HyPEF

TRACING CLEAN HYDROGEN

Promoting an environmentally-responsible Hydrogen economy by enabling Product Environmental Footprint studies

D2.1 | LEARNINGS FROM RELEVANT EXISTING P(EF)CRs

Author(s): Till M. Bachmann, Jonathan van der Kamp EIFER;
Simone Maranghi, ECOINNOVAZIONE;
Claudio Carbone, ENEA;
Sumanth K. R. Maddula, Diego Iribarren, IMDEA Energy

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Executive Summary

Within the HyPEF project (grant agreement number: 101137575), Product Environmental Footprint Category Rules (PEFCRs) will be defined for three hydrogen-related product categories. To this end, relevant guidance documents have been identified and analysed according to specific criteria. The criteria list was developed by identifying the specific requirements and flexible aspects according to the latest PEF recommendations (European Commission 2021)[1]. In total, six documents related to FCH systems and four documents unrelated to FCH systems were analysed. The documents related to FCH systems were grouped according to the steps hydrogen production, hydrogen storage and hydrogen usage.

The analysis showed the following:

- The first thing to note is that there is no specific guidance for **hydrogen storage** (i.e. without including hydrogen production). Hydrogen storage is therefore largely disregarded in this executive summary.
- Hydrogen can be produced and used as an energy carrier or also for chemical or transport reasons. Thereby, it also needs to be distinguished whether hydrogen is a final or an intermediate product and whether it is the only product, a co-product or a by-product. This all has bearings on the definition of the **functional unit** (including its unit).
- None of the analysed guidance documents for hydrogen production requires a given **purity, pressure or temperature**. Due to the comparability objective stated in European Commission (2021), this aspect needs further consideration. In the end, this might mean that conditioning processes (e.g. compression and purification) may have to be included in the PEFCRs on hydrogen production (e.g. in the form of modules) which is already permitted by the hydrogen production-related guidelines analysed. It is suggested that neither hydrogen of low purity nor mixtures (e.g. syngas) should be considered for the drafting of PEFCRs.
- **Temporal aspects** (lifetime) and changes or weaknesses in technical performance (e.g. cell **degradation** or **leakage** during storage) are not commonly considered in the analysed documents. These should be taken into account in the definition of the functional unit.
- The **representative product** might be another criterion to distinguish product categories or sub-categories.
- If the PEFCRs to be drafted are designed in a **modular** way, the PEFCR for hydrogen usage might need to exclude hydrogen production.

[1] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32021H2279, last accessed on 10.6.2024

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- A decision needs to be made whether or not to include **capital goods** (infrastructure and equipment). European Commission (2021) generally recommends excluding them, but permits their inclusion if a "clear and extensive explanation" is provided.
- European Commission (2021) rules that a PEFCR states the most relevant impact categories, life-cycle stages, processes and elementary flows per product category or sub-category. Examples for **relevant impact categories and processes** could be identified in the FCH-related documents analysed. In contrast to the specific Life Cycle Impact Assessment methods to be used, neither European Commission (2021) nor the analysed PEFCRs specify how specific processes are to be modelled.
- Notable **additional environmental information** that are addressed in the analysed documents and that might be considered in WP4 include carbon neutrality considerations regarding hydrogen derived from biomass/biofuels, analysing raw material criticality, or stating the absence or level of presence of certain trace elements or heavy metals for the manufacturing phase.
- What to write as disclaimers (e.g. in terms of data uncertainty or missing elements) should also receive attention in WP4.

Several other aspects have been analysed. However, the PEFCR guidelines in European Commission (2021) do not leave room for adaptation in these cases which is why these are not stated in this executive summary but can nevertheless be found in this deliverable.

This deliverable (D2.1) concerns the rules to be defined for a given product category without specifically knowing which product categories will be distinguished (subject of D2.2). In general, there is a **dilemma** to avoid proliferation of PEFCRs (by distinguishing too many product categories) and nevertheless be sufficiently specific to allow comparability (grouping too many products into the same product category despite having significantly different functions). One common way for dealing with this dilemma is to define:

- Horizontal rules, i.e., rules that describe the common modelling aspects for all the products/applications covered by a given PEFCR; and
- Vertical rules, i.e., rules that apply only to the specific product groups (so-called sub-categories), such as done in the PEFCRs for PV (First solar 2020) and for metal sheets (Eurometaux 2019).

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List of Acronyms and Abbreviations

BoP	Balance of Plant
CFF	Circular Footprint Formula
CH	Clean Hydrogen
CHP	Combined Heat and Power
CPA	Classification of Products by Activity
CPC	Central Product Classification (by the United Nation Statistics Division - Classification Registry)
DC	Direct Current
EC	European Commission
EF	Environmental Footprint
EFTA	European Free Trade Association
EoL	End of Life
EPD	Environmental Product Declaration
EU	European Union
FCH	Fuel Cell and Hydrogen
FU	Functional Unit
ICS	International Classification for Standards
IEC	International Electrotechnical Commission
IES	Institute for Environment and Sustainability
ILCD	International Reference Life Cycle Data System
JRC	Joint Research Centre
JU	Joint Undertaking
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LHV	Lower Heating Value
NCV	Net Calorific Value
PCR	Product Category Rule
PED	Primary Energy Demand
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rule
UPS	Uninterruptible Power Supply
WP	Work Package

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Introducing the HyPEF project

In the urgent exploration of alternative energy sources and solutions, it is vital not to overlook sustainability and environmental impact. As a promising key energy vector to decarbonise multiple sectors, hydrogen is already crucially involved in energy and climate strategies, opening the hydrogen economy to accountability and sustainability checks. While the EU is increasingly promoting the deployment of fuel cell and hydrogen (FCH) systems, the spotlight is also on ensuring the environmental sustainability of such systems across their lifecycle.

Although science-based macro-level guidelines are available for Product Environmental Footprint (PEF) studies to report on life-cycle environmental profiles, there is a need for further specification both to categorise FCH products and outline specific criteria and procedures able to guarantee their environmental suitability.

In response to this need for qualification and further specification of FCH products as an environmentally-responsible investment, HyPEF (Promoting an Environmentally-Responsible **Hy**drogen Economy by Enabling **P**roduct **E**nvironmental **F**ootprint Studies) sets out to formulate and test the first Product Environmental Footprint Category Rules (PEFCRs) specifically tailored to FCH products.

HyPEF aims to complement the general methodological guidelines for Product Environmental Footprint (PEF) and the latest recommendations on LCA (Life Cycle Assessments) of FCH systems by developing category rules that are specific to FCH products. HyPEF will focus on 3 specific FCH product categories (electrolysers for hydrogen production, tanks for hydrogen storage, and fuel cells for hydrogen stationary use) that will serve as pilots for the drafting of tailored FCH-PEFCRs to be tested in 12 life-cycle case studies.

To promote the growth of an environmentally-responsible hydrogen economy and maximise the project's contribution to the Clean Hydrogen value chain, HyPEF brings together top European FCH technologists, environmental research institutes and consultancies. The interdisciplinary approach behind HyPEF will develop along two main project streams to deliver both short and medium-term insights at methodological and framework levels:

FCH Product level - definition of FCH product categorisation; development and application of PEFCRs specific to FCH products (FCH-PEFCRs).

FCH Framework level – analysis of medium-term potential implications of FCH-PEFCRs in specific regulations, codes, and standards (RCS) and supply of high-quality data relevant for future analyses at the economic, social and sustainability level.

The combination of these two approaches will allow HyPEF to advance methodological specifications and inspire the development of regulatory frameworks for FCH systems to support policy-making for an eco-friendly hydrogen economy and promote market benchmarking for FCH products' safe and responsible deployment.

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1. Context and objective

Funded by the Clean Hydrogen Joint Undertaking under the powers delegated by the European Commission, the HyPEF project (grant agreement number: 101137575) promotes the consolidation of an environmentally-responsible hydrogen economy by enabling product environmental footprint studies which are specific to Fuel Cell and Hydrogen (FCH) systems. This is achieved by developing and testing the first Product Environmental Footprint Category Rules (PEFCRs) specific to FCH systems, while paving the way for subsequent related initiatives in the FCH sector. The HyPEF project is conceptualised as the natural step forward in methodological specification towards policy- and market-relevant environmental life cycle assessment (LCA) and benchmarking of FCH products.

The interdisciplinary approach leads to crucial advancements regarding (i) the first development and application of well-accepted PEFCRs tailored to three pre-selected FCH product categories (electrolysers for hydrogen production, tanks for hydrogen storage, and fuel cells for hydrogen stationary use), (ii) increased high-quality data availability for consistent environmental assessment and benchmarking of FCH products, and (iii) first PEF-oriented policy recommendations towards official qualification of a FCH product as an environmentally-responsible investment.

PEFCRs have already been developed for product categories not specific to FCH systems. As of April 2024, PEFCRs related to energy had been developed only for rechargeable batteries (Recharge 2020), uninterrupted power supply (Schneider Electric 2020) and PV modules (First solar 2020). Moreover, LCA guidelines (i.e., product category rules not compliant with PEF) specific to FCH systems exist thanks to past initiatives such as the FC-HyGuide project[2], specific documents framed within the International EPD® System (Capello, et al. 2015) and the International Electrotechnical Commission (IEC/TS, 62282-9-102 2021). The latest guidelines for environmental, economic, social and sustainability life-cycle assessment of FCH systems have been developed within the SH2E project (Bargiacchi, et al. 2022). Based on a list of criteria defined and presented in the current report, methodological specifications (e.g., system boundaries, multifunctionality approach, and impact categories) are analysed in order to inform the drafting of the FCH-PEFCRs in HyPEF WP3.

In the European market context, guidance is provided concerning the development and drafting of PEFCRs. The latest requirements are described in Annex II of the Commission recommendation of 16.12.2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations (European Commission 2021).

Critically, as mentioned therein, beyond the general requirements to be respected, a "*PEFCR may further specify requirements made in the PEF method and add new requirements, if the PEF method leaves more than one choice*" (Annex 1, p. 18, ibid.).

[2] Home - FC-HyGuide, last accessed on 5.6.2024.

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Moreover, "*PEFCRs should, as far as possible, and recognising the different application contexts, be compliant with existing relevant international product category rules (PCR). If other PCRs are available from other schemes, these are to be listed and evaluated. They may be used as a basis for developing a PEFCR, in line with the requirements provided in Annex II*" (Annex 1, p. 18, ibid.).

As described in the following chapter, the focus of the task underlying the current report was thus to analyse existing PEFCRs and other relevant international PCRs or related literature in terms of those requirements allowing flexibility in the drafting of new PEFCRs, to be carried out in HyPEF's WP3.

With the over-arching goal to prepare the ground and set criteria for the development of FCH system PEFCRs, the following objectives are pursued in the current deliverable:

- Identifying those requirements and aspects where the official guidance by European Commission (2021) grants flexibility in the drafting of PEFCRs.
- Identifying already existing documents providing guidance on how to conduct LCA and being of relevance (i.e. product category rules and similar documents).
- Summarising and evaluating how the identified relevant guidance documents interpret this flexibility and what can be concluded from them for the drafting of new FCH system PEFCRs.

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2. Approach

The global approach consists of the following steps, which are detailed in the subsequent sections and chapters:

- Development of a criteria list → which requirements and aspects of existing guidance documents to analyse/compare more deeply? (section 2.1)
- Identification of the relevant literature (up to end of April 2024) and evaluation of these guidance documents (e.g. PEF or other category rules) → which documents to include in the evaluation? (section 2.2)
- Creation of a working table for the documentation and comparison of the identified documents → what are the key elements and learnings? (section 2.3)
- Summary of results (see chapters 3 and 4)

2.1. Development of a criteria list

The latest PEF methodology (European Commission 2021) does not leave a lot of degrees of freedom when drafting PEFCRs of a given product category. The list of criteria against which the identified documents are evaluated therefore consists of items for which European Commission (2021) allows to provide specific rules. These are the essential items in Table 1 for which information was sought to be collected from the identified documents. In addition, information useful for example for product classification (in Task 2.2) or for drafting of the PEFCRs (in WP 3) was also collected to the extent identifiable, also stated in Table 1.

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Section in EC (2021)	Essential (E) or Useful (U)	Item
-	E	Description of the document: - type (PEFCR, PCR, …) - standardisation body/program operator - scope (geographic) - applicability to PEFCR and H_2 systems
B.3.1	U	Product classification
B.3.2	E	Representative product(s)
B.3.3	E	Functional unit and reference flow
B.3.4	E	System boundary
B.3.7	U	Additional environmental information
B.3.8	U	Limitations (including Data gaps and proxies)
B.4.1	U	Most relevant (EF) impact categories (here: "impact categories" in general, i.e. not limited to Environmental Footprint, EF)
B.4.2	U	Most relevant life cycle stages
B.4.3	U	Most relevant processes
B.5.7	E	Allocation rules
B.5.8	E	Electricity modelling
B.5.10	E	Modelling of end of life and recycled content
B.7	U	PEF Results

Table 1- Items for the literature review

In this document, not only PEFCRs are analysed but also documents that do not follow the provisions of European Commission (2021) (see section 2.2). This also concerns the impact categories and/or their specific assessments. Therefore, the item to be evaluated according to B.4.1 of European Commission (2021) are the impact categories in general.

In chapter 3, the essential items are given as fourth level headings. Useful information is provided to the extent available at the end of the description of the essential information from a given document.

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2.2. Identification of the relevant literature

Guidance documents that at least in parts address FCH systems had already been identified at the project proposal writing stage. These were known to the experts of the project consortium, i.e. two PCRs from the FC-HyGuide project (Masoni and Zamagni 2011) (Lozanovski, Schuller and Faltenbacher 2011), one PCR by the International EPD® System (Capello, et al. 2015), one PCR by the International Electrotechnical Commission (IEC) (IEC/TS, 62282-9-102 2021) and the latest guidance documents from the SH2E project (Bargiacchi, et al. 2022) (Martín-Gamboa, et al. 2023). Three PEFCRs that are not specific to FCH systems had also been identified because they were at least addressing energy-related systems (i.e. First solar (2020), Recharge (2020) and Schneider Electric (2020)). Therefore, one could not preclude that additional learnings for FCH systems could be gained. The only further document that could be identified was another PEFCR on metal sheets (Eurometaux 2019). This was included because it addresses different products within the same product category.

2.3. Creation of a working spreadsheet for documentation

The essential and useful items listed in Table 1 together with further items addressed in European Commission (2021) were transferred into a summarising spreadsheet in order to evaluate the identified guidance documents. The results from the analysis relevant for this deliverable are presented in chapter 3.

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3. Results

The results are presented in four parts:

1. H_2 production (section 3.1);
2. H_2 storage (section 3.2);
3. H_2 use (section 3.3); and
4. Other relevant documents unrelated to H_2 (section 3.4).

3.1. H_2 production

Two documents providing guidelines for environmental life cycle assessment (LCA) of hydrogen production were identified and evaluated:

- “Guidance document for performing LCA on hydrogen production systems” (FC-HyGuide) by Lozanovski et al. (2011) (see section 3.1.1);
- “Definition of FCH-LCA guidelines” (SH2E) by Bargiacchi et al. (2022) (see section 3.1.2).

3.1.1. FC-HyGuide guidance document on H_2 production (Lozanovski, Schuller and Faltenbacher 2011)

The document by Lozanovski et al. (2011), titled “Guidance document for performing LCA on hydrogen production systems”, builds on the International Reference Life Cycle Data System (ILCD) coordinated by the Joint Research Centre Institute for Environment and Sustainability (JRC-IES) through the European Platform on LCA. This helps in the provision of quality-assured life cycle data and also in robust decision support for hydrogen production related policies and businesses, while it technically guides the conducting of LCA of hydrogen production systems and helps in dealing with key methodological aspects.

The Fuel Cells and Hydrogen Joint Undertaking (FCH JU), i.e. the predecessor of the Clean Hydrogen Joint Undertaking (CH JU), funding this project, can be said to be the program operator. The geographic reference is Europe (or more specifically: the European Union).

3.1.1.1. Representative product(s)

Lozanovski et al. (2011) do not describe a representative product.

3.1.1.2. Functional unit and reference flow

The functional unit (FU) defined by Lozanovski et al. (2011) is:

- *What?* - high purity hydrogen, produced in multi-functional or single functional process, not produced in a negligible amount (as co-product) or in low quality
- *How much?* - 1 MJ hydrogen (net calorific value, NCV)
- *How well?* – it is required to state the following hydrogen properties:

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Purity (e.g. 99.995 %)
Aggregate state (e.g. liquid)
Pressure (e.g. 200 bar)
Temperature (e.g. ambient temperature)

- *How long?* – Even though not explicitly stated in relation to the functional unit, a reference year or period or technical service life are suggested to be defined. In addition, the time period to which assumptions apply shall be stated.

The reference flow is defined as: 1 MJ of hydrogen (NCV) with *xx* % purity at *yy* bar and *zz* °C.

3.1.1.3. System boundary

According to Lozanovski et al. (2011), the system boundary diagram should clearly indicate the processes and life cycle stages up to hydrogen production. The primary step in hydrogen production, as shown in Figure 1, encompasses the conversion stage alone. However, it is important to consider the related stages as well, which includes stages such as purification and conditioning, as depicted in Figure 1. The system boundary shall ensure consistency with the study's goal, visualising the chosen system boundary with all product flows (input and output) included and stated. Any generic and secondary data gaps should also be described.

For partly terminated systems (i.e. aggregated data set with at least one product flow in the input/output list that needs further modelling), processes pre-decided for exclusion from the system boundary still have their corresponding product and/or waste flows considered in the overall assessment. These flows must be shown in the system boundary diagram. When used in another system, the model must be completed for these products and/or waste flows. Adopting a 5% cut-off value for each environmental impact category is mandatory, and any different value must be justified and its effects on the final results checked through sensitivity analysis.

Lozanovski et al. (2011) allow the consideration of the infrastructure including its dismantling.

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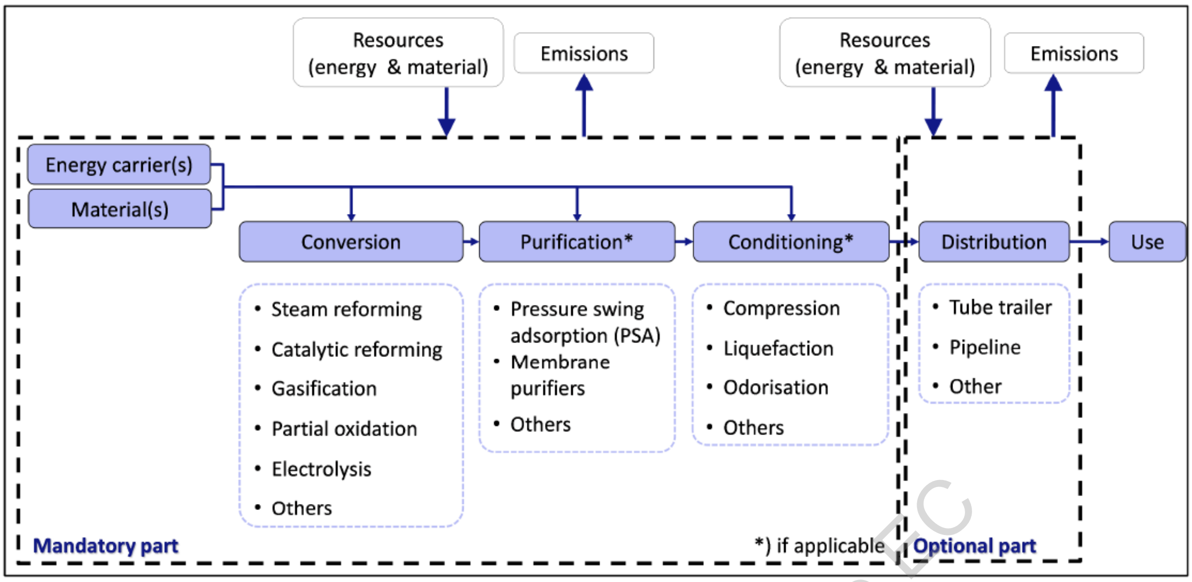

Figure 1 – System boundary according to Lozanovski et al. (2011).

3.1.1.4. Allocation rules

The allocation procedure by Lozanovski et al. (2011) for the multifunctional processes follows this hierarchy:

1. Sub-division
2. System expansion
3. Allocation according to the following sub-hierarchy:
   - Physical relationship between the products: Energy (NCV) is the primary factor to be considered.
   - Mass factor: If the energy factor is not used, then the mass factor should be considered.
   - Other relationships: If neither energy nor mass factors are suitable, other relationships, such as market value, are considered.

3.1.1.5. Electricity modelling

Lozanovski et al. (2011) require the use of the European electricity mix (EU-27). Specific mixes (country, company etc.) regarding electricity may be used, but not as an alternative to the EU-27 mixes.

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3.1.1.6. Modelling of end of life and recycled content

Lozanovski et al. (2011) allow the consideration of the infrastructure including its dismantling. Given the cradle-to-gate system boundary for the hydrogen value chain, the end-of-life of hydrogen is not considered.

3.1.1.7. Useful information (as far as provided)

Among the useful pieces of information, Lozanovski et al. (2011) only provide information on limitations, on the most relevant impact categories and on additional environmental information.

Regarding **limitations** such as data gaps, Lozanovski et al. (2011) require reporting how the data gaps are filled and also to check relevancy of initially missing data. Documentation should be done in a transparent and consistent way. Data gaps shall generally be filled with methodologically consistent data. Only data that increases the overall quality of the final inventory of the analysed system shall be used to fill data gaps. If data estimates cannot be made available that would meet the above requirements, the data gaps shall be kept and documented on missing quality instead.

According to Lozanovski et al. (2011), the **most relevant impact categories** are:

- Global warming potential.
- Acidification potential.
- Eutrophication potential.
- Photochemical ozone creation potential.

When available, Lozanovski et al. (2011) require using the methods, models and characterisation factors identified in the guidance document by the JRC-IES, through the European Platform on LCA.

As **additional environmental information**, it is required to quantify the following environmental indicators:

- Non-renewable primary energy demand (PED non-renewable);
- Renewable primary energy demand (PED renewable).[3]

[3] PED indicators are not classified as impact category indicators because Lozanovski et al. (2011) refer to them as “environmental indicators”.

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3.1.2. SH2E LCA guidelines for H_2 production

The document by Bargiacchi et al. (2022), titled "Definition of FCH-LCA Guidelines", presents methodological guidance on how to perform Life Cycle Assessment (LCA) of fuel cells and hydrogen (FCH) systems. Recently developed within the SH2E project, it provides a consistent methodology for LCA of FCH systems. This guidance is not specific to a given hydrogen system (e.g. production, storage, or use) but addresses all hydrogen systems, including those for hydrogen production. The SH2E project aimed to provide a consistent methodology that includes underdeveloped topics such as prospective assessment and material criticality. Hence, the SH2E LCA guidelines represent not only an update but also an enhanced version of the guidelines originally developed within the FC-HyGuide project (i.e. Masoni & Zamagni (2011) and Lozanovski et al. (2011)).

The Clean Hydrogen Joint Undertaking (CH JU), funding the SH2E project, can be said to be the program operator. The geographic reference is Europe.

3.1.2.1. Representative product(s)

Bargiacchi et al. (2022) do not describe a representative product.

3.1.2.2. Functional unit and reference flow

The functional unit (FU) defined by Bargiacchi et al. (2022) is:

- *What?* - Concerning the concept of system function, a high-level classification is provided in SH2E. Bargiacchi et al. (2022) define three functional cases for hydrogen production:
  - Single function system: The function of the system is exclusively to produce hydrogen (only one function).
  - Multifunctional system with hydrogen production as the main function: The system delivers multiple functions, with hydrogen being the main product.
  - Multifunctional system with hydrogen as an additional product: The system delivers multiple functions, with hydrogen being a co-product or by-product (e.g. chlor-alkali electrolysis).
- *How much?* - Mass of produced hydrogen (kg) or energy output (MJ) in terms of hydrogen. For the latter, the energy basis must be stated (e.g. lower heating value, LHV).
- *How well?* – A specific hydrogen purity, pressure and temperature are not prescribed but shall be stated.
- *How long?* - Not available

The system's reference flow must be clearly indicated and precisely quantified.

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3.1.2.3. System boundary

The system boundary diagram in SH2E offers a high level of detail for each stage (Figure 2). Different cradle-to-gate system boundaries for the H_2 production step are distinguished. These are sequentially numbered, ranging from 1 to 6 corresponding to the smallest and largest scope, respectively. The system boundary for hydrogen production systems, as per the SH2E LCA guidelines, must be at least cradle-to-gate 1 (i.e. mining & preparation, and hydrogen production; Figure 2). The scope is recommended to be extended up to cradle-to-gate 3 (i.e. mining and preparation, hydrogen production, hydrogen purification, and hydrogen compression; Figure 2). It can further extend to cradle-to-gate 6 (Figure 2), additionally incorporating transportation (i.e. long-distance transport or "transmission"), storage, and distribution stages. Relevant flows subject to the study should be included, encompassing processes such as resource extraction, manufacturing, and hydrogen production.

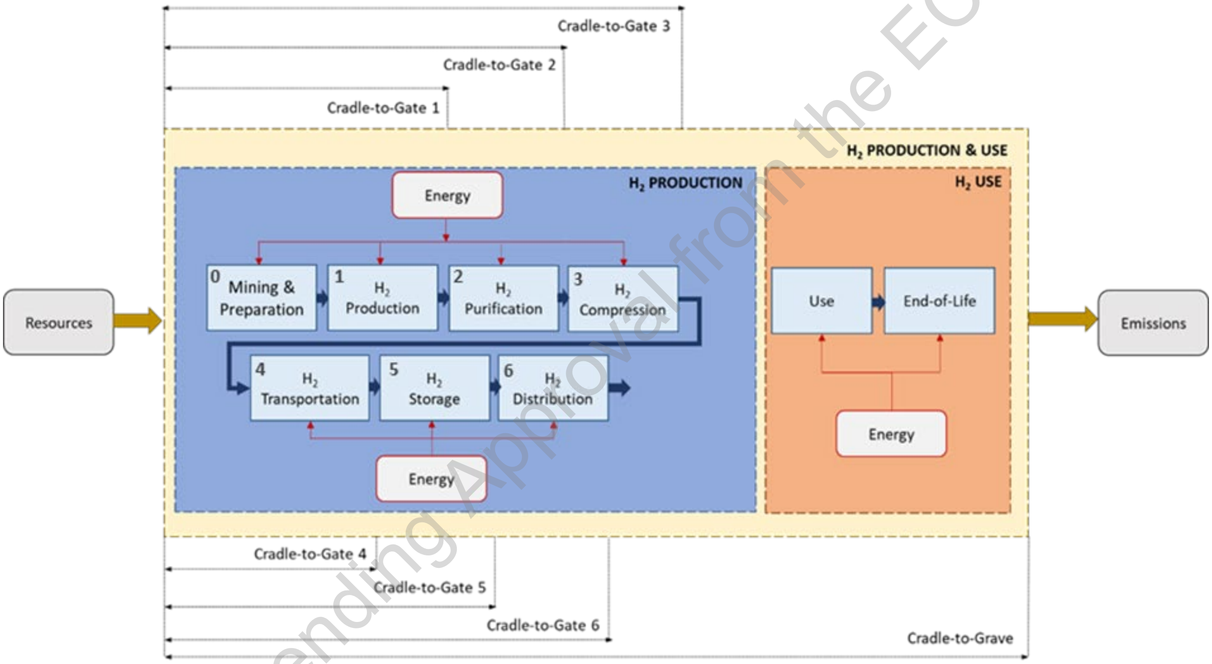

Figure 2 – System boundary for FCH systems according to Bargiacchi et al. (2022).

Bargiacchi et al. (2022) avoid the use of "shall/must" for cut-off rules, which are present in FC-HyGuide, requesting to avoid cut-off rules altogether. Capital goods must be included in all life cycle phases along with their respective lifetimes. Any non-inclusion must be justified. Data sources and assumptions should be thoroughly documented.

3.1.2.4. Allocation rules

Provisions by Bargiacchi et al. (2022) on the multifunctionality approach are similar to those in Lozanovski et al. (2011). When feasible, allocation must be avoided by dividing unit processes into different subprocesses according to the output produced. If division is not possible, then

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system expansion must be considered as an alternative to avoid allocation. If allocation cannot be avoided, it must be applied by partitioning inputs/outputs according to physical relationships between them or other possible relationships (e.g. economic).

3.1.2.5. Electricity modelling

Bargiacchi et al. (2022) do not make general provisions regarding electricity modelling.

3.1.2.6. Modelling of end of life and recycled content

The EoL of FCH technologies shall be considered. Preparatory steps (collection, transport, pre-treatment [sorting, separation]) of EoL flows shall be considered, if not excluded by method. Downstream activities of waste treatment, such as landfill operation and maintenance as well as ash disposal, shall be included. The choice of the modelling approach to EoL shall be documented and justified. System boundaries shall be drawn in line with the underlying EoL modelling approach.

3.1.2.7. Useful information (as far as provided)

Bargiacchi et al. (2022) do not make general provisions regarding product classification, the most relevant processes or PEF results. However, they make provisions on the other useful pieces of information.

3.1.2.7.1. Additional environmental information

Bargiacchi et al. (2022) do not make general provisions regarding additional environmental information but do address raw material criticality as an additional topic.

3.1.2.7.2. Limitations (including data gaps and proxies)

According to Bargiacchi et al. (2022), it is imperative to clearly state every data source to ensure data traceability. Additionally, it is recommended to assess the transparency and credibility of each data source used.

3.1.2.7.3. Most relevant impact categories

Bargiacchi et al. (2022) do not make general provisions regarding most relevant impact categories. All the impact categories are required. If it is decided not to include a specific impact category, this must be justified.

3.1.2.7.4. Most relevant life cycle stages

Bargiacchi et al. (2022) do not make general provisions regarding most relevant life cycle stages beyond the requirements and recommendations already included in the section on "System boundary" (see section 3.1.2.3).

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3.1.3. Summary on H_2 production documents

In summary, the hydrogen production-related documents by Lozanovski et al. (2011) and Bargiacchi et al. (2022) do not describe a **representative product**. They offer differing approaches to defining the **functional unit**. In the FC-HyGuide guidance document (Lozanovski, Schuller and Faltenbacher 2011), the functional unit is mentioned only in terms of energy (MJ), whereas in SH2E, it is stated on either a mass (kg) basis or an energy (MJ) basis. Both documents allow to produce H_2 in single functional or multi-functional processes. Additionally, the SH2E Life Cycle Sustainability Assessment (LCSA) guidelines (Martín-Gamboa, et al. 2023) mandate a mass-based functional unit to ensure harmonisation with other assessment guidelines. Neither Lozanovski et al. (2011) nor Bargiacchi et al. (2022) make clear provisions regarding the "how long" criterion.

When there is multifunctionality, Lozanovski et al. (2011) only consider hydrogen as a **co-product**, i.e. in case it is produced in non-negligible amounts. Bargiacchi et al. (2022), by contrast, considers hydrogen as both, a co-product or a **by-product** (i.e. "Multifunctional system with hydrogen production as the main function" and "Multifunctional system with hydrogen as an additional product", respectively).

The **reference flow** is expressed in units corresponding to the functional unit allowed in the two guidance documents. Lozanovski et al. (2011) in addition requires an indication of purity, pressure and temperature, while their specification is only a recommendation according to Bargiacchi et al. (2022).

The **system boundaries** of the FC-HyGuide document (Figure 1) correspond at least to the cradle-to-gate 1 scope and at most to the cradle-to-gate 3 scope of the SH2E document (Figure 2). For hydrogen production, Bargiacchi et al. (2022) mandate considering the scope from cradle-to-gate 1 (Figure 2), while recommending to extend the system boundary to cradle-to-gate 3 (compression, Figure 2). So, both documents suggest the same system boundaries for hydrogen production.

In Lozanovski et al. (2011), the **cut-off rule** of 5% is obligatory. In Bargiacchi et al. (2022), by contrast, the use of cut-off is discouraged, and any application of cut-off rules must be well justified.

Lozanovski et al. (2011) merely allow the consideration of the infrastructure including its dismantling (**end-of-life, recycling**). According to Bargiacchi et al. (2022), by contrast, the production, use and end-of-life of so-called capital goods are required to be included.

Provisions by Bargiacchi et al. (2022) on the **multifunctionality** approach are similar to those in the FC-HyGuide document by Lozanovski et al. (2011).

Lozanovski et al. (2011) require the use of the European electricity mix (EU-27), while Bargiacchi et al. (2022) do not make provisions related to **electricity modelling**.

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In terms of useful information, different kinds of **additional environmental information** are required or allowed to be provided in the different documents on hydrogen production:

- Bargiacchi et al. (2022) address raw material criticality;
- Lozanovski et al. (2011) require including energy-related indicators, i.e. Non-renewable Primary Energy Demand (PED non-renewable) or Renewable Primary Energy Demand (PED renewable).

Lozanovski et al. (2011) state the **most relevant environmental impact categories** (i.e. Global warming potential, Acidification potential, Eutrophication potential, and Photochemical ozone creation potential. According to Bargiacchi et al. (2022), by contrast, all impact categories in the latest version of the Environmental Footprint method (European Commission 2021) are to be considered. Primary energy demand (renewable/non-renewable) can be seen as a potentially interesting additional environmental indicator.

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3.2. H_2 storage

Only one document providing guidelines for environmental life cycle assessment (LCA) of hydrogen storage was identified and evaluated, i.e. “Definition of FCH-LCA guidelines” (SH2E) by Bargiacchi et al. (2022) (see section 3.2.1).

3.2.1. SH2E LCA guidelines for H_2 storage

As stated in section 3.1.2, the document by Bargiacchi et al. (2022) is not specific to a given H_2 system (e.g. production, storage or use) but addresses all H_2 systems, including those for H_2 storage.

3.2.1.1. Representative product(s)

Bargiacchi et al. (2022) do not describe a representative product.

3.2.1.2. Functional unit and reference flow

The functional unit (FU) and the reference flow are not defined for hydrogen storage in Bargiacchi et al. (2022) but for hydrogen production only (see section 3.1.2.2).

3.2.1.3. System boundary

The system boundary for hydrogen storage must be cradle-to-gate 5 (Figure 2). As depicted in Figure 2, the processes involved within this boundary include mining & preparation, hydrogen production, hydrogen purification, hydrogen compression, hydrogen transportation, and hydrogen storage. Apart from this, the remaining provisions are the same as for hydrogen production in Bargiacchi et al. (2022) (see section 3.1.2.3).

3.2.1.4. Allocation rules

The multifunctionality rules considered in Bargiacchi et al. (2022) for hydrogen storage align with those in the same document for hydrogen production (see section 3.1.2.4).

3.2.1.5. Electricity modelling

Bargiacchi et al. (2022) do not make general provisions regarding electricity modelling.

3.2.1.6. Modelling of end of life and recycled content

The modelling of end of life and recycled content considered in Bargiacchi et al. (2022) for hydrogen storage aligns with those in the same document for hydrogen production.

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3.2.1.7. Useful information (as far as provided)

Bargiacchi et al. (2022) do not make general provisions regarding product classification, the most relevant processes or PEF results. However, they make provisions on the other useful pieces of information.

3.2.1.7.1. Additional environmental information

Bargiacchi et al. (2022) do not make general provisions regarding additional environmental information but address raw material criticality as an additional topic.

3.2.1.7.2. Limitations (including data gaps and proxies)

The limitations (including data gaps and proxies) considered in Bargiacchi et al. (2022) for hydrogen storage align with those in the same document for hydrogen production (see section 3.1.2.7.2).

3.2.1.7.3. Most relevant impact categories

Bargiacchi et al. (2022) do not make general provisions regarding most relevant impact categories. All the impact categories are required. If it is decided not to include a specific impact category, this must be justified.

3.2.1.7.4. Most relevant life cycle stages

Bargiacchi et al. (2022) do not make general provisions regarding most relevant life cycle stages beyond the requirements and recommendations in the section "System boundary" (section 3.2.1.3).

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3.2.2. Summary on H_2 storage documents

For hydrogen storage, the SH2E document by Bargiacchi et al. (2022) is the sole reference available. Although all product-related rules applied to hydrogen storage align with the hydrogen production guidelines in that document, Bargiacchi et al. (2022) do not provide specific instructions for hydrogen storage. However, there is an explicit inclusion of hydrogen storage within the system boundary when choosing 'cradle-to-gate 5' (Figure 2). As depicted in Figure 2, the processes involved within this boundary include mining & preparation, hydrogen production, hydrogen purification, hydrogen compression, hydrogen transportation, and hydrogen storage. As a result, Bargiacchi et al. (2022) do not provide guidance on the assessment of hydrogen storage without considering all upstream processes including hydrogen production which is expected to become a separate product category. No specific definition of the functional unit nor of the reference flow for hydrogen storage is available from Bargiacchi et al. (2022).

As for hydrogen production, Bargiacchi et al. (2022)

- do not make clear provisions regarding the "how long" criterion for the functional unit of the PEFCRs (European Commission (2018), (2021));
- recommend specifying –in the initial flow diagram of the LCA– purity, pressure and temperature for the reference flow; and
- do not make provisions related to electricity modelling.

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3.3. H_2 use

In the context of hydrogen applications, four documents involving guidelines for environmental life cycle assessment (LCA) were identified and evaluated:

- "Definition of FCH-LCA guidelines" (SH2E) by Bargiacchi et al. (2022) (see section 3.3.1);
- FC-HyGuide guidance document on fuel cells by Masoni and Zamagni (2011) (see section 3.3.2);
- A PCR on domestic fuel cell application (IEC/TS, 62282-9-102 2021) (see section 3.3.3);
- A PCR on electricity production by the International EPD® system (Capello, et al. 2015) (see section 3.3.4).

3.3.1. SH2E LCA guidelines for H_2 use

As stated in Section 3.1.2, the document by Bargiacchi et al. (2022) is not specific to a given H_2 system (e.g. production, storage or use) but addresses all H_2 systems, including those for H_2 use.

3.3.1.1. Representative product(s)

Bargiacchi et al. (2022) do not describe a representative product.

3.3.1.2. Functional unit and reference flow

The functional unit (FU) defined by Bargiacchi et al. (2022) is:

- *What?* - Five functional cases that are defined in the SH2E LCA guidelines document for hydrogen use:
    - Hydrogen usage in transportation.
    - Hydrogen use for fuels and chemicals production.
    - Hydrogen use for electricity and/or heat generation, with two sub-cases:
        - Electricity or heat generation.
        - Co-generation (electricity and heat).
- *How much?* - The functional cases that are also defined in Bargiacchi et al. (2022) for hydrogen use are:
    - Transportation: Distance travelled for a given demand (e.g. in passenger-kilometres or tonne-kilometres).
    - Fuels and chemicals: Quantity of produced chemical/fuel in mass (energy also possible in the case of fuels).
    - Electricity and/or heat:
        - Electricity or heat generation: energy-based functional unit.

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    - Cogeneration: Exergy-based functional unit.

- *How well?* - The functional cases that are also defined in Bargiacchi et al. (2022) for hydrogen use are:
    - Transportation: Demand must be specified together with the lifetime measured in terms of mileage.
    - Fuels and chemicals: Purity, pressure and temperature for fuels and chemicals. For fuels, energy content must be stated clearly (e.g. net calorific value).
    - Electricity and/or heat: Considering upstream systems efficiencies to convert hydrogen to electricity.
- *How long?* - Not available

The reference flow considered in Bargiacchi et al. (2022) for hydrogen use aligns with those in the same document for hydrogen production regarding the requirement for indication and quantification.

3.3.1.3. System boundary

The system boundary for hydrogen use according to Bargiacchi et al. (2022) includes a cradle-to-grave approach (Figure 2), which is obligatory for any hydrogen use system. This encompasses two types of cases: hydrogen use (but nevertheless considering hydrogen production in the background The use of cut-off is strongly discouraged. If cut-off is applied, it must be thoroughly justified. The use of cut-off is strongly discouraged. If cut-off is applied, it must be thoroughly justified.

3.3.1.4. Allocation rules

In the case of multifunctionality, Bargiacchi et al. (2022) avoids allocation as in the hydrogen production and hydrogen storage cases. However, in scenarios where electricity and heat are cogenerated, and system subdivision or expansion is not viable, then physical allocation based on exergy must be applied to calculate partitioning factors between electricity and heat. If physical allocation based on exergy is not feasible, economic allocation should be considered.

3.3.1.5. Electricity modelling

Bargiacchi et al. (2022) do not make general provisions regarding electricity modelling.

3.3.1.6. Modelling of end of life and recycled content

The modelling of end of life and recycled content considered in Bargiacchi et al. (2022) for hydrogen use aligns with those in the same document for hydrogen production.

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3.3.1.7. Useful information (as far as provided)

Bargiacchi et al. (2022) do not make general provisions regarding product classification, the most relevant processes or PEF results. However, they make provisions on the other useful pieces of information.

3.3.1.7.1. Additional environmental information

Bargiacchi et al. (2022) do not make general provisions regarding additional environmental information but do address raw material criticality as an additional topic.

3.3.1.7.2. Limitations (including data gaps and proxies)

The limitations (including data gaps and proxies) considered by Bargiacchi et al. (2022) for hydrogen use aligns with those in the same document for hydrogen production (see section 3.1.2.7.2).

3.3.1.7.3. Most relevant impact categories

Bargiacchi et al. (2022) do not make general provisions regarding most relevant impact categories. All the impact categories are required. If it is decided not to include a specific impact category, this must be justified.

3.3.1.7.4. Most relevant life cycle stages

Bargiacchi et al. (2022) do not make general provisions regarding most relevant life cycle stages beyond the requirements and recommendations in the section "System boundary" (see section 3.3.1.3).

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3.3.2. FC-HyGuide guidance document on fuel cells (Masoni and Zamagni 2011)

The analysed document is entitled "Guidance Document for performing LCAs on Fuel Cells and H_2 Technologies" (Masoni and Zamagni 2011). Adapted from the ILCD Handbook and the ISO 14040 series, the document gives an overview of how to carry out an LCA on fuel cells. The document is the final deliverable of a project on Fuel Cells and Hydrogen, funded by the FCH JU. The FCH JU can be said to be the program operator. The geographic reference is Europe (or more specifically: the European Union).

Most relevant outcomes are summarised and reported in the following.

Since the document is not directly related to PEF and PEFCRs, the suggestions reported in the next paragraphs might need to be adapted to the PEFCRs context.

3.3.2.1. Representative product(s)

Masoni & Zamagni (2011) do not describe a representative product. They note that FCs are complex systems that can have different applications (e.g., stationary, transport, portable). The suggested approach is to analyse the FCs as a system in terms of its main parts, namely: FC stack and Balance of Plant (BoP). Given the numerous options of available materials and compositions, a detailed description of the major properties and characteristics of FC and BoP shall be included. Some examples are reported in Masoni & Zamagni (2011).

3.3.2.2. Functional unit and reference flow

According to Masoni & Zamagni (2011), the function of the FCs is the production of electricity and, in many cases, heat (multifunctionality). In some cases, FCs can have the additional function of producing water. However, production of water is not covered by the guidance document. In order to take into account the multi-functionality of the system, i.e., the production of both electricity and heat, the concept of exergy is adopted.

Masoni & Zamagni (2011) allow two different kinds of functional unit (FU): at stack level and at system level. For the purpose of HyPEF, only the system level is considered relevant whose functional unit is defined by Masoni & Zamagni (2011) as the "production of a certain amount of electricity and useful thermal energy in a given number of years", expressed in MJex. The share of electricity and heat shall be declared. If the thermal output of the FC is not used, the FU is only the production of electricity, expressed in MJel.

- *What?* – electricity and thermal energy production
- *How much?* – a certain (not-defined) amount of electricity and thermal energy, expressed in MJex
- *How well?* – Electricity given at a certain voltage level, and thermal energy given at a certain temperature

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- *How long?* - Service life span shall be defined consistently with the expected lifetime and taking into account the time the facility has already been running, adequately supported with experimental results and/or other technical analysis.

The reference flow is defined as the number of FC systems required to produce the amount of energy or exergy defined in the functional unit.

A degradation of 10% of the FC performance during the lifetime should be considered.

3.3.2.3. System boundary

The system boundary chosen in Masoni & Zamagni (2011) is cradle-to-grave. The production of fuel (i.e., hydrogen) is not included. The foreground system is represented by the manufacturing, the assembly, and the maintenance of the stack components (e.g., anode, cathode, matrix), the manufacturing of the BoP and the start-up system. The use phase is included as well when analysing at system level. The background system is represented by the relevant materials and energy flows going to and coming from the manufacturing process.

Company-specific primary data are required for all the processes of the foreground system. Process steps related to the background system may be site specific if available. Data on the production of materials and energy carrier should reflect the geographical region where they are purchased.

Regarding the environmental significance of results, a cut-off of 2% on the impact on each relevant environmental category is adopted.

3.3.2.4. Allocation rules

Masoni & Zamagni (2011) suggest using exergy as the unit for the functional unit to avoid allocation in case that heat is considered a valuable (co- or by-) product.

3.3.2.5. Electricity modelling

Masoni & Zamagni (2011) require the use of the European electricity mix (EU-27).

3.3.2.6. Modelling of end of life and recycled content

Masoni & Zamagni (2011) require the consideration of the end-of-life of the fuel cell stack or system at least in qualitative terms.

3.3.2.7. Useful information (as far as provided)

Among the useful pieces of information, Masoni & Zamagni (2011) only provide information on additional environmental information, on the most relevant impact categories and on the potentially (i.e. not most) relevant processes.

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As **additional environmental information**, energy-related indicators, i.e. Non-renewable Primary Energy Demand (PED non-renewable) and Renewable Primary Energy Demand (PED renewable),[4] shall be included.

According to Masoni & Zamagni (2011), the **most relevant impact categories** are:

- Global warming potential.
- Acidification potential.
- Eutrophication potential.
- Photochemical ozone creation potential.

When available, Masoni & Zamagni (2011) require using the methods, models and characterisation factors identified in the guidance document by the JRC-IES, through the European Platform on LCA.

Masoni & Zamagni (2011) optionally recommend further impact categories to be assessed.

The following **potentially relevant processes** for fuel cells should be included according to Masoni & Zamagni (2011):

- Chemicals and electricity consumption as well as emissions of the fuel cell stack manufacturing (e.g., anode, cathode, matrix, electrolyte).
- Energy consumption and emissions of the stack assembling and steel parts (e.g., anodic and cathodic collectors, bipolar plates).
- Materials used for the BoP assembling (e.g., copper, aluminium, palladium, platinum, cast ironed) and the related energy consumption and emissions.
- Fuel consumption during the operation phase and the related emissions.

[4] PED indicators are not classified as impact category indicators because Masoni & Zamagni (2011) refer to them as "environmental indicators".

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3.3.3. A PCR on domestic fuel cell application (IEC/TS, 62282-9-102 2021)

The document being analysed is titled (IEC/TS, 62282-9-102 2021). It provides Product Category Rules (PCR) technical specifications developed to allow for an EPD of stationary fuel cell combined heat and power (CHP) systems and alternative systems for residential applications.

It is based on:

- ISO 14020: environmental labels and declarations - general principles;
- ISO 14021: environmental labels and declarations - self-declared environmental claims (Type II environmental labelling);
- ISO 14025 (and thus in line with ISO 14040 and ISO 14044): environmental labels and declarations - Type III environmental declarations - principles and procedures. Publication date: 14/01/2021 (stability period 2024).

The IEC Quality Assessment System For Electronic Components (IECQ) is the program operator. The geographic scope is worldwide.

3.3.3.1. Representative product(s)

The IEC PCR does not specify a representative product but it requires to refer to the general product group and provides a list of specific properties and characteristics regarding the device itself (IEC/TS, 62282-9-102 2021).

3.3.3.2. Functional unit and reference flow

The functional unit is clearly defined as the annual satisfaction of the space heating and hot water demand of a given home with indications of a reference lifetime of 10 years; if devices or components last shorter, respective replacements are considered (IEC/TS, 62282-9-102 2021). In order to obtain specific environmental performances of a specific type of device, the functional unit is split into: 1) the supply of a given heat-related device or CHP generator to the regional market where it is used; 2) the system operation.

- What? – Specifically, the installer shall calculate the overall environmental impact score per impact category for the appropriate heating demand-hot water share combination: heating demand [kWh/year] and which percentage of hot water demand.
- *How much?* – Annual satisfaction in terms of kWh of heating demand and percentage of hot water demand.
- *How well?* – Degradation shall be considered. Average efficiencies over the system’s lifetime shall be determined.

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- *How long?* - The reference lifetime is 10 years; replacements shall be considered if a shorter lifetime applies.

The reference flow must be expressed in heating demand [kWh/year]. Different scenarios are reported in terms of specifications of the space heating demand and hot water demand for which the environmental related performances shall be provided. For each scenario, the overall lifetime and the frequency of replacement of components shall be documented.

3.3.3.3. System boundary

A cradle-to-grave approach is recommended (IEC/TS, 62282-9-102 2021). The considered heat-related device or CHP generator system is distinguished into foreground and background system. Foreground: manufacturing, use, end-of-life. Background: Technosphere (fuel and electricity supply).

What kind of data are recommended or not are indicated. Specifically for the foreground system:

- MANUFACTURING: Primary data shall be used for: material composition of the components, of auxiliary equipment; energy use for constructing and assembling the devices; distances by mode of transport, and related energy uses and releases for material supply. Secondary data may be used for energy uses and releases associated with transport. All hazardous and toxic materials shall be included, regardless of their contribution to the final results.
- OPERATION: Primary data shall include operation of the heat-related device or CHP; amounts of fuel and electricity and other auxiliary operational inputs; fuel preparation processes; maintenance; waste practices for fuel and for other waste.
- END-OF-LIFE: Quantitative assessment not required but encouraged.
- MANUFACTURING SITE: If primary not available, secondary data should be used for fuel, heat and electricity supply (background system). For the background system (fuel, heat and electricity supply) unless primary data are available, specification on the secondary data that should be used are provided.

Given that the IEC PCR is a commercial product, the figure depicting the system boundary is not reproduced here.

3.3.3.4. Allocation rules

CHP generators are considered multifunctional as they produce heat and electricity at the same time (IEC/TS, 62282-9-102 2021).
During the operation phase, system expansion is used to deal with multifunctionality. When the demand is satisfied, the credit depends on the electricity production avoided and varies by

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region or country as specified in Table 2 page 20 (credits by impact category associated with a kWhe). Or for cold produced (indications for calculation are provided).
During the manufacturing phase: If a CHP generator is installed at the manufacturing site(s) of a heat-related device, allocation shall be performed using exergy. The IEC PCR also requires using specific values for reference temperature and pressure when computing exergy (IEC/TS, 62282-9-102 2021).

3.3.3.5. Electricity modelling

In general, the electricity supply within or to the manufacturing site(s), and within or to the regional market on which the EPD of the heat-related device or CHP generator is employed is distinguished (IEC/TS, 62282-9-102 2021). For the operation of the device (using hydrogen), the electricity supply effective in the regional market concerned shall be used. The same applies to the manufacturing site (i.e. using the electricity supply representative for the country or region where it is located), unless a guarantee of origin can be proven.

3.3.3.6. Modelling of end of life and recycled content

A quantitative assessment is not required but encouraged (IEC/TS, 62282-9-102 2021). Information on practices or programmes specific for the specific country involved are recommended. Notably, this information is required to be provided separately from LCA results. Information on the recyclability shall be provided.

3.3.3.7. Useful information (as far as provided)

Except for most relevant processes and (PEF) results, the IEC PCR only provides the following pieces of useful information (IEC/TS, 62282-9-102 2021):

- Product classification: International Classification for Standards (ICS) 27.070 Fuel cells.
- Additional environmental information: some specifications regarding the case of carbon neutrality and market mediated impacts of biofuels shall be reported in the EPD.
- Limitations (including data gaps and proxies): The EPD shall make a statement that the environmental information provided is limited to the reported impact categories.
- Most relevant impact categories: The most relevant impact categories that shall be addressed are the following: climate change; abiotic resource depletion (minerals and metals); particulate matter; acidification; photochemical ozone formation. Also specifications on the methods are reported.
- Most relevant life cycle stages: divided into foreground and background stages as mentioned above.

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3.3.4. The International EPD® System (Capello, et al. 2015)

The International EPD® System, as the program operator, has published only one PCR that covers a H_2 system. The document by Capello et al. (2015) is entitled "Electricity, steam and hot/cold water generation and distribution". It is applicable to the whole world. Fuel cells are only one type among several technical solutions. It is version 3 of this PCR that is stated to be valid until 5 February 2019. According to the International EPD® System's website[5], "*An updating process was initiated 2022-06-14 to update the PCR in alignment version 4 of the GPI and to prolong the validity period. … Publication is expected for May or June 2024*". According to one of its authors, the fuel cell part of the document remains unchanged in this update. It is valid at global level.

3.3.4.1. Representative product(s)

Capello et al. (2015) do not describe a representative product. At the level of the International EPD® System (programme level, not PCR level), however, a sector-level EPD is possible, by relying on "*average values for an entire or partial product category (specifying the percentage of representativeness)*" and noting that "*the declared unit is not available for purchase on the market*" (section 10.1, ibid.).

3.3.4.2. Functional unit and reference flow

"Functional unit" is mentioned only once in the report, otherwise "declared unit" is used. It appears that "functional unit" used once should read "declared unit".

Capello et al. (2015) states in Chapter 3: "*The declared unit is defined as 1 kWh net[6] of electricity generated and thereafter distributed and/or 1 kWh of steam or hot water generated and thereafter distributed to the customer. The declared unit shall be stated in the EPD. The environmental impact shall be given per declared unit during the technical service life of the energy conversion plant based on the status of the plant in the defined reference period.*"

- *What?* – electricity (net), steam or hot water; it appears that fuel cells are included only by considering their capability of producing electricity (i.e. using the heat is not explicitly dealt with)
- *How much?* – 1 kWh
- *How well?* – generated and distributed to the customer
- *How long?* - technical service life of the energy conversion plant based on the status of the plant in the defined; Annex 3 (ibid.) specifies the typical technical service life of Fuel cells to be 20 years.

[5] see https://environdec.com/pcr-library, last accessed on 4.6.2024.
[6] "1 kWh net means that electricity used within the power plant is subtracted from the amount of kWh generated in that plant".

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The reference flow is the same for the core and upstream module[7], i.e. for the infrastructure it is: "*an annual average of produced kWh multiplied by the expected technical service life of the system, i.e. the expected lifetime production of the system*"; and for the rest it is: "*annual average of generated kWh for one year or a period of years. It shall be described in the EPD how the reference flow was calculated*" (sections 6.5 and 7.5, ibid.). For the downstream module, the reference flow is defined as: "*the technical service lifetime multiplied by the amount of kWh distributed in the system during an annual average of a reference period*" (section 8.5, ibid.).

Nothing is specified explicitly for the unit of the reference flow. Presumably, it is the same as for the declared unit.

3.3.4.3. System boundary

According to Capello et al. (2015), the system boundary consists of the three modules (upstream, core and downstream) each of which includes the construction and decommissioning of the infrastructure as well as specific processes:

- Upstream module: production of fuel and auxiliary substances;
- Core module: operation of energy conversion plant and fuel preparation at site; and
- Downstream module: distribution of electricity, steam, hot/cold water.

Capello et al. (2015) do not use the terms "primary data", "company-specific data" or "product-specific data". So, they do not list processes for which company-specific data are required. However, it requires the use of "specific data", notably for the core module (i.e. not its infrastructure).

In various parts of the document, Capello et al. (2015) explicitly state specific exclusions:

- Mobile applications are not included (chapter 2, ibid.)
- The use stage of electricity … fulfils various functions in different contexts and is therefore excluded from the downstream module as well as the end-of-life of the products which is always thermal energy (section 5.4, ibid.).
- The technical system shall not include: Business travel of personnel; Travel to and from work by personnel; Research and development activities (section 6.1.1, ibid.).
- Cut-off rules
    - Core processes: LCI data for a minimum of 99 % of total inflows to the core module shall be included (section 6.2, ibid.).

[7] In general, Capello et al. (2015) distinguish between three modules, i.e. core, upstream and downstream. Within the core module, the infrastructure is dealt with differently from the rest.

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  - All other parts (i.e. core infrastructure, upstream module and downstream module): compliance with the 1%-rule should be aimed for (sections 6.2 and 7.2 and 8.3, ibid.).

3.3.4.4. Allocation rules

Fuel cells are only included by Capello et al. (2015) for their capability to produce electricity. So, there is no need to allocate between the electricity and heat produced. The general provisions by Capello et al. (2015) regarding allocation are:

- Allocation between different products and co-products shall be based on physical relationships. If physical relationships cannot be established or used, allocation can be based on other relationships, for example economical allocation. Any other allocation procedures shall be justified (section 6.3, ibid.).
- Additional environmental information based on LCA may be provided for example results calculated with other allocation methods than required by the mandatory rules (section 9.5.1, ibid.).

3.3.4.5. Electricity modelling

No guidance on electricity modelling other than data sources is provided by Capello et al. (2015).

3.3.4.6. Modelling of end of life and recycled content

Beyond waste specific information (see section 3.3.4.7.4 below), Capello et al. (2015) require a procedure in line with the general International EPD® System programme that is most similar to the recycled content approach described by Frischknecht (2010) (see section 6.1.5, ibid.).

3.3.4.7. Useful information (as far as provided)

Capello et al. (2015) provide the following pieces of useful information.

3.3.4.7.1. Product classification

Capello et al. (2015) deal with product groups “Electrical energy” and “Steam and hot water”, codes 171 and 173 of the United Nation Statistics Division - Classification Registry’s Central Product Classification (CPC)[8].

3.3.4.7.2. Additional environmental information

Capello et al. (2015) do not require specific additional environmental information for fuel cells.

[8] See https://unstats.un.org/unsd/classifications/Econ/cpc, last accessed on 4.6.24.

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Nevertheless, Capello et al. (2015) require the following environmental information for all product groups (i.e. at the same level as impact categories):

- Use of resources (material, energy, water);
- Waste production (evaluated at inventory level; different sub-categories);
- LCI emissions of radioactive isotopes;
- LCI emissions of particle matter;
- LCI emissions of toxic substances;
- LCI emissions of oil to water and ground.

Additional environmental information is required for the product group “Electrical energy”:

- Risk related issues: Radiology and human toxicological risks; and Environmental risks (i.e., mishaps with environmental impact, that happen less frequent than once in three years should be identified and the impacts quantified; and potential undesired events with high or very high impact but low or minute probability (e.g. nuclear reactor meltdown, dam bursts, etc.) shall be identified and described qualitatively).
- Electro Magnetic Fields: Description of the producer’s measures to keep fields low and some information on limits and recommendations by different bodies.
- Noise
- Land use: 1) Land use and land use change expressed in square meters of specified land category according to Corine Land Cover Classes, level one at a minimum (5 classes) before and after exploitation where before is the area in the situation before the start of the activities within the lifecycle and after is the area in the time period corresponding to the validity of the EPD. 2) Number of years that the areas are occupied expressed as the area occupied per year of operation. 3) Description of activities on the occupied areas.
- Impacts on biodiversity: Direct regional impacts concerning nature conservation issues like biodiversity and visual impact connected to land use.

Note that Capello et al. (2015) recommend and allow to provide further additional environmental information.

3.3.4.7.3. Limitations (including data gaps and proxies)

Capello et al. (2015) do not make general provisions regarding limitations but provide detailed guidance on data quality.

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3.3.4.7.4. Most relevant impact categories

Capello et al. (2015) requires reporting the following impact categories:

- Emission of greenhouse gases (evaluated at midpoint level);
- Emission of acidifying gases (evaluated at midpoint level);
- Emissions of gases that contribute to the creation of ground level ozone (evaluated at midpoint level);
- Emission of substances to water contributing to oxygen depletion (evaluated at midpoint level).

It needs to be noted that Capello et al. (2015) requires further environmental indicators at the same level as impact categories (see section 3.3.4.7.2).

3.3.4.7.5. Most relevant life cycle stages

At the level of the International EPD® System (programme), three different life cycle stages are distinguished:

- Upstream processes (from cradle-to-gate);
- Core processes (from gate-to-gate);
- Downstream processes (from gate-to-grave).

The core module also includes the handling/treatment/transportation of the core module's waste as well as its infrastructure (cradle-to-grave). The downstream module comprises distribution of the products to the customer.

3.3.4.7.6. Most relevant processes

Capello et al. (2015) list processes for the core, upstream and downstream modules and specifies whether specific data are required or recommended. For some processes, generic data are permitted to be used. If the requirement to provide specific data can be taken as an indication for the most relevant processes, the following processes related to the product group "Electrical energy" can be mentioned (all belonging to the core module):

- operation of energy conversion plant (system of energy conversion plants);
- amounts of fuel and other auxiliary operational inputs;
- fuel preparation processes at energy conversion site e.g. drying and grinding;
- maintenance activities e.g. inspection trips, lubrication;
- operation (also test operation) of reserve power and reserve heat;
- distances for the transportation of fuel related waste and type of vehicles;
- handling/treatment/storage of fuel related waste;

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- amounts and type of treatment of other waste.

3.3.4.7.7. PEF Results

Capello et al. (2015) do neither provide (PEF) results nor benchmark values.

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3.3.5. Summary on H_2 usage documents

None of the H_2 usage related documents describes a **representative product**.

Given that H_2 can be used in different ways, the **functional unit** differ between the documents: electricity production alone (Capello, et al. 2015) or combined heat and power generation (IEC/TS, 62282-9-102 2021). Masoni & Zamagni (2011) and Bargiacchi, et al. (2022) cover both of these functions and additionally transport, while hydrogen use for fuels and chemicals production is only covered by Bargiacchi, et al. (2022). Except for Bargiacchi, et al. (2022), the functional unit for hydrogen use is always expressed in units of energy, noting that Masoni & Zamagni (2011) also allow limiting the functional unit to the fuel cell stack. For transport and chemical use, Bargiacchi, et al. (2022) define the distance travelled (e.g. in passenger-kilometres or tonne-kilometres) or the quantity of produced chemical/fuel (in mass), respectively.

The **reference flow** varies across the documents. Capello et al. (2015) defines different reference flows for the upstream and core modules (thereby distinguishing between the infrastructure and the rest) on the one hand side and for the downstream module on the other hand side. For the infrastructure in the upstream and core modules and for the downstream module, the service life (lifetime) is part of the defined reference flow. Similarly, reference flows for the infrastructure and its operation including the lifetime (and thus replacements needed) are defined in the IEC PCR (IEC/TS, 62282-9-102 2021). Masoni & Zamagni (2011) by contrast define the reference flow in terms of number of devices needed for the production of a given amount of energy or exergy defined in the functional unit. It is open which reference flow applies to the different hydrogen uses as distinguished by Bargiacchi, et al. (2022), but it must be indicated and quantified.

The **system boundary** notably differs in terms of whether or not the hydrogen production is included in the hydrogen use LCA. While the fuel supply is included (IEC/TS, 62282-9-102 2021) (Capello, et al. 2015) or may be included (i.e. hydrogen production in Bargiacchi, et al. (2022)), Masoni & Zamagni (2011) exclude it.

When heat is a valuable product during hydrogen use, Masoni & Zamagni (2011) and Bargiacchi, et al. (2022) suggest using exergy to avoid **allocation**. While system expansion is suggested during the operation phase, the IEC PCR also uses exergy allocation for sites where CHP generators are manufactured (IEC/TS, 62282-9-102 2021). Given that fuel cells are considered by Capello et al. (2015) to only produce electricity, no allocation is needed; general allocation rules are, however, provided. The IEC PCR also requires specific values for reference temperature and pressure when computing exergy (IEC/TS, 62282-9-102 2021).

Only two documents make provisions how to **model electricity**: the electricity supply shall be representative for the region in which a process takes place (IEC/TS, 62282-9-102 2021) (Masoni and Zamagni 2011).

Two of the documents on hydrogen usage do not require to quantify the **end of life** (Masoni and Zamagni 2011) (IEC/TS, 62282-9-102 2021). While requiring considering the EoL, Bargiacchi, et al. (2022) allow different approaches to be followed. Capello et al. (2015) require

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a procedure in line with the general International EPD® System programme that is most similar to the recycled content approach described by Frischknecht (2010). The IEC PCR require to provide information on the recyclability (IEC/TS, 62282-9-102 2021).

In terms of useful information, two of the analysed documents provide a **product classification** according to International Classification for Standards (ICS) 27.070 Fuel cells (IEC/TS, 62282-9-102 2021) and "Electrical energy" and "Steam and hot water", codes 171 and 173 of the United Nation Statistics Division - Classification Registry's Central Product Classification (CPC).

Different kinds of **additional environmental information** are required or allowed to be provided in the different documents on hydrogen usage:

- Bargiacchi et al. (2022) address raw material criticality;
- Masoni & Zamagni (2011) require including energy-related indicators, i.e. Non-renewable Primary Energy Demand (PED non-renewable) or Renewable Primary Energy Demand (PED renewable).
- For the case of biofuels, some specifications regarding carbon neutrality and market mediated impacts shall be reported in the IEC EPD (IEC/TS, 62282-9-102 2021).
- Capello et al. (2015) do not require additional environmental information for fuel cells specifically, but in general. Besides the impact category-related information, the following is required for all product groups covered: Use of resources (material, energy, water), Waste production (evaluated at inventory level, different sub-categories), LCI emissions of radioactive isotopes, LCI emissions of particle matter, LCI emissions of toxic substances, LCI emissions of oil to water and ground, and Specifically for the product group "Electrical energy", the following information is required: risk-related issues, electromagnetic fields, noise, land use, and impacts on biodiversity.

All of the analysed documents on hydrogen usage address **limitations** in terms of data quality. Because of the limitation of the results to only a few prioritised impact categories, the IEC PCR requires that the EPD of the domestic fuel cell application shall make a statement that the environmental information provided is limited to the reported impact categories (IEC/TS, 62282-9-102 2021).

While Bargiacchi et al. (2022) require reporting on all EF impact categories, the other documents define a shortlist of **most relevant impact categories**:

- Masoni & Zamagni (2011): Global warming potential, Acidification potential, Eutrophication potential, and Photochemical ozone creation potential; results for further (optional) impact categories can be provided;
- IEC/TS, 62282-9-102 (2021): climate change, abiotic resource depletion (minerals and metals), particulate matter, acidification, photochemical ozone formation;

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- Capello, et al. (2015): Use of resources (material, energy, water), Emission of greenhouse gases (evaluated at midpoint level), Emission of acidifying gases (evaluated at midpoint level), Emissions of gases that contribute to the creation of ground level ozone (evaluated at midpoint level), Emission of substances to water contributing to oxygen depletion (evaluated at midpoint level), Waste production (evaluated at inventory level; different sub-categories), LCI emissions of radioactive isotopes, LCI emissions of particle matter, LCI emissions of toxic substances, LCI emissions of oil to water and ground.

In terms of the **most relevant life cycle stages**, none of the analysed documents on hydrogen usage highlights one or several life cycle stages.

None of the analysed documents on hydrogen usage explicitly states **most relevant processes**. Masoni & Zamagni (2011) only state potentially relevant processes. If the requirement to provide specific data can be taken as an indication for the most relevant processes, Capello et al. (2015) also lists important processes (see section 3.3.4.7.6).

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3.4. Other relevant documents (H_2 unrelated)

The analysis was also extended to documents unrelated to H_2. All of the identified documents are PEFCRs that have been selected for different reasons:

- PEFCR on Metal sheets (Eurometaux 2019): addressing different products within the same product category (see section 3.4.1);
- PEFCR on Uninterruptible Power Supply (Schneider Electric 2020): a power system including energy storage devices, such as batteries (see section 3.4.2);
- PEFCR on Photovoltaics (First solar 2020): a power production device (see section 3.4.3);
- PEFCR on Batteries (Recharge 2020): a power storage device (see section 3.4.4).

For the PEFCRs, there is no program operator. The PEFCRs mentioned above were developed as part of the PEF pilot phase conducted by the European Commission, which coordinated the process. PEFCRs are applicable to Europe (or more specifically: the European Union).

3.4.1. PEFCR on Metal sheets *(Eurometaux 2019)*

The analysed document is entitled "Product Environmental Footprint Category Rules (PEFCR) for Metal Sheets for Various Applications" (Eurometaux 2019). It was developed by a consortium of European metal industries, a mining association and LCA consultants. The geographic scope is EU + EFTA.

Eurometaux (2019) has been included in the analysis because it covers not only one but several representative products, i.e., different types of metal sheets made of aluminium, copper, lead, and steel.

3.4.1.1. Representative products

According to Eurometaux (2019), metal sheets are classified as intermediate products and categorised in subcategories based on two main applications:

- Subcategory construction: copper, lead, aluminium, steel; and
- Subcategory appliances: aluminium and steel.

The differences between the subcategories are mainly related to technical parameters and characteristics of the metal sheets, such as thickness or grammage. LCA parameters, such as life cycle stages and system boundaries, are not dependent on the subcategory definition.

An 'intermediate' metal sheet is typically subject to additional manufacturing steps in order to be transformed into the final product. Those manufacturing steps are not covered by this PEFCR.

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Some technical parameters, such as the grade of metal, the thickness of the sheet and the surface finish will be dependent on the specific end use. Eurometaux (2019) reports some examples of 'representative products'[9]. However, it should be stressed that these examples do neither specify exact technical parameters, nor should they be used as criteria for benchmarking.

The examples of representative products are the ones mentioned before, i.e. copper sheet, lead sheet, aluminium sheet, and steel sheet for the subcategory construction as well as aluminium sheet and steel sheet for the subcategory appliances. After the extensive analysis performed in the screening studies of the PEF pilot phase, the final outcome is that the basic principles related to the function of all the metal sheets can be considered as equal.

The PEFCR by Eurometaux (2019) is applicable only to pure metal sheets (in the case of copper and lead) and sheets that include low level of alloying elements and/or coatings (in the case of aluminium and steel).

3.4.1.2. Functional unit and reference flow

Metal sheets, as intermediate products, can have many different functions depending on industrial transformation they undergo after their production. Depending on the application, the metal sheets may differ in the final composition, alloying elements usage, coatings employing. The PEFCR by Eurometaux (2019) reports the detailed description of the technical parameters related to the composition, alloying elements, and coating that shall be included in the environmental assessment.
The functional unit (FU) defined by Eurometaux (2019) is 1m^2 of metal sheet with the following key aspects:

- *What?* - The functional unit includes a non-exhaustive list of functions to the level required by the most relevant, international, regional, national or technical standards to a reference extent of 1m^2.
- *How much?* - The extent of the function expressed in the reference flow is defined as 1m^2 of metal sheet.
- *How well?* - Metal sheets can be used in a very wide variety of applications. For metal sheets as an intermediate product to be used in final applications, the 'how well' strongly depends on the downstream application and its specific requirements and cannot be generalized.
- *How long?* - The lifetime of the metal sheet ('how long'?) is determined by its specific application. The use phase and the related lifetime are not relevant for the PEFCR for the intermediate state of the metal sheets but will be required for all final products PEFs.

[9] The definition of 'representative products' is reported between single quote marks also in the PEFCR.

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The reference flow is the amount of product needed to fulfil the function defined by the FU. Since the representative products have different characteristics, such as specific mass, thickness, grammage, the calculated reference flows are specific for each representative product. In the PEFCR by Eurometaux (2019), an example on how to calculate the reference flow of the aluminium sheet is provided.

3.4.1.3. System boundary

The cradle-to-gate approach has been chosen by Eurometaux (2019) because metal sheets are intermediate products. Life cycle stages included in the system boundary are mining, beneficiation, scrap preparation, hydrometallurgical or pyrometallurgical process, melting, casting, rolling mill, and finishing (red dotted line in Figure 3). The declaration of the EoL stage is part of the mandatory additional environmental information.

For the core process (rolling and finishing which includes in some cases melting and casting before the rolling process), primary data shall be collected. Exploration, fabrication, and the transport of the metal sheet for the final product fabrication are outside of the PEFCR scope.

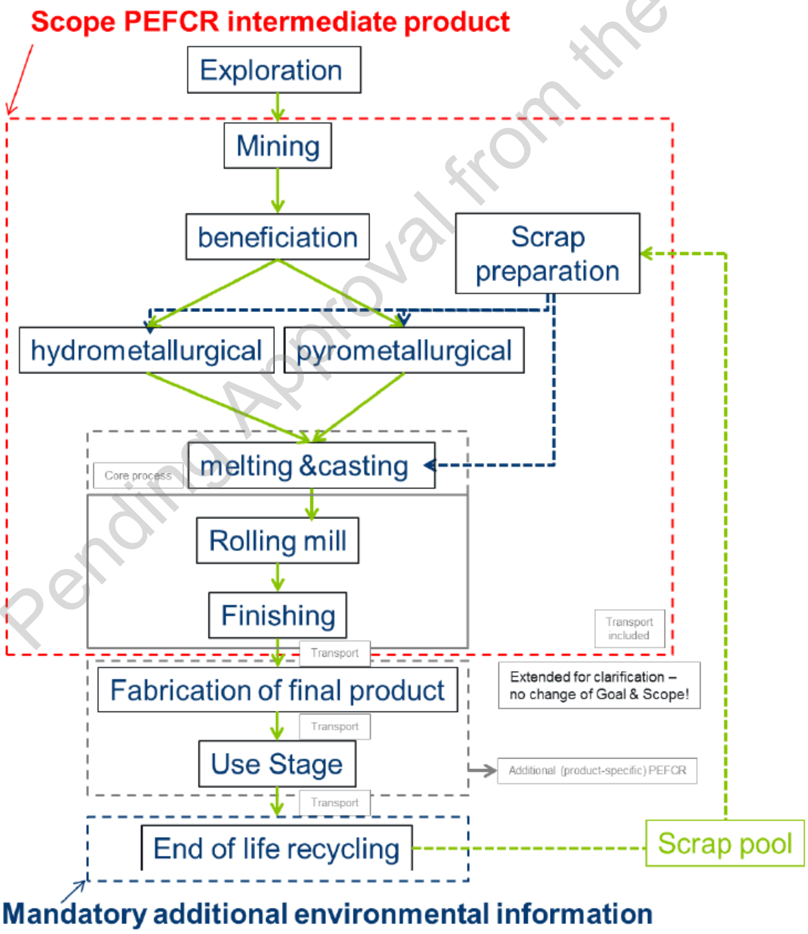

Figure 3 – Metal sheets system boundary, taken from Eurometaux (2019)

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3.4.1.4. Allocation rules

Many different process-specific allocation rules are reported in Eurometaux (2019) for each representative product and detailed for each life cycle phase or process in which they have been applied. Table17 in Eurometaux (2019) reports the process, the applied allocation rules, and the modelling instructions. A hierarchy of allocations is suggested, i.e. 1) system expansion, 2) sub-division based on physical relationships, and 3) other relationships.

3.4.1.5. Electricity modelling

Eurometaux (2019) restates the then latest general PEFCR recommendations by European Commission (2018). Specific allocation rules for modelling of electricity for upstream processes are reported (i.e., physical relationship allocation).

3.4.1.6. Modelling of end of life and recycled content

Eurometaux (2019) requires that the Circular Footprint Formula (CFF) for intermediate products is applied. A section reporting the definition of the point of substitution for each representative product is provided.

3.4.1.7. Useful information (as far as provided)

Among the useful pieces of information, Eurometaux (2019) only provides information on product classification and on limitations.

The four different representative products are classified with the following Classification of Products by Activity (CPA) codes: Steel C24.1, Lead C24.4.3, Copper C24.4.4, Aluminum C24.4.2.

Limitations result from the intermediate product scope. Each representative product has its own environmental footprint at the intermediate level that cannot be compared to any of the other representative products at this level. Only when a function is well-defined and the life cycle assessment is performed on the entire life cycle of this final function (including the use phase and the end-of-life stage), benchmarking and comparison could be performed. If benchmarking is to be performed on the final product, it should be conducted with data collected with consistent and comparable system boundaries.

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3.4.2. PEFCR on Uninterruptible Power Supply *(Schneider Electric 2020)*

An Uninterruptible Power Supply (UPS) is a "*is a "combination of convertors, switches and energy storage devices (such as batteries) constituting a power system. (…) The primary function of the UPS is to ensure continuity of an a.c. power source. The UPS may also serve to improve the quality of the power source by keeping it within specified characteristics*" (Definition from IEC 62040-3:2011. 3.1.1, according to Schneider Electric (2020)).

This PEFCR was developed by a technical consortium of UPS manufacturers with the company Schneider Electric serving as the main contact with the EPD programme operator and LCA consultants. The geographic scope is EU and EFTA (European Free Trade Association), and the results are not directly linked to H2 (storage) systems but rather representative for an (emergency) power system including battery storage as one component amongst others.

3.4.2.1. Representative product(s)

For the definition of the representative product different size classes, functional aspects and EU-27 market shares have been considered by Schneider Electric (2020), resulting in:

- 4 size ranges (in terms of output power)
- 3 UPS topologies or input dependency characteristics (characterised by functional aspects such as voltage and frequency control).

A list of typical, size range-independent components is provided, to be included in the Bill of Materials.

3.4.2.2. Functional unit and reference flow

The functional unit (FU) defined by Schneider Electric (2020) is

- to ensure power supply to equipment *(What)*, more precisely
- 100 Watt for 5 minutes, in case of power shortages *(How much)*
- without interruption *(How well)*
- during 1 year *(How long)*

The reference flow is defined as "kg UPS/100W/y", i.e. the amount needed to provide the needed capacity during 1 year of service life.

3.4.2.3. System boundary

The system boundaries are presented by Schneider Electric (2020) through a diagram, including information on cut-off criteria and data gaps (Figure 4). Relevant processes and life cycle stages are also described in a table. For two processes, company-specific data is required, i.e. "Product Packagings" and "Energy Consumption for UPS Assembly".

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As a **deviation from PEFCR guidance**, an aggregation of life cycle stages is described and explained: the stages "raw material acquisition and pre-processing" and "production" are aggregated to become the "manufacturing" stage due to inherent variable system boundaries of individual UPS manufacturers, supply and use of intermediate products and compliance with an existing related PCR.

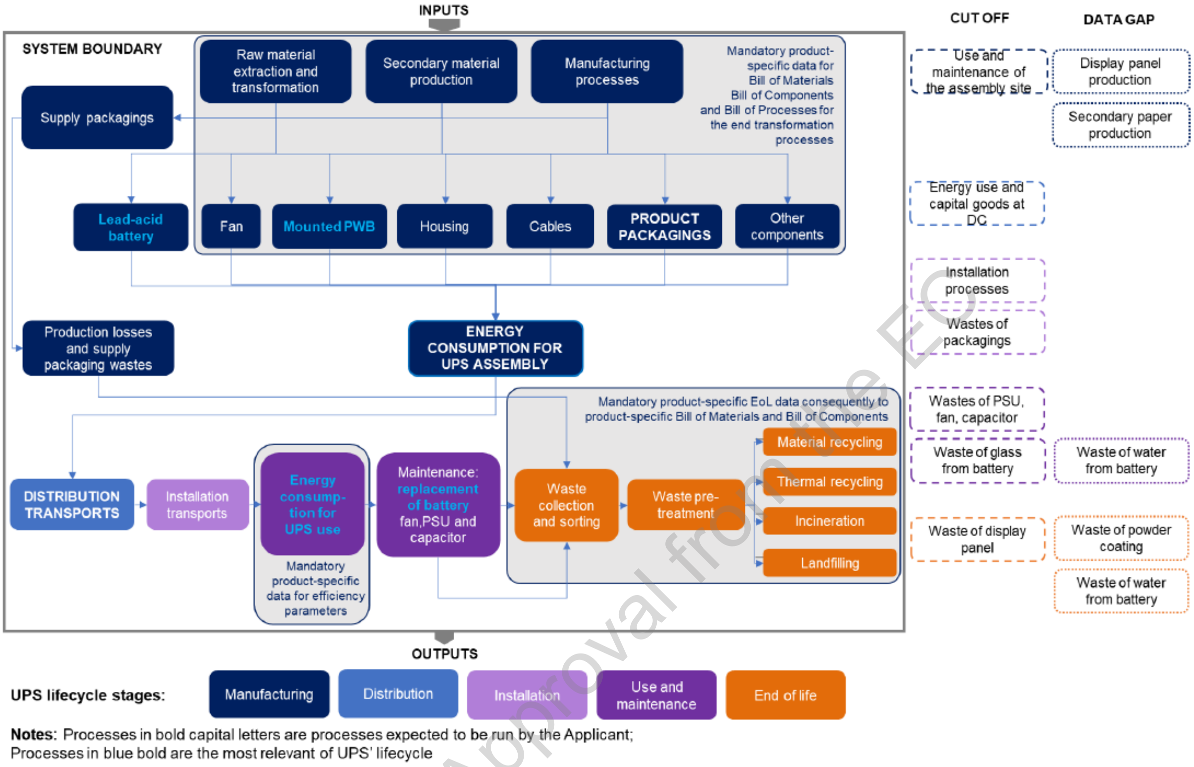

Figure 4 – UPS system diagram, taken from Schneider Electric (2020)

3.4.2.4. Allocation rules

Allocation is generally not recommended for UPS by Schneider Electric (2020) and default allocations in datasets shall not be modified. When unavoidable, subdivision may be used or allocation for specific materials or components. No default allocation values are provided.

3.4.2.5. Electricity modelling

For company-specific processes, Schneider Electric (2020) follows the default hierarchy as stated in the then latest PEF recommendations (European Commission 2018).[10] Additional instructions are provided, however, not going beyond the general guidance provided by European Commission (2018).

[10] The latest recommendation by the European Commission foresees a fourth option in the hierarchy, i.e. the EU residual grid mix (European Commission 2021).

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3.4.2.6. Modelling of end of life and recycled content

Schneider Electric (2020) provides the Circular Footprint Formula (CFF) with distinct parameters for certain materials (metals, plastics, glass, resins, fibres and fillers). Specific instructions concerning end of life modelling are provided for lead-acid batteries, certain plastics, and fans.

3.4.2.7. Useful information (as far as provided)

Schneider Electric (2020) provides the following useful information:

- Product classification: as no specific code for UPS exists, most appropriate proxies were chosen (electrical machines, power supply units).
- Additional environmental information: for the manufacturing, notably the absence or level of presence of antimony and lead may be stated; for use and EoL, technical parameters may be stated.
- Limitations (including data gaps and proxies): mainly data quality limitations highlighted, e.g. concerning battery materials or related to product complexity.
- Most relevant impact categories: “climate change”, “ionising radiation - human health” (for 1 subcategory), “resource use - energy carriers”, “resource use - minerals and metals” (based on 80% rule).
- Most relevant life cycle stages: generally “use and maintenance”, “end of life” and “manufacturing”.
- Most relevant processes: provided per sub-system as table.
- PEF results provided per representative sub-system.

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3.4.3. PEFCR on Photovoltaics *(First solar 2020)*

The PEFCR on Photovoltaics was developed by a consortium of photovoltaic (PV) manufacturers (First Solar as main contact), industry associations, energy industry, research and LCA consultants (First solar 2020). Its geographic scope is EU + EFTA and the results are not directly linked to H_2 (production) systems but rather representative of a power system for electricity generation.

3.4.3.1. Representative product(s)

The representative product in First solar (2020) is an average EU PV module (virtual product). Five different technologies are considered, then merged into an average representative product using a technology mix based on global production volumes (from 2012) and individual technology shares. The Bill of Materials is based on studies (scientific and by producers) and LCA databases. Material losses (during manufacturing) were considered.

3.4.3.2. Functional unit and reference flow

The functional unit (FU) defined by First solar (2020) is:

- DC [direct current] electricity at the outlet of a junction box *(What)*
- 1 Kilowatt-hour (kWh) DC electrical energy (without considering intermittency and considering the lifetime) *(How much)*
- At a given voltage level *(How well)*
- Over a service life of 30 years *(How long)*

The reference flow is the amount (capacity) of PV module needed to produce a kWh (over the lifetime), given in kWp (kilowatt peak, standard conditions).

3.4.3.3. System boundary

First solar (2020) describes the system boundaries in a diagram (Figure 5), including the description of processes and life cycle stages and highlighting those processes requiring company-specific data (panel pre-processing, transport and PV system production, operation and dismantling). Cut-off is not applicable.

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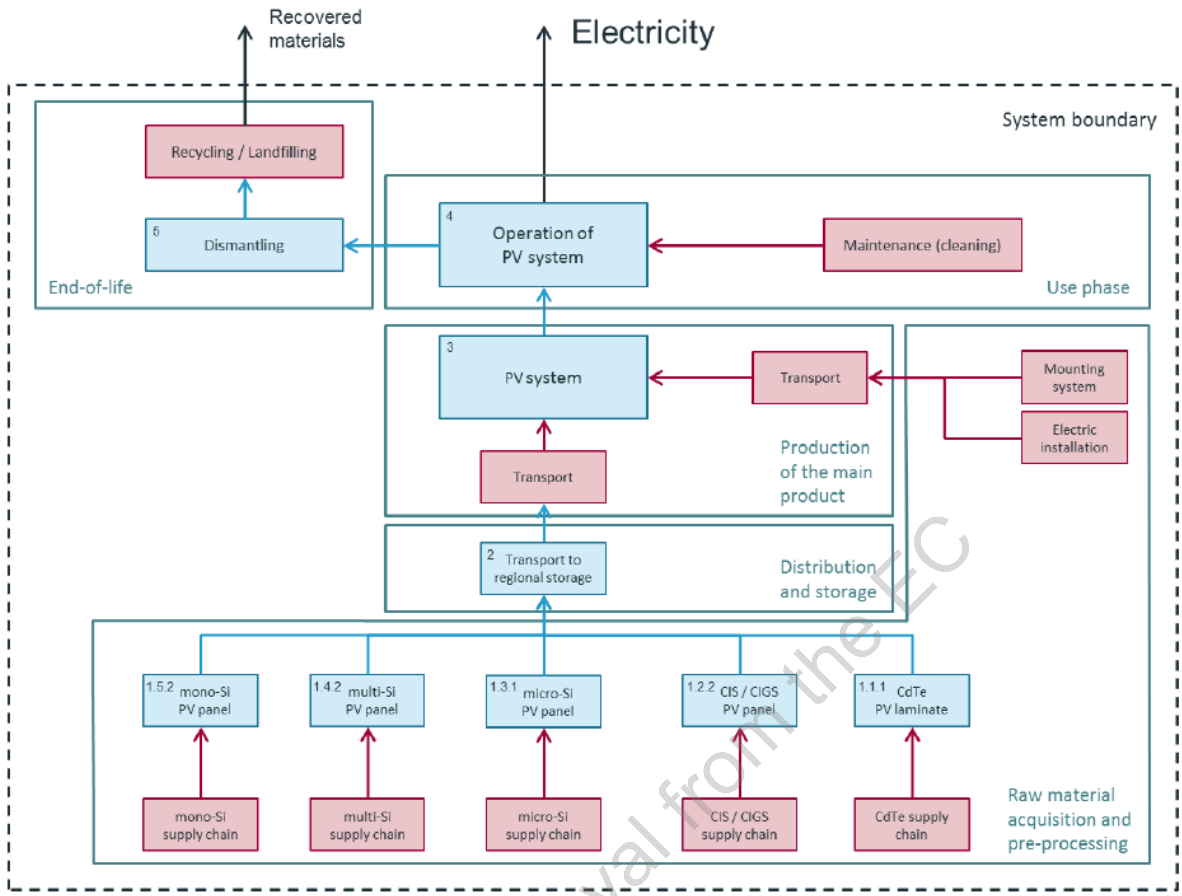

Figure 5 – PV system boundary, taken from First solar (2020). Processes to be modelled using company-specific data are shown in blue.

3.4.3.4. Allocation rules

First solar (2020) describes a multiproduct process (cuttings from monocrystalline wafer production fed into multicrystalline silicon casting). Economic allocation according to internal book-keeping standards is recommended.

3.4.3.5. Electricity modelling

For company-specific processes, First solar (2020) follows the default hierarchy as stated in the then latest PEF recommendations (European Commission 2018).[11] Additional instructions are provided concerning allocation (in case it cannot be avoided and for on-site electricity generation) according to European Commission (2018). Specific rules are provided for PV cell production, PV module production, PV cell and module production in the same plant, and PV modules at regional storage.

[11] The latest recommendation by the European Commission foresees a fourth option in the hierarchy, i.e. the EU residual grid mix (European Commission 2021).

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3.4.3.6. Modelling of end of life and recycled content

First solar (2020) provides the Circular Footprint Formula for material, energy and disposal (default formula). Specific parameters given in a separate table (for metals and glass).

3.4.3.7. Useful information (as far as provided)

First solar (2020) provides the following useful information:

- Product classification: CPA code 27.90 “Manufacturing of other electrical equipment”.
- Additional environmental information: nuclear waste (radiotoxicity potential), but not for benchmarking; biodiversity is not considered relevant.
- Limitations (including data gaps and proxies): inherent uncertainties of comparing systems with different technical characteristics or at different locations. Value judgements needed, e.g. on lifetime or degradation. Uncertainty of toxicity-related impact categories.
- Most relevant impact categories: for the average representative product: “particulate matter”, “climate change”, “resource use – fossil fuels”, “resource use – minerals and metals” (based on 80% rule).
- Most relevant life cycle stages: “raw material acquisition and pre-processing”, “end of life”.
- Most relevant processes: provided in tables for the representative product and sub-categories.
- PEF results: provided in tables for the representative product and sub-categories.

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3.4.4. PEFCR on Batteries *(Recharge 2020)*

Recharge (2020) presents the PEFCR on high specific energy rechargeable batteries used in mobile application developed during the Commission PEF Project by RECHARGE - the advanced rechargeable & Lithium Batteries Association – together with the Technical Secretariat of the Batteries Pilot. Publication date Feb 2018, valid up to 31 Dec 2020.

3.4.4.1. Representative product(s)

Four representative products (average products) are identified in Recharge (2020), 1 for each of the 4 applications based on the market share of the lithium chemistry (CPT Li-ion; ICT Li-ion; e-mobility Li-ion) and on the Nickel metal hybrid chemistry (ICT Ni-MH).

3.4.4.2. Functional unit and reference flow

The functional unit (FU) defined by Recharge (2020) is the amount of energy delivered:

- *What?* – Wh, kWh
- *How much?* - 1 kWh of the total energy delivered over service life
- *How well?* - Maximum specific energy (measured in Wh/kg).
- *How long?* - The amount of cumulative energy delivered over service life of the high specific energy rechargeable batteries (quantity of Wh, obtained from the number of cycles multiplied by the amount of delivered energy over each cycle).

The reference flow is the amount of product needed to fulfil the defined function and shall be measured in kg of battery per kWh of the total energy required by the application over its service life.

3.4.4.3. System boundary

The system boundaries are divided by Recharge (2020) into foreground and background data as exemplified through a diagram (Figure 6). A 1% cut-off rule is set for all impact categories based on environmental significance of the following processes: Detailed transport operations description for raw materials, product distribution or end of life; Manufacturing of equipment for batteries assembly and recycling; OEM manufacturing.

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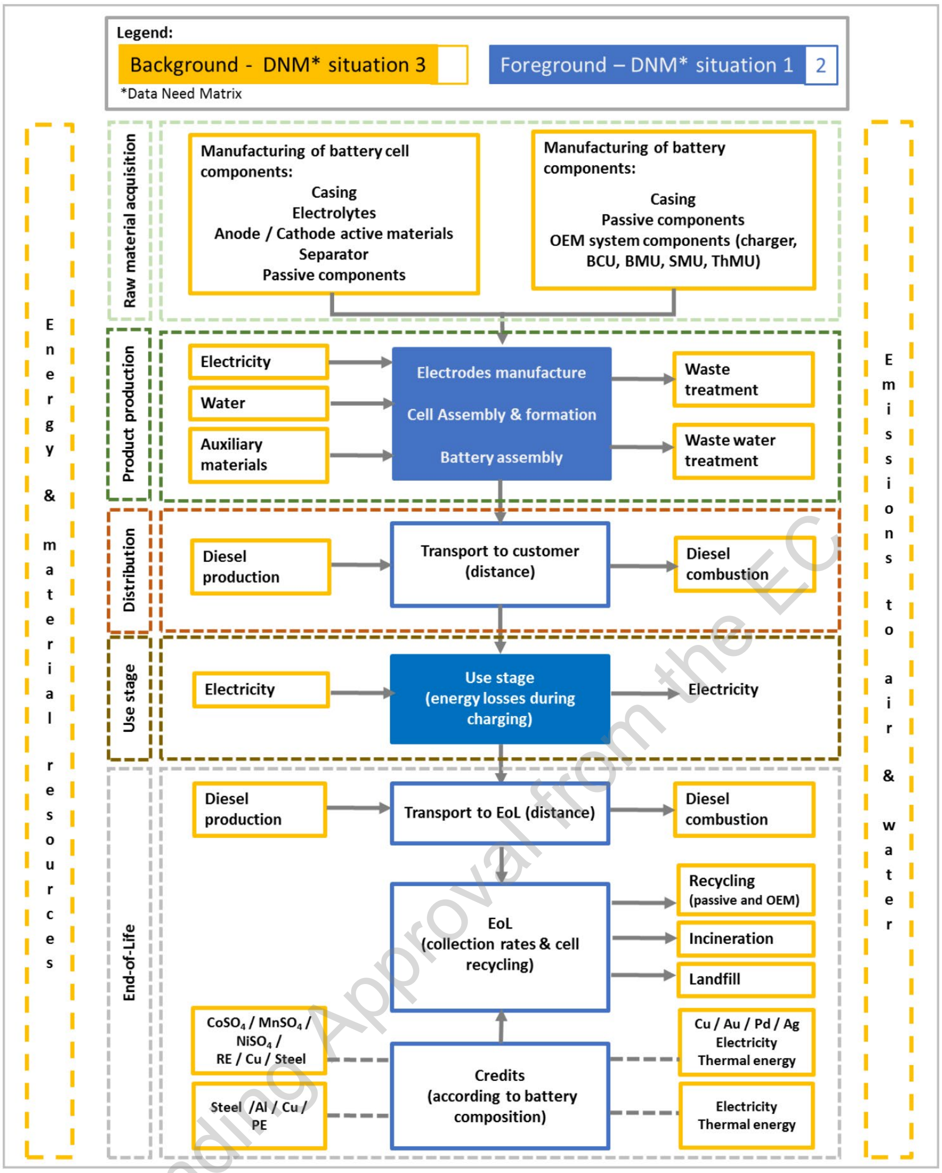

Figure 6 – System boundary for a life cycle of a battery, taken from Recharge (2020).

3.4.4.4. Allocation rules

No specific guidance is provided by Recharge (2020) for allocation rules. However, allocation may be needed: (i) to subdivide the electricity consumption among multiple products for each process and (ii) to reflect the ratios of production/ratios of sales between EU countries/regions when a product is produced in different locations or sold in different countries.

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3.4.4.5. Electricity modelling

For company-specific processes, Recharge (2020) follows the default hierarchy as stated in the then latest PEF recommendations (European Commission 2018).[12] Additional instructions are provided concerning allocation (in case it cannot be avoided and for on-site electricity generation) according to European Commission (2018). Specific rules are provided for battery manufacturing and battery usage.

3.4.4.6. Modelling of end of life and recycled content

Recharge (2020) uses the Circular Footprint Formula to model the End-of-Life of products as well as the recycled content.

3.4.4.7. Useful information (as far as provided)

Recharge (2020) provides the following useful information:

- Product classification: CPA code 27.20.23.
- Additional environmental information: impact on biodiversity.
- Limitations (including data gaps and proxies): the PEFCR limits the process and component analysis to the battery-specific parts. In case of unspecific components, secondary data shall be used.
- Most relevant impact categories: provided in tables for the representative products.
- Most relevant life cycle stages: provided in tables for the representative products.
- Most relevant processes: provided in tables for the representative products.
- PEF results: provided in tables for the representative products.

[12] The latest recommendation by the European Commission foresees a fourth option in the hierarchy, i.e. the EU residual grid mix (European Commission 2021).

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3.4.5. Summary on other documents (unrelated to H_2)

As part of the analysed documents unrelated to H_2, PEFCRs of different products were analysed that are not directly related to FCH systems, but that share similar functionality (e.g. power supply, electrical storage) or components (metal sheets). Due to their dates of publication, all examples comply with the PEFCR guidance from 2018 (European Commission 2018), which is largely in line with the 2021 guidance (European Commission 2021)[13]. The following conclusions draw on observations from all of these documents, aiming to highlight only items considered relevant for the construction of PEFCRs of FCH systems.

Product categories were all classified according to the CPA codes. The were defined based on different criteria, such as applications/product use, specific technologies, materials and size ranges. Only in one case, a single representative product was derived (i.e. First solar (2020)). In all other cases, different representative products were defined, typically considering market shares of the different sub-products included. A particular case is the PEFCR on metal sheets (Eurometaux 2019), as it mainly deals with intermediate products to be used in different final products and with multiple functions.

This also translates into the definition of the **functional unit**, which is highly dependent on the downstream application in the case of metal sheets, thus involving higher flexibility, whereas it is well defined for the other (final) products. For the other PEFCRs, a single functional unit is defined.

Concerning **system boundaries,** it is notable that **cut-off criteria** are defined very differently (sometimes also being not applicable) and that there is a lack of consistent rules to be applied across different product categories. Both, cradle-to-gate (Eurometaux 2019) and cradle-to-grave (Schneider Electric (2020), First solar (2020) and Recharge (2020)) system boundaries have been chosen in line with the type of product analysed (i.e. intermediate vs. final product).

The same is true for **allocation rules**, where guidance is again very product- and process-specific. In some cases, allocation is not applicable (Recharge 2020) and in others not recommended (Schneider Electric (2020)). In general, the default PEF multi-functionality hierarchy is noted as a backup solution.

In terms of **electricity modelling**, the then latest general PEF guidance by European Commission (2018) is followed. This includes cases where more than one country electricity mix is used or electricity is generated on-site. All PEFCRs except those for UPS (Schneider Electric 2020) provide allocation rules for electricity consumption for selected processes.

The **end of life and recycled content modelling** relies on the circular footprint formula. The different PEFCRs generally provide specific values for the different parameters used within this formula.

[13] One exception that was noted concerns electricity modelling, where the EU residual mix as last option was only introduced with the latest guidelines.

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Regarding **additional environmental information**, all PEFCRs mention biodiversity, presumably triggered by the example mentioned in European Commission (2018). Despite acknowledging that particularly mining activities have impacts on biodiversity (Schneider Electric (2020), Eurometaux (2019) and Recharge (2020), none of the PEFCRs requires their reporting. This is because most biodiversity impacts are said to be site-based, as opposed to product-based and therefore depending on the specific conditions of a product. Schneider Electric (2020) allow to state the absence or level of presence of certain trace elements or heavy metals for the manufacturing phase and technical parameters for the use and EoL phases. First solar (2020) appears to require radioactive waste information to be additionally reported.

Limitations and data gaps are important information and the most-mentioned items in these categories are data quality uncertainties (related to the complexity of products and their supply chains), uncertainty regarding value judgements (e.g. on product degradation), limitations when comparing intermediate products or when comparing products with different technical characteristics, produced at different locations etc..

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4. Discussion, conclusions and next steps

Within the HyPEF project, Product Environmental Footprint Category Rules (PEFCRs) will be defined for three H_2-related product categories. To this end, relevant guidance documents have been identified and analysed against criteria. The criteria have been defined according to the degrees of freedom permitted by the latest PEF recommendations (European Commission 2021)[14]. Essential information that was collected concerns: Representative product(s), Functional unit and reference flow, System boundary, Allocation rules, Electricity modelling, Modelling of end of life and recycled content. Information that might be useful were also tried to be identified: Product classification, Additional environmental information, Limitations (including Data gaps and proxies), Most relevant impact categories, Most relevant life cycle stages, Most relevant processes, PEF Results.

In total, only a rather limited number of documents have been identified (up to end of April 2024):

- two documents on hydrogen production (Bargiacchi, et al. 2022) (Lozanovski, Schuller and Faltenbacher 2011);
- one document that also treats hydrogen storage (Bargiacchi, et al. 2022);
- four documents on hydrogen usage (Masoni and Zamagni 2011) (Capello, et al. 2015) (IEC/TS, 62282-9-102 2021) (Bargiacchi, et al. 2022); and
- four PEFCR documents unrelated to hydrogen systems (Schneider Electric 2020) (Eurometaux 2019) (First solar 2020) (Recharge 2020).

From a high-level perspective, the analysis showed that there is no specific guidance for **hydrogen storage** (i.e. without including hydrogen production). This has two implications. First, hydrogen storage will not be discussed in the following. Second, the work in WP3 of HyPEF therefore needs to carefully reflect upon the specific provisions to be made.

The function (as reflected in the **functional unit**) is of key importance which has also bearings for the classification of the FCH systems into product categories; this topic is addressed in Task 2.2. Hydrogen can be produced and used as an energy carrier or also for chemical or transport reasons. This then has bearings on whether the functional unit can be expressed in units of energy, mass, or person- or tonne-kilometres. Martín-Gamboa et al. (2023) advocate mass. Another option is to stay at the stack level (e.g. Masoni & Zamagni (2011)). Drawing on the metal sheets PEFCR (Eurometaux 2019), a distinction might need to be made between whether hydrogen is a final or an intermediate product. This has implications on the function that can reasonably be considered and on the potential inclusion of downstream steps and processes.

Hydrogen can be the only (used) **product**, a **co-product** or a **by-product**. Likewise, hydrogen use can lead to one (e.g. electricity) or more outputs (e.g. additionally heat). A careful definition of the functional unit in terms of multifunctionality is therefore needed. When energy is the

[14] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32021H2279, last accessed on 10.6.2024

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only output, exergy is recommended by three documents (Bargiacchi, et al. 2022) (Masoni and Zamagni 2011) (IEC/TS, 62282-9-102 2021). The IEC PCR even defines specific values for reference temperature and pressure when computing exergy. It can be noted that European Commission (2021) does not explicitly mention energetic relationships as a way to deal with multi-functionality; it can, however, be considered to be part of the last option within the decision hierarchy, i.e. "Allocation based on some other relationship" (i.e. other than "physical").

None of the analysed guidance documents for hydrogen production prescribes a given **purity, pressure or temperature**. European Commission (2021) emphasises the importance of comparability: "*An equally important* ***objective*** *is to* ***enable comparisons*** *and comparative assertions in all cases where this is feasible, relevant and appropriate. … The objective is to ensure that PEFCRs are developed according to the PEF method and that they* ***provide the specifications needed to achieve the comparability****, increased reproducibility, consistency, relevance, focus and efficiency of PEF studies.*" (chapter 1 of Annex 1, ibid., emphasis added). To the knowledge of the authors, there is little (if any) demand for hydrogen of low purity. At the same time, hydrogen mixtures (e.g. syngas) should not be considered. This in turn would mean that conditioning processes (e.g. compression and purification) may have to be included in the PEFCRs on hydrogen production (e.g. in the form of modules).

Only the PEFCRs that are, however, unrelated to H_2 describe a **representative product**. This is because the definition of a representative product is a PEF-specific feature. The representative product might be another criterion to distinguish product categories or sub-categories.

Except for the PEFCRs, **temporal aspects** of the functional unit (how long) are only addressed by some documents (Capello, et al. 2015) (IEC/TS, 62282-9-102 2021) (Masoni and Zamagni 2011). Changes in the technical performance, notably the **degradation** of cells, are only addressed in three cases (IEC/TS, 62282-9-102 2021) (Masoni and Zamagni 2011) (First solar 2020). Likewise, **leakages** during storage are not considered at all. When defining the functional unit according to European Commission (2021), all of this needs to be considered regarding aspects "how long" and "how well" and presumably also "how much".

In terms of **system boundaries**, both analysed documents on hydrogen production allow to include purification and compression (Bargiacchi, et al. 2022) (Lozanovski, Schuller and Faltenbacher 2011). For hydrogen usage, the main question appears to be whether the documents follow a modular approach or not. In the case of the FC-HyGuide project, one document on hydrogen production was issued (Lozanovski, Schuller and Faltenbacher 2011), and one on fuel cells (Masoni and Zamagni 2011). The latter excludes hydrogen production from the fuel cell LCA. If the PEFCRs to be drafted are designed in a modular way, the PEFCR for hydrogen usage might need to exclude hydrogen production.

While **capital goods** (infrastructure and equipment) are allowed or required to be included by some documents (Bargiacchi, et al. 2022) (Capello, et al. 2015) (Lozanovski, Schuller and Faltenbacher 2011), European Commission (2021) generally recommends to exclude them. However, European Commission (2021) permits their inclusion if a "clear and extensive explanation" is provided.

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Because back then **end-of-life** treatment of fuel cells was less developed and thus little data was available, Masoni & Zamagni (2011) did not require to quantify this step. However, a qualitative description was required. European Commission (2021), by contrast, require the inclusion of the end-of-life of the product under consideration (i.e. not necessarily its infrastructure, see above).

Three documents make provisions for **modelling electricity**, relying on country or regional (e.g. EU27) electricity mixes (IEC/TS, 62282-9-102 2021) (Lozanovski, Schuller and Faltenbacher 2011) (Masoni and Zamagni 2011). This guidance corresponds to the third and fourth (last) option in the hierarchy of modelling electricity in European Commission (2021), generally preferring a market-based (supplier-specific) approach over a location-based approach.

European Commission (2021) rules that a PEFCR states the most relevant impact categories, life-cycle stages, processes and elementary flows per product category or sub-category. It might be interesting to verify whether the (most or potentially) relevant items stated in the following can also be identified in the hotspot analyses in Task 2.4 and WP4.

In terms of **most relevant impact categories**, only four documents make related requirements:

- Lozanovski et al. (2011) and Masoni & Zamagni (2011): Global warming potential, Acidification potential, Eutrophication potential, and Photochemical ozone creation potential;
- IEC/TS, 62282-9-102 (2021): climate change, abiotic resource depletion (minerals and metals), particulate matter, acidification, photochemical ozone formation; and
- Capello, et al. (2015): Emission of greenhouse gases (evaluated at midpoint level), Emission of acidifying gases (evaluated at midpoint level), Emissions of gases that contribute to the creation of ground level ozone (evaluated at midpoint level), Emission of substances to water contributing to oxygen depletion (evaluated at midpoint level), Waste production (evaluated at inventory level; different sub-categories).

It appears that climate change and acidification are always prioritised, while photochemical ozone formation come second, noting that Capello, et al. (2015) is not specific to FCH systems. If the additional environmental information requirement by Capello, et al. (2015) to provide information on resource use (material, energy, water) are additionally considered, resources appear to be another important impact category.

In terms of the **most relevant life cycle stages**, none of the analysed documents highlights one or several life cycle stages.

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Among the analysed non-PEFCR guidelines, only Masoni & Zamagni (2011) indicate **potentially (not "most") relevant processes** specific for FCH systems (i.e. fuel cells)[15]:

- Chemicals and electricity consumption as well as emissions of the fuel cell stack manufacturing (e.g., anode, cathode, matrix, electrolyte).
- Energy consumption and emissions of the stack assembling and steel parts (e.g., anodic and cathodic collectors, bipolar plates).
- Materials used for the BoP assembling (e.g., copper, aluminium, palladium, platinum, cast ironed) and the related energy consumption and emissions.
- Fuel consumption during the operation phase and the related emissions.

In contrast to the specific Life Cycle Impact Assessment (LCIA) methods to be used, neither the PEFCR guidelines (European Commission 2021) or nor the analysed PEFCRs specify how specific processes are to be modelled. However, company-specific data may be required for specific processes (see e.g. sections 5.1. and 5.2 in First solar (2020)).

Notable **additional environmental information** that are addressed in the documents and might be considered in WP4 include:

- Bargiacchi et al. (2022): analysing raw material criticality;
- Lozanovski et al. (2011) and Masoni & Zamagni (2011): quantifying Non-renewable Primary Energy Demand (PED non-renewable) or Renewable Primary Energy Demand (PED renewable).[16]
- For the case of biofuels, some specifications regarding carbon neutrality and market mediated impacts shall be reported (IEC/TS, 62282-9-102 2021).
- Capello et al. (2015) do not require additional environmental information for fuel cells specifically, but for the product group "Electrical energy" in general. These include risk-related issues, electromagnetic fields, noise, land use, and impacts on biodiversity.
- Capello, et al. (2015) require providing results for Use of resources (material, energy, water), Waste production (evaluated at inventory level; different sub-categories), LCI emissions of radioactive isotopes, LCI emissions of particle matter, LCI emissions of toxic substances, and LCI emissions of oil to water and ground.

[15] If the requirement to provide specific data can be taken as an indication for the most relevant processes, Capello et al. (2015) also lists important processes that are, however, not specific to FCH systems (see section 3.3.4.7.6).

[16] PED indicators are not classified as impact category indicators because Lozanovski et al. (2011) and Masoni & Zamagni (2011) refer to them as "environmental indicators".

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- Schneider Electric (2020): it is allowed to state the absence or level of presence of certain trace elements or heavy metals for the manufacturing phase and technical parameters for the use and EoL phases of PV plants.

In terms of **limitations**, data quality is addressed in all analysed documents. However, European Commission (2021) prescribes the evaluation of data quality for PEFCRs, i.e. does not leave room for manoeuvre. Nevertheless, the following aspects might be worthwhile to be considered in terms of **disclaimers (or limitations)** when drafting the PEFCRs in WP4:

- The most-mentioned items in the PEFCRs are data quality uncertainties (related to the complexity of products and their supply chains), uncertainty regarding value judgements (e.g. on product degradation), limitations when comparing intermediate products or when comparing products with different technical characteristics, produced at different locations etc.
- Making a disclaimer that not all impact categories are covered inspired by the IEC PCR (IEC/TS, 62282-9-102 2021).

This deliverable (D2.1) is about which rules to define for a given product category without specifically knowing which product categories will be distinguished (subject of D2.2). In general, there is a **dilemma** to avoid proliferation of PEFCRs (by distinguishing too many product categories) and nevertheless be sufficiently specific to allow comparability (grouping too many products into the same product category with rather different functions). One common way for dealing with this dilemma is to define:

- Horizontal rules, i.e., rules that describe the common modelling aspects for all the products/applications covered by a given PEFCR; and
- Vertical rules, i.e., rules that apply only to the specific product groups (so-called sub-categories), such as done in the PEFCRs for PV (First solar 2020) and for metal sheets (Eurometaux 2019).

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