eGHOST
eco-design Guidelines for Hydrogen Systems and Technologies

D2.4 Evaluation according to the MEErP methodology of base case

WP2 Definition of FCH products systems

Grant No. 101007166

Project start date: 01.01.2021
Project duration: 36 months
Project Coordinator: *IMDEA Energy*

WP LEADER	*IMDEA Energy*
DELIVERABLE AUTHORS	*Eleonora Bargiacchi, Felipe Campos Carriedo, Diego Iribarren, Javier Dufour (IMDEA Energy); Agata Horwacik, Darío Cortés (FHa)*
REVIEWER	*CEA*
STATUS	*FD: Final Draft*
DISSEMINATION LEVEL	*PU*
DELIVERABLE TYPE	*R*
DUE DATE	*30/09/2021 (M9)*

Co-funded by the European Union

Clean Hydrogen Partnership

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe Research.

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

DOCUMENT CHANGE CONTROL

VERSION NUMBER	DATE OF ISSUE	AUTHORS	BRIEF DESCRIPTION OF CHANGES
1	31/08/2021	Eleonora Bargiacchi, Felipe Campos Carriedo, Diego Iribarren, Javier Dufour (IMDEA Energy); Agata Horwacik, Darío Cortés (FHa)	Final draft for internal review
2	30/09/2021	Eleonora Bargiacchi, Felipe Campos Carriedo, Diego Iribarren, Javier Dufour (IMDEA Energy); Agata Horwacik, Darío Cortés (FHa)	Final version with revisions implemented after internal peer-review
3	22/11/2022	Eleonora Bargiacchi, Felipe Campos Carriedo, Diego Iribarren, Javier Dufour (IMDEA Energy)	Final version including revisions and comments of the project officer and reviewers

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

EXECUTIVE SUMMARY

This deliverable explores the application of the Methodology for Eco-design of Energy-related Products (MEErP) and its associated EcoReport tool to one of the two products investigated in the eGHOST project: a 48 kW Proton-Exchange Membrane Fuel Cell (PEMFC) stack. The goal of this application is to explore the suitability and practicality of the European Eco-design Directive (and associated tools) to support the development of sustainable-by-design hydrogen products. The functional unit refers to the PEMFC stack, in coherence with the project scope and the previous deliverables, though other phases besides manufacturing and end of life (distribution, use) are included in the analysis to fully illustrate the use of the EcoReport tool and provide a picture of the overall system. Regarding the use phase, a sensitivity analysis on the type of hydrogen (green, grey, blue) fed to the PEMFC stack and the associated impacts and costs is provided. The Critical Raw Materials (CRMs) present in the stack are identified and a CRM assessment is carried out.

Platinum extraction and production represents more than 50% of the contribution in all of the considered impact categories. Recycling and reuse of the materials give moderate benefits by reducing the total impact in each of the categories. Overall, the results qualitatively confirm the Life Cycle Assessment (LCA) results presented in eGHOST Deliverable 2.3. Concerning both the LCA and the Life Cycle Costing (LCC), the use phase constitutes a relevant share of the total impacts and costs, but a more detailed and case-specific modelling is needed.

Nevertheless, the main conclusion of the application of the EcoReport tool to the case study is that it should be updated in order to be an effective and consistent simplified tool for LCA and LCC of Fuel Cells and Hydrogen (FCH) systems. In particular, the list of extra materials should be enlarged to comprise the typical hotspots of these systems, and the characterisation factors (CF) of the methodology should be updated and made consistent with the current LCA ones.

Co-funded by the European Union

Clean Hydrogen Partnership

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

CONTENTS

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

LIST OF FIGURES

Co-funded by the European Union
Clean Hydrogen Partnership
This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

LIST OF TABLES

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

ABBREVIATIONS

AP	Acidification impact Potential
BoP	Balance of Plant
CAGR	Compound Annual Growth Rate
CCS	Carbon Capture Storage
CF	Characterisation Factor
CRM	Critical Raw Material
EoL	End of Life
EU	European Union
FCH	Fuel Cells and Hydrogen
FU	Functional Unit
GWP	Global Warming impact Potential
HREEs	Heavy Rare Earth Elements
LREEs	Light Rare Earth Elements
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
MEErP	Methodology for Ecodesign of Energy-related Products
OE	Operating Expense
PEMFC	Proton-Exchange Membrane Fuel Cell
PGMs	Platinum Group Metals
PP	Purchasing Price
PWF	Present Worth Factor
REEs	Rare Earth Elements
SOEC	Solid Oxide Electrolysis Cell
WP	Work Package

Co-funded by the European Union

Clean Hydrogen Partnership

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

REPORT

1. INTRODUCTION

This report is framed in the Work Package 2 (WP2) of the eGHOST project: Definition of Reference Products. To that end, simplified environmental **Life Cycle Assessment (LCA)**, **Life Cycle Costing (LCC)** and **Critical Raw Material (CRM) assessment** studies are performed on one of the eGHOST reference products (a Proton Exchange Membrane Fuel Cell - PEMFC - stack), following the Methodology for Eco-design of Energy-related Products (MEErP).

MEErP is a methodology for **eco-design preparatory studies of energy-related products** that enables carrying out the above-mentioned assessments in a standardised manner. It was developed in 2011, as a review and an extension of the previously established Methodology for Eco-design of Energy-using Products (MEEuP) (1). Its main goal is to evaluate whether and to which extent new energy-related products (with a minimum market penetration of 200,000 units) fulfil certain economic and sustainability criteria under the European Eco-design Directive 2009/125/EC (2). Hence, the MEErP methodology aims to contribute to sustainable development by providing a harmonising framework and legislation to ease the functioning of the internal market. The MEErP is complemented by the EcoReport software tool, publicly available for download as a .xls file (3), to generate environmental and economic performance results that facilitate comparisons between systems and subsequent policy- and decision-making regarding energy-related technologies. As done in the past for other energy-related products such as batteries (4), this methodology along with the related **EcoReport tool is, for the first time, applied herein to an FCH (fuel cells and hydrogen) system**, using a PEMFC stack as the reference product. It was selected because this is the type of product that will likely meet the requirement of 200,000 products in the market, the amount required to be considered in the Directive.

2. OBJECTIVE

The objective of this report is to illustrate and discuss the application of the EcoReport tool, according to the Eco-design Directive, to an FCH system. Besides the LCA and LCC of the base case (PEMFC stack), a CRM assessment is also performed using the EcoReport tool. The main goal of this application is to test and discuss the suitability and practicality of the European Eco-design Directive to effectively support the production of sustainable-by-design hydrogen products. In this sense, this deliverable is intended as complementary, and not a replacement, to "D2.3 – Definition and evaluation of base case studies" since it discusses the suitability and practicality of this legislative framework for a preliminary analysis (e.g., hotspot identification), eventually by a broader public than LCA/LCC experts.

Co-funded by the European Union

Clean Hydrogen Partnership

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

3. SYSTEM DEFINITION AND METHODOLOGY

The EcoReport tool included in the MEErP allows carrying out LCA and LCC studies for energy-related products in a simplified and standardised manner. Results are generated by default from a **cradle-to-grave perspective**, taking into account the phases of extraction & production of materials, manufacturing, distribution, use and end of life (EoL). Within the context of the eGHOST project, which focuses on the eco-design of hydrogen technologies, the first two of the mentioned stages are the ones modelled and analysed with a closer scrutiny. An approximated model of other phases (distribution, use and EoL) is also presented to quantify their contribution to cost and environmental impacts and fully employ the tool potential.

The impact categories included in the tool and found to be relevant to the present study, together with their linked units, **can be found in Table 1**. It is important to remark that not all of them are considered in every phase of the life cycle of the product. Further detail on this issue is included in Section 3.2.

Table 1. Impact categories within the EcoReport tool

LCA		
Impact category		**Unit**
Mass	Weight	g
Energy	Primary energy demand	MJ
Emissions to air	Global warming impact potential (GWP)	kg CO_2-eq
	Acidification impact potential (AP)	g SO_2-eq
	Volatile organic compounds (VOC)	mg
	Persistent organic pollutants (POP)	ng i-Teq
	Heavy metals (HM)	mg Ni-eq
	Polycyclic aromatic hydrocarbons (PAH)	mg Ni-eq
	Particulate matter (PM)	g
Emissions to water	Heavy metals (HM)	mg Hg-eq
	Eutrophication	mg PO_4^{---} -eq

LCC	
Impact category	**Unit**
Life cycle cost	€
Life cycle cost (with externalities)	€

3.1 Base case and functional unit

The base case selected to be assessed through the EcoReport tool is **one 48 kW PEMFC stack** with the bill of materials (BoM) as defined in eGHOST Deliverable 2.3 (5), which

Co-funded by the European Union
Clean Hydrogen Partnership
This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

constitutes the functional unit (FU) of the present deliverable. The environmental impacts and costs associated to stack production, distribution and use are addressed as explained in Section 3.2.

Furthermore, some of the calculations and results presented in the following sections refer to the prospective full European product system. This provides an overview of the impacts' relevance over the EU totals.

The scope of the study does not include a Solid Oxide Electrolysis Cell (SOEC) stack (the other hydrogen technology that the eGHOST project addresses) since this technology is not expected to reach –in the short term– the minimum market penetration established as a threshold to be evaluated by the MEErP (200,000 units per year sold).

3.2 Product life cycle information

3.2.1 Stack production phase

The BoM employed to assess the production phase of the PEMFC stack derives from eGHOST Deliverable 2.3 (5) and it is reported in Table 2.

Table 2. BoM of the evaluated 48 kW PEMFC stack

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !
1	Platinum	26.0	8-Extra	102-Platinum
2	Carbon black particles	591.8	8-Extra	103-Carbon black particles
3	Ionomer	172.4	8-Extra	104-Ionomer
4	PET	5678.0	1-BlkPlastics	10 -PET
5	Thermoactive glue	1420.0	8-Extra	105-Thermoactivable glue
6	GDL (Carbon fibre+PTFE)	883.1	8-Extra	106-Carbon fibre reinforced plastic
7	Stainless steel	21622.5	3-Ferro	26 -Stainless 18/8 coil
8	Silicone	5000.0	8-Extra	107-Silicone
9	Glass-reinforced thermoplastic	3800.0	2-TecPlastics	19 -E-glass fibre
10	Copper	950.0	4-Non-ferro	30 -Cu wire
11	Steel	3672.0	3-Ferro	23 -St tube/profile

For the materials that do not match a default category (with a life cycle inventory, LCI, pre-defined inside the tool), the option "Extra" is selected. An inventory for unit impacts (per kg) of the production of each of these **"extra" materials** needs to be built (see Table 3). In order to do so, data are retrieved from ecoinvent v3 and processed with SimaPro v9 software[1]. The impact assessment method is built using the characterisation factors (CFs) provided in the MEErP Methodology Part 2 document. Among the impact

[1] The carbon footprint of the ionomer is inferred from eGHOST Deliverable 2.3 LCA results.

Co-funded by the European Union
Clean Hydrogen Partnership
This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

categories reported in the MEErP, those reported in Table 1 are considered. Categories such as electric energy, feedstock, water (process), water (cooling) and waste (hazardous and non-hazardous) are instead excluded because not fully specified in the MEErP document.

Table 3. Impacts (per kg of material) of the materials modelled in the "Extra" category (production phase)

nr	Name material	Mass	Primary Energy	GWP	AP	VOC	POP	Hma	PAH	PM	HMw	EUP
unit	New Materials production phase (category '**Extra**')	kg	MJ	kg CO2 eq.	g SO2 eq.	mg	ng i-Teq	mg Ni eq.	mg Ni eq.	g	mg Hg/20	mg PO4
102	**Platinum**	0.03	1133551.00	70122.35	3901566.60	81975.66	29703.96	209450.40	381327.96	59902.93	529967.00	39521199.00
103	**Carbon black particles**	0.59	81.12	1.84	10.00	0.48	0.35	5.06	23.63	2.61	25.84	3507.82
104	**Ionomer**	0.17		959.00								
105	**Thermoactive glue**	1.42	71.20	3.39	13.34	26.42	1.11	19.92	28.20	4.08	34.01	5902.44
106	**Carbon fibre reinforced plastic**	0.88	1199.39	85.85	429.67	24.84	31.81	171.00	603.78	136.83	689.47	37729.45
107	**Silicone**	5.00	60.91	2.93	13.29	2.82	0.69	9.47	15.85	2.82	21.53	1602.14

From the BoM, the tool automatically calculates the impacts associated to the production of those materials and to the common manufacturing processes that enable obtaining the final product (the only value that can be edited at this point is the percentage of sheet metal scrap, which is set at 25% by default).

3.2.2 Additional phases

Distribution

Once stated that the product under scrutiny is neither a consumer electronic device nor an installed appliance, the impacts associated to the distribution phase are calculated from fixed values within the tool. The only parameter to be modified at this point is the packaged volume of the product, which is 0.03 m^3 (from specifications provided in eGHOST Deliverable 2.3 and assuming a 2 cm offset per dimension).

Use

The product service life is assumed to be 10 years. This value takes into account: 1) an average duration of **3,000 hours** for transport applications (considering 300 hours per year of vehicle usage) or 2) an average duration of 40,000-60,000 hours for stationary applications (6). Since duration and lifetime depend on several factors (e.g., vehicle usage), average and conservative values which reflect the current state of the art of PEMFCs are adopted (7). Higher values of equivalent hours per year (e.g., 500 hours per year) would imply a higher hydrogen consumption per year and therefore a more relevant contribution of the use phase to the environmental impacts and LCC results.

Co-funded by the European Union

Clean Hydrogen Partnership

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

Although the direct impact of the use phase of a PEMFC stack is negligible, it is necessary to assess its indirect impact in order to avoid missing relevant contributions. In the scope of the present study and acknowledging the limitations of the tool, **the impacts associated to hydrogen production** (considering alternative origins: "Green" from water electrolysis, "Grey" from steam methane reforming without Carbon Capture and Storage (CCS), and "Blue" from steam methane reforming with CCS) **and the balance of plant (BoP) are modelled as auxiliary materials** in the GWP and AP categories (see Table 4). In this way, it is possible to contextualise the results beyond the (more detailed) stack production phase by following a cradle-to-grave approach. These auxiliary materials are introduced in the tool as mass per year consumptions.

Table 4. Unit impacts of the auxiliary materials modelled for the use phase

	GWP [kg CO_2-eq/kg H_2]	AP [kg SO_2-eq/kg H_2]
Hydrogen (Green)	1.17 (8)	0.01 (8)
Hydrogen (Grey)	11.51 (8)	0.02 (8)
Hydrogen (Blue)	5.8 (9)	0.02 (9)
BoP	7.03 (10)[2]	0.02 (10)

Since in 2030 it is forecasted that the major PEMFC application could be mobility, typical values to calculate the PEMFC yearly hydrogen consumption were chosen. The hydrogen fuel rate is set at 96 kg/yr (assuming 0.008 kg H_2/km and 12,000 km/yr (11)) (10). The BoP mass of 33 kg (10) (55 kg before scaling to the base case power) is distributed along the 20 years estimated as its lifetime (6), resulting in a consumption per year of 1.65 kg. In particular, the BoP includes four management systems (air, water, thermal, and fuel) in the following components: air filtration and a compressor/expander module for air supply, an enthalpy wheel humidifier for cathode air and a membrane humidifier for anode hydrogen, high-temperature radiators and a high-temperature coolant pump, a hydrogen recirculation blower and ejectors (10).

End of life

The annual sales of the base case are set at 200,000 units in 2030 (threshold for a product to be evaluated by the MEErP). If a market penetration of 50,000 units/yr is assumed in 2020, this results in a compound annual growth rate (CAGR) of 14.9%. The tool uses these economic parameters to estimate the maximum amount of mass that is available from secondary raw materials (*recymax* value) to be used in the production of new products.

It is also necessary to define the EoL scenarios for each of the groups of materials selected in the production phase. **Every component of the PEMFC stack but the membrane is considered to be 100% reused after the service lifetime of ten years** (thus assuming a more extended lifetime for these components). The EoL scenarios for the materials contained in the membrane are established as defined in Table 5.

[2] Value scaled to base case power.

Co-funded by the European Union
Clean Hydrogen Partnership
This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

Table 5. EoL scenarios assumed for the materials contained in the membrane of the PEMFC

	Platinum	Carbon black particles	Ionomer	Gas diffusion layer	Thermoactive glue	PET
Reuse	0%	0%	0%	0%	0%	0%
Recycling	75% (12)	0%	0%	0%	0%	100%
Recovery	0%	0%	0%	0%	0%	0%
Incineration	0%	0%	50% (13)	0%	100%	0%
Landfilling/ fugitives	25%	100%	50%	100%	0%	0%

These fractions, with respect to the maximum recyclable mass (*recymax*) previously calculated, are multiplied by a credit (in the case of reuse, recycling and recovery options) or a debit (for incineration and landfilling) available as default percentages that, when applied to the impact calculated before considering the EoL, result in an avoided (negative) or aggregated (positive) impact to be added to the full life cycle of the product system. Concerning the category "Extra", it is important to remark that the tool only allows assigning EoL scenarios to the category as a whole. For the purpose of this study, the internal structure of the spreadsheet was modified in order to assess each "extra" material separately.

3.3 Economic parameters

The case study under evaluation is assumed to achieve the market penetration established as a threshold in 2030. This is the reference year for the economic analysis.

The LCC is performed according to the MEErP methodology (14) (see Eq. 1):

$$LCC = PP + PWF \cdot OE + EoL \quad \text{(Eq. 1)}$$

where: LCC = Life Cycle Costs to end-users in €

PP = purchasing price including installation costs in €

OE = annual operating expense in €

PWF = Present Worth Factor = $1 - \left(\frac{1+e}{1+d}\right) \cdot \left[1 - \left(\frac{1+e}{1+d}\right)^N\right]$

Where *N* is the product life in years, *d* is the discount rate in % and *e* is the aggregated annual growth rate of the operating expense.

The PEMFC stack price is retrieved from the LCC presented in eGHOST Deliverable 2.3 (5), considering the use of only virgin platinum (conservative approach). This is 2,233 €/stack for an annual production capacity of 50,000 units. Since, as stated in the aforementioned deliverable, the economy of scale is not expected to affect the price from that production capacity upwards, the same value is accepted for the reference year. A discount rate of 8% is reported in the same document.

Co-funded by the European Union

Clean Hydrogen Partnership

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

Delivered hydrogen prices (Table 6) are estimated from internal sources for production costs, assuming that this phase of the full supply chain accounts for 36% of the final hydrogen price (15). These costs (which are set for 2020) are also made prospective considering that they will be 60% lower by 2030 (15).

The cost per year of the BoP is 13.03 €. This is calculated considering the unit costs of each of the systems inside the BoP (15), scaling them to the power of the base case, making a prospective 50% reduction (16) and dividing the economic flow by the 20 years set as lifetime.

The escalation rate (projected annual growth of running costs) is assumed to be 3%, as this is the global inflation rate predicted for 2030 (17). The considered ratio efficiency (efficiency of products in 2020 over expected efficiency in 2030) is 0.86 (18).

Table 6. Estimated delivered hydrogen prices

	€/kg H_2 (2020)	€/kg H_2 (2030)
Green H_2	13.83	5.53
Grey H_2	4.83	1.93
Blue H_2	5.27	2.11

3.4 Critical Raw Material assessment

The CRM list 2020 covers a wide range of materials, including 83 individual materials or 66 candidate raw materials comprising 63 individual materials and 3 grouped materials (10 individual heavy rare earth elements −HREEs−, 5 individual light rare earth elements −LREEs− and 5 individual platinum-group metals −PGMs−) (19). Among the raw materials assessed in the CRM list 2020, 30 were classified as critical (Table 7).

Table 7. Updated list of Critical Raw Materials 2020

Critical Raw Materials in 2020		
Antimony	Germanium	Phosphate rock
Baryte	Hafnium	Phosphorus
Bauxite	Heavy rare earth elements	Platinum group metals
Beryllium	Indium	Scandium
Bismuth	Light rare earth elements	Silicon metal
Borates	Lithium	Strontium
Cobalt	Magnesium	Tantalum
Coking coal	Natural graphite	Titanium
Fluorspar	Natural rubber	Tungsten
Gallium	Niobium	Vanadium

The 2020 list identifies 26 CRMs in common with the 2017 list, 3 CRMs not previously qualified as critical (bauxite, lithium and titanium), and a new candidate material found critical (strontium) (19).

Co-funded by the European Union

Clean Hydrogen Partnership

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

The CRM indicator used in this study is calculated according to the MEErP Methodology Part 2 document (14). **Within the PEMFC stack, there are two raw materials classified as critical: platinum and natural graphite**. The calculation of the CRM indicator for each of these materials is calculated by multiplying the weight of the CRM under investigation (in kg) by a material-specific CF (in kg Sb eq per kg CRM). The following formula is applied for CF calculation (14):

$$CF\ [kg\ Sb\ eq/kg\ CRM] = 12254.4/(A * B * C * (1 - D))$$

Where,

A = EU consumption [t/yr]
B = import dependency rate
C = substitutability supply risk
D = recycling rate

The number 12254.4 is the resultant of (A * B * C * (1 – D)) for the reference material (antimony) based on 2020 data (20,21).

4. RESULTS

4.1 EcoReport LCA results

Table 8 presents the contribution to the impact categories considering each of the life-cycle stages. **Platinum extraction and production represents more than 50% of the contribution to all of the considered impact categories**. Recycling and reuse of the materials provide moderate benefits by slightly reducing the total impacts in each of the categories, according to the EoL scenarios defined in Section 3.2.2.

The results are qualitatively in line with the LCA results presented in eGHOST Deliverable 2.3 (5). Indeed, with both methodologies, and focusing on the PEMFC stack manufacturing, platinum accounts for the major contribution (>60%) in all of the selected categories (apart from freshwater eutrophication in D2.3), arising as the technology hotspot. Nevertheless, as expected, the results in absolute values differ from the LCA results: the EcoReport tool provides an aggregated GWP of 2,304 kg CO_2-eq per stack for the materials production and manufacturing life cycle phases, while the LCA in Deliverable 2.3 estimates a significantly lower value. This difference is ascribable to the different impact assessment methods (therefore different impact categories, units and CFs), and the aggregation of materials into categories using average LCIs in the EcoReport tool. In this sense, the MEErP methodology should be updated with a more recent impact assessment method to make the two methodologies fully comparable and aligned, which is currently being addressed by the European Commission.

Tables 9-11 provide the environmental impact results in absolute values for the considered functional unit (one PEMFC stack) under different use scenarios: green hydrogen (Table 9), grey hydrogen (Table 10), and blue hydrogen (Table 11).

Co-funded by the European Union
Clean Hydrogen Partnership
This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

Table 8. Results breakdown per FU (1 stack) based on the EcoReport LCA results (green hydrogen)

Description	Phase	Weight [g]	Primary energy [MJ]	GWP [kg CO_2-eq]	AD [g SO2-eq]	VOC [mg]	POP [ng iT-eq]	HM [mg Ni-eq]	PAH [mg Ni-eq]	PM [g]	Heavy metals [mg Hg-eq]	Eutrophication [mg PO4-eq]
Platinum	**Extraction/ Production**	26	29472.33	1823.18	101440.73	2131.37	772.30	5445.71	9914.53	1557.48	13779.14	1027551.17
Carbon black particles	**Extraction/ Production**	591.8	48.00	1.09	5.92	0.28	0.21	2.99	13.99	1.54	15.29	2075.93
Ionomer	**Extraction/ Production**	172.4	0.00	165.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PET	**Extraction/ Production**	5678	447.43	17.66	195.15	7.38	0.00	12.87	8.24	28.39	0.01	2159.13
Thermoactive glue	**Extraction/ Production**	1420	101.10	4.82	18.95	37.51	1.58	28.29	40.05	5.80	48.30	8381.46
GDL (Carbon fibre+PTFE)	**Extraction/ Production**	883.1	1059.19	75.81	379.44	21.94	28.09	151.01	533.20	120.83	608.87	33318.88
Stainless steel	**Extraction/ Production**	21622.5	1341.50	134.17	1211.31	2.94	166.49	3206.72	0.61	171.12	1867.48	50335.67
Silicone	**Extraction/ Production**	5000	304.53	14.64	66.45	14.09	3.46	47.34	79.27	14.08	107.66	8010.70
Glass-reinforced thermoplastic	**Extraction/ Production**	3800	250.15	12.75	110.88	0.02	0.00	0.00	0.25	30.95	179.90	11975.24
Copper	**Extraction/ Production**	950	110.72	5.89	277.50	0.01	3.56	52.31	5.11	2.70	89.39	146.79
Steel	**Extraction/ Production**	3672	60.83	5.05	13.19	0.43	44.06	9.50	0.12	3.68	5.76	140.75
OEM Plastics Manufacturing	**Manufacturing**	0	387.18	21.48	92.62	0.03	0.00	0.00	0.12	14.28	0.00	226.32
Foundries Fe/Cu/Zn	**Manufacturing**	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Foundries Al/Mg	**Manufacturing**	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sheetmetal Manufacturing	**Manufacturing**	0	327.14	18.15	78.26	0.02	0.00	0.00	0.10	12.07	0.00	129.74
PWB Manufacturing	**Manufacturing**	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other materials	**Manufacturing**	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sheetmetal Scrap	**Manufacturing**	0	64.73	4.33	19.40	0.47	58.20	135.14	0.04	2.79	4.38	0.24
Appliannce per product	**Distribution**	0	51.50	4.52	12.16	0.05	0.29	2.62	2.62	0.26	0.08	1.36
Appliance per volume	**Distribution**	0	351.38	23.42	75.36	7.89	0.79	7.03	17.94	1608.13	0.22	3.69
Retail per volume	**Distribution**	0	250.75	14.71	41.93	2.52	0.91	8.24	4.27	107.78	0.25	4.29
Product volume	**Distribution**	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Retail per product	**Distribution**	0	58.97	4.03	12.74	0.04	0.31	2.79	0.09	0.27	0.09	1.45
Hydrogen fuel	**Use**	960000	13800.00	1120.80	10.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BoP	**Use**	16500	0.00	115.95	268.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Spare parts	**Use**	438.158	339.75	23.04	1039.10	22.16	10.78	90.92	105.96	19.66	167.06	11444.52
Re-use	**EoL**	53948.0046	-424.69	-37.99	-379.51	-4.66	-40.79	-624.14	-17.50	-41.24	-388.18	-9896.69
Recycle	**EoL**	3857.07152	-2235.44	-138.01	-7619.14	-159.85	-57.92	-408.43	-743.61	-119.91	-1051.43	-1197.52
Recovery	**EoL**	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Incineration	**EoL**	1521.01614	25.23	1.89	3.77	0.05	0.00	6.78	0.00	32.01	2.15	122.38
Landfill/ Fugitives	**EoL**	961427.866	26.78	2.00	3.79	0.11	3.31	7.84	0.00	34.86	2.22	127.20

Co-funded by the European Union

Clean Hydrogen Partnership

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

Table 9. EcoReport LCA results per FU (1 stack) in case of green hydrogen

	Life Cycle phases -->		PRODUCTION			DISTRIBUTION	USE	END-OF-LIFE				TOTAL
	Resources Use and Emissions		Material	Manuf.	Total			Disposal	Recycl.	Stock	Total	
	Materials	**unit**										
1	Bulk Plastics	g			5.678		57	0	1.434	4.301	5.735	4.301
2	TecPlastics	g			3.800		38	0	959	2.879	3.838	2.879
3	Ferro	g			25.295		253	0	6.387	19.161	25.547	19.161
4	Non-ferro	g			950		10	0	240	720	960	720
5	Coating	g			0		0	0	0	0	0	0
6	Electronics	g			0		0	0	0	0	0	0
7	Misc.	g			0		0	0	0	0	0	0
8	Extra	g			8.093		81	776	1.267	6.131	8.174	6.131
9	Auxiliaries	g			0		976.500	240.000	4.166	732.499	976.665	732.499
10	Refrigerant	g			0		0	0	0	0	0	0
0	Total weight	g	0	0	43816	0	976938	240776	14454	765689	1020919	765689
	Other Resources & Waste											
11	Total Energy (GER)	MJ	33.196	779	33.975	713	14.132	52	-2.660		-2.608	46.211
12	of which, electricity (in primary MJ)	MJ	382	457	839	1	4	0	-65		-65	780
13	Water (process)	ltr	1.885	6	1.892	0	19	0	-335		-335	1.575
14	Water (cooling)	ltr	1.418	203	1.621	0	14	0	-176		-176	1.459
15	Waste, non-haz./ landfill	g	26.280	3.212	29.492	407	263	89	-4.824		-4.735	25.427
16	Waste, hazardous/ incinerated	g	36	0	36	8	0	0	-4		-4	40
	Emissions (Air)											
17	GWP	kg CO2 eq.	2.260	44	2.304,357	47	1.259,36	4	-176		-172	3.438,28
18	AP	g SO2 eq.	103.720	190	103.910	142	1.318	8	-7.999		-7.991	97.379
19	Volatile Organic Compounds (VOC)	g	2.216	1	2.216	11	22	0	-165		-164	2.085
20	Persistent Organic Pollutants (POP)	ng i-Teq	1.020	58	1.078	2	10	3	-99		-95	995
21	Heavy Metals	mg Ni eq.	8.957	135	9.092	21	90	15	-1.033		-1.018	8.184
22	PAHs	mg Ni eq.	10.595	0	10.596	25	106	0	-761		-761	9.965
23	Particulate Matter (PM, dust)	g	1.937	29	1.966	1.716	19	67	-161		-94	3.607
	Emissions (Water)											
24	Heavy Metals	mg Hg/20	16.702	4	16.706	1	167	4	-1.440			15.439
25	Eutrophication	g PO4	1.144	0	1.144	0	11	0	-11			1.145

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

Table 10. EcoReport LCA results per FU (1 stack) in case of grey hydrogen

	Life Cycle phases -->		PRODUCTION			DISTRIB.	USE	END-OF-LIFE				TOTAL
	Resources Use and Emissions		Material	Manuf.	Total			Disposal	Recycl.	Stock	Total	
	Materials	**unit**										
1	Bulk Plastics	g			5.678		57	0	1.434	4.301	5.735	4.301
2	TecPlastics	g			3.800		38	0	959	2.879	3.838	2.879
3	Ferro	g			25.295		253	0	6.387	19.161	25.547	19.161
4	Non-ferro	g			950		10	0	240	720	960	720
5	Coating	g			0		0	0	0	0	0	0
6	Electronics	g			0		0	0	0	0	0	0
7	Misc.	g			0		0	0	0	0	0	0
8	Extra	g			8.093		81	776	1.267	6.131	8.174	6.131
9	Auxiliaries	g			0		976.500	240.000	4.166	732.499	976.665	732.499
10	Refrigerant	g			0		0	0	0	0	0	0
0	Total weight	g	0	0	43816	0	976938	240776	14454	765689	1020919	765689
	Other Resources & Waste											
11	Total Energy (GER)	MJ	33.196	779	33.975	713	200.732	52	-2.660		-2.608	232.811
12	of which, electricity (in primary MJ)	MJ	382	457	839	1	4	0	-65		-65	780
13	Water (process)	ltr	1.885	6	1.892	0	19	0	-335		-335	1.575
14	Water (cooling)	ltr	1.418	203	1.621	0	14	0	-176		-176	1.459
15	Waste, non-haz./ landfill	g	26.280	3.212	29.492	407	263	89	-4.824		-4.735	25.427
16	Waste, hazardous/ incinerated	g	36	0	36	8	0	0	-4		-4	40
	Emissions (Air)											
17	GWP	kg CO2 eq.	2.260	44	2.304,357	47	11.188,16	4	-214		-210	13.329,11
18	AP	g SO2 eq.	103.720	190	103.910	142	1.327	8	-8.000		-7.993	97.386
19	Volatile Organic Compounds (VOC)	g	2.216	1	2.216	11	22	0	-165		-164	2.085
20	Persistent Organic Pollutants (POP)	ng i-Teq	1.020	58	1.078	2	10	3	-99		-95	995
21	Heavy Metals	mg Ni eq.	8.957	135	9.092	21	90	15	-1.033		-1.018	8.184
22	PAHs	mg Ni eq.	10.595	0	10.596	25	106	0	-761		-761	9.965
23	Particulate Matter (PM, dust)	g	1.937	29	1.966	1.716	19	67	-161		-94	3.607
	Emissions (Water)											
24	Heavy Metals	mg Hg/20	16.702	4	16.706	1	167	4	-1.440			15.439
25	Eutrophication	g PO4	1.144	0	1.144	0	11	0	-11			1.145

Co-funded by the European Union

Clean Hydrogen Partnership

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

Table 11. EcoReport LCA results per FU (1 stack) in case of blue hydrogen

	Life Cycle phases -->		PRODUCTION			DISTRIB.	USE	END-OF-LIFE				TOTAL
	Resources Use and Emissions		Material	Manuf.	Total			Disposal	Recycl.	Stock	Total	
	Materials	**unit**										
1	Bulk Plastics	g			5.678		57	0	1.434	4.301	5.735	4.301
2	TecPlastics	g			3.800		38	0	959	2.879	3.838	2.879
3	Ferro	g			25.295		253	0	6.387	19.161	25.547	19.161
4	Non-ferro	g			950		10	0	240	720	960	720
5	Coating	g			0		0	0	0	0	0	0
6	Electronics	g			0		0	0	0	0	0	0
7	Misc.	g			0		0	0	0	0	0	0
8	Extra	g			8.093		81	776	1.267	6.131	8.174	6.131
9	Auxiliaries	g			0		976.500	240.000	4.166	732.499	976.665	732.499
10	Refrigerant	g			0		0	0	0	0	0	0
0	Total weight	g	0	0	43816	0	976938	240776	14454	765689	1020919	765689
	Other Resources & Waste											
11	Total Energy (GER)	MJ	33.196	779	33.975	713	205.718	52	-2.660		-2.608	237.798
12	of which, electricity (in primary MJ)	MJ	382	457	839	1	4	0	-65		-65	780
13	Water (process)	ltr	1.885	6	1.892	0	19	0	-335		-335	1.575
14	Water (cooling)	ltr	1.418	203	1.621	0	14	0	-176		-176	1.459
15	Waste, non-haz./ landfill	g	26.280	3.212	29.492	407	263	89	-4.824		-4.735	25.427
16	Waste, hazardous/ incinerated	g	36	0	36	8	0	0	-4		-4	40
	Emissions (Air)											
17	GWP	kg CO2 eq.	2.260	44	2.304,357	47	5.706,56	4	-193		-189	7.868,47
18	AP	g SO2 eq.	103.720	190	103.910	142	1.327	8	-8.000		-7.993	97.386
19	Volatile Organic Compounds (VOC)	g	2.216	1	2.216	11	22	0	-165		-164	2.085
20	Persistent Organic Pollutants (POP)	ng i-Teq	1.020	58	1.078	2	10	3	-99		-95	995
21	Heavy Metals	mg Ni eq.	8.957	135	9.092	21	90	15	-1.033		-1.018	8.184
22	PAHs	mg Ni eq.	10.595	0	10.596	25	106	0	-761		-761	9.965
23	Particulate Matter (PM, dust)	g	1.937	29	1.966	1.716	19	67	-161		-94	3.607
	Emissions (Water)											
24	Heavy Metals	mg Hg/20	16.702	4	16.706	1	167	4	-1.440			15.439
25	Eutrophication	g PO4	1.144	0	1.144	0	11	0	-11			1.145

Co-funded by the European Union

Clean Hydrogen Partnership

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

As shown in Figure 1, the production phase is the life cycle stage with the largest impact in terms of carbon footprint when using green hydrogen. On the other hand, the use phase represents the major contribution when using grey and blue hydrogen. As introduced in Section 3.2.2, a higher vehicle usage (i.e., higher annual consumption of hydrogen) would increase the relevance of the use phase over the production and manufacturing phases.

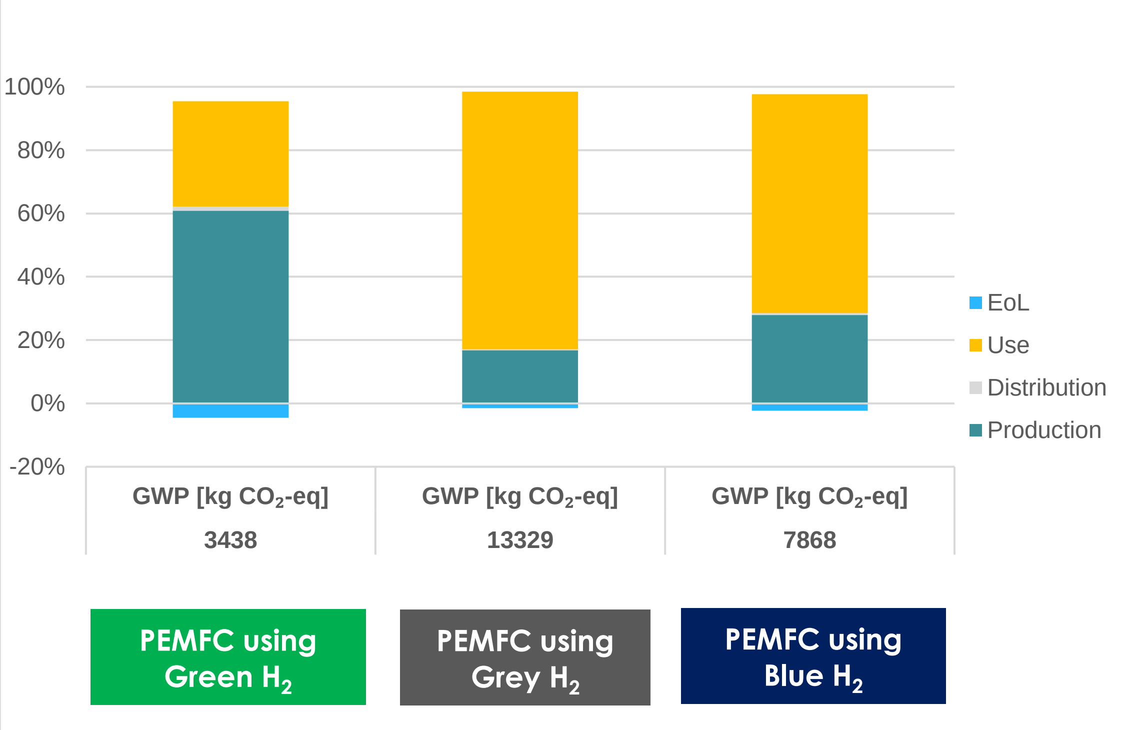

Figure 1. Carbon footprint breakdown per FU (1 stack) over lifetime under different use phase scenarios

4.2 EcoReport LCC results

The LCC cost breakdown performed according to the assumptions in Section 3.3 is reported in Figure 2.

Co-funded by the European Union

Clean Hydrogen Partnership

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

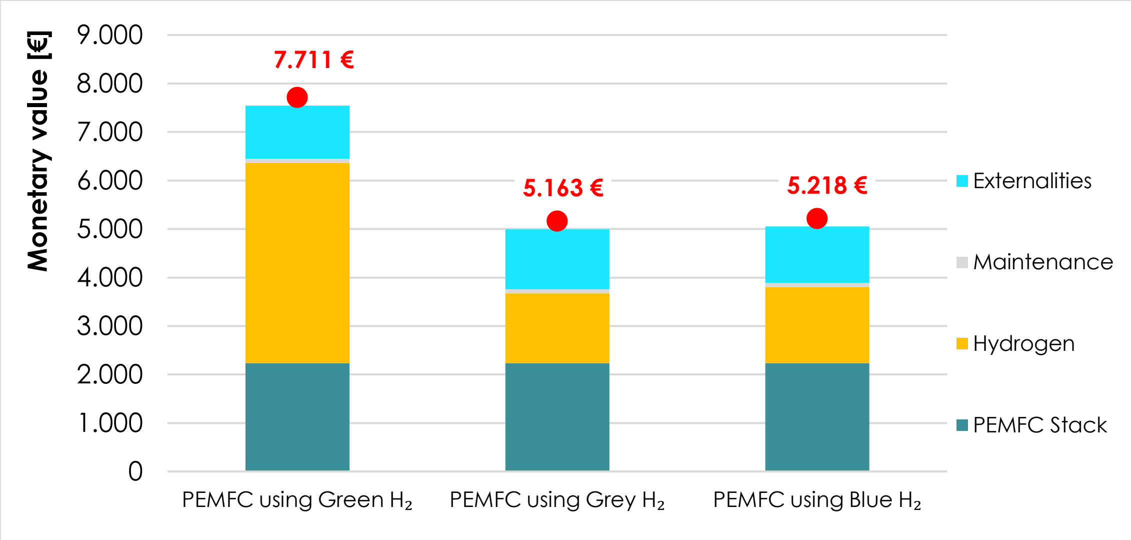

Figure 2. LCC results and cost breakdown per FU (1 stack) in reference year (2030) under different use phase scenarios

For a fixed cost of the stack, the BoP and maintenance, the PEMFC using green hydrogen reports a higher cost due to the significantly higher cost of the use phase (production and distribution of green hydrogen). Externalities account for 14%-22% of the total cost, with the lowest relevance when using green hydrogen. It should be remarked that in the EcoReport tool externalities are only calculated based on the emissions to the air, which could lead to their underestimation.

Finally, it should be noted that the LCC results of the EcoReport tool are necessarily aligned with the LCC in eGHOST D2.3 (5) since the results from this deliverable (regarding manufacturing and production phase) are used as inputs inside the tool.

4.3 Critical Raw Material assessment results

The first step of this analysis is the assessment of the materials of which each product is composed, considering the inventories provided for the reference product in eGHOST Deliverable 2.3 (5). Among the 2020 CRM list, only platinum and natural graphite are present in the reference product. It is assumed that the only carbonaceous compounds produced from natural graphite are the carbon particles in the catalyst support.

Afterwards, the CFs of the CRMs comprised within the PEMFC stack are calculated according to the MEErP (14). The results can be found in Table 12.

The data used for the CF calculation are retrieved entirely from the European Commission Critical Raw Materials Factsheet 2020 and Final Report 2020 (20,21). Further, the specific CF of each CRM is assessed in terms of its weight within the FU, and additionally expressed as a percentage to show its impact on the cumulated CRM indicator.

Co-funded by the European Union
Clean Hydrogen Partnership
This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

Based on Table 13, **the highest contribution in the criticality assessment comes from the use of platinum**. This is closely linked to its high CF compared to the other CRM contained in the PEMFC (i.e., natural graphite).

Table 12. Calculation of the updated and additional CRM characterisation factors

2020 CRM	EU consumption (A) [t/yr] (20)	Import dependency rate (B) [%] (21)	Substitutability supply risk (C) [%] (21)	Recycling rate (D) [%] (21)	A*B*C*(1-D)	CF [kg Sb eq/kg]
Antimony	18,500	100	92	28	12,254.40	1
Platinum	64.5	98	85	25	40.30	304.11
Natural graphite	84,000	98	99	3	79,051.90	0.16

Table 13. Overview of the PEMFC critical raw materials

Total PEMFC	Weight [g/FU]	34,684.00
	CRM indicator	7.93
Platinum (CRM)	Weight [g/FU]	26.04
	Mass fraction [%]	0.08
	CRM indicator	7.92
	CRM share [%]	99.92
Natural graphite (CRM)	Weight [g/FU]	38.92
	Mass fraction [%]	0.11
	CRM indicator	$6.23 \cdot 10^{-3}$
	CRM share [%]	0.08

CONCLUSIONS

The main conclusion that arises from the application of the EcoReport tool to the PEMFC stack is that **this tool needs to be updated in order to be effective, practical and consistent when applied to FCH systems**. In particular, the available list of materials and the corresponding categories should be enlarged to embrace the typical materials that constitute FCH systems. In the case of the investigated PEMFC stack, platinum inclusion is crucial since it constitutes the main economic and environmental hotspot, in agreement (qualitatively) with the results previously reported in eGHOST Deliverable 2.3. The EcoReport results also highlight that appropriate EoL scenarios could reduce the impacts of the product system.

Quantitative differences between environmental impacts in analogous phases (production & extraction and manufacturing) under the MEErP in this deliverable and the

Co-funded by the European Union

Clean Hydrogen Partnership

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

LCA in eGHOST Deliverable 2.3 are linked to the use of different impact assessment methods. Economic parameters are coherent between studies, since results from Deliverable 2.3 are used as inputs in the EcoReport tool.

The use phase of the PEMFC stack arose as very relevant under the assessed impact categories, especially when using hydrogen obtained from fossil sources (with or without carbon capture systems). LCC results show that the cost of the delivered hydrogen is crucial to determine the final product economic impact.

Regarding the CRM assessment, platinum and natural graphite were identified as the only CRMs contained in the PEMFC stack. A quantitative analysis was carried out to establish a criticality indicator following MEErP guidelines, identifying platinum as the main source of criticality concerns.

REFERENCES

1. Kemna R, Elburg M van, Li W, Holsteijn R van. MEEUP Methodology Report. 2005.

2. European Union. DIRECTIVE 2009/125/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL. Official Journal of the European Union. 2009.

3. European Commission. Ecoreport Tool [Internet]. 2014 [cited 2021 Sep 17]. Available from: https://ec.europa.eu/docsroom/documents/5308/attachments/1/translations/en/renditions/native

4. VITO, Fraunhofer, Viegand Maagøe. Ecodesign preparatory Study for Batteries [Internet]. 2020 [cited 2021 Sep 17]. Available from: https://ecodesignbatteries.eu/

5. Bargiacchi E, Campos Carriedo F, Puig-Samper G, Iribarren D, Dufour J, Cren J, et al. D2.3 Definition and evalutation of base case studies. 2021. https://eghost.eu/

6. Bareiß K, de la Rua C, Möckl M, Hamacher T. Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems. Appl Energy 2019;237:862–72. Available from: https://doi.org/10.1016/j.apenergy.2019.01.001

7. Jouin M, Bressel M, Morando S, Gouriveau R, Péra M, Zerhouni N, et al. Estimating the end-of-life of PEM fuel cells : Guidelines and metrics. 2019.

8. Valente A, Iribarren D, Candelaresi D, Spazzafumo G, Dufour J. Using harmonised life-cycle indicators to explore the role of hydrogen in the environmental performance of fuel cell electric vehicles. Int J Hydrogen Energy 2020;45(47):25758–65. Available from: https://doi.org/10.1016/j.ijhydene.2019.09.059

9. Regnan. H_2 beyond CO_2. Filling the gaps in the environmental case for hydrogen.

Co-funded by the European Union

Clean Hydrogen Partnership

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.

2021.

10. Evangelisti S, Tagliaferri C, Brett DJL, Lettieri P. Life cycle assessment of a polymer electrolyte membrane fuel cell system for passenger vehicles. J Clean Prod 2017;142:4339–55. Available from: http://dx.doi.org/10.1016/j.jclepro.2016.11.159

11. Fuel Cells and Hydrogen Joint Undertaking (FCH JU). Hydrogen Roadmap Europe [Internet]. 2019. Available from: fch.europa.eu

12. Duclos L, Svecova L, Laforest V, Mandil G, Thivel PX. Process development and optimization for platinum recovery from PEM fuel cell catalyst. Hydrometallurgy 2016;160:79–89. Available from: http://dx.doi.org/10.1016/j.hydromet.2015.12.013

13. DuPont Fuel Cells. Safe Handling and Use of Perfluorosulfonic Acid Products. 2009.

14. Kemna R. Methodology for Ecodesign of Energy-related Products MEErP 2011. 2011.

15. Yang Y. PEM Fuel Cell System Manufacturing Cost Analysis for Automotive Applications. 2015.

16. Thompson ST, James BD, Huya-Kouadio JM, Houchins C, DeSantis DA, Ahluwalia R, et al. Direct hydrogen fuel cell electric vehicle cost analysis: System and high-volume manufacturing description, validation, and outlook. J Power Sources 2018;399:304–13. Available from: https://doi.org/10.1016/j.jpowsour.2018.07.100

17. Official Inflation Data - Alioth Finance. 2030 Inflation Prediction | Future Inflation Calculator [Internet]. 2021 [cited 2021 Sep 17]. Available from: https://www.officialdata.org/2017-dollars-in-2030?amount=5&future_pct=0.03

18. Satyapal S. DOE Hydrogen and Fuel Cell Perspectives and Overview of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). DOE Hydrog Fuel Cells Progr. 2020.

19. European Commission. Raw Material Information System (RMIS) [Internet]. Available from: https://rmis.jrc.ec.europa.eu/?page=crm-list-2020-e294f6

20. Latunussa C EL, Georgitzikis K, Matos CT de, Grohol M, Eynard U, Wittmer D, et al. Study on the EU's list of Critical Raw Materials - Critical Raw Materials Factsheets [Internet]. Critical Raw Materials Factsheets. 2020. Available from: https://op.europa.eu/en/publication-detail/-/publication/7345e3e8-98fc-11e7-b92d-01aa75ed71a1

21. Blengini GA, Latunussa CEL, Eynard U, Torres de Matos C, Wittmer D, Georgitzikis K, et al. Study on the EU's list of Critical Raw Materials (2020) Final Report. 2020.

Co-funded by the European Union

Clean Hydrogen Partnership

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 101007166. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe research.