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D2.1 Assessment methodologies

WP2: Definition of FCH products systems

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EXECUTIVE SUMMARY

The eGHOST project addresses the eco-(re)design of mature products (Proton-Exchange Membrane Fuel Cell – PEMFC – stack) and those emerging with Technology Readiness Level (TRL) around 5 (Solid Oxide Electrolysis Cell – SOEC) in such a way that sustainable design criteria can be incorporated since the earliest stages of the product development. This deliverable defines the assessment methodologies that will be applied to both eGHOST PEMFC and SOEC systems to evaluate their environmental, social and economic performances throughout the project. Conventional Life Cycle Assessment (LCA), Prospective LCA (P-LCA), Conventional Life Cycle Costing (LCC), Environmental LCC, and Social LCA (S-LCA) approaches used in the context of this project are described in this document. The results of the application of these assessment methodologies will be used later in the project as a support to define eco-design guidelines for hydrogen-related systems.

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ABBREVIATIONS

AE	Accumulated Exceedance
ADP	Abiotic Depletion Potential
BoM	Bill of Materials
BoP	Balance of Plant
EE	Eco-efficiency
EF	Environmental Footprint
EoL	End of Life
EU	European Union
FCH	Fuel Cells and Hydrogen
GWP	Global Warming Impact Potential
ILCD	International Reference Life Cycle Data System
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MEA	Membrane Electrode Assembly
OEF	Organization Environmental Footprint
P-LCA	Prospective Life Cycle Assessment
PED	Primary Energy Demand
PEF	Product Environmental Footprint
PEMFC	Proton-Exchange Membrane Fuel Cell
PSILCA	Product Social Impact Life Cycle Assessment
S-LCA	Social Life Cycle Assessment
SOEC	Solid Oxide Electrolysis Cell
SOFC	Solid Oxide Fuel Cell
TCO	Total Cost of Ownership
TRL	Technology Readiness Level
UN	United Nations
UNEP	United Nations Environment Programme
WP	Work Package

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REPORT

1. INTRODUCTION

The eGHOST project aims to support the whole Fuel Cells and Hydrogen (FCH) sector. Therefore, it addresses the eco-(re)design of mature products (Proton-Exchange Membrane Fuel Cells - PEMFC - stack) and those emerging with a Technology Readiness Level (TRL) around 5 (Solid Oxide Electrolysis Cell - SOEC) in such a way that sustainable design criteria can be incorporated since the earliest stages of the product development. eGHOST will be the first milestone for the development of eco-design criteria in the European hydrogen sector and will go a step beyond the current state of the art in eco-design.

This deliverable is related to **Work Package 2 (WP2) of the project: Definition of FCH Products Systems**. The key objective of WP2 is to define the two FCH systems (PEMFC & SOEC) that will be subject to eco-design for the rest of the project. A second objective is **to define the assessment methodologies** that will be applied to the systems **to evaluate their environmental, social and economic performances**.

This deliverable is related to this second objective and includes therefore a description of the methodologies that will be used by the consortium to evaluate the two reference eGHOST hydrogen-related systems:

- Conventional Life Cycle Assessment (LCA) for the PEMFC.
- Prospective Life Cycle Assessment (P-LCA) for the SOEC.
- Conventional and environmental Life Cycle Costing (LCC) for the two systems.
- Social Life Cycle Assessment (S-LCA) for the two systems.

This deliverable aims at defining a clear framework for the assessment methodologies employed in the project for the evaluation of the involved FCH systems. This deliverable includes methodologies for assessing categories that are not considered in the current EU (European Union) taxonomy for sustainable activities.

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2. LCA METHODOLOGY APPLIED TO PEMFC STACK

The LCA methodology applied to PEMFC includes four phases:

i. goal and scope,
ii. life cycle inventory (LCI) analysis,
iii. life cycle impact assessment (LCIA), and
iv. interpretation of the results.

The study will be conducted taking into account the ISO standards 14040, 14044 [1, 2] and the International Reference Life Cycle Data System (ILCD) guidelines [3]. The suggestions given in the guidance document for performing an LCA on FCH technologies by HyGuide [4, 5] will also be considered.

2.1 Goal and scope definition

The main goal of this environmental LCA study is to evaluate environmental impacts of one PEMFC stack. The PEMFC stack will be analysed for the production phase and the End-of Life (EoL) phase (Figure 1). The operation phase will not be included in the analysis because it is not in the control of the manufacturers. Of course, the operational phase is very important, but if included, the boundaries of the system should be expanded beyond the borders where the manufacturer and also the recycling company have control. The operational phase will have to be considered separately, since in the case of grey hydrogen use it is so dominant that it completely obscures the production and end-of-life phases. The **functional unit (FU)** quantifies the function of the product system and provides a reference unit. The choice of the FU can strongly affect the conclusions of the study (especially in comparative studies) and must be defined in accordance with the goal and scope of the study.

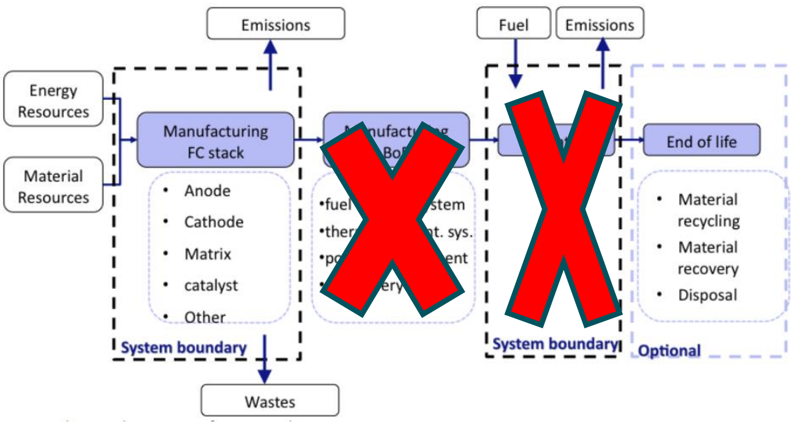

Figure 1: Schematic steps of the system scope [4]

The key boundary parameters of this study are:

- <u>**Functional unit:**</u> ***1 PEMFC stack of 48 kW electrical power output***
- <u>**Reference flow**</u>: ***1 piece, i.e., one 48 kW PEMFC stack***

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2.1.1 System boundary

The **foreground system** comprises all processes related to the production and EoL of the PEMFC stack itself. In the case of a fuel cell stack, this includes in the first place the main production processes such as the manufacturing of the anode, the cathode and the matrix, their assembly and stack test. In the case of a fuel cell system, which is not included in this study, the foreground would also include the manufacturing of the Balance of Plant (BoP) and the start-up of the whole PEMFC system.

The **background system** supports the foreground system and its processes. It deals with almost all material and energy flows going to and coming from the foreground system (e.g., for the electricity supply includes the extraction of resources, production and distribution of the electricity generated and used in our foreground system). In practice it is not recommended to collect primary data for all background processes and set up background systems individually. In this case secondary data for the background system from existing high-quality databases (ecoinvent, GaBi Professional) will be used.

2.2 Life cycle inventory (LCI)

The methodology used to create the LCI is to collect data for all necessary materials and processes used during the study for the proposed scope. All data on the properties of the materials used and the associated processes performed during the production phase and the EoL phase of the PEMFC stack will be collected in common tables (e.g., Excel spreadsheets), which will be supplemented and updated with the data received from the manufacturers of the PEMFC technology in the consortium (Symbio France) during the LCI preparation. The data from the manufacturers are provided in the form of Bill of Materials (BoM). For new and specific FCH materials for which the LCI database does not yet exist, they will be further analysed in terms of their production and associated processes to obtain an even more accurate inventory. If these data do not exist, we will analyse possible alternative materials in the design phase of the inventory, and we will re-model new, specific materials and provide details on their composition and processes to create a new best estimate of the inventory (e.g., by referring to scientific contributions, chemical composition, processes used to produce substitute materials...). The initial dataset and BoM for the PEMFC stack materials and processes used has already been provided by Symbio France. In addition, for background analysis and missing data (materials and processes), the secondary databases ecoinvent [6] and, when needed, GaBi Professional [7] and extended databases for precious metals [8] and critical materials will be used. In the EoL phase the data will be retrieved from the EU-funded project BEST4Hy, which is engaged in EoL processes of critical materials and ionomer.

Based on the described methodology and intermediate iterative improvements, we will obtain a well-defined LCI for the defined scope of the study, which will serve for further analysis of the environmental impacts of the PEMFC stack.

2.2.1 Production phase

The LCI for the production phase is based on the BoM provided by Symbio France. This implies that the processes needed to produce the core PEMFC components (mixing of compounds, film casting, stamping/pressing, sintering, etc.) are within the scope of this analysis. To successfully determine the LCI for the production phase, the materials must be available in the LCA databases, or we must have all the primary data regarding the production process for a specific material to model it from zero. However, in some cases, the material is rather new; therefore, some of them are still not available in the LCA

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databases. If a material is missing in the database, it should be replaced by a comparable material that exhibits similar properties with some assumptions. Some datasets of materials will be integrated from past FCH 2 JU-funded projects such as HyTechCycling and the current FCH 2 JU-funded BEST4Hy project.

2.2.2 End of life

The EoL phase is very important when addressing LCA and ecodesign of FCH technologies. EoL will be modelled and evaluated using the common recycling approach for conventional materials (aluminium, copper, steel, plastic, etc.), meanwhile recycled critical and rare earth materials will be integrated from the FCH 2 JU-funded project BEST4Hy. In BEST4Hy, PEMFC and Solid Oxide Fuel Cell (SOFC) technologies are observed, evaluated, studied and modelled in EoL phase to recover critical, rare earth materials and ionomer [9]. When applying ecodesign, all actions in EoL phase will be assessed and evaluated using LCA.

In PEMFC technology, datasets of recycled platinum and recycled ionomer will be used and integrated from the BEST4Hy project. Datasets will be established based on industry laboratory-scale data. In addition, the reuse of bipolar and end plates will be assessed and evaluated with LCA.

Open and closed loop recycling will be assessed with an LCA approach for each technology. Recycling efficiency (the success of the recycling process) and mass yield (mass of material that is not lost during pre-process, cutting, milling) will be important parameters in the EoL phase of the product.

2.3 Life cycle impact assessment (LCIA)

The Environmental Footprint 3.0 (EF3.0) LCIA method will be used to evaluate selected environmental impact categories. Even though EF3.0 is not commonly used for FCH technologies, the European Commission has proposed the PEF (Product Environmental Footprint) and the OEF (Organization Environmental Footprint) as a common method for measuring environmental performance [10]. The overarching purpose of PEF information is to enable the reduction of the environmental impact of goods and services, taking into account activities in the supply chain (from raw material extraction through production and use to final waste disposal) [11]. The selection of environmental indicators follows the guidelines of one of the main documents for LCA of FCH technologies, the HyGuide [4], while in recent years the European Commission and the Joint Research Centre (JRC) support the EF3.0 method. For this reason, we will use the EF3.0 method, which is currently in a transitional phase in the development of EF characterisation and is strongly supported by the JRC. The EF3.0 method includes 16 environmental impact indicators, which will provide good additional insight into the environmental impacts of the production processes of PEMFC technology, namely PEMFC stack. The specific environmental indicators under study, based on the literature reviewed [12, 13] and the recommendations of HyGuide [4], are:

- Climate change (GWP in HyGuide).
- Acidification.
- Eutrophication (terrestrial/freshwater/marine).
- Resource use, minerals and metals (AD in HyGuide).
- Resource use, energy carriers (PED in HyGuide).

Additional description of the used EF 3.0 impact indicators is presented in Table 1. It should be noted that, while the remaining indicators within the EF3.0 method (ionizing radiation, ozone depletion, particulate matter, land use, water use, etc.) could also be directly

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considered, this idea was discarded due to the nature of the eGHOST project. In this sense, eGHOST addresses sustainability criteria belonging to the environmental, economic and social dimensions. Hence, the implementation of multiple environmental indicators could jeopardize the identification and interpretation of sustainability-oriented design actions, and thus the formulation and prioritisation of new product concepts.

Table 1: Proposed EF impact categories, including indicator, units, and method package

EF IMPACT CATEGORY	INDICATOR	UNIT	RECOMMENDED DEFAULT LCIA METHOD
CLIMATE CHANGE	Global Warming Impact Potential (GWP)	kg CO_2 eq	Baseline model of 100 years of the IPCC (based on IPCC 2013)
ACIDIFICATION	Accumulated Exceedance (AE)	mol H^+ eq	Accumulated Exceedance
EUTROPHICATION, TERRESTRIAL	Accumulated Exceedance (AE)	mol N eq	Accumulated Exceedance
EUTROPHICATION, AQUATIC FRESHWATER	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	EUTREND model as implemented in ReCiPe
EUTROPHICATION, AQUATIC MARINE	Fraction of nutrients reaching marine end compartment (N)	kg N eq	EUTREND model as implemented in ReCiPe
RESOURCE USE, MINERALS AND METALS	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq	CML
RESOURCE USE, ENERGY CARRIERS	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	CML

2.4 Interpretation of the results

To obtain a detailed interpretation of the environmental impact of the PEMFC stack, the LCA model will be set up separately for all the materials and processes occurring in the production phase of the PEMFC technology. Sensitivity analysis of LCIA results is an important step to study the robustness of the results and their sensitivity to uncertain factors in LCA. Potential sensitivity parameters will be, e.g., energy consumption (electricity, heat, etc.), materials used, critical materials in core components, recycling ratio of materials in EoL phase, etc.

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3. PROSPECTIVE LCA METHODOLOGY APPLIED TO SOEC SYSTEM

3.1 Overview

An LCA is defined as prospective "when the (emerging) technology studied is in an early phase of development (e.g., small-scale production), but the technology is modelled at a future, more-developed stage (e.g., large-scale production)" [14]. This approach is crucial to assess the environmental impacts of relatively low TRL technologies, but it poses challenges in terms of consistency, comparability, data availability, and uncertainty [15].

In the EoL phase, the data will be provided from the EU-funded project BEST4Hy, which is engaged in EoL processes of rare earth (solid oxide technology) materials. In solid oxide technology the datasets of recycled rare earth materials obtained on laboratory scale in the BEST4Hy project will be integrated into ecodesign actions of the prospective SOEC stack to evaluate the reduction of environmental impacts.

3.2 Methodology

In this project, a prospective LCA based on predictive scenarios [14] will be conducted to assess the potential environmental impacts of a SOEC stack. **The functional unit will be one SOEC stack of 5 kW electrical power input produced in 2030, BoP excluded**. **The system will be modelled for the year 2030 because it is the time horizon in which SOECs are expected to reach maturity (TRL 9)** [16]. **The prospective nature of the study will be ensured by the system definition itself, and by examining the effect of key performance parameters**. Besides, a hotspot analysis of the LCA results obtained for a present scenario (baseline) will allow to decide about the potential need for a prospective study of certain background processes. This is typically the case of the national or regional electricity mixes employed for the manufacturing of SOEC components.

The SOEC will be placed in 2030 by considering the evolution of the following parameters: **stack degradation, lifetime, and capacity factor**. Besides system definition, **current density** will also be updated, having a direct influence on the stack manufacturing (i.e., higher current density leads to a lower number of cells within the stack). Background processes will be modelled using the ecoinvent database [6], being subject to the above-mentioned hotspot analysis.

The choice of impact categories (**climate change, acidification, eutrophication, resource use – minerals and metals, and resource use – energy carriers**) and life cycle impact assessment method (**EF3.0**) will ensure a common LCIA framework for both products, the PEMFC stack and the SOEC stack.

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4. CONVENTIONAL LCC

4.1 Overview

Conventional LCC is a method for evaluating all relevant costs over the lifetime of a product, project, or measure. It takes into consideration all costs including first costs, such as manufacturing costs, purchase, and installation costs; future costs, such as energy costs, operating costs, maintenance costs, capital replacement costs, financing costs; and any resale, salvage, or disposal cost, over the lifetime of the product or project.

4.2 Goal and scope

The study applied to PEMFC and SOEC stacks will be conducted following the same scope as the LCA. Stacks will be analysed for the production phase and the EoL phase. The operation phase will not be included in this analysis, but will still be described in this methodological part (Section 4.3.2) for informative purposes.

High level of data alignment between LCA and LCC will include:

- Scope definition including:
  - Functional unit.
  - System boundaries.
  - Method for solving multifunctionality.
  - Temporal and geographical representation.
- Inventory.
- Scenarios applied.

4.3 Life cycle inventory

The methodology used to create the LCI for the LCC will be the same as for the environmental analysis, with additional information related to cost and financial aspects as described in Figure 2. As for environmental analysis, the operation phase and BoP manufacturing will not be considered in this first version of the analysis. In further work packages of the project, the analysis could be extended to the operation phase as it can be an important aspect of eco-design.

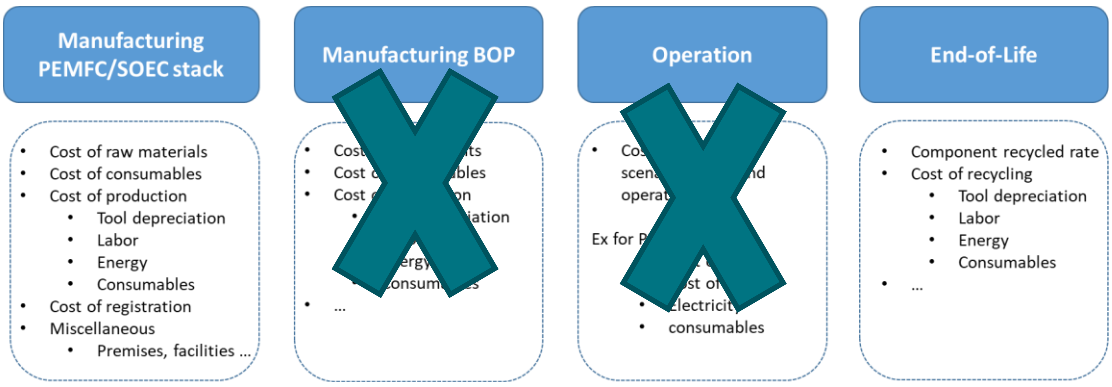

Figure 2: Schematic steps of the LCC with required financial inputs

Concerning the performance of the SOEC technology at horizon 2030, it may rely on the Strategic Research and Innovation Agenda (SRIA) document proposed by Hydrogen

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Europe and Hydrogen Europe Research with technology development roadmap on SOEC among other H_2 production ways [17].

4.3.1 Manufacturing phase

The objective will be to determine the production cost of the stack. To do so, the process of stack manufacturing is decomposed into elementary process steps from Membrane Electrode Assembly (MEA) fabrication to stack assembly and control. For each step, the different contributions to the production cost are quantified like raw materials, tool depreciation, labour, energy and consumables, maintenance and quality control. This detailed analysis has the advantage of giving the structure of the cost by process steps or cost components. The calculation of the manufacturing cost is then made through the formula:

$$C = MP + P + D$$

with:

C	cost of the stack
MP	cost of raw materials and consumables
P	cost of production involving tool depreciation, labour, energy and consumables
D	miscellaneous cost (premises, facilities…)

General hypotheses on the **fabrication plant location** and **production volume** have to be fixed as they have an important impact on the final result.

Production volume: The current PEMFC stack manufacture capacity will be validated with the industrial partner of the project. For the SOEC stack, projection on the market in 2030 and link with existing SOFC production plants will be assessed.

Location: Plant location will impact several costs like energy consumables and labour cost.

4.3.2 Operating phase

To remain consistent with the scope of the other assessments, this operating phase will not be considered in the LCC. The principle is still described below for information.

The operating phase of the stack will depend on the usage scenario. For instance, for a PEMFC stationary application, it will be linked to the production of electricity to satisfy a demand and could be expressed in kWh provided during the lifetime of the PEMFC stack. For an automotive application this will be linked to a distance expressed in km travelled during its lifetime.

It would include cost of fuel used over the lifetime of the system, operating and maintenance expenses. In this phase, phenomena of performance degradation will be taken into account by considering an increase in fuel consumption over time and stack replacement cost.

4.3.3 End-of-life phase

This final stage includes cost of decommissioning and recycling credit. The financial benefit of the recycling process could be assessed taking into account the recycling rate

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on the most valuable components of the stack and the entire cost of the recycling process.

4.4 Total cost of ownership

The total life cycle cost or total cost of ownership (TCO) enables to take into account the initial purchase price but also cost of fuel used over the lifetime of the system, system decommissioning costs and recycling credits, operating and maintenance expenses, degradation effect with increasing fuel consumption and stack replacement. All these costs are discounted to the present value using a discounted cash flow methodology.

In the scope of the project, only the production and end-of-life steps are taken into account, as presented in Figure 2. Then in the LCC formula, only the components in red will be considered:

$$LCC = C_i + \sum_t \frac{\left(O\&M_t + Fuel_0 + Fuel_{deg} + (stack_{replac.})_t + ((decom.) - (recycl.))_{tf}\right)}{(1+\tau)^t}$$

with:

with:	LCC:	Life cycle cost - €/stack
	C_i:	Initial stack cost - €
	$O\&M$:	Operating and maintenance annual cost - €
	$stack_{replac}$:	Stack replacement cost - €
	$Recycl.$:	Recycling credit - €
	$Fuel_0$:	Annual fuel cost without degradation - €
	$Fuel_{deg}$:	Additional fuel cost due to degradation - €
	$decom.$:	Decommissioning - €
	τ:	Discount rate
	t:	Operating year (*tf*: final operating year)

Nota bene: The financial formula with the discount rate τ and the operating year *t* is a method of valuing a project, giving a present value to all future cash flows, incoming and outgoing. This method allows reflecting "the time value of money", meaning that money available or spent immediately has a more important value than money available or spent in the future. Usually, in cost analysis of PEMFC or SOEC systems, the discount rate is 8% for an operating time of 20 years or less when we refer to the whole plant. When dealing only with the stack, lifetimes are shorter (around 25,000 hours for SOEC to be commercially available).

By comparing life cycle costs of different technologies, it is possible to determine whether an inexpensive but inefficient system (low initial capital cost but high operating and fuel expenses) or an expensive but efficient system (high initial capital cost but low operating and fuel expenses) has a better financial value to the customer over the entire system lifetime.

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5. ENVIRONMENTAL LCC AND ECO-EFFICIENCY ASSESSMENT

5.1 Environmental LCC

5.1.1 Overview

Conventional LCC estimates the life cycle costs of products and services without further considerations about the consequences that these goods have on the environment. These costs are known as private costs. However, **goods manufacturing involves a certain degree of environmental impacts, which are then responsible for positive or negative effects on society**. These effects, **commonly known as externalities when translated into monetary values**, fall out of the market mechanism. As a result, the equilibrium point obtained from the use of private costs does not show the complex interaction between production/consumption systems and the ecosphere and society. In the case of environmental externalities, they usually represent a damage, which translates to a subsequent loss of social welfare. This loss of welfare is a cost to society caused by the uncompensated economic burden of negative externalities.

The challenge of an environmental LCC is to accurately measure the marginal damage cost. This is, to translate the different LCA impact categories into monetary values. When measuring costs based on environmental degradation, different methods are available. They could be divided into two approaches [18]: (i) costs related to pollutant discharge and environmental degradation, and (ii) costs of the processes needed to prevent pollutant discharge. The former category is often linked to LCA (i.e., costs are calculated based on impact levels) and thus selected for this project.

5.1.2 Methodology

Within methods based on environmental damage, the Environmental Prices method will be used to carry out the environmental LCC. This method quantifies the loss of welfare due to an additional unit of environmental impact [19]. Different levels of characterisation factors are available (emissions, midpoint, and endpoint). In particular, the midpoint characterisation factors will be used in eGHOST to convert the environmental LCA results into common monetary values referred to 2015 (€$_{2015}$). Table 2 presents the average EU28 midpoint-level environmental prices for climate change, acidification, and eutrophication [19]. The environmental prices shown are expressed as external costs [19].

Table 2: Midpoint environmental prices for external costs calculation

Midpoint indicator	Unit	Characterisation factor
Climate change	€/kg CO_2 eq	0.0566
Acidification	€/kg SO_2 eq	4.97
Freshwater eutrophication	€/kg P eq	1.86
Marine eutrophication	€/kg N eq	3.11

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For the SOEC case study, the prospective approach of the LCC will be given by the prospective inventory to be built as explained in Section 3. Nevertheless, the same environmental prices will be employed for the calculation of future externalities. This approach is commonly adopted when performing prospective environmental LCAs.

5.2 Eco-efficiency assessment

5.2.1 Overview

Eco-efficiency analysis combines the economic and environmental spheres to get a holistic image of a product efficiency while allowing its benchmarking. It is a ratio between two indicators expressing the economic value and the environmental performance of a good or service. The indicators used for each single dimension are variable, but they should always follow a life-cycle perspective [20]. Different definitions of eco-efficiency were proposed based on the specific aspect to be addressed, but with the same underlying philosophy. The main two approaches to eco-efficiency are the creation of value and the reduction of cost [21].

5.2.2 Methodology

In this project, eco-efficiency will be assessed in accordance with the internationally standardised framework for eco-efficiency assessment (ISO 14045) [20]. Therefore, the employed indicator must be comparable in a way that a higher numerical value corresponds to a higher eco-efficiency. In other words, a high numerator and a low denominator are pursued. This definition corresponds to environmental productivity as defined in [21]. The general formula followed is shown in the following equation:

$$EE = \frac{\frac{1}{LCC\ economic\ indicator}}{LCA\ environmental\ impact}$$

According to the proposed eco-efficiency definition [22], the inverse of the LCC economic indicator (stack/€) defined in Section 4 will be used as the numerator. The specific environmental impact categories included in the denominator will be those evaluated for each product, as established in Sections 2 and 3.

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6. SOCIAL LIFE CYCLE ASSESSMENT METHODOLOGY

6.1 Overview

S-LCA is a methodology to estimate the potential social impacts of product systems through their supply chain. Updated guidelines for S-LCA of products have been developed within the framework of the United Nations Environment Programme (UNEP) [23] and will be considered in eGHOST. As in the case of environmental LCA, an S-LCA comprises four ISO-like phases (Figure 3).

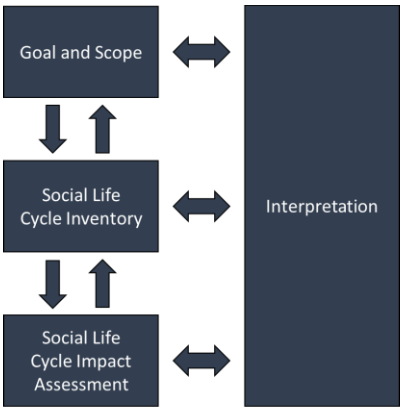

Figure 3: S-LCA stages

6.2 Goal and scope

In eGHOST, the S-LCA of both a SOEC stack and a PEMFC stack will be carried out. **The functional unit (FU) in both cases will be one stack (BoP excluded, as specified in the LCA sections)**. The system boundaries refer to the supply chain definition as detailed in Section 6.3. Spain will be considered as the stack manufacturing country. Regarding the time scope, consistency issues between background and foreground data for the SOEC stack study should be understood as inherent in the goal of the specific study, which will aim at identifying the system's social hotspots of the future technology but according to the present social and socio-economic context.

6.3 Supply chain definition

The supply chain of both products – PEMFC stack and SOEC stack – will involve, at least, three tiers (as shown later in Figure 4): tier 1 for the stack manufacturing plant itself, tier 2 for the plants related to the production of the components and energy flows required by the stack manufacturing plant, and tier 3 for the plants related to the material and energy flows required by the components manufacturing plants. Spain is set as the manufacturing country in tier 1 in order to facilitate comparative studies [24, 25].

The identification of the countries involved in the supply chain will consider the protocol available in [26]. Global trade data will be acquired and analysed for every component included in tier 2. If the export-import balance is positive (more exports than imports measured in economic value), then the component under scrutiny will be considered to be manufactured also in Spain. If this is not the case, the main country-specific exporter

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will be set as the component manufacturing country. The result of this step is one manufacturing country for each of the product components.

After the identification of the manufacturing countries for every component in tier 2, a similar procedure will be followed for the materials included in tier 3. Each component manufacturing country will be set as declarant for every material flow within that component. Its global trade data will then be acquired and analysed. If the export-import balance is positive, then the material under scrutiny will be assumed to be manufactured in the same country as the component. If this is not the case, the most relevant country-specific exporters will be identified according to [26]. The result of this step is a mix of manufacturing countries for each of the materials in tier 3.

Trade information will be gathered mainly from the UN Comtrade database [27], using the commodity code that better adjusts to the component/material characteristics. If the information available on this site is not considered to be specific enough for a particular component/material, alternative sources will be explored (such as the Eurostat database [28]).

6.4 Inventory

The inventories used for LCA and LCC will constitute the main source of data for the social life cycle inventories, along with the use of the Product Social Impact Life Cycle Assessment (PSILCA) database [29]. **At each tier, the working hours per FU will be directly or indirectly quantified for each block in Figure 4**. This information will preferably be gathered from the project partners to be as product-specific as possible. When *working hours* are not directly available for an entity (e.g., for those related to energy flows and materials), they will be estimated based on the economic cost by using country- and sector-specific information from the PSILCA database [29].

Finally, for details on the choice and definition of social life-cycle indicators and their quantification approach, please refer to the eGHOST deliverable D2.2.

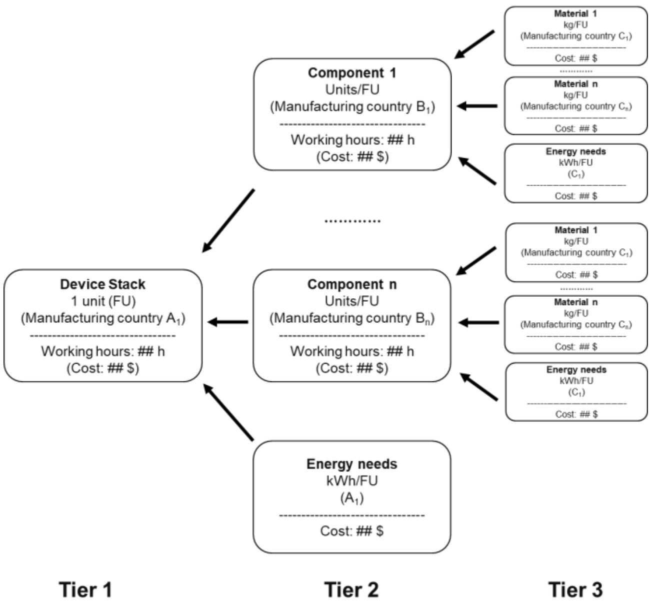

Figure 4: Inventory segmentation for S-LCA

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7. CONCLUSION

This deliverable **sets the methodological framework for the LCA, S-LCA and LCC evaluation of the PEMFC and SOEC systems** that are under study in the eGHOST project for the development of eco-design guidelines for hydrogen systems.

A conventional LCA will be applied to **evaluate the environmental impacts of one 48 kW PEMFC stack** for its production phase and its EoL phase. For the evaluation of the potential environmental impacts of **one 5 kW SOEC stack**, **a prospective LCA based on expected technology evolution** will be conducted. This approach is crucial to assess the environmental impacts of relatively low TRL technologies. The prospective nature of the study will be ensured by the system definition itself, and by examining the effect of key performance parameters on the environmental performance of the stack.

For both systems (PEMFC & SOEC), **conventional LCC and environmental LCC** will be performed. Conventional LCC will be applied for **the evaluation of all relevant costs over time of the PEMFC & SOEC stacks**, whereas environmental LCC will **measure the marginal damage costs** for both systems. With environmental LCC, the different LCA impact categories will be translated into monetary values, using the Environmental Prices method.

Finally, in order to address social aspects in the future eGHOST guidelines, an **S-LCA will be performed on both systems** to identify their potential social impacts through their supply chains. The updated guidelines for S-LCA of products that have been developed within the framework of **UNEP** will be considered and used in eGHOST.

The detailed technical description of both systems under study and the results of the application of the methodological framework described in this deliverable D2.1 will be presented in deliverable **D2.3: "Definition and evaluation of base case studies"**.

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REFERENCES

[1] ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework. International Organization for Standardization.

[2] ISO 14044:2006 Environmental management - Life cycle assessment - Requirements and guidelines. International Organization for Standardization.

[3] European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010. General guide for Life Cycle Assessment - Detailed guidance.

[4] Masoni, P., Zamagni, A., 2011. Guidance Document for performing LCAs on Fuel Cells and Hydrogen Technologies (FC-HyGuide).

[5] Lozanovski, A., Schuller, O., Faltenbacher, M., 2011. Guidance Document for performing LCAs on Fuel Cells and H_2 Technologies (FC-HyGuide).

[6] Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

[7] PE International, 2016. GaBi Professional Database. PE International.

[8] Sphera. Extension database VI: Precious metals. [Online]. Available: https://gabi.sphera.com/support/gabi/gabi-database-2020-lci-documentation/extension-database-vi-precious-metals/ [Accessed: 19-May-2021]

[9] Best4Hy. [Online]. Available: https://best4hy-project.eu/ [Accessed: 19-May-2021]

[10] European Commission. European Platform on Life Cycle Assessment: Environmental Footprint. [Online]. Available: https://eplca.jrc.ec.europa.eu//EnvironmentalFootprint.html [Accessed: 18-May-2021]

[11] Zampori, R., Pant L. JRC Publications Repository - Suggestions for updating the Product Environmental Footprint (PEF) method. [Online]. Available: https://publications.jrc.ec.europa.eu/repository/handle/JRC115959 [Accessed: 18-May-2021]

[12] Valente, A., Iribarren, D., Dufour, J., 2017. Life cycle assessment of hydrogen energy systems: a review of methodological choices. Int J Life Cycle Assess 22, 346–363. https://doi.org/10.1007/s11367-016-1156-z

[13] European Commission – Joint Research Centre, 2020. Life cycle assessment of Hydrogen and Fuel Cell Technologies: inventory of work performed by projects funded under FCH JU. Publications Office.

[14] Arvidsson, R., Tillman, A., Sandén, B.A., Janssen, M., Nordelöf, A., Kushnir, D., Molander, S., 2018. Environmental Assessment of Emerging Technologies:

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Recommendations for Prospective LCA. Journal of Industrial Ecology 22, 1286–1294. https://doi.org/10.1111/jiec.12690

[15] Thonemann, N., Schulte, A., Maga, D., 2020. How to Conduct Prospective Life Cycle Assessment for Emerging Technologies? A Systematic Review and Methodological Guidance. Sustainability 12, 1192. https://doi.org/10.3390/su12031192

[16] Bazzanella, A. M., & Ausfelder, F., 2017. Low carbon energy and feedstock for the European chemical industry. DECHEMA, www.dechema.de.

[17] Hydrogen Europe, 2020 [online]. Available: https://www.hydrogeneurope.eu/wp-content/uploads/2021/04/20201027-SRIA-CHE-final-draft-1.pdf [Accessed: 18-May-2021]

[18] Pirmana, V., Alisjahbana, A. S., Yusuf, A. A., Hoekstra, R., & Tukker, A., 2021. Environmental costs assessment for improved environmental-economic account for Indonesia. Journal of Cleaner Production, 280, 124521. https://doi.org/10.1016/j.jclepro.2020.124521

[19] de Bruyn, S., Bijleveld, M., de Graaff, L., Schep, E., Schroten, A., Vergeer, R., & Ahdour, S., 2018. Environmental Prices Handbook. CE Delft.

[20] ISO 14045:2012 Environmental Management — Eco-efficiency Assessment of Product Systems — Principles, Requirements and Guidelines. International Organization for Standardization.

[21] Huppes, G., & Ishikawa, M., 2007. An introduction to quantified eco-efficiency analysis. In G. Huppes & M. Ishikawa (Eds.), Quantified Eco-Efficiency: An Introduction with Applications (pp. 1–38). Springer. https://doi.org/10.1007/1-4020-5399-1_1

[22] Valente, A., Iribarren, D., Gálvez-Martos, J. L., & Dufour, J., 2019. Robust eco-efficiency assessment of hydrogen from biomass gasification as an alternative to conventional hydrogen: A life-cycle study with and without external costs. Science of the Total Environment, 650, 1465–1475. https://doi.org/10.1016/j.scitotenv.2018.09.089

[23] UNEP, 2020. Guidelines for Social Life Cycle Assessment of Products and Organizations 2020. United Nations Environment Programme. https://www.lifecycleinitiative.org/

[24] Valente, A., Iribarren, D., & Dufour, J., 2019. Life cycle sustainability assessment of hydrogen from biomass gasification: A comparison with conventional hydrogen. International Journal of Hydrogen Energy, 44(38), 21193-21203. https://doi.org/10.1016/j.ijhydene.2019.01.105

[25] Valente, A., Iribarren, D., & Dufour, J., 2021. Comparative life cycle sustainability assessment of renewable and conventional hydrogen. Science of The Total Environment, 756, 144132. https://doi.org/10.1016/j.scitotenv.2020.144132

[26] Martín Gamboa, M., Cláudia Dias, A., Arroja L., & Iribarren, D., 2020. A protocol for the definition of supply chains in product social life cycle assessment: application to

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bioelectricity. Sustainable Energy & Fuels, 4, 5533-5542. https://doi.org/10.1039/D0SE00919A

[27] United Nations. UN Comtrade Database. [Online]. Available: https://comtrade.un.org/ [Accessed 18-May 2021]

[28] European Union. Eurostat Database. [Online]. Available: https://ec.europa.eu/eurostat/web/international-trade-in-goods/data/database [Accessed 18-May 2021].

[29] Maister, K., Di Noi, C., Ciroth, A., & Srocka, M., 2020. PSILCA database v.3 documentation. GreenDelta.

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