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

# Deliverable D5.2

## LCA and LCC impacts of novel EoL technologies and ecolabelling of FCH products

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# Abbreviations

| | |
|---|---|
| BoM | Bill of Materials |
| BPP | Bipolar Plate |
| CRMs | Critical raw materials |
| EoL | End-of-Life |
| FCH | Fuel Cells and Hydrogen technologies |
| FCs | Fuel Cells |
| FU | Functional unit |
| HMT | Hydrometallurgical Process |
| HRD | Hensel Recycling Deutschland |
| IRR | Internal Rate of Return |
| KO | Key Outcome related to BEST4Hy goals |
| LC | Levelized Cost |
| LCA | Life Cycle Assessment |
| LCC | Life Cycle Cost |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| LPR | Low Pressure Reactor process (sub-process in AD process) |
| LSC | Lanthanum Strontium Cobaltite |
| LSC64 | Lanthanum Strontium-doped Cobaltite ($La_{0.6}Sr_{0.4}CoO_3$) |
| MEA | Membrane Electrode Assembly |
| NPV | Net Present Value |
| PEMFC | Proton Exchange Membrane Fuel Cell |
| Pt | Platinum |
| QI | Quality Indicator |
| REC | Recycling |
| SOFCs | Solid Oxide Fuel Cells |
| TRLs | Technology readiness levels |
| WP | Work Package |

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# 1 Executive Summary


Within Work Package 5 (WP5), which is under the leadership of University of Ljubljana (UL) with collaboration of all BEST4Hy EU project partners, Deliverable D5.2, focuses on *environmental life cycle assessment (LCA) and life cycle cost (LCC) impacts of novel End-of-Life (EoL) technologies,* which also serve as additional input for *ecolabelling of FCH products*, thus presenting the results of the second part of the BEST4Hy project with important work done and interaction between all work packages.

The first part of D5.2 is an environmental LCA (E-LCA) study for novel recycling technologies developed within the BEST4Hy EU project for PEMFC and SOFC technology, focusing on critical/precious/strategic and rare earth materials, i.e., platinum and ionomer for PEMFC and lanthanum and cobalt for SOFC. For **PEMFC, two newly developed recycling processes** are analysed at TRL5 level, namely the Alcohol dissolution (AD) process for platinum and ionomer recycling, which is applicable for closed-loop FCH recycling, and the electrochemical metallic platinum recovery process, for open-loop options. In the case of SOFC technology, a novel recycling process at TRL3 level is presented **for the recovery of lanthanum and cobalt from the cathode side of the EoL SOFC** cell via nitric acid route.

The second part of the report presents the methodology developed to assess the life cycle costs (LCC) of FCH recycling technologies (EoL). As part of the LCC assessment, the newly developed LCC model, which was tested on a hydrometallurgical (HMT) process for Pt recovery from the PEMFC stack as Pt salt, is described in detail and contains all important inputs for the economic assessment of FCH technologies. The LCC model enables the quantification and assessment of the feasibility of investments in the recycling process of FCH technology. The LCC model was validated, and the results are presented using a case study for the HMT-Pt recovery process of BEST4Hy, as relatively good data (cash flows) were available from the recycling industry partner within BEST4Hy (HRD) at TRL 5 (highest level in BEST4Hy). The results presented are based on a set of input data reflecting the current situation on the market and in the recycling industry, and the model also allows for testing or simulation of different possible scenarios. The results based on this set of input data show very promising results regarding the economic perspective of managing EoL FCH technologies for the recycling industry.

At the end of this public deliverable 5.2, the summary of all newly developed life cycle inventories developed within BEST4Hy projects is presented with additional valuable information for all LCA experts and analysts of FCH technologies.


**Life cycle inventories (LCI), LCA models and LCC model developed within BEST4Hy**

*It should be noted that all LCI, LCA and LCC models are based on laboratory-scale processes (low TRL levels: SOFC at TRL 3 and PEMFC at TRL 5) and are still in the development phase, which must be considered when interpreting the results on the environmental and economic impact of these technologies or using available primary data in LCA assessments. Nevertheless, the results presented in this D5.2 provide very good and essential inputs for FCH technologies for further development and optimization of LCI, LCA and LCC models!*

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# 2 Introduction

This document *D5.2: LCA and LCC impacts of novel EoL technologies and ecolabelling of FCH products* is a deliverable of project BEST4Hy, which has the main objective of bringing to TRL5 recycling technologies adapted or developed specifically for the recovery of valuable materials from EoL or scrap fuel cell and hydrogen (FCH) technologies. The project focused specifically on recovery of critical raw materials (CRMs) including PGMs, rare earth elements, cobalt and nickel from PEMFC and SOFC waste stacks, and evaluated the use of such materials in new cells (close loop recycling) or other applications (open loop recycling). To ensure the sustainability of the recovery processes and recycling with minimal impact on the environment and to strengthen the circular economy approach while making these technologies economically attractive, an environmental and economic life cycle analysis (E-LCA, LCC) of valuable materials recycling from SOFC and PEMFC technologies was carried out as part of BEST4Hy project in WP5.

In the context of the main objectives of the project, this report D5.2 presents an environmental impact assessment of novel recycling processes in the context of BEST4Hy Key Outcomes 4 and 5 (KO4 & KO5). Two novel EoL technologies for the recovery of Pt and ionomer in PEMFC technology are addressed: **Pt and ionomer recovery with an alcohol dissolution (AD) process (TRL5)** and **Pt recovery with an electrochemical process (TRL 5)**. In the case of SOFC technology, this report describes a novel EoL process, namely the recovery of **lanthanum** (rare earth and expensive metal) and **cobalt** (critical raw material) from EoL SOFC cathodes (LSC) via **nitric acid route recovery (TRL 3)** in the form of lanthanum oxide ($La_2O_3$) and cobalt oxide ($Co_3O_4$).

For Pt and ionomer recovery technologies, the main inputs and data were provided by the BEST4Hy project partners from WP1 (CEA, HRD, EKPO and IDO-Lab), who developed and optimized the processes at TRL5 level. For the EoL PEMFC stack, the goal of the BEST4Hy project was to recover at least 80% of the Pt content using a hydrometallurgical process (HTM - described in D5.1 [1] and D1.2 [2], related to KO1), while the newly developed alcohol dissolution process (AD) was expected to recover at least 90% of the Pt and more than 80% of the ionomer for closed-loop scenarios (related to KO2). Finally, with the electrochemical Pt recovery process (electroleaching and electrodeposition) developed and patented by CEA, a yield of more than 95 % was expected to be achieved in one step for the recovery of Pt (in metallic form) in open loop scenarios. The data presented in this D5.2 for novel PEMFC EoL technologies are described in detail in the BEST4Hy project reports: *D1.1: Lab scale optimization results on the 3 PEMFC recycling technologies report (PU)* [3]*, D1.3 Technical report on novel recycling technologies development and validation (MEA gaseous phase dismantling; Platinum electroleaching and electrodeposition) at CEA (CO), D1.4: Technical report on the design of novel technologies (alcohol dissolution) at HRD/IDO-Lab (CO)* [4] and *Deliverable D1.5: Pilot-scale plant (TRL5) based on 3 recycling technologies for PEMFCs (PU).*

For La and Co recovery, the main inputs and data for the analysis were provided by the BEST4Hy project partners from WP4 (POLITO, Elcogen). The data for the SOFC cathode EoL are described in detail in the BEST4Hy project reports: *D4.2 Technical report on developed recovery technologies for LSC cathode materials (CO),* public light version *D4.3 Technical report on developed recovery technologies for LSC cathode materials by*

*POLITO* [5] and *D4.4 Technical report on lab-scale validation of developed recovery technology for LSC cathode materials.*

At this point, we need to be aware that novel EoL processes and all life cycle inventories (LCI) used for E-LCA and LCC are at a relatively low TRL level (TRL3-TRL5), especially for SOFC technology, and this should be considered when interpreting the results. Nevertheless, this report represents a significant advance in terms of developing and understanding recycling processes for FCH technologies, especially for the development of LCI for LCA practitioners, **and highlights the hotspots for EoL management** and processing of FCH technologies, paving the way for a wider application of circular economy for the recovery of critical materials from FCH technologies and their recycling in close an open loop scenario.

Furthermore, a very important progress in the economic assessment of recycling technologies for FCH technologies has been achieved within the BEST4Hy project: a new innovative **model for the calculation of the life cycle cost (LCC)** of a materials recovery process from EoL FCH technologies has been developed and presented through a case study based on the HMT recovery of Pt, covering from the dismantling of PEMFC stacks up to the obtainment of Pt salt. The HMT process was used as sufficient data and relevant inputs from BEST4Hy industrial partners (HRD, IDO-Lab) are available. This LCC model can be extrapolated and used for other treatment technologies of EoL FCH devices if sufficient data is available over the whole product value chain system for upscaled recovery technologies (higher TRL levels within the whole value chain).

The findings of this report D5.2 and the overview of EoL processes will also be used to identify challenges and improve ecolabel certification (connected with BEST4Hy D5.3 and WP6).

The Deliverable 5.2 is structured as follows:

- **Chapter 1** gives a short overview of the D5.2.
- **Chapter 2** provides introduction and role of the WP5 related to the BEST4Hy objectives and defines LCA and LCC study of BEST4Hy novel EoL technologies.
- **Chapter 3** presents the LCA methodology used and boundary conditions for environmental impact assessment of BEST4Hy novel EoL technologies.
- **Chapter 4** presents the LCC methodology and boundary conditions.
- **Chapter 5** presents the result of environmental LCA study of BEST4Hy novel EoL technologies and the results of LCC study.
- **Chapter 6** summarises the conclusions and findings of LCA and LCC studies.
- **Chapter 7** summarises the references used in this report.

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# 3 Environmental impact assessment of novel end of life technologies

The methodological approach used for environmental impact assessment in this document D5.2 is the same as in previous BEST4Hy report within work package 5 (WP5), *D5.1 "Environmental profile of existing EoL technologies and effects in the scope of circular economy in the manufacturing phase"* [1], i.e., Life Cycle Assessment (LCA) methodology, based on ISO 14040 [6] and 14044 [7] standards, International Reference Life Cycle Data (ILCD) [8] system guidelines and guidance documents for performing LCA on FCH technologies by FC-HyGuide [9], [10].

Based on BEST4Hy goals and work done within WP5, the environmental impact assessment is presented in this document for novel recycling technologies (BEST4Hy novel EoL) for two reference FCH products: proton exchange membrane fuel cell (PEMFC) and solid oxide fuel cell (SOFC) waste stack, focusing on **platinum and ionomer recovery from EoL PEMFC stack** and on **lanthanum and cobalt recovery from EoL SOFC stack**.

## 3.1 Goal and scope

The main objective of this environmental LCA study is to assess the environmental impact of novel recycling technologies developed within the BEST4Hy project, focusing on critical key materials in PEMFC and SOFC stacks. For PEMFC technology, the environmental LCA study was conducted for the following materials:

- **Platinum** (as Pt salt) and **ionomer recovery** with **alcohol dissolution (AD) process** for closed-loop recycling at **TRL 5** and
- **Platinum** (metallic Pt) recovered by an **electrochemical process (electroleaching and electrodeposition)** for open loop recycling at **TRL 5**.

In the case of SOFC technology, the environmental LCA study was carried out for the following critical materials:

- **Lanthanum and cobalt recovery** (lanthanum oxide ($La_2O_3$) and cobalt oxide ($Co_3O_4$)) from SOFC waste cathode cells via **nitric acid route** at **TRL 3**.

The scope of the environmental LCA study for all three novel recycling technologies is *"gate-to-gate"*, so that only the recovery processes and material flows (from extraction of raw materials to end of material production) in the EoL phase of the PEMFC and SOFC waste stacks are assessed, without additional treatment of waste flows. The boundary conditions of the environmental LCA study are described in the next chapter.

### 3.1.1 Novel EoL technologies for EoL PEMFC stack recovery

#### Alcohol dissolution (AD) process

The ***functional unit*** for the platinum and ionomer recovery (from EoL PEMFC stack) with **alcohol dissolution (AD) process** is ***55.71g of Pt ink solution and 1g of recovered ionomer***. The Pt ink solution is further process **via Existing BEST4Hy HMT process**

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**(TRL5)** to obtain **Pt salt** (for close loop recycling), which can be used as the precursor for manufacturing of a new CCM. The **physical and methodological boundaries** of the AD process are:

- Functional unit: **1g of recovered ionomer and 55.71g of Pt ink solution**.
- Scope: From ''**gate to gate''** (EoL phase of PEMFC stack with Pt (as Pt salt) and ionomer recovery)**.**
- Life Cycle Inventory (LCI): **materials and processes** used are provided by **project partners within the BEST4Hy project**.
- LCIA Method: **Environmental footprint 3.0** (EF 3.0), focus on target environmental impact indicators (D5.1).
- Software environment used for LCA modelling: **LCA for experts Sphera software**.
- Generic databases used: **Gabi professional** [11] and **Ecoinvent** [12].

### Electrochemical metallic Pt recovery process

The ***functional unit*** for the platinum recovery (from EoL PEMFC stack) with **electrochemical process (electroleaching and electrodeposition process),** which is also the reference flow in the LCA model, is ***1g of recovered metallic Pt*** on GDL ***(TRL5)***. The **physical and methodological boundaries** for LCA study of Pt electrochemical process are:

- Functional unit: **1g of recovered metallic Pt** for open loop.
- Scope: From ''**gate to gate''** (EoL phase of EoL PEMFC stack with metallic Pt**.**
- Life Cycle Inventory (LCI): **materials and processes** used are provided by **project partners within the BEST4Hy project**.
- LCIA Method: **Environmental footprint 3.0** (EF 3.0) focus on target environmental impact indicators (D5.1).
- Software environment used for LCA modelling: **LCA for experts Sphera software**.
- Generic databases used: **Gabi professional** [11] and **Ecoinvent** [12].

## 3.1.2 Novel EoL technologies for EoL SOFC stack recovery

The ***functional unit*** for SOFC case with nitric acid route recovery of EoL SOFC cells, which is also the reference flow in the LCA model, is ***1g of recovered cobalt oxide ($Co_3O_4$)*** at ***TRL3***. The **physical and methodological boundaries** LCA study of the SOFC cathode recovery with nitric acid route recovery are:

- Functional unit: ***1g of recovered cobalt oxide ($Co_3O_4$)*** and **1.36 g of recovered Lanthanum oxide ($La_2O_3$).**
- Scope: From ''**gate to gate''** (EoL phase of EoL SOFC stack with cobalt oxide $Co_3O_4$ and Lanthanum oxide ($La_2O_3$) recovery)**.**
- Life Cycle Inventory (LCI): **materials and processes** used are provided by **project partners within BEST4Hy project**.
- Life Cycle Impact Assessment (LCIA): **Environmental footprint 3.0** (EF 3.0) focus on target environmental impact indicators (D5.1).
- Software environment used for LCA modelling: **LCA for experts Sphera software**.
- Generic databases used: **Gabi professional** and **Ecoinvent** [12].

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## 3.2 Life cycle inventory analysis

In this chapter, life cycle inventories (LCI) for all three novel BEST4Hy EoL processes with main mass and energy balances are presented and described in detail.

### 3.2.1 Pt and ionomer recovery from EoL PEMFC stack

***Alcohol dissolution process (AD process)***

As already described in BEST4Hy D1.1 [3] and D1.4 [4], the development of the highly efficient (>80%) ionomer and Pt recovery process by Hensel Recycling Deutschland and IDO-Lab with an alcohol dissolution (AD) process is a very important goal of the BEST4Hy project.

The AD process consists of an alcohol dissolution in a high temperature and high-pressure autoclave reactor fed with CCM from a PEMFC waste stack in an alcohol/water mixture, followed by a two-stage centrifugation step to separate the ionomer solution from the Pt ink, and finally a vacuum filtration to filter the ionomer solution to ensure high quality of the ionomer and avoid any particles in the solution. After that the water/ethanol is evaporated (can be reused) and the main product of this process is the recovered ionomer. Pt ink solution is then treated with the HMT process developed and described in D5.1 [1] and D1.2 [2], to obtain Pt salt with recycled Pt. All main steps are shown in Figure 1.

*Table 1: Life cycle inventory for BEST4Hy AD process (TRL5)*

| Material/energy flow | Quantity | Unit | Database used |
|---|---|---|---|
| **INPUTS for AD** | | | |
| **CCM from EoL PEMFC** | **1.42** | **g** | |
| Ethanol | 11.21 | g | DE: Ethanol (96%), Sphera |
| Water | 72.34 | g | RER: Water (deionised), Sphera |
| Electricity (low pressure reactor) | 0.26 | kWh | DE: Electricity grid mix Sphera |
| Electricity (2-step centrifugation) | 0.82 | kWh | DE: Electricity grid mix Sphera |
| Electricity vacuum pump | 0.00045 | kWh | DE: Electricity grid mix Sphera |
| Energy for evaporation | 0.02 | kWh | DE: Electricity grid mix Sphera |
| **OUTPUTS from AD** | | | |
| **Recovered ionomer** | **1.00** | **g** | |
| **Pt ink solution** | **55.71** | **g** | |
| Evaporated ethanol and water | 28.27 | g | |

Based on the energy and mass balances (Table 1) for the AD process (with 1 g ionomer output), the LCA model for the AD process (see Figure 1) was created in the LCA for experts Sphera software. The main input in the model is CCM from the PEMFC waste stack (1.42 g) and the main outputs of the novel BEST4Hy AD process are 1 g of recovered ionomer and 55.71 g of Pt ink solution.

The Pt ink solution is then further processed in the BEST4Hy HMT process (TRL5), from which we obtain Pt salt with recycled Pt (see Figure 1). According to the efficiencies of the BEST4Hy TRL5 EoL process (D5.1 [1] and D1.2 [2]), 524.22 g of Pt ink solution is required to obtain 1 g of Pt salt, and at the same time, 9.41 g of recovered ionomer is obtained as a by-product of the AD process.

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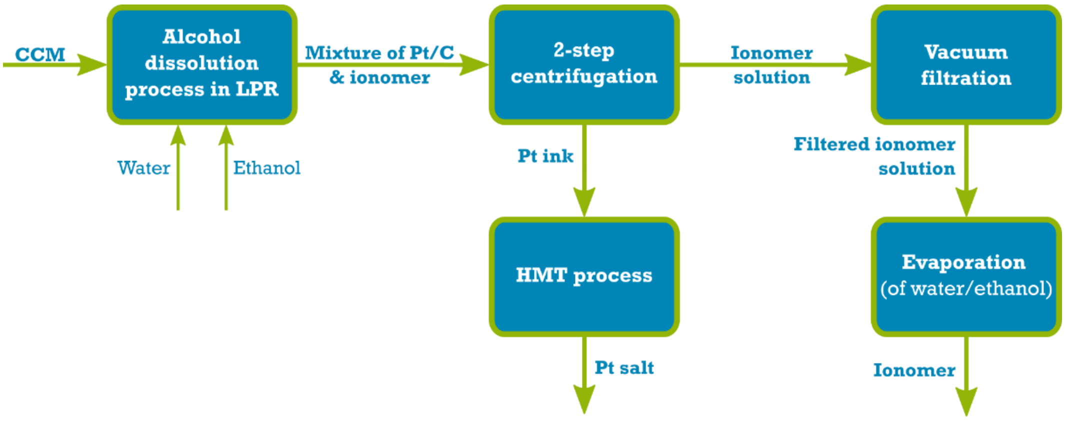


*Figure 1: BEST4Hy AD process workflow with Existing BEST4Hy HMT process for Pt ink*

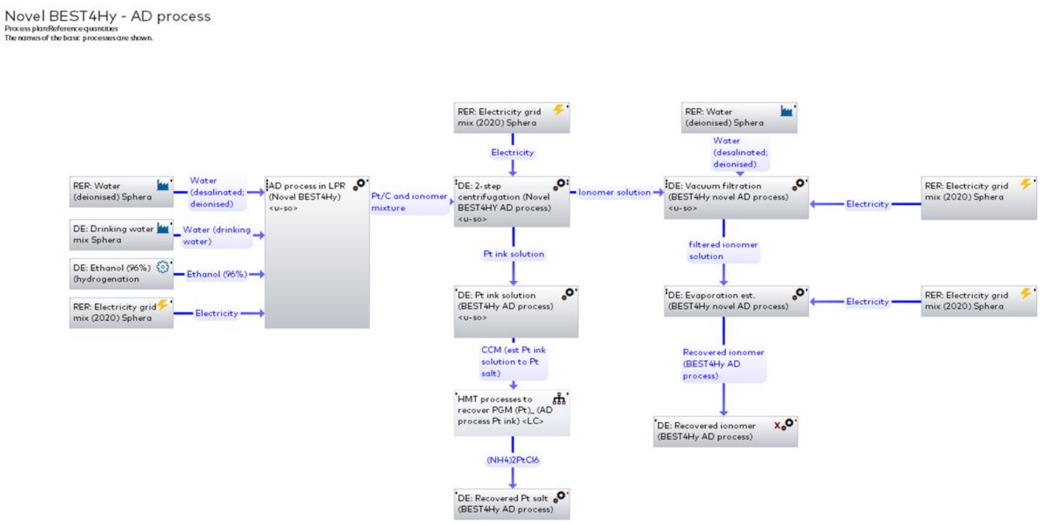


*Figure 2: LCA model for BEST4Hy AD process with HMT processing of Pt ink.*

### *Electrochemical metallic Pt recovery process*

The electrochemical metallic Pt recovery process is based on a patented process from the CEA Institute (EP3263744 A1 2018-01-03), which is a partner in the BEST4Hy project, and enables the recovery of platinum without the use of organic solvents or acids, is free of toxic gas emissions during operation and it is convenient as it can be carried out in just one step (electroleaching & electrodeposition process together).

The entire process consists of three steps: i) manual disassembly of the membrane electrode assembly (MEA) into the catalyst coated membrane (CCM) and the gas diffusion layer (GDL), ii) anode preparation with CCM and iii) electro leaching & electrodeposition of Pt. After manual disassembly, a GDL is used as a cathode electrode and the CCM is bonded to a Dimensionally Stable Anode (DSA) with resins. The used DSA is $IrO_2$-$Ta_2O_5$ coated Titanium anode (coating ratio assumption is 50/50%). The main step is then the electrochemical Pt recovery process (electro leaching & electrodeposition) to recover metallic Pt from the CCM, where the platinum is recovered by electrochemical leaching in a mixture of ionic liquids (1-butyl-3-methylimidazolium bis-trifluoromethylsulfonylimide (BMIM TFSI) and 1-butyl-3-methylimidazolium chloride (BMIM Cl)) containing chloride ions.


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The Pt nanoparticles are electrochemically leached at the anode (CCM on DSA), forming platinum and chloride complexes, and zero-valent platinum is electrochemically deposited at the cathode (GDL) of the same electrochemical cell. The recovered Pt on the GDL is in metallic form and can be used for open loop recycling routes.

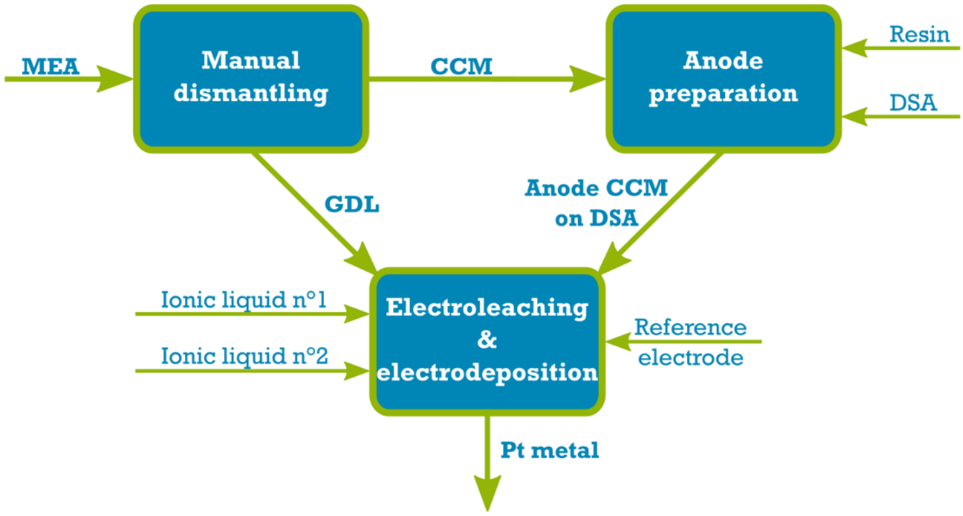


*Figure 3: BEST4Hy Pt electrochemical recovery process workflow*

*Table 2: Life cycle inventory for BEST4Hy Pt electrochemical recovery process (TRL5)*

| Material/energy flow | Quantity | Unit | Database used |
|---|---|---|---|
| **INPUTS** | | | |
| **EoL PEMFC CCM** | **9.2** | **g** | |
| Phenol formaldehyde-resin (Novolac) | 0.4 | g | RER: Phenol formaldehyde-resin (Novolac) Sphera |
| Tetrahydrofuran resins | 0.8 | g | GB: Tetrahydrofuran via 1,4-Butanediol Sphera |
| Methyl ethyl ketone | 0.1 | g | RER: Methyl ethyl ketone (2-butanone, MEK) Sphera |
| Titanium | 176.1 | g | RER: Market for Titanium Ecoinvent |
| Iridium oxide (coating) | 2.5 | g | GLO: Iridium (coating) IPA |
| Tantalum oxide (coating | | | DE: Tantalum (coating) Sphera |
| EoL PEMFC GDL | 15.2 | g | |
| BMIM TFSI (ionic liquid n°1) | 8264.8 | g | RER: Ionic Liquid (Salt of Imidazole) Sphera |
| BMIM C (ionic liquid n°2) | 1195.1 | g | RER: Ionic Liquid (Salt of Imidazole) Sphera |
| Silver wire | 0.014 | g | GLO: Silver mix Sphera |
| Electricity (potentiostat) | 1.5 | kWh | RER: Electricity grid mix Sphera |
| Electric heater (Heat) | 0.8 | kWh | RER: Electricity grid mix Sphera |
| **MAIN OUTPUTS** | | | |
| **Recovered metallic Pt** | **1.0** | **g** | |

Based on all energy and mass balances (Table 2) the LCA model for Pt electrochemical recovery process (see Figure 4) was built in the LCA for experts Sphera software. The main input in the model is CCM (9.2 g) and GDL from EoL PEMFC stack and main output of the novel BEST4Hy Pt electrochemical process is 1g of recovered platinum (metallic form on GDL cathode) for open loop recycling options. The cumulative platinum recovery efficiency based on the lab scale (TRL5) from aged MEA (EKPO) to 1g of recycled platinum is assumed based on electro leaching and electrodeposition processes and for this LCA study is defined as 95% (according to the CCM active area and declared Pt loading by CCM manufacturer).

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*Figure 4: LCA model for BEST4Hy Pt electrochemical recovery process*

## 3.2.2 Cathode materials recycling from EoL SOFC

The novel lanthanum strontium cobaltite (LSC - SOFC cathode)) recycling via nitric acid route, with recovery of **lanthanum** as lanthanum oxide ($La_2O_3$) and **cobalt** as cobalt oxide ($Co_3O_4$), is schematically presented in Figure 5 at TRL3 level.

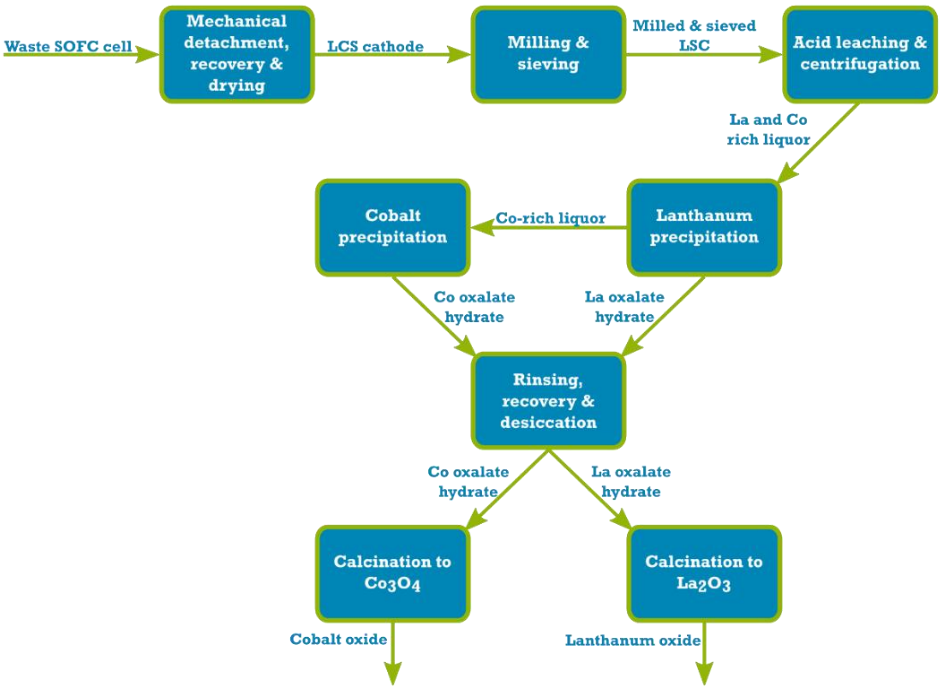


*Figure 5: BEST4Hy recovery process workflow of the Lanthanum oxide and Cobalt oxide from waste (EoL) cathode SOFC cell (TRL3)*

The main input of the recycling process is **waste (EoL) SOFC cell.** The EoL SOFC cell is firstly mechanically treated, to detach the LSC cathode. LSC cathode is then milled and sieved into dust, which is the main input for acid leaching and centrifugation step. After centrifugation follows the Lanthanum precipitation, which has two main outputs: Cobalt-rich

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liquor and lanthanum oxalate hydrate. Cobalt-rich liquor goes into cobalt precipitation step where cobalt oxalate hydrate is obtained. Lanthanum oxalate hydrate and cobalt oxalate hydrate are then rinsed, recovered, and desiccated. In the last step, Lanthanum oxalate hydrate is calcinated into **lanthanum oxide ($La_2O_3$)** and Cobalt oxalate hydrate into **cobalt oxide ($Co_3O_4$)**. More detailed description of the novel BEST4Hy EoL SOFC cell recycling process via nitric acid route recovery is available in BEST4Hy D4.2 [13] and D4.4 led by POLITO BEST4Hy partner. Since there are two main outputs (lanthanum oxide, cobalt oxide) the life cycle inventory is set as cobalt oxide as the main output reference flow, meaning that all other values of flows are correlated to get 1 g of cobalt oxide.

Within the recovery sub-processes of lanthanum and cobalt via nitric, two routes can be identified**: i) lanthanum route** and **ii) cobalt route** (see Figure 5). The following processes: mechanical detachment, recovery and drying; milling and sieving; acid leaching and centrifugation; and rinsing, recovery and desiccation are part of both recovery routes, while lanthanum precipitation and calcination to lanthanum oxide ($La_2O_3$) are only part of lanthanum route and cobalt precipitation and calcination to cobalt oxide ($Co_3O_4$) are only part of cobalt route. Based on these **two routes mass allocation of environmental impact results** was made.

The LCI of the recovery process via nitric acid route of lanthanum oxide and cobalt oxide is presented in Table 3. Table 3 presents total values of aggregated LCI of chemicals, electricity consumption and used databases via nitric acid route recovery process of BEST4Hy EoL SOFC cathode (TRL3). The electricity source is selected European grid mix (EU grid mix for 2020, [14]). If possible, geographical location of all materials is also Europe average or a country in Europe. If this was not possible, global geographical location is selected (in the case of oxalic acid).

*Table 3: Life cycle inventory for BEST4Hy lanthanum oxide and cobalt oxide recovery from EoL SOFC stack (TRL3)*

| Material/energy flow | Quantity | Unit | Database used |
|---|---|---|---|
| **INPUTS** | | | |
| **EoL SOFC Cell** | **402.6** | **g** | |
| Deionized $H_2O$ | 5298.69 | g | RER: Water (deionised) Sphera |
| Electricity | 10.453 | kWh | RER: Electricity grid mix Sphera |
| $HNO_3$ (65%) | 43.40 | mL | DE: Nitric acid Sphera |
| $H_2O_2$ (30%) | 9.53 | mL | DE: Hydrogen peroxide Sphera |
| Oxalic acid | 6.88 | g | GLO: market for oxalic acid Ecoinvent |
| NaOH (40%) | 59.38 | mL | RER: Sodium hydroxide mix Sphera |
| **MAIN OUTPUTS** | | | |
| **Lanthanum oxide** | **1.36** | **g** | |
| **Cobalt oxide** | **1** | **g** | |

Since nitric acid, hydrogen peroxide, and sodium hydroxide were provided by POLITO in millilitres the recalculation to mass units was done with the following densities: 1.39 g/mL for nitric acid, 1.11 g/mL for hydrogen peroxide and 1.43 g/mL for sodium peroxide.

The LCA model of novel BEST4Hy EoL SOFC recycling with nitric acid route is made using LCA for experts software presented in Figure 6.

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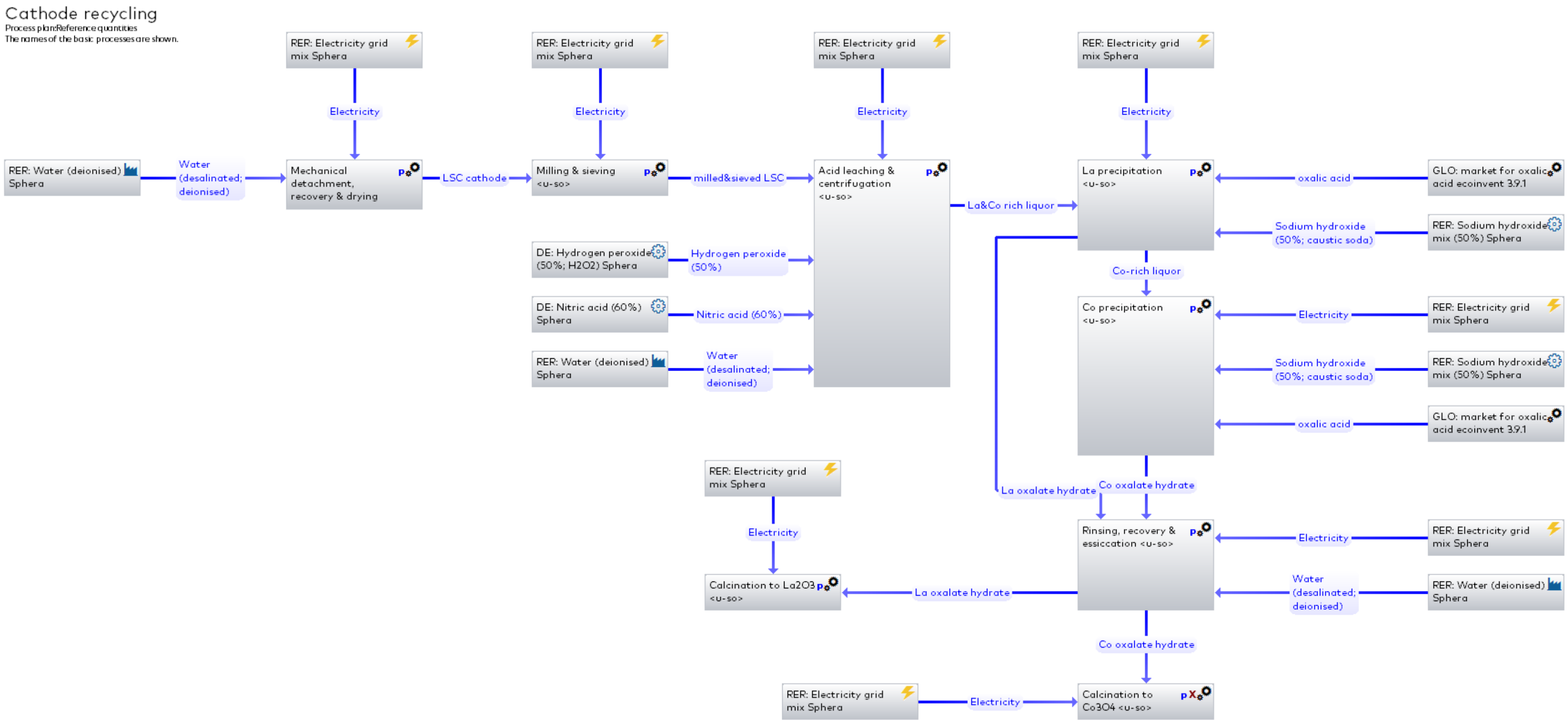


*Figure 6: LCA model for novel BEST4Hy EoL SOFC cathode recovery of lanthanum oxide and cobalt oxide.*

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## 3.3 Life cycle impact assessment methodology

In this document (D5.2) the same life cycle impact assessment (LCIA) methodology is used as in D5.1, where all environmental impact indicators are presented and described. Furthermore, in ongoing partnering EU project eGHOST [15] the same LCIA methodology (Environmental Footprint 3.0) and environmental impact indicators are used. European Commission and the Joint Research Centre (JRC) support the EF3.0 methodology quite intensively in recent years.

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# 4 Life cycle cost assessment of FCH recycling technologies

Adopting a definition by the European Commission, *Life Cycle Costing (LCC) means considering all the costs that will be incurred during the lifetime of the product, work, or service*. It can include cost associated with design, research, operations, maintenance, decommissioning, etc. In BEST4Hy project, the LCC calculation methodology developed within SH2E EU project [16] was used. In general, costs are divided into **Capital expenditures (CAPEX)** and **Operational expenditures (OPEX)**. CAPEX cost is related to the acquisition and construction of equipment and facilities, and end-of-life costs. It typically includes engineering, procurement, and construction costs. OPEX is related to operation of facilities and equipment. These costs typically include labour, maintenance, feedstock, consumables, utilities (such as electricity and gas), insurance, and administrative costs.

The LCC methodology follows the LCA methodology, and it is therefore composed of the same four phases: (i) Goal and scope definition, (ii) Inventory analysis, (iii) Impact assessment, and (iv) Interpretation. The same structure is also adopted in this deliverable. The LCC methodology adopted in this project follows the one developed within SH2E project. Although that LCC methodology was made primarily for FCH systems, it is generic enough to be also used for other FCH technology recycling process with some modifications related to the specific EoL technology. For the LCC calculation, a sophisticated LCC model was created in Microsoft Excel software within BEST4Hy project and it can be applied to a wide range of other FCH systems and applications.

To understand LCC calculation, some basic definition must be clarified. **Amortisation** is the depreciation of goods (equipment, installations…) due to their use or obsolescence. In LCC it is used to calculate the taxes paid during operation. **Cash flow** is a payment especially from one bank account to another. It is mostly used to describe payments that are expected to happen in the future. It also includes cash flows which occur during the initial investment. **Discounting** is a mean of comparing the value of money that is available now with money that will become available at some time in the future. **Inflation rate** is an increase in the general price level of goods and services in an economy during a period of time caused by imbalances between supply and demand. **Interest rate** is the price of money or capital expressed as a percentage. **Levelized cost of product** is a discounted lifetime cost of building and operating a production asset, expressed as a cost per unit of produced product. **Net present value (NPV)** is a value of all future cash flows (positive and negative) over the entire life of an investment discounted to the present. **Real discount rate** is an interest rate adjusted to remove the effect of actual or expected inflation.

## 4.1 Goal and scope definition

The goal of the present LCC study is to estimate the NPV of the existing Pt recovery technology from EoL PEMFC stack to Pt salt for the operational time of 20 years. This is used as case study to validate the LCC model built within the project considering the availability of data. The LCC calculation includes the dismantling of the EoL PEMFC stacks and the HMT process; the main product for the market is Pt salt, which serves as the precursor for Pt based catalysts use for CCM production. The technology boundaries of the LCC calculation are presented in Figure 7.

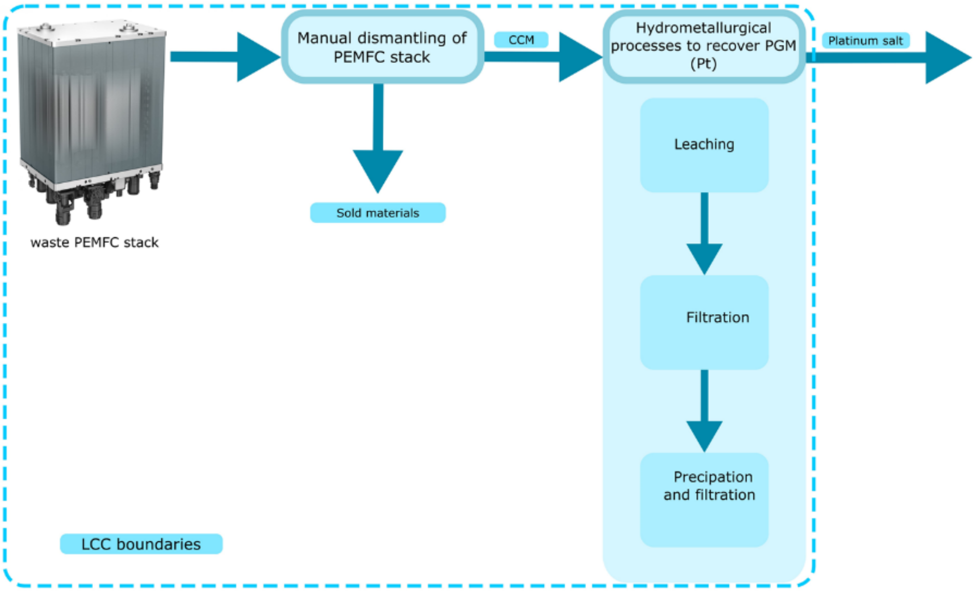


*Figure 7 LCC assessment boundaries for Pt salt production from EoL PEMFC stack*

The **functional unit** of the system is 1 kg of produced Pt salt (containing recovered Pt) from EoL PEMFC stack. The LCC boundaries and all assumptions were defined in cooperation with the BEST4Hy industry partner Hensel Recycling Deutschland (HRD), including the size of the upscaled plant. The system boundaries include the purchase of the land, the construction of the building with all necessary planning and the purchase of all equipment. The decommissioning of the factory is not included in the study. More detailed cost breakdown is presented in the chapter 4.2. The factory is estimated to **operate for 20 years**. The **operation starts** in the **year 2026** and **ends in 2045**. In the year 2025 all needed construction (capital costs) is made, which means that the **year 2025 is the first year** of the LCC calculation. **In the first 10 years** of the operation the throughput rate of the factory is defined as **1000 processed** EoL PEMFC stacks per year. **After 10 years** all the equipment is replaced, and the **throughput rate is increased to 2000** EoL PEMFC stacks per year. To simplify the LCC calculation, a lifetime of 10 years is assumed for the equipment. Although the throughput rate doubles, the cost of new equipment does not double, due to the increased knowledge and economies of scale, meaning that the price of the new equipment needed to fulfil the same function will be lower after 10 years.

The factory for Pt recovery as Pt salt from EoL PEMFC stacks is assumed to be located in Germany, since HRD is a German company. Therefore, all additional assumptions are made for Germany. The **inflation rate (f)** is assumed to be **2,08%** [17], which is the average inflation in Germany in the last 10 years. **Interest rate (i)** is assumed to be **5%,** which is a used value according to the $SH_2E$ guidelines [16], and **tax on profit 30%,** which approximates Germany corporate income tax and trade tax [18]**. Real discount rate (r*)** depends on inflation rate (f) and interest rate (i) and is **2,86%.** A linear amortization is

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considered with period of 10 years for equipment and 20 years for building. Also, maintenance is increased by 1% every year, to simulate degradation effects of the equipment.

LCC model, with all inputs and outputs, is presented in Figure 8. Inputs of the LCC model are money flows (CAPEX, OPEX, and incomes) and other assumptions needed for calculation e.g. tax rate on profit and production rate of the plant. Each of those inputs can be changed in the model, resulting in different results (outputs). Outputs of the LCC model are different LCC indicators.

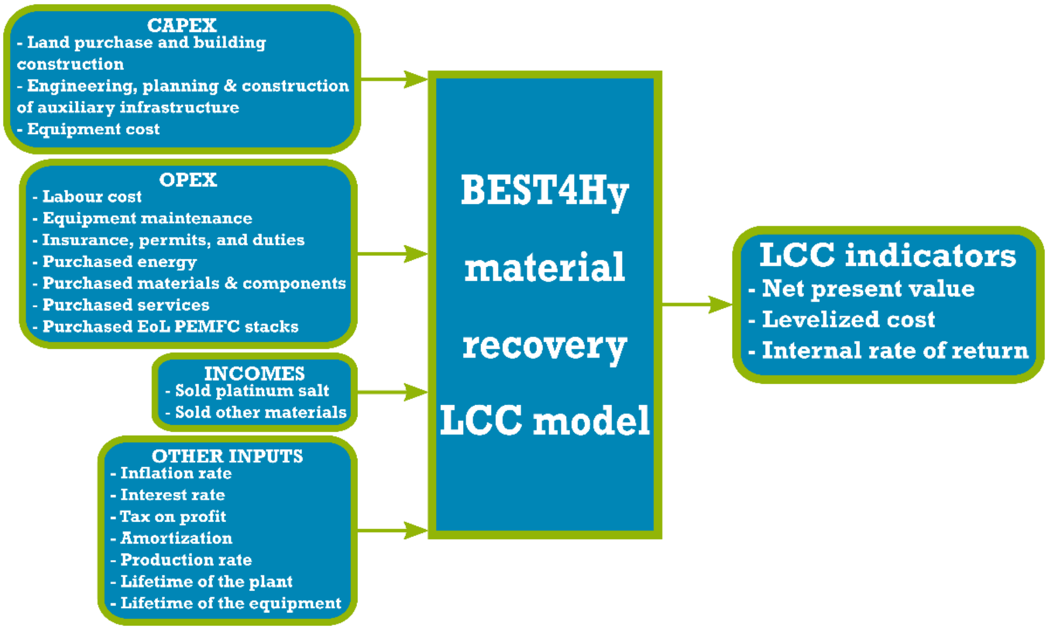


*Figure 8 Innovative newly developed BEST4Hy LCC model for FCH material recycling technologies with all considered inputs and outputs*

## 4.2 Life cycle inventory for LCC

All the data (LCI) for Pt recovery as Pt salt from EoL PEMFC stacks for LCC has been defined by BEST4Hy industry partner Hensel Recycling Deutschland (HRD), based on their experiences, facilities, and estimation of needed capital expenditures (CAPEX) and operation expenditures (OPEX). **CAPEX** is divided into land purchase and building construction cost, cost of engineering, planning and construction of auxiliary infrastructure and equipment/production line cost. **Land purchase and building construction** consist of all cost connected with the land purchase for production site and construction of the factory building. **Engineering, planning, and construction of auxiliary infrastructure** is associated with costs of all the engineering, planning and construction of the auxiliary infrastructure needed for the production lines in the factory. **Equipment cost** consists of the cost of all the equipment for the production lines.

The **OPEX** is divided into labour costs; equipment maintenance; insurance, permits, and duties; transport of EoL PEMFC stacks; purchased materials and services; and purchase of EoL PEMFC stacks. **Labour cost** consists of the gross salaries of the workers needed to operate the factory. It is assumed that 1 engineer, 1 researcher, 1 manager, and 4 blue-

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collar workers are needed to operate the factory at max capacity of 1000 recycled EoL PEMFC stacks per year. After the production rate doubles, additional 4 blue-collar workers are needed for operation of the factory. The salaries of all the types of workers are also provided by HRD. **Equipment maintenance** consist of all the cost associated with maintaining the equipment. The cost of equipment maintenance is increased every year by 1% due to aging of the plant. **Insurance, permits, and duties** are included in the LCC calculations, as relevant/needed for this industry sector. **Transport of EoL PEMFC stacks** consists of all the cost associated with the transport of the EoL PEMFC stacks from the waste holders to the factory. **Purchased materials and services** is further divided into cost of electricity purchase, cost of waste treatment generated within the factory, and consumables purchase. The electricity price is assumed to be the price of electricity in Germany (S12023) for companies (0.1904 €/kWh,[19]). **Purchase of EoL PEMFC** stacks is the main input of the process. The price of EoL PEMFC stack depends on the price of Pt and mass of the Pt in the EoL PEMFC stack. HRD provided estimation of EoL PEMFC cost, based on average mass of Pt within the EoL PEMFC stack and current Pt market prices, and this amounts to 490 €/stack.

The main product that creates revenue within the LCC system is Pt salt, which is sold on the global market. Along with Pt salt, the company also sells other materials recovered from EoL PEMFC stacks, like aluminium, stainless steel, and copper. The revenue of those is much lower, but nevertheless it is included in the LCC calculation model. The price to customers of Pt salt is assumed by HRD to be **27 € per g of Pt salt** [20,21]. Because the price of Pt salt on the market relates to the market price of the Pt, the cost of the EoL PEMFC stack and the price of the Pt salt are connected. The HRD estimates that the correlation is linear, meaning that if the price of the Pt salt doubles, also the cost of the EoL PEMFC stack doubles. Other important boundary (assumptions) conditions are:

- all the costs (salaries, material cost, etc.) and revenues (Pt salt and other materials sales) are aligned with inflation, and
- the quantity of Pt (Pt loading) in the EoL PEMFC stacks stays the same over the 20 years.

It is recognised that with improvements in the FCH technologies, the quantity of the Pt in the PEMFC stack will be lower (some other materials will increase), but to simplify the LCC calculation and results interpretation, this was neglected in this round of calculations.

## 4.3 Economic life cycle indicators

The LCC results can be quantified through different life cycle indicators. Typical indicators include **net present value (NPV)**, levelized cost (LC), payback period, internal rate of return (IRR), etc. The **NPV** is calculated with the eq. 1, where $CF_n$ represents the cash flow in the year n, i represents interest rate, t represents lifetime of the project, and n represents number of years since year 0 (beginning of factory operation). If the NPV is higher than 0 (NPV > 0), the project will generate profit. If the NPV is lower than 0 (NPV < 0), the project will not recover the initial investment, and if the NPV is equal to 0, the project does not increase wealth, but allows shareholders to be remunerated.

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$$\boldsymbol{NPV} = \sum_{n=1}^{t} \frac{CF_n}{(1+i)^n} \qquad \text{eq. 1}$$

The **Internal rate of return (IRR)** is a metric used in financial analysis to estimate the profitability of potential investments. is the interest rate at which the cumulative NPV at the end of the project is zero. It is calculated from the same formula of NPV, with the interest rate *i'* changed so that the NPV is 0, as is presented in eq. 2.

$$NPV = \sum_{n=1}^{t} \frac{CF_n}{(1+i')^n} = 0\,; i' = \boldsymbol{IRR} \qquad \text{eq. 2}$$

The higher an internal rate of return, the more desirable an investment is to undertake.

The **Levelized cost (LC) of Pt Salt** is the discounted lifetime cost expressed as a cost per unit of Pt salt produced. It is used to express the minimum selling price of the Pt salt that makes NPV zero at the end of the operational lifetime. It is very useful for benchmarking the LCC results. The calculation of LC of Pt Salt is presented in eq. 3, where $E_n$ represents the Pt salt output in year n in mass units.

$$\boldsymbol{LCPtSalt} = \frac{\sum_{n=1}^{t} \frac{CF_n}{(1+i)^n}}{\sum_{n=1}^{t} \frac{E_n}{(1+i)^n}} \qquad \text{eq. 3}$$

The results of the LCC along with interpretation are presented in paragraph 5.2.

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# 5 Results and discussion

## 5.1 Environmental impact results for novel recycling technologies

In this 5.1 chapter, results of the environmental LCA study are presented for novel EoL technologies developed within BEST4Hy project for EoL PEMFC and SOFC stack in the following order:

1) In the 1st part of the results (chapter 5.1.1), the environmental impacts of novel EoL technologies **for PEMFC waste/EoL stack** are presented, namely for:

    a. **Platinum and ionomer recovery with AD process (Pt ink and ionomer output)** and further Pt ink treatment via BEST4Hy HMT process to obtain Pt salt at **TRL5**.

    b. **Metallic Pt recovery with electrochemical** (electroleaching and electrodeposition) **recovery process** *at* ***TRL5***.

2) In the 2nd part (chapter 5.1.2), the environmental impacts of novel EoL technology **for SOFC waste/EoL stack** is presented, namely:

    **a.** for **lanthanum** (lanthanum oxide ($La_2O_3$)) and **cobalt** (as cobalt oxide ($Co_3O_4$)) **recovery** via **nitric acid route** from EoL SOFC cathode at **TRL3**.

**Life cycle inventories (LCI) and LCA models for material recycling**
*All LCI and LCA models are based on laboratory-scale processes (low TRL levels: SOFC at TRL3 and PEMFC at TRL5) and are still in the development phase, which must be considered when interpreting the results of the environmental impact of these technologies. Nevertheless, these results provide very good and essential inputs for FCH technologies for further development and optimization of LCI and LCA models!*

### 5.1.1 Novel recycling technologies for PEMFC stack

***Alcohol dissolution process (AD process)***

The results, based on LCA study boundaries described in chapter 3.1.1 and at Figure 1, of the total environmental impact for the novel BEST4Hy (AD + HMT) process are presented in Table 4. Results shows the absolute values of the EF3.0 environmental indicators for acidification, climate change, eutrophication, and resource consumption for the recovered materials. The novel BEST4Hy AD process recovered materials (Pt ink and ionomer) with additional Pt ink treatment with BEST4Hy HMT process to recovered Pt salt.

The final recovered materials from EoL PEMFC stack are Pt salt and ionomer (1 g of Pt salt and 9.41 g of ionomer, see chapter 3.1.1) whose economic value is very different, so that **an economic allocation was used to apportion the environmental impacts for the first two sub-processes** (AD process in LPR and 2-step centrifugation - see Figure 1Figure 2). The ratio between ionomer (average price for ionomer used €9.95/g, [22]) and Pt salt (average price used €90/g, [20,21]) in terms of market price is the economic

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allocation ratio used for the environmental impact, 90% Pt salt to 10% ionomer. Additionally, for a more detailed analysis, the relative contribution of each subprocess is shown in Table 4 with a hotspot identification (red color represents high, yellow medium and green low impact). From results presented in Table 4, the main summary and conclusions for novel BEST4Hy (AD + HMT) process to recover Pt salt and ionomer at TRL5 are:

- The **highest contribution** to environmental impact comes from the **2-step centrifugation** with 67.8% on average for all impact indicators, followed by **AD process in low pressure reactor (LPR)** (25.2%) and **HMT process** (6.1%) for recovering Pt as Pt salt. The lowest overall contribution to total environmental impact is from vacuum filtration of ionomer.
- The total environmental impact for climate change indicator of the novel BEST4Hy (AD + HMT) process is **3.385 kg $CO_2$eq. per 1g of recovered Pt salt and 9.41 g of recovered ionomer** (without economic allocation), in reference case where EU electricity grid mix is used for year 2020.
- With economic allocation for ionomer and Pt salt, the results for Climate Change indicator are **3.01 kg $CO_2$eq./1g Pt salt** and **0.091 kg $CO_2$eq./1g ionomer**.

*Table 4: Environmental impact indicator results of the Novel BEST4Hy (AD + HMT) process for Pt and ionomer recovery with relative contribution of each step*

| | Acidification [Mole of H+ eq.] | Climate Change – total [kg CO2 eq.] | Eutrophication, freshwater [kg P eq.] | Eutrophication, marine [kg N eq.] | Eutrophication, terrestrial [Mole of N eq.] | Resource use, fossil [MJ] | Resource use, mineral and metals [kg Sb eq.] |
|---|---|---|---|---|---|---|---|
| Total (EU grid mix) | 0.0102 (100%) | 3.385 (100%) | 1.65E-05 (100%) | 1.85E-03 (100%) | 0.0189 (100%) | 72.51 (100%) | 7.81E-07 (100%) |
| AD process in LPR | 25% | 28% | 21% | 26% | 26% | 30% | 20% |
| 2 step centrifugations | 73% | 69% | 60% | 69% | 71% | 68% | 61% |
| Vacuum filtration | <0.1% | <0.1% | <0.1% | <0.1% | <0.1% | <0.1% | <0.1% |
| HMT process | 1% | 1% | 18% | 4% | 1% | 1% | 18% |
| Solvent evaporation | 1% | 1% | 1% | 1% | 1% | 1% | 1% |

Figure 9 shows the results of the additional analysis of the electricity consumption, ethanol and other processes (HMT) to the total environmental indicators for the novel BEST4Hy (AD + HMT) process in the case of electricity used from EU grid mix (2020).

- The highest contribution to total environmental impact of process comes from **electricity consumption (89.8 % in average**, see Figure 9).
- **Ethanol consumption** (AD process in LPR) contributes from **1%** (for Resource use, mineral and metals indicator) to **9%** (for Resource use, fossils indicator) to total environmental impact of the novel BEST4Hy (AD + HMT) process.

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- The other contribution comes from **BEST4Hy HMT process** (see D5.1), from **1%** (for Acidification, Climate change, Eutrophication, terrestrial and Resource use, fossil indicators) to **18%** (for Resource use, mineral and metals and Eutrophication, freshwater indicators) to total environmental impact of the novel BEST4Hy (AD + HMT) process.

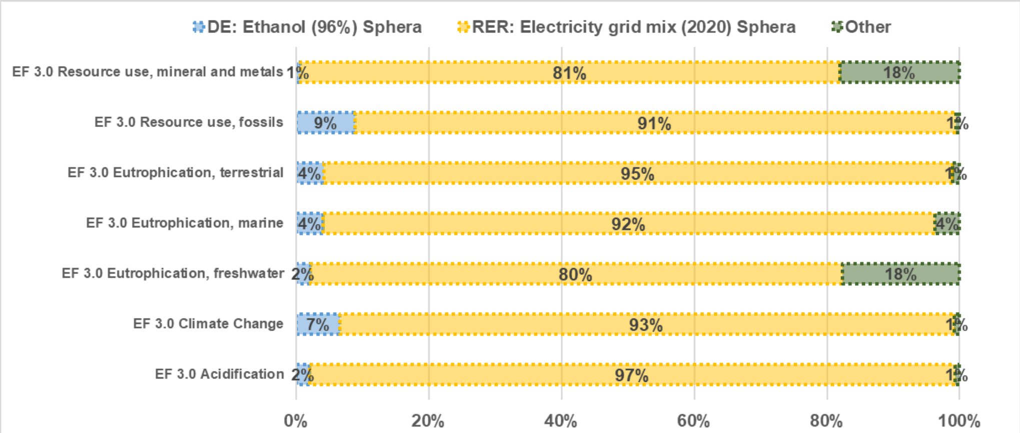


*Figure 9: Electricity consumption and ethanol use contribution to total environmental impact of BEST4Hy AD process (EU grid mix)*

The scenario analysis (Table 5 and Figure 10) for the case where a different electricity mix (electricity source) is used, which compares for the novel BEST4Hy (AD + HMT) process: the base case (EU grid mix for 2020, [14]), European green electricity grid mix 100% from renewable energy resources (RES grid mix, [23]) and European 100 % electricity from a nuclear power plant (nuclear, [24]).

*Table 5: Total values of environmental impact indicators for novel BEST4Hy (AD + HMT) process at TRL5 level*

| | EU grid mix | RES grid mix | Nuclear el. |
|---|---|---|---|
| EF 3.0 Acidification [Mole of H+ eq.] | 0.010 | 0.006 | 0.001 |
| EF 3.0 Climate Change - total [kg CO2 eq.] | 3.385 | 1.020 | 0.299 |
| EF 3.0 Eutrophication, freshwater [kg P eq.] | 1.65E-05 | 6.97E-05 | 3.61E-06 |
| EF 3.0 Eutrophication, marine [kg N eq.] | 1.85E-03 | 2.23E-03 | 2.75E-04 |
| EF 3.0 Eutrophication, terrestrial [Mole of N eq.] | 1.89E-02 | 2.11E-02 | 1.87E-03 |
| EF 3.0 Resource use, fossils [MJ] | 7.25E+01 | 1.06E+01 | 1.22E+02 |
| EF 3.0 Resource use, mineral and metals [kg Sb eq.] | 7.81E-07 | 2.18E-06 | 1.57E-07 |

The results (Figure 10 and Table 5) show that the use of electricity from renewable energy sources (RES grid mix) and from nuclear energy can significantly reduce the environmental impact. Namely, for climate change environmental impact indicator the reduction for **RES electricity is 70%** (from 3.385 kg $CO_2$eq. to **1.02 kg$CO_2$eq.**) and for **nuclear electricity is 91%** (from 3.385 kg $CO_2$eq. to **0.299 kg $CO_2$eq.**). With economic allocation, the results are **0.91 kg $CO_2$eq./1g Pt salt** and **0.026 kg $CO_2$eq./1g ionomer** for RES case and **0.27 kg $CO_2$eq./1g Pt salt** and **0.007 kg $CO_2$eq./1g ionomer** for nuclear case.

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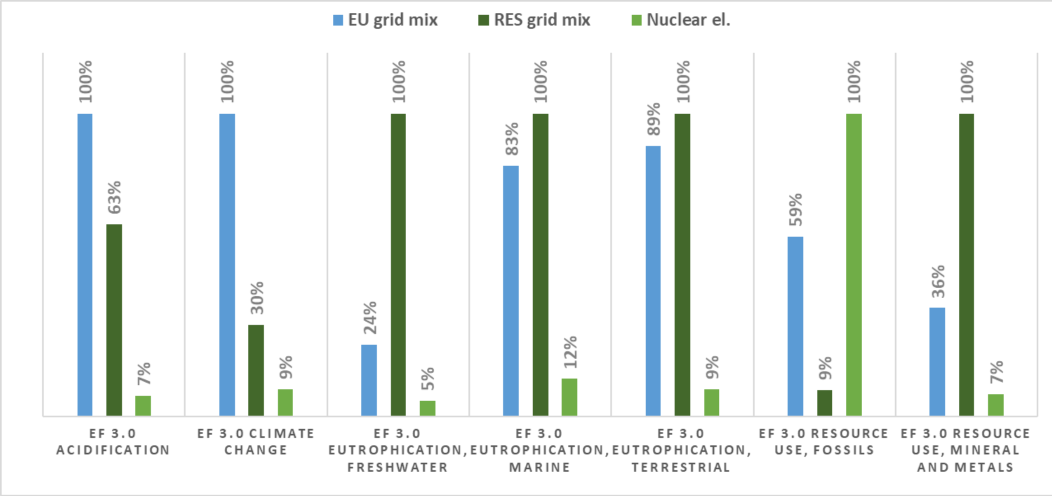


*Figure 10: Electricity source impact on environmental impact indicators for novel BEST4Hy (AD + HMT) process at TRL5 level*

### *Electrochemical metallic Pt recovery process*

The environmental impact results for electrochemical metallic Pt recovery process (electroleaching & electrodeposition), based on LCA study boundaries described in chapter 3.1.1 and at Figure 3, are presented in Table 6, which shows the absolute values of the EF3.0 environmental indicators for acidification, climate change, eutrophication, and resource consumption for the **1 g of recovered metallic Pt.** Additionally, for a more detailed analysis, the relative contribution of each material/input is shown in Table 6 with a hotspot identification (red color represents high, yellow medium and green low impact). The electricity source used is average EU grid mix for 2020, [22].

From results presented in Table 6 the summary and conclusions for novel BEST4Hy metallic Pt electrochemical process at TRL5 are:

- The **highest contribution** to total environmental impact of BEST4Hy electrochemical Pt recovery process comes from the **Iridium coating on DSA** with **62.1%** on average for all impact indicators (ranging from 9.8% for eutrophication, freshwater to 99.8% for resource use), followed by **ionic liquid** 25.2%) and **Titanium** (11.9%) used for DSA substrate.
- Due to the **very high impact of Iridium** (Ir is PGM material, which is on the EU CRM list, [25]), a very low environmental impact comes from resins and reference electrode production process.
- It has to be mentioned that the **DSA coating (iridium and tantalum) and substrate (titanium) is on EU CRM 5$^{th}$ list** [26] and marked as strategic and critical materials for EU economy.
- Iridium coating has the greatest impact on acidification, marine and soil eutrophication and resource use, while titanium is responsible for freshwater eutrophication. Ionic liquids and iridium have the same contribution to the climate change impact (48.8%). For fossil resource use, ionic liquid has the highest contribution if it is used only once.

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- The total environmental impact for climate change of the electrochemical metallic Pt recovery process is **72.35 kg $CO_2$eq. per 1g Pt** for the case **when ionic liquids are not reused**.

*Table 6: Environmental impact results for BEST4Hy Pt electrochemical process with relative contribution of each material (no reuse of IL)*

| | EF 3.0 Acidification [Mole of H+ eq.] | EF 3.0 Climate Change [kg CO2 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** | **0,7954 (100%)** | **72,35 (100%)** | **4,10E-04 (100%)** | **7,42E-02 (100%)** | **0,7825 (100%)** | **1374,6 (100%)** | **4,42E-03 (100%)** |
| DSA coating (Tantalum) | 0,1% | 0,2% | 0,0% | 0,3% | 0,3% | 0,2% | 0,0% |
| Resins (Tetrahydrofuran) | 0,0% | 0,0% | 0,0% | 0,0% | 0,0% | 0,0% | 0,0% |
| DSA coating (Iridium) | 91,0% | 48,8% | 9,8% | 76,1% | 79,3% | 30,1% | 99,8% |
| Reference electrode (silver wire) | 0,0% | 0,0% | 0,0% | 0,0% | 0,0% | 0,0% | 0,0% |
| EU Electricity grid mix | 0,3% | 1,0% | 0,7% | 0,5% | 0,5% | 1,1% | 0,0% |
| Ionic Liquid (Salt of Imidazole) | 6,0% | 48,8% | 13,1% | 21,7% | 18,8% | 67,8% | 0,1% |
| DSA substrate (Titanium) | 2,6% | 1,2% | 76,3% | 1,4% | 1,1% | 0,8% | 0,1% |
| Resins (methyl ethyl ketone) | 0,0% | 0,0% | 0,0% | 0,0% | 0,0% | 0,0% | 0,0% |
| Resins (Phenol formaldehyde (Novalac)) | 0,0% | 0,0% | 0,0% | 0,0% | 0,0% | 0,0% | 0,0% |

The results in Figure 11 show an additional analysis of the reduction in environmental impact in the **case of 4 times, 8 times** (experimentally demonstrated by CEA) and **theoretically infinite reuse of the ionic liquid (IL)** for the electrochemical process for the recovery of metallic Pt. They show that the **reduction in environmental impact is highest for climate change and resource use** (fossil) indicator.

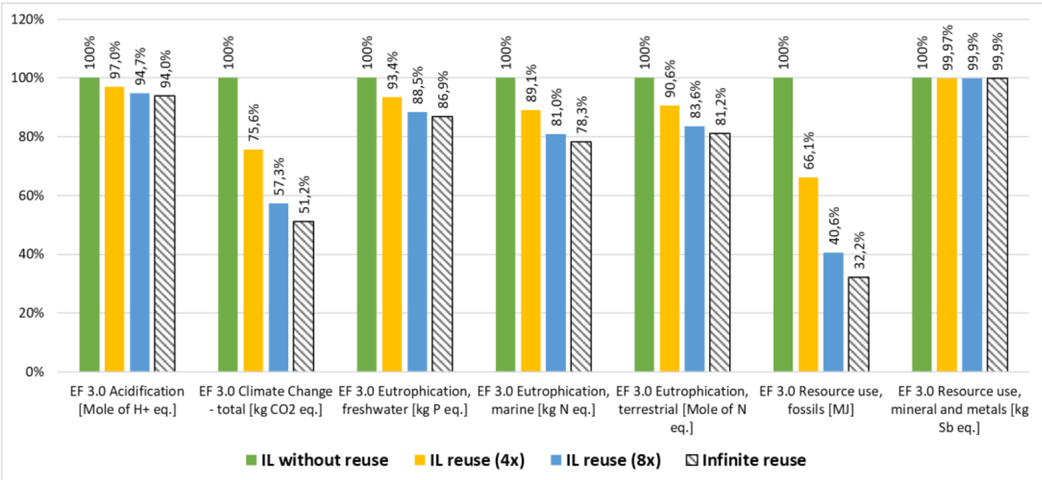


*Figure 11: Environmental impacts reduction for electrochemical metallic Pt recovery in the case of without, 4-times, 8-times and infinite IL reuse*

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A reduction is also achieved for the other environmental impact indicators shown in Figure 11. An additional theoretical analysis for the infinite reuse of IL is presented in the last collum (Figure 11), in which the impact of IL production was limited to zero, which represents an additional reduction in environmental impacts of the electrochemical recovery of metallic Pt. The **total environmental impact for climate change with 8 times IL reuse** is **41.47 kg $CO_2$eq./1g Pt**, which corresponds to **42.7% reduction** compared to the case of IL without reuse**.** Since DSA (coating (tantalum, iridium) and substrate (titanium)) has the greatest impact on the environmental indicators for electrochemical metallic Pt recovery process, we have carried out an additional analysis for the case of a **theoretical reuse of DSA (infinite reuse),** in which a negligible impact of DSA on the environmental impacts of recycled metallic platinum would be obtained in the infinite number of reuse cases. In this case, at 8-times IL reuse and a theoretically infinite reuse of DSA, the climate change indicator for 1 g of recovered metallic Pt would be reduced to 5.13 $CO_2$eq.or by 88.6 %.

To evaluate the novel BEST4Hy electrochemical metallic Pt recovery, Figure 12 shows a comparison of the environmental indicator climate change [kgCO2eq.] for 1g of metallic Pt. For virgin Pt, the two most used LCI databases (Ecoinvent and Sphera (formerly known as Gabi) professional) were used to compare the environmental impact of climate change for the production of virgin and secondary Pt. In addition, virgin Pt used in automotive catalysts provided by the International Platinum Association (IPA 2017 study with 2022 update, [27]) was also included and compared to other Pt production/recovery routes. The results indicate that the BEST4Hy electrochemical Pt recovery process shows quite promising results in terms of the climate change indicator.

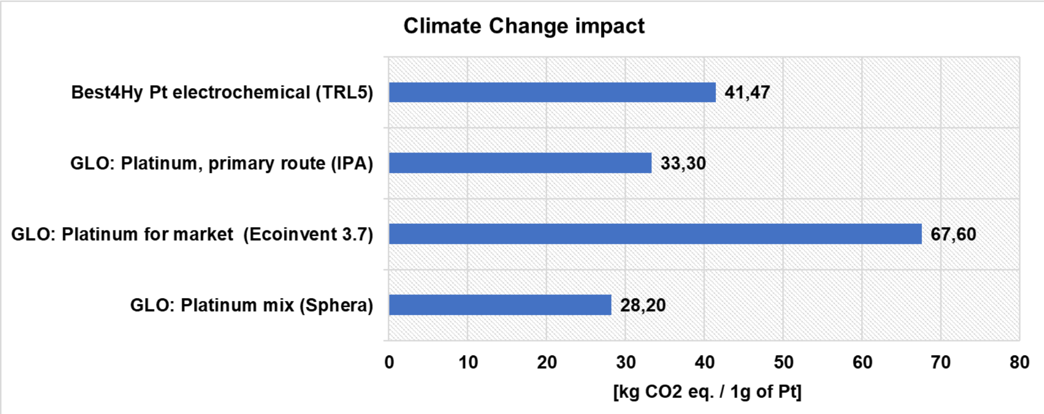


*Figure 12: Comparison of climate change impact per 1g of Pt for different Pt recovery routes within LCA secondary databases*

**DSA impact**

*At the current stage of development, for novel BEST4Hy Electrochemical metallic Pt recovery process by the BEST4Hy partner CEA, it has not yet been validated whether DSA can be reused several times (due to degradation processes) and which additional processes would be necessary. In D5.2 only the theoretical reuse potential (best-case scenario) as an initial indication have been assessed. For more precise results, further validation, and development at higher TRL scales is required.*

**Climate change environmental impact indicator comparison**

*It must be stressed out, that the above data are derived from fully industrialized process (automotive catalysts recycling), hence the comparison is purely indicative given that the novel BEST4Hy recovery processes are at TRL5 level.*

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## 5.1.2 Novel recycling technologies for SOFC stack

The results, based on LCA study boundaries described in chapter 3.1.2, of the environmental impact for the novel BEST4Hy process for recovering lanthanum oxide and cobalt oxide from EoL SOFC stacks, presented in Figure 5, are shown in absolute values in Table 7. In addition, the results are presented in Figure 13, where the relative impacts of the sub-processes are shown. The environmental impacts within the sub-processes are caused by electricity generation or the extraction and production of raw materials for the chemicals used in novel BEST4Hy EoL SOFC cathode via nitric acid route lanthanum and cobalt recovery. The results present recovery of **1.36g lanthanum oxide** and **1g cobalt oxide**.

Furthermore, the novel recovery process is divided into sub-processes and for each sub-process the relative environmental impact is indicated with a hotspot label (red colour represents high, yellow medium and green low environmental impact).

*Table 7: Total environmental impacts of the novel BEST4Hy EoL SOFC stack recycling with recovery of 1.36g lanthanum oxide and 1g cobalt oxide*

| | Acidification [Mole of H+ eq.] | Climate Change – total [kg CO2 eq.] | Eutrophication, freshwater [kg P eq.] | Eutrophication, marine [kg N eq.] | Eutrophication, terrestrial [Mole of N eq.] | Resource use, fossils [MJ] | Resource use, mineral and metals [kg Sb eq.] |
|---|---|---|---|---|---|---|---|
| **Total** | **0.0102 (100%)** | **3.638 (100%)** | **3.33E-05 (100%)** | **2.88E-03 (100%)** | **0.0308 (100%)** | **73.5 (100%)** | **1.23E-06 (100%)** |
| Acid leaching & centrifugation | 3% | 5% | 2% | 4% | 3% | 4% | 2% |
| Calcination to $Co_3O_4$ | 10% | 13% | 5% | 8% | 8% | 14% | 6% |
| Co precipitation | 15% | 2% | 30% | 19% | 20% | 1% | 28% |
| La precipitation | 15% | 3% | 31% | 20% | 21% | 2% | 29% |
| Calcination to $La_2O_3$ | 21% | 28% | 11% | 18% | 17% | 29% | 13% |
| Mechanical detachment, recovery & drying | 23% | 31% | 13% | 20% | 19% | 31% | 14% |
| Milling & sieving | 12% | 16% | 7% | 10% | 10% | 17% | 7% |
| Rinsing, recovery & desiccation | 1% | 2% | 1% | 1% | 1% | 2% | 1% |

From the Table 7 and Figure 13 the conclusions for the novel BEST4Hy lanthanum oxide and cobalt oxide recovery process via nitric acid route are:

- The environmental impacts for all impact categories are distributed **across the sub-processes**, so there is **no clear hotspot within the sub-processes** that would cause most of the environmental impacts for the entire recovery process of lanthanum and cobalt.

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- Since there are two valuable outputs of the recovery process, mass allocation (3.2.2) of the results is made. In the case of climate change indicator, cobalt route represents 40.2% of the total climate change impacts and lanthanum route 59.8%. Similar shares of La and Co routes are also for other environmental impact indicators, where lanthanum route represents from 54% to 60% of the environmental impacts. For climate change indicator, lanthanum has 1.60 kg $CO_{2\ eq.}$ per 1 g of lanthanum recovered and cobalt has 1.47 kg $CO_{2\ eq.}$ per 1g of cobalt recovered. This means that the impact of lanthanum is 8.7% higher than that of cobalt.
- Mechanical detachment with recovery and drying contributes the most to the category of effects on acidification, namely 23%, followed by the sub-process calcination to lanthanum oxide (21%) and the precipitation steps (15%). The same two sub-process also contribute the most to the climate change (31% and 28%) and to the Resource use – fossils (31% and 29%).
- Lanthanum precipitation (30% and 28%) and cobalt precipitation (30% and 28%) are the main contributors to eutrophication - freshwater and resource use - minerals and metals.
- The environmental impacts on eutrophication – marine and on eutrophication – terrestrial are most evenly distributed among the sub-processes. The sub-processes cobalt precipitation, lanthanum precipitation, calcination to lanthanum oxide and calcination to cobalt oxide contributes between 18 % and 21 %.
- The total environmental impact for climate change of the novel BEST4Hy EoL SOFC cathode lanthanum and cobalt recovery at TRL3 is **3.638 kg $CO_2$eq. per 1.36g lanthanum oxide and 1g of cobalt oxide.**

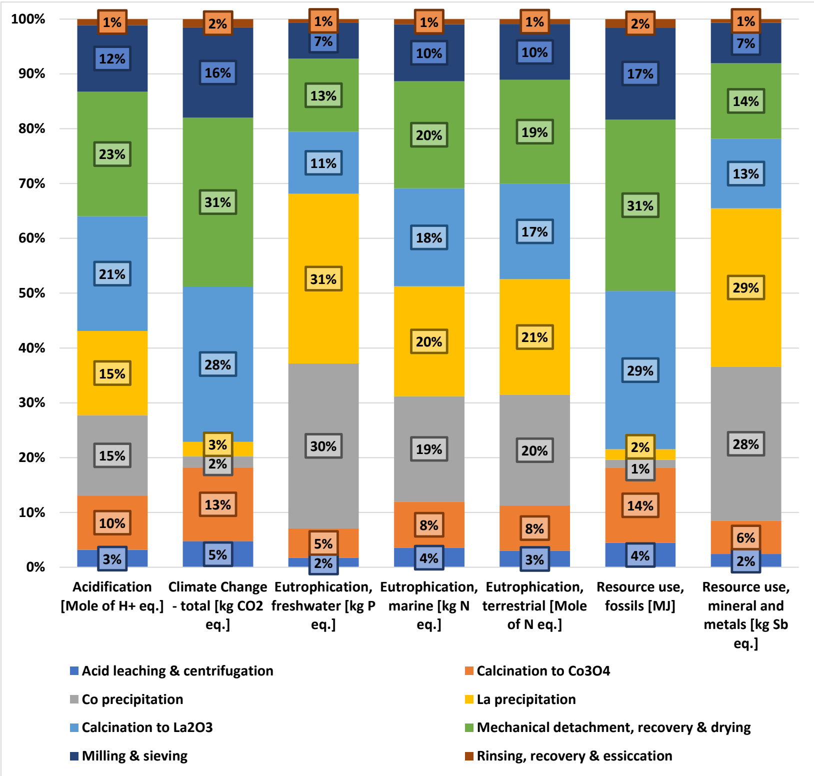


*Figure 13: Relative impacts of subprocesses of novel BEST4Hy EoL SOFC cathode recycling for 1.36g of Lanthanum oxide and 1g of cobalt oxide recovery.*

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An additional analysis of electricity and chemical consumption for the novel BEST4Hy EoL SOFC cathode recovery process was performed to allocate the contribution of chemical production and electricity consumption to all environmental impacts (see Figure 14). The results presented show that:

- On average, **66% of total environmental impacts** comes from **electricity consumption** and **34% from materials, chemical used** for the process.
- The impacts of resource consumption – fossil fuels, climate change and acidification - are closely linked to electricity consumption (97%, 95% and 70%). On the other hand, the impacts of resource use – minerals and metals and eutrophication – freshwater are mainly caused by chemical production (58% and 62%).

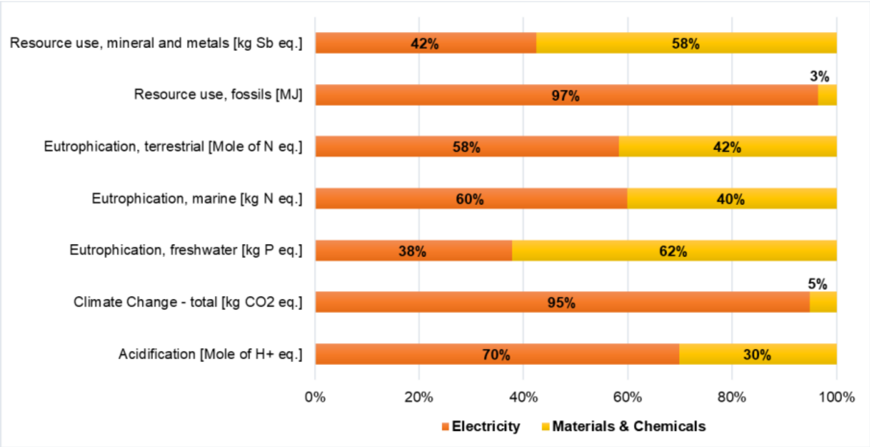


*Figure 14: Environmental impact contribution due to the electricity consumption (EU grid mix) and materials/chemicals used to total environmental impact of La and Co recovery.*

Since electricity consumption is the hotspot in most impact categories, sensitivity analyses are carried out for different electricity mixes (EU grid mix [14]– base case, French grid mix [28] and EU RES grid mix [23]), presented in Figure 15.

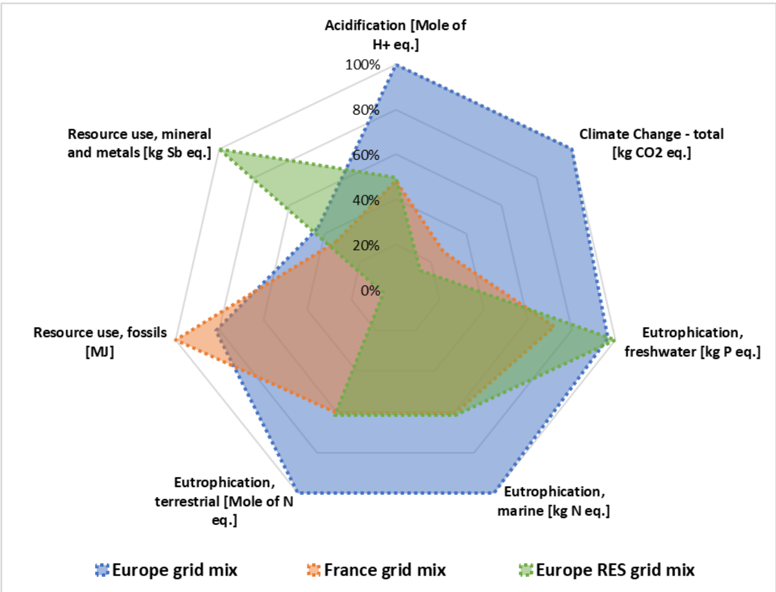


*Figure 15: Relative environmental impacts of 1.36g of lanthanum oxide and 1g of cobalt oxide recycling processes with EU electricity, France electricity and RES EU electricity grid mix*

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With future development and higher TRL levels of lanthanum and cobalt recovery from the EoL SOFC cathode, a lower relative electricity consumption and thus a significant reduction in environmental impact is expected, especially in resource consumption (fossil fuels) and climate change indicator, which are two main hotspots (see Figure 14). The results show that the climate change indicator is reduced by 86% in the case of the recycling process with the EU RES grid mix, compared to the recycling process with the average EU grid mix. On the other hand, the resource use (minerals and metals) increases by 127% due to the renewable energy sources that consume many valuable minerals and metals.

**LCI and LCA models for BEST4Hy EoL SOFC cathode recycling**

*All LCI and LCA models are based on laboratory-scale processes (low TRL levels - TRL3) and are still in the development phase, which must be considered when interpreting the results of the environmental impact of these technologies. Nevertheless, these results provide very good and essential inputs for FCH technologies for further development and optimization of LCI and LCA models!*

## 5.2 Life Cycle Cost results for Pt salt recovery

In this 5.2 chapter, results of the LCC study are presented for HMT Pt recovery process developed within BEST4Hy project as existing EoL technology, described in chapter 4. The main result of the LCC is NPV. Additionally, IRR and LC of Pt salt are also calculated. The results are presented in Figure 16.

For the defined LCC boundary conditions, defined in chapter 4.1, the **NPV is 5,004,114 €** at the end of the project. The NPV reaches positive values in the year 2036, one year after the additional investment and increase of the production rate. The biggest cost in the whole lifetime is the purchase of EoL PEMFC stacks, which represent 50% of all costs, followed by cost of salaries, which represent 31% of all costs, as is presented in Figure 16. The CAPEX costs represent only 10% share of total costs. The biggest revenue comes from selling of Pt salt, revenue from selling of other materials is insignificant (3%).

The **IRR is 15.62%** which shows, how profitable is the investment to Pt salt production from EoL PEMFC stacks (defined interest rate is 5%). The interest rate could increase of further 10% and the company would still be in profit.

The **LC of Pt salt is 17,05 €/g Pt salt**. The LC could be used to compare different technologies. Since this is the first LCC study on Pt recycling at this level, there is no benchmark of LC of Pt salt produced with recycled Pt from EoL PEMFC stacks. The LC could only be compared with current market price of Pt salt. According to the reference [29], the Pt salt (Ammonium hexachloroplatinate (IV) - 43.25-43.95% Pt content) commercial price is between approx. 40-140 €/g [20,21,29] Pt salt. According to these prices the LC of Pt salt with recycled Pt is lower than market commercial price of virgin materials. In the case of LC of the Pt salt is the cost of EoL PEMFC stacks also lower, due to the linear connection between the two prices. For LC of Pt salt the cost to buy EoL PEMFC stack is 309,43 €/stack according to the presented boundary conditions.

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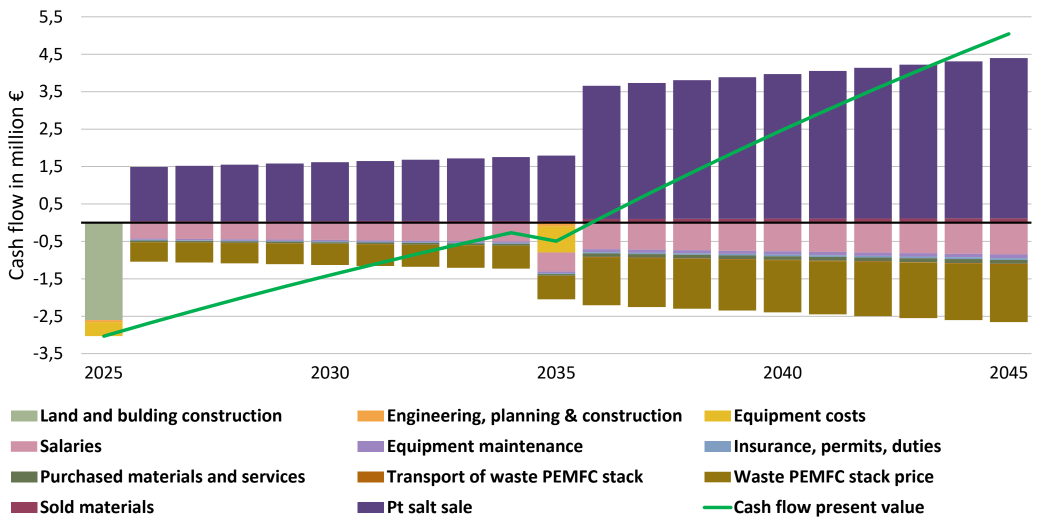


*Figure 16 Cash flow present value and cost distribution over operational lifetime*

The results of the LCC can be directly linked to **BEST4Hy KO5**, which states that the cost of recycled materials in a scenario with industrialised recycling processes should be comparable to the market cost of virgin materials (±10%) and is considered as achieved.

**LCC model for material recycling**

***When interpreting the LCC results, all assumptions made must be recognised*** *as they can significantly influence the final LCC result. Although all assumptions and boundary conditions were made to the best of our knowledge and taking into account the relevant inputs from the recycling industry (HRD, IDO-Lab), the LCC results in this study may turn out differently due to unexpected events in the future. When interpreting the results, it must be clear that the results are based on these assumptions and the system definition in order to avoid unnecessary confusion.*

***Innovative, universally applicable LCC model for FCH recycling***

*The innovative, newly developed LCC model is built in such a way that each money flow input and assumption can be changed based on boundary conditions (see Figure 8). Therefore,* ***(i) the model is universally applicable and can be used for different processes in different sectors and for different purposes, (ii) it can be easily used to calculate different scenarios with different assumptions****. Changing money flow inputs or assumptions can have a significant impact on the results, which means that a clear definition of inputs and assumptions is required for each analysis. The current model is used for the LCC analysis of the recycling process of the EoL PEMFC stack with the recycled Pt end product as Pt salt.*

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# 6 Summary of life cycle assessment inventories developed in BEST4Hy

At the end of the BEST4Hy project, there are many results from LCA and LCC that (i) can be used directly or (ii) require further improvement in the life cycle inventory. As part of BEST4Hy, many processes were developed from the idea on the laboratory level, which are normally at lower technology readiness levels (TRLs). Therefore, when using the newly developed processes in the LCA software, it must be taken into account that the material and energy flows could be overestimated as the processes have not yet been scaled up to industry level – higher TRLs are not yet possible.

This chapter summarizes the BEST4Hy development status and the status of life cycle inventories (LCI) in relation to the environmental (LCA) and economic (LCC) assessment of the observed FCH technologies in order to help all LCA practitioners to integrate the BEST4Hy results into their LCI, LCA and LCC models.

Table 8 and Table 9 show the summary of the recovery processes (EoL) of critical materials in PEMFC and SOFC technology developed within the BEST4Hy project. Based on the process development at laboratory/pilot scale, the LCIs were defined, and the processes were set up in an LCA environment (LCA for experts - before Gabi Sphera) for further environmental and economic assessment. The processes are assumed to be black boxes with inputs and outputs for the most important value flows, which are shown in the tables below. Tables 8 and 9 serve as important information for all LCA partitioners and experts who want to use the developed LCI or the results of the BEST4Hy project. They need to be aware that EoL processes are not yet fully developed and optimized (low TRL level, assumptions), so the environmental impact per functional unit (mass of recovered critical or rare earths) is usually overestimated compared to industry TRLs (high TRL level, [30]). Nevertheless, the developed LCI includes all relevant mass and energy flows and processes that are important for the recovery of the targeted critical materials and will not change (apart from the quantities per FU) even at higher TRLs. Ten new LCI and LCA models were developed as part of the BEST4Hy project, which represent significant progress compared to the baseline at the end of the EU HytechCycling project [31]. For all LCI/LCA models developed within the BEST4Hy project, the overall assessment of the technical level, completeness and assumptions included in the models was carried out using the newly developed BEST4Hy LCI/LCA Quality Indicator (QI), which ranges from 1 to 5 and represents the overall usability of the developed models for LCA experts and analysts:

1. Additional/further investigation of all mass and energy flows is mandatory.
2. Additional updating of most mass and energy flows required.
3. Additional partial update of mass and energy flows required.
4. Can be used for LCA studies with mandatory sensitivity analysis.
5. Can be used in other LCA studies with reliable quality.

The developed LCI/LCA for the **PEMFC EoL recovery processes** (see Table 8) with boundaries are:

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i. ***Hydrometallurgical (HMT) Pt recovery process**:* The LCI and LCA models for the BEST4Hy HMT process include Pt recovery from EoL CCM to produce Pt salt, using all relevant waste streams and other material/energy flows without additional waste stream treatment. The LCA model includes primary data from (IDO-Lab) and secondary data from Gabi Sphera and Ecoinvent databases. The LCI/LCA model is based on technology level TRL 5 with a geographical reference to the EU, Germany, and the year 2023 as the reference year. Based on the completeness of the LCA/LCI model and the technological assumptions, the BEST4Hy Quality Indicator (QI) is 4.

ii. ***Pt/C polyol synthesis:*** The LCI and LCA models for the BEST4Hy Pt/C catalyst synthesis based on polyol synthesis include the Pt salt and carbon Vulcan synthesis to obtain the Pt/C catalyst with all relevant waste streams and other material/energy flows used for these processes without additional waste stream treatment. The LCA model includes primary data from (CEA) and secondary data from Gabi Sphera and Ecoinvent databases. The LCI/LCA model is based on technology level TRL 5 with a geographical reference to the EU, France, and the reference year 2023. Based on the completeness of the LCA/LCI models and the technological assumptions, the BEST4Hy quality indicator (QI) is 3.

iii. ***PEMFC MEA disassembly (5th hybrid method):*** The LCI and LCA models for the BEST4Hy PEMFC MEA disassembly process include the dismantling of EoL PEMFC MEA to recover EoL CCM for further treatment with all relevant waste streams and other material/energy flows used for these processes without additional waste stream treatment. The LCA model includes primary data from (HRD) and secondary data from Gabi Sphera and Ecoinvent databases. The LCI/LCA model is based on technology level TRL 5 with a geographical reference to the EU, Germany, and the reference year 2023. Based on the completeness of the LCA/LCI models and the technological assumptions, the BEST4Hy quality indicator (QI) is 3.

iv. ***Alcohol dissolution (AD) process:*** The LCI and LCA models for the BEST4Hy-AD process include the recovery of Pt ink and ionomer from EoL CCM with all relevant waste streams and other material/energy flows used without additional waste stream treatment. The LCA model includes primary data from (IDO-Lab) and secondary data from Gabi Sphera and Ecoinvent databases. The LCI/LCA model is based on technology level TRL 5 with a geographical reference to the EU, Germany, and the year 2023 as the reference year. Based on the completeness of the LCA/LCI model and the technological assumptions, the BEST4Hy Quality Indicator (QI) is 3.

v. ***Electrochemical metallic Pt recovery process**:* The LCI and LCA models for the BEST4Hy electrochemical recovery process include the recovery of metallic Pt from EoL CCM and GDL with all relevant waste streams and other material/energy flows used without additional waste stream treatment. The LCA model contains primary data from (CEA) and secondary data from Gabi Sphera and Ecoinvent databases. The LCI/LCA model is based on technology level TRL 5 with a geographical reference to the EU, Germany, and the year 2023 as the reference year. Based on the completeness of the LCA/LCI model and the technological assumptions, the BEST4Hy Quality Indicator (QI) is 3.

And for the **SOFC EoL recovery processes** (see Table 9) with boundaries are:

i. ***SOFC anode recovery process**:* The LCI and LCA models for the BEST4Hy SOFC anode recovery include the YSZ and NiO recovery from the EoL SOFC cell with all relevant waste streams and other material/energy flows used without additional waste stream treatment based on technology level TRL 5. The LCA model includes primary data from (POLITO) and secondary data (Gabi Sphera and Ecoinvent) with a geographical reference to the EU, Italy, and the year 2023 as reference year. Based on the completeness and technological assumptions, the BEST4Hy Quality Indicator (QI) is 3.

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*Table 8: BEST4Hy matrix with main information regarding PEMFC EoL recovery processes, valuable flows, TRL level and LCI/LCA quality indicator*

| PEMFC EoL recovery processes | Main input valuable flows | | Main output valuable flow | | TRL level[1] | LCI/LCA data used[4] | System boundaries[3] | LCI/LCA QI[2] |
|---|---|---|---|---|---|---|---|---|
| | **Description** | **Mass** | **Description** | **Mass** | **TRL scale (1 to 9)** | **1. Primary<br>2. Generic<br>3. Assumptions** | **1. LCA scope<br>2. Geographical<br>3. Time horizon** | **Scale (1-5)** |
| Hydrometallurgical (HMT) Pt recovery process | **EoL CCM** | 5.237 g | **Pt salt** | 1.0 g | TRL 5 | 1,2 | 1. ''gate to gate''<br>2. EU, GER<br>3. 2023 | 4 |
| Pt/C polyol synthesis | **Pt salt**<br>**Carbon Vulcan (XC-72)** | 2.822 g<br>1.497 g | **Pt/C catalyst** | 2.5 g | TRL 5 | 1,2,3 | 1. ''gate to gate''<br>2. EU, FR<br>3. 2023 | 3 |
| EoL PEMFC MEA disassembly (5th hybrid method) | **EoL PEMFC MEA** | 14.4 g | **EoL CCM** | 1.1 g | TRL 5 | 1,2,3 | 1. ''gate to gate''<br>2. EU, GER<br>3. 2022 | 3 |
| Alcohol dissolution (AD) process (economic allocation) | **EoL CCM** | 1.42 g | **Pt ink,**<br>**Ionomer** | 55.71 g<br>1.0 g | TRL 5 | 1,2,3 | 1. ''gate to gate''<br>2. EU, GER<br>3. 2023 | 3 |
| Electrochemical metallic Pt recovery (electroleaching & electrodeposition) | **EoL CCM** | 9.153 g | **metallic Pt** | 1.0 g | TRL 5 | 1,2,3 | 1. ''gate to gate''<br>2. EU, FR<br>3. 2023 | 3 |

1 - Technology Readiness Levels is from TRL1 (basic technology research) to TRL 9 (system test, launch and operations) [30].
2 - LCI/LCA QI (BEST4Hy quality indicator) is a value from 1 to 5. It gives information regarding the quality level of LCI developed within EU BEST4Hy project.
3 – The system boundaries defined the technical boundaries of the LCA study, geographical reference of the technology and energy consumption as well as the time horizon of the reference year. For all processes, the ''gate to gate'' scope was analyzed without additional treatment of the waste streams with included extraction or raw materials until the end of production for all materials used in the EoL recovery processes.

*Table 9: BEST4Hy matrix with main information regarding SOFC EoL recovery processes, valuable flows, TRL level and LCI/LCA quality indicator*

| SOFC EoL recovery processes | Main input valuable flow | | Main output valuable flow | | TRL level[1] | LCI/LCA data used[4] | System boundaries[3] | LCI/LCA QI[2] |
|---|---|---|---|---|---|---|---|---|
| | **Description** | **Mass** | **Description** | **Mass** | **TRL scale (1 to 9)** | **1. Primary<br>2. Generic<br>3. Assumptions** | **1. LCA scope<br>2. Geographical<br>3. Time horizon** | **QI Scale (1-5)** |
| SOFC anode recovery process | **EoL SOFC cell** | 5.06 g | **YSZ**<br>**NiO** | 2.02 g<br>1.0 g | TRL 5 | 1,2,3 | 1. ''gate to gate''<br>2. EU, IT<br>3. 2023 | 3 |
| Lanthanum and cobalt recovery (**nitric** acid route) | **EoL SOFC cathode** | 18.02 g | **$La_2O_3$**<br>**$Co_3O_4$** | 1.36 g<br>1.0 g | TRL 3 | 1,2,3 | 1. ''gate to gate''<br>2. EU, IT<br>3. 2023 | 2 |
| Lanthanum and cobalt recovery (**sulfuric** acid route) | **EoL SOFC cathode** | 19.71 g | **$NaLa(SO_4)_2 \cdot 2H_2O$**<br>**$Co_3O_4$** | 2.125 g<br>1.0 g | TRL 2 | 1,3 | 1. ''gate to gate''<br>2. EU, IT<br>3. 2022 | 1 |
| Lanthanum and cobalt recovery (**citric** acid route) | **EoL SOFC cathode** | 17.05 | **La oxide + Co oxide + La St Co oxide**<br>**La oxide + Co oxide** | 1.0 g<br>0.892 g | TRL 2 | 1,3 | 1. ''gate to gate''<br>2. EU, IT<br>3. 2023 | 1 |
| Recovery of SOFC scrap cells | **NiO-YSZ scrap SOFC cell** | 11.0g | **NiO-YSZ <25μm** (after 3rd milling**)** | 5.06 g | TRL 3 | 1,2 | 1. ''gate to gate''<br>2. EU, IT<br>3. 2023 | 3 |

1 - Technology Readiness Levels is from TRL1 (basic technology research) to TRL 9 (system test, launch and operations) [30].
2 - LCI/LCA QI (BEST4Hy quality indicator) is a value from 1 to 5. It gives information regarding the quality level of LCI developed within EU BEST4Hy project.
3 – The system boundaries defined the technical boundaries of the LCA study, geographical reference of the technology and energy consumption as well as the time horizon of the reference year. For all processes, the ''gate to gate'' scope was analyzed without additional treatment of the waste streams with included extraction or raw materials until the end of production for all materials used in the EoL recovery processes.

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ii. ***Lanthanum and cobalt recovery (nitric acid route):*** The LCI and LCA models for La and Co recovery of BEST4Hy include the recovery of La oxide and Ni oxide from the EoL SOFC cathode via the nitric acid route, using all relevant waste streams and other material/energy flows used without additional waste stream treatment based on technology level TRL 3. The LCA model includes primary data from (POLITO) and secondary data (Gabi Sphera and Ecoinvent) with a geographical reference to the EU, Italy, and the year 2023 as reference year. Based on the completeness and technological assumptions, the BEST4Hy Quality Indicator (QI) is 2.

iii. ***Lanthanum and cobalt recovery (sulfuric acid route):*** The LCI and LCA models for the La and Co recovery of BEST4Hy include sodium lanthanum sulphate hydrate and the recovery of Ni oxide from the EoL SOFC cathode via the sulphuric acid route, using all relevant waste streams and other material/energy flows used without additional waste stream treatment at technology level TRL 2. The LCA model includes primary data from (POLITO) and secondary data (Gabi Sphera and Ecoinvent) with a geographical reference to the EU, Italy, and the year 2023 as reference year. Based on the completeness and technological assumptions, the BEST4Hy Quality Indicator (QI) is 1.

iv. ***Lanthanum and cobalt recovery (citric acid route):*** The LCI and LCA models for the La and Co recovery of BEST4Hy include the recovery of lanthanum oxide, cobalt oxide and lanthanum strontium cobalt oxide from the EoL SOFC cathode via the citric acid route, using all relevant waste streams and other material/energy flows used without additional waste stream treatment at technology level TRL 2. The LCA model includes primary data from (POLITO) and secondary data (Gabi Sphera and Ecoinvent) with a geographical reference to the EU, Italy and the year 2023 as reference year. Based on the completeness and technological assumptions, the BEST4Hy Quality Indicator (QI) is 1.

v. ***Recovery of SOFC scrap cells:*** The LCI and LCA models for the BEST4Hy SOFC scrap cells include NiO-YSZ recovery from SOFC scrap cells based on milling and sieving with all relevant waste streams and other material/energy flows used without additional waste stream treatment at technology level TRL 3. The LCA model includes primary data from (POLITO) and secondary data (Gabi Sphera and Ecoinvent) with a geographical reference to the EU, Italy, and the year 2023 as reference year. Based on the completeness and technological assumptions, the BEST4Hy Quality Indicator (QI) is 3.

## 6.1 Final remarks

The main conclusions for PEMFC EoL technologies in the context of sustainability assessment and development within BEST4Hy are:

- In M36 of the EU project BEST4Hy, a fairly high level (TRL5) of EoL process development was achieved, with good quality of LCI/LCA models for the manufacturing phase and for the EoL phase**. All processes and materials required for modelling are available in generic LCA databases of good quality**. A solid starting point for the further development of EoL processes and the extension of these processes to higher TRL levels and the upscale to industrial level.

The main conclusions for SOFC EoL technologies in the context of sustainability assessment and development within BEST4Hy are:

- At M36 of the EU BEST4Hy project, there are still very few databases for critical materials and rare earths available in generic databases for SOFC technology for the

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manufacturing phase, so further improvements are needed to get better results and insights into the sustainability assessment of this technology**. Future work will therefore focus on the definition of life cycle inventories for material production of SOFC technology**.

- The LCA study and the novel LCI of SOFC EoL technologies, even at low TRL level and under numerous assumptions, **provide a very good insight and basis for the environmental impact of SOFC recycling technologies with the identification of critical steps and hotspots** that need to be addressed on the path of further development and transition to upscaling of these technologies to higher TRL level.
- All developed EoL processes with associated mass and energy balances (LCI) represent a **significant advance for the LCA of SOFC EoL processes and technologies**, which were not previously available and should be further improved and upscaled to be more promising in terms of environmental and economic impact assessment and to be utilized by LCA practitioners.

**Life cycle inventories (LCI) and LCA models for material recycling**

*All LCI and LCA models are based on laboratory-scale processes (low TRL levels: SOFC at TRL 3 and PEMFC at TRL 5) and are still in the development phase, which must be taken into account when interpreting the results on the environmental impact of these technologies. Nevertheless, these results provide very good and essential inputs for FCH technologies for further development and optimization of LCI and LCA models.*

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# 7 Conclusions

The main objective of D5.2 was to conduct an environmental LCA study for three novel EoL technologies developed within the EU project BEST4Hy, namely for the PEMFC technology the alcohol dissolution (AD) process for Pt and ionomer recovery, the electrochemical Pt recovery process for open loop Pt recycling and for the SOFC technology the recovery of lanthanum and cobalt from EoL-SOFC cathode cells. In addition, the economic evaluation based on the life cycle cost (LCC) method was developed for the EoL FCH technology and the results were presented based on the platinum recycling process with hydrometallurgical treatment of CCM waste from PEMFC stacks. The LCA models were created using the software LCA for experts (formerly Gabi Sphera) with the integrated generic databases Gabi Professional and Ecoinvent. Some processes and materials for which no data was available were additionally modelled based on LCI from the literature by other authors, with additional inputs and assumptions from the BEST4Hy partners. The scope of the study was "gate to gate" (end-of-life phase), as the focus was on demonstrating the impact of novel BEST4Hy EoL technologies.

One of the objectives of the BEST4Hy project was to present the environmental profile of novel BEST4Hy EoL processes with the definition of all relevant energy and material flows for the recovery of Pt and ionomer (AD process at TRL5) and the electrochemical recovery of metallic Pt (TRL5) in the case of the PEMFC stack and in the case of the SOFC stack of lanthanum oxide and cobalt oxide (nitric acid at TRL3).

The results of the environmental LCA study show that for the AD process, the highest contribution to the overall environmental impact comes from two-step centrifugation at 67.8% of total impact, followed by AD in the LPR process (25.2%). The total climate change indicator of the BEST4Hy AD process is 3.385 kg $CO_2$eq. per 1 g of recovered Pt salt and 9.41 g of recovered ionomer (without economic allocation) if the EU grid mix is used and a 70% reduction can be achieved for renewable electricity (from 3.385 kg $CO_2$eq. to 1.02 kg$CO_2$eq. per reference output flow). In the electrochemical recovery of metallic Pt, the iridium-tantalum coating on DSA makes the largest contribution to the overall environmental impact with 62.1%, followed by the ionic liquid (25.2%) and the titanium used for the DSA substrate (11.9%). The total climate change of the electrochemical Pt recovery process BEST4Hy (TRL5) is 72.35 kg $CO_2$eq. per 1g Pt for the case that ionic liquids are not reused, and a reduction of 42.7% could be achieved with 8-fold reuse of the ionic liquid (41.47 kg $CO_2$eq./1g Pt). In the case of lanthanum and cobalt recovery, the environmental impact results are evenly distributed across all sub-processes and there is no clear hotspot within the sub-processes. The total environmental impact for climate change from lanthanum and cobalt recovery from the BEST4Hy SOFC cathode (TRL3) is 3.638 kg $CO_2$eq. per reference flow (1.36 g lanthanum oxide and 1 g cobalt oxide).

In addition to the environmental LCA, the first innovative life cycle cost (LCC) model for the EoL technology within the FCH technologies was developed and the results based on Pt recycling via the HMT process from the PEMFC waste stack were presented as a case study. The results of the LCC study show a promising economic potential for the recycling industry, **and BEST4Hy KO5 is achieved**, which states that the cost of recycled materials in a scenario with industrialized recycling processes should be comparable to the market cost of virgin materials (±10%). In addition, a total GHG reduction of -20% or more in the

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entire production life cycle (presented in D5.1) was achieved and presented as part of WP5 of the **BEST4Hy project KO4**, which defines the LCA and LCC of the EoL processes for sustainability benchmarking.

In M36 of the BEST4Hy project, the main results of WP5 are **ten newly developed life cycle inventories** (LCI) and LCA models for FCH technologies related to the recycling processes. A detailed analysis of all LCI and LCA models developed within BEST4Hy is presented in a separate chapter (Chapter 6) with a quality assessment based on a new **BEST4Hy Quality Indicator (QI)** – a valuable contribution for LCA experts and analysts of FCH technologies beyond the BEST4Hy project.

The LCA analysis and the novel LCI of SOFC EoL technologies, even at low TRL level and under numerous assumptions, provide a very good insight and basis for the environmental impact of SOFC recycling technologies **with the identification of critical steps and hotspots** that need to be addressed on the path of further development and transition to upscaling of these technologies (at higher TRL level).

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