventory datasets and finally the LCA models for each EoL process with data available at TRL3 phase of development.

LCA models were created using Gabi Sphera software with integrated generic databases Gabi Professional and Ecoinvent. Some processes and materials for which data were not available were additionally modelled based on LCI from the literature by other authors with additional input from BEST4Hy partners. The scope of the study was cradle to grave with a focus on the manufacturing and end-of-life phase (the operational phase was excluded), as the focus was to demonstrate the impact of existing BEST4Hy EoL technologies for certain critical materials in the context of the circular economy in the manufacturing phase of FCH technologies. The main objective of this work was to present the environmental profile of EoL processes for the recovery of Pt in the case of PEMFC and YSZ, NiO in the case of SOFC.

The results for PEMFC show that recovered Pt has a climate change impact of 6.22 $kgCO_2eq./g$: this is very good, despite the lower TRL of the recycling process and it compares favourably with the impact of the virgin Pt (33.3 $kgCO_2eq./g$). In the context of the circular economy, Pt recycling based on existing EoL technology shows promising results in the two closed-loop scenarios analysed, including one with BEST4Hy targets.

The main conclusion for SOFC is that the lab-scale EoL processes for NiO and YSZ recovery provide good insight into the environmental impact indicators, and the lab-scale analysis was developed to identify critical steps for transitioning to upscaling (TRL5) of these EoL processes. These impacts will be carefully studied to identify hotspots that should be effectively considered in scaling up the SOFC EoL process.

BEST4Hy project partners are working to upscale to TRL5 the processes and provide further updates to the LCI. It is also hoped that more reliable LCI datasets for production of virgin SOFC materials (REE, CRM) would become available before the end of the project.

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