HyPEF

TRACING CLEAN HYDROGEN

*Promoting an environmentally-responsible **Hy**drogen economy by enabling **P**roduct **E**nvironmental **F**ootprint studies*

D2.2 | FCH Product Categories

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Executive Summary

The following document is a fundamental pillar of the HyPEF project, which aims to promote an environmentally responsible hydrogen economy by developing and testing Product Environmental Footprint Category Rules (PEFCRs) specific to FCH products. HyPEF deliverable 2.2 offers, for the first time, an in-depth analysis and a comprehensive categorisation of Fuel Cells and Hydrogen (FCH) products tailored for Product Environmental Footprint (PEF) studies. In order to ensure a proper definition of FCH products categories, the steps followed to review and screen existing hydrogen technologies are outlined, paving the way to the categorisation process. This process is based on horizontal and vertical PEF rules, ensuring a robust and comprehensive framework that captures the complexity and diversity of hydrogen technologies.

Product categories and subcategories (when necessary) particular to FCH systems are defined in accordance with methodological criteria (PEF horizontal and vertical rules). In particular, this deliverable identifies 11 main product categories and 14 subcategories, covering the entire hydrogen value chain from production to utilisation. This list is divided into five main stages (families) within the hydrogen value chain. The document concludes with a call for continued stakeholder engagement to refine and implement PEFCRs, ensuring the sustainable growth of the hydrogen economy.

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List of Acronyms and Abbreviations

AEC	Alkaline electrolysis cell
AEMEC	Anion-exchange membrane electrolysis cell
AFC	Alkaline fuel cell
CcH2	Cryo-compressed hydrogen
CCS	Carbon capture and storage
CGH2	Compressed gaseous hydrogen
CHP	Combined heat and power
DMFC	Direct methanol fuel cell
EU	European Union
FCH	Fuel cells and hydrogen
ICE	Internal combustion engine
LH2	Liquid hydrogen
MCFC	Molten carbonate fuel cell
NG	Natural gas
PAFC	Phosphoric acid fuel cell
PC	Product category
PEF	Product environmental footprint
PEFCR	Product environmental footprint category rule
PEMEC	Proton-exchange membrane electrolysis cell
PEMFC	Proton-exchange membrane fuel cell
PSC	Product subcategory
SOEC	Solid oxide electrolysis cell
SOFC	Solid oxide fuel cell
TRL	Technology readiness level
UHS	Underground hydrogen storage

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1. Introduction

The demand for hydrogen as a promising option for the global energy transition is estimated to reach 115 Mt by 2030 (IEA, 2022). Although the use of hydrogen as a fuel is not associated with direct carbon emissions, concerns about the environmental impacts associated with its entire supply chain may arise. In this regard, sustainability criteria are progressively being implemented in energy transition initiatives, e.g., by promoting low-carbon renewable hydrogen in Europe. To ensure the environmental suitability of Fuel Cells and Hydrogen (FCH) products, the current project considers the general methodological guidance for Product Environmental Footprint (PEF) studies to report their life-cycle environmental profile in accordance with the principles of transparency, traceability, reproducibility, and consistency for comparability (European Commission, 2021).

The HyPEF project (Table 1) aims to support and promote the establishment of an environmentally-responsible hydrogen economy by developing and testing the first Product Environmental Footprint Category Rules (PEFCRs) specific to FCH products. In particular, the current report focuses on the first FCH products categorisation based on the review of available technologies associated with each step of the hydrogen life cycle, from production to use. Furthermore, the diversity of hydrogen technologies adds complexity to the definition of categories. This complexity underscores the need to apply additional criteria for the definition of different categories, such as the Technology Readiness Level (TRL) during the screening phase and the need for PEF horizontal and vertical rules for an appropriate representation of the FCH product categories and subcategories.

Table 1. HyPEF project information

Project Title	Promoting an environmentally-responsible Hydrogen economy by enabling Product Environmental Footprint studies		
Project Acronym	HyPEF		
GA Nº	101137575		
Call Topic	HORIZON-JTI-CLEANH2-2023-05-01		
Project Start Date	01/01/2024	Project End Date	31/12/2026
Project Budget	1,499,431.25€	EU Funding Rate	100%
Participants	• IMDEA Energy (IME, Spain; coordinator) • Istituto di Studi per L'integrazione Dei Sistemi (I.S.I.S) – Società Cooperativa (ISINNOVA, Italy) • Agenzia Nazionale per le Nuove Tecnologie, L'energia e Lo Sviluppo Economico Sostenibile (ENEA, Italy) • EIFER Europäisches Institut für Energieforschung EDF KIT EWIV (EIFER, Germany) • Ecoinnovazione srl (ECOI, Italy) • ENGIE (France) • Advanced Energy Technologies Ae Ereunas & Anaptyxis Ylikon & Proiontonananeosimon Pigon Energeias & Synafon Symvouleftikon Y Piresion (ADVENT, Greece) • Hexagon Purus GmbH (HexPur, Germany)		

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2. Methodological framework

To provide a clear understanding of the report structure, and the steps considered for product categorisation, the methodology followed for the definition of categories and subcategories within the hydrogen value chain is depicted in Figure 1. These steps include: (i) review and screening, and (ii) products categorisation.

First, within the review and screening step, an overview of the specific devices and equipment used throughout the hydrogen value chain is given. At this level, data collection activities are carried out, which require deep scrolling and documentation of already existing technologies within each life cycle stage in the hydrogen value chain. A preliminary classification of the FCH reported technologies, based on TRL and market availability, is made possible through a comprehensive screening step.

The second block presents a PEF and FCH-specific classification based on the differences in system specifications and PEFCR guidelines for product category and subcategory definition (system function and vertical rules). Overall, the procedure leads to the proposal of different FCH product categories and subcategories present within each stage of the hydrogen value chain (i.e. hydrogen production, conditioning, storage, transportation, and use).

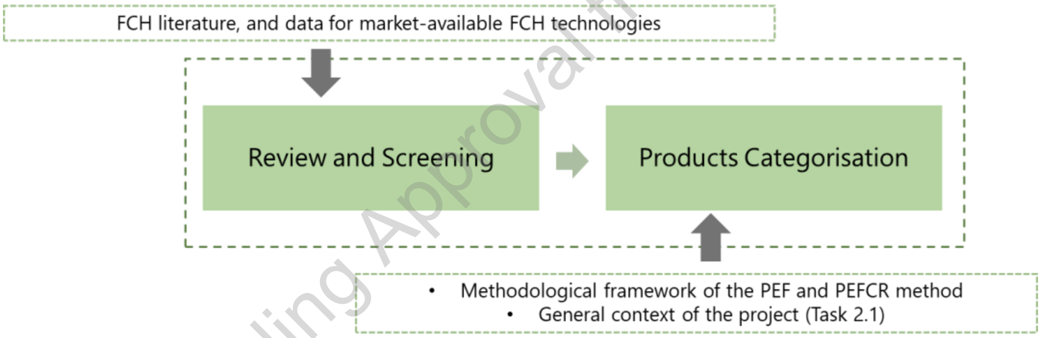

Figure 1. Steps for FCH products categorisation

2.1. Key definitions

The descriptions presented below are largely based on the definitions provided by the Commission Recommendation 2021/2279 (European Commission, 2021):

Hydrogen

In this deliverable, in accordance with IEA et al. (2023) and the methodological convention adopted in energy statistics, hydrogen is defined at 98% purity or higher. To comply with this definition of hydrogen, a purification step is implemented whenever necessary.

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PEF

A general method to measure and communicate the potential life cycle environmental impact of a product (European Commission, 2021).

Product category

A product category is defined as a group of products (or services) that can fulfil equivalent functions (European Commission, 2021).

Horizontal rules

Rules that are common to all products in the scope of a given PEFCR set (European Commission, 2021).

Vertical rules

Rules that are applicable only to a given product subcategory within a PEFCR set (European Commission, 2021).

Product environmental footprint category rules (PEFCRs)

Product category-specific, life cycle-based rules that complement general methodological guidance for PEF studies by providing further specification for a specific product category (European Commission, 2021).

Representative product (model)

This may be a real or virtual (non-existing) product. The virtual product should be calculated based on average European market sales-weighted characteristics for all existing technologies/materials covered by the product category or subcategory (European Commission, 2021).

2.2. Inputs and outputs

The present document proposes a product categorisation of FCH systems, based on a general overview of the FCH products that are already on the market or market/technology ready. In the following sections, the hydrogen value chain involving production, conditioning, storage, transport and use devices is considered.

The main output of this document is a list of FCH product categories first classified based on TRL (when data are available) and, at a second level, the difference in PEFCR horizontal and vertical rules. Moreover, all products within a product (sub)category are classified according to the relevant Statistical Classification by Activity (CPA) code (Eurostat, 2024).

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2.3. Product environmental footprint category rules

PEFCRs is a ruleset providing category-specific guidance used for calculating and reporting life cycle environmental impacts of products in a harmonised way. A proper setting of the product category allows the harmonisation of PEF evaluation of products having the same methodological specifications. In this sense, the work carried out within the framework of the HyPEF project aims to develop and test the first PEFCRs specific to FCH products, in compliance with which future PEF studies of hydrogen-related products could be conducted. The present document suggests a categorisation of FCH products based on which PEFCRs will be suggested, for some product categories, to serve for future hydrogen-related PEF studies.

The PEFCR template (Annex II of Commission Recommendation 2021/2279) requires a set of sections and rules when drafting PEFCRs. These sections shall have the same title as in the guidelines and shall appear in the same order: (i) general information about the PEFCR, (ii) PEFCR scope, (iii) most relevant impact categories, life cycle stages, processes and elementary flows, (iv) life cycle inventory, (v) life cycle stages, (vi) PEF results, and (vii) verification (European Commission, 2021).

According to subsection A.3.1 of the Commission Recommendation 2021/2279, the definitions of categories and subcategories should be based on the differences in horizontal rules for categories definition, and vertical rules for subcategories definition (European Commission, 2021). In this sense, a clear description of the considered horizontal rules shall be given in the PEFCR set. Similarly, for each subcategory, a section specifying the vertical rules applicable to it shall be included in the PEFCR set.

3. Review and screening

3.1. Review

The review process involved a thorough examination of the FCH devices available through the hydrogen value chain (production, conditioning, storage, transportation/distribution, and use). First, a web search was conducted to identify different technologies available for each of the aforementioned stages. For the sake of clarity, the references used in this specific exercise are presented separately in Table 2.

Subsequently, based on the outcomes of the online search, the most relevant technologies were selected. The associated products were identified, and their key characteristics were considered. Moreover, whenever publicly available, the TRL and data on the current market size of the selected technologies were included.

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Table 2. References associated with the review of available FCH products

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3.1.1. Hydrogen production

Steam reforming is currently the main hydrogen production technology, with a TRL of 11 (extended TRL scale) according to IEA (2023). In the sample (Table 2, D2.2), steam reforming plants can produce between 50 and 50,000 Nm^3/h of hydrogen, with a purity ranging between 99.999% and 99.9999% [1-4]. Hydrogen can also be produced through methanol reforming with similar ranges of hydrogen production and purity [5,6]. Technologies such as partial oxidation and coal gasification with CO_2 capture (TRLs of 5-6 and 9, respectively) have also been reported. As for thermochemical processes with waste and biomass use, future implementation of gasification and pyrolysis plants is expected, with a TRL of 6 (IEA, 2023).

Electrolysis is expected to become the predominant technology in hydrogen production. The search results of these available technologies highlighted four types of electrolysers: PEMEC (Proton-Exchange Membrane Electrolysis Cell), AEC (Alkaline Electrolysis Cell), SOEC (Solid Oxide Electrolysis Cell), and AEMEC (Anion-Exchange Membrane Electrolysis Cell). Currently, PEMEC and AEC options are the most widely offered technologies in the market, both with a TRL of 9 (IEA, 2023). In the sample, available PEMEC modules have hydrogen production capacities ranging from 0.2 to 4920 Nm^3/h, with purities between 99.5% and 99.9999% [7-18]. Similarly, AEC options have production capacities ranging from 2.6 to 4000 Nm^3/h, with purities between 99.5% and 99.9995% [19-26]. On the other hand, SOEC and AEMEC electrolysers (with TRLs of 8 and 6, respectively (IEA, 2023)) are not yet extensively available in the market. In the sample, SOEC options can produce between 3 and 32000 Nm^3/h of hydrogen with purities between 99% and 99.999% [27-30] (Drasbæk et al., 2021), while AEM electrolysers have capacities between 0.5 and 231 Nm^3/h [31,32]. It is anticipated that, due to current hydrogen policies, hydrogen production via electrolysis will increase significantly, expanding the market for these electrolysers in the medium to long term.

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3.1.2. Hydrogen conditioning

Regarding the conditioning stage, the review focus was placed on hydrogen compressors. In this regard, different compressors available on the market were explored. The compressors considered are diaphragm compressors, piston compressors, hydraulic compressors, and continuous radial compressors. Table 3 outlines the range of some key characteristics for each type of compressor.

Table 3. Ranges of characteristics for each compressor type

Type of compressor	Nominal power (kW)	Maximum volumetric flow (Nm^3/h)	Outlet pressure (bar_g)	References
Diaphragm	1.5 – 220	2.5 – 10000	60 – 1155	[33,34]
Piston	4 – 20000	10 - 33389	10 – 800	[35-39]
Hydraulic	-	5.1 – 18.3	49 – 1000	[40]
Radial continuous	0.8 – 960	4.8 – 11000	0.8 – 12	[41,42]

3.1.3. Hydrogen storage

For hydrogen storage, several modalities were considered: compressed and liquid hydrogen storage, sites for geological storage, and solid-state storage. Regarding compressed hydrogen storage, four different types of tanks were identified: Type I (metal tank of steel or aluminium), Type II (steel tank with fibreglass or carbon fibre filament wound around the midsection of the cylinder), Type III (composite material tanks of fiberglass or carbon fibre with an aluminium metal liner), and Type IV (composite material tanks of carbon fibre with thermoplastic polymer liners) [43]. In the sample, available tanks vary in pressures between 60 and 1060 bar and hydrogen storage capacities from 0.2 to 512 m^3 H_2 [43-50]. They can be used for stationary storage or during hydrogen transportation. The TRL for compressed hydrogen tanks is 11 (IEA, 2023), explaining the wide variety available. For liquid hydrogen storage, the TRL is lower, which limits the variety of available tanks for consideration in HyPEF. Currently, in the sample, these tanks have capacities ranging from 0.05 to 317.2 m^3 H_2, with pressures between 1 and 12 bar.

Geological hydrogen storage includes salt caverns, aquifers, depleted reservoirs, rock caverns, and artificial cavities. Salt caverns are the most utilised, with a TRL of 9-10. Four salt caverns store hydrogen with a 95% hydrogen content in Teesside (UK), Clemens (USA), Moss Bluff (USA), and Spindletop (USA), with a total storage capacity of 21.22 kt H_2 (Sambo et al., 2022). In aquifers, hydrogen is not stored in its pure form but as natural gas with a hydrogen content between 62% and 50%. Aquifer storage has a TRL of 3, indicating the need for continued research in this area. Similarly, the TRL for hydrogen storage in depleted reservoirs and artificial cavities is 4 and 5, respectively (IEA, 2023).

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Finally, in solid-state hydrogen storage, metal hydrides and sorbent-based systems (carbon-based materials, metal-organic frameworks, and zeolites) were considered. These technologies have low TRLs, from 2-3 for sorbent-based systems to 4-5 for metal hydrides, explaining the limited availability of these options in the market. In the sample, three companies commercialise metal hydrides, with storage capacities between 0.02 and 10 m^3 H_2 [51-53].

3.1.4. Hydrogen transport

For the transportation of hydrogen, both stationary (pipelines) and mobile technologies were considered. Mobile technologies include trucks specifically designed and equipped to transport hydrogen exclusively [54]. In stationary technologies, pipelines dedicated to hydrogen transport already exist. Literature indicates that pipelines exceeding 5 kilometres in length are operational [55].

3.1.5. Hydrogen use

The use of hydrogen includes various applications, classified into three main groups in the review phase. Firstly, chemical processes involving the use of hydrogen, such as ammonia production, methanol production, and its use in refineries, were included. Additionally, the production of e-fuels and biofuels was considered herein, which are emerging areas of significant interest. Ammonia production plants have production capacities ranging from 1000 to 1500 t/day (Jabarivelisdeh et al., 2022), while, in the sample, methanol production plants have capacities ranging from 10 to 100 t/day [56].

Secondly, combustion technologies, particularly turbines, were examined. In the evaluated turbines, only two are capable of operating with 100% hydrogen, with nominal power from 1902 to 37400 kW [57,58]. The other identified turbines can operate with hydrogen mixtures ranging from 30% to 75%, with nominal power varying between 5400 and 62000 kW [58].

Finally, electrochemical processes, specifically fuel cells, were addressed. The types of fuel cells considered in the study are PEMFC (Proton-Exchange Membrane Fuel Cell), SOFC (Solid Oxide Fuel Cell), PAFC (Phosphoric Acid Fuel Cell), and AFC (Alkaline Fuel Cell). The DMFC (Direct Methanol Fuel Cell) and MCFC (Molten Carbonate Fuel Cell) types were not considered, as DMFC cells operate exclusively with methanol and the identified MCFC cells do not use hydrogen directly. A wide variety of PEMFCs are available in the market, many of which have multiple applications, including stationary use and transportation, such as in the maritime, rail, or automobile sectors. In the sample, these fuel cells, or fuel cell modules, have nominal power outputs ranging from 0.7 to 1608 kW, with hydrogen consumption varying from 0.14 to 147.4 kg/h [59-63]. Regarding SOFCs, PAFCs and AFCs, their market availability is more limited, and their primary use is for stationary applications. In the sample, SOFCs have nominal power outputs from 1 to 300 kW [64,65], PAFCs have nominal power outputs of 100 kW [66] and 440 kW [67], and AFCs have a nominal power output of 5 kW [68].

3.2. Screening

The screening phase was conducted based on Section 3.1 outcomes. This step is essential for pre-categorising FCH products across all stages of the hydrogen value chain. Hence, it facilitates product categorisation and PEF development in the field of FCH products, while helping analysts to focus data collection activities and prioritise data quality for the PEFCR supporting study. The screening process was based on the existing FCH technologies, considering factors such as TRL and market size, whenever available. Accordingly, technologies with relatively low TRL such as anion-exchange membrane electrolysis, methanol reforming and biomass/waste thermochemical conversion technologies for hydrogen production were excluded within the hydrogen production phase. Similarly, solid hydrogen storage and depleted fields and aquifers for geological hydrogen storage were excluded due to their relatively low TRL. Moreover, technologies that are not fully specific to hydrogen (e.g. those specific to hydrogen carriers) were excluded.

On the other hand, further research into the hydrogen value chain led to additionally including FCH technologies not available in the review section but considered relevant, such as hydrogen liquefaction and regasification units, ships for hydrogen transmission, and hydrogen Internal Combustion Engines (ICEs).

4. Product categorisation

Figure 2 illustrates the methodology followed for the definition of FCH product categories and subcategories for PEF purposes. This visual representation aids in understanding the logical flow and rationale behind the categorisation procedure. The horizontal rule 'system function' is the first relevant rule for the identification of product categories within the FCH systems (European Commission, 2021). At the product category level, a difference in vertical rules (differences in representative product, benchmark, most relevant processes and life cycle stages) leads to the definition of a subcategory, thus involving a highly relevant system variant. Other differences not leading to a subcategory (e.g. extended scope due to the implementation of CO_2 capture, onsite power generation, etc.) could be addressed as an additional specification when describing the product category.

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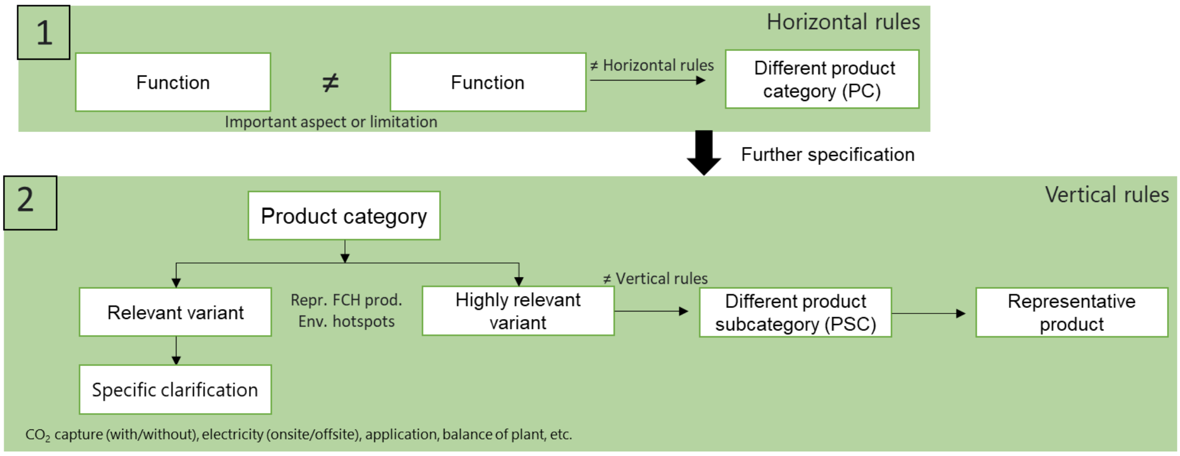

Figure 2. Methodological approach to the definition of FCH product categories and subcategories

For a proper definition of FCH product categories, the relevant FCH devices within the hydrogen value chain were classified into five stages hereinafter referred to as "product families": hydrogen production, conditioning, storage, transport, and use. Figure 3 shows the intricacy of the assessment of FCH systems, underlined by the important interaction between different families. This interaction complicates the categorisation process and necessitates a thorough examination and screening of available FCH technologies (Section 3), as well as the adaptation and proper implementation of these families in accordance with PEF requirements.

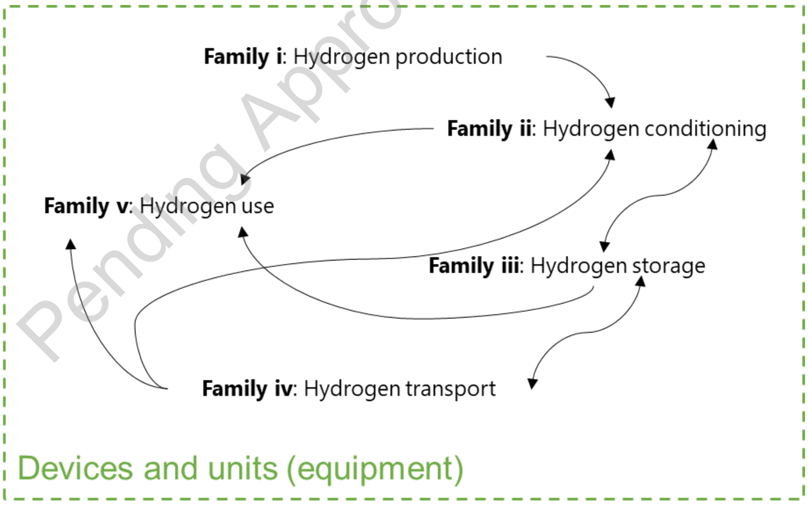

Figure 3. Hydrogen value chain interconnections

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4.1. Family i: Devices for hydrogen production

Hydrogen is produced through various pathways and from different feedstocks. Among the available technologies for hydrogen production, reforming is the most mature and widely adopted technique for industrial hydrogen production. Most of the hydrogen produced worldwide is from fossil fuels, either through steam reforming of natural gas or through coal gasification (Clean Hydrogen JU, 2024). These mature technologies are associated with high TRL. However, with the rising environmental concerns associated with the consumption of fossil resources, alternative feedstocks (e.g. biomass) and technologies (e.g. water electrolysis) are needed. The screening of the existing and emerging technologies reported in Section 3 for hydrogen production allows the classification of a group of technologies based on TRL, system function, and PEFCR vertical rules criteria. Under this family, one product category, involving two product subcategories, is proposed.

4.1.1. PC1: Devices for hydrogen production

In the case of this family (devices for hydrogen production), the function of the system is the same, leading to the inclusion of all hydrogen production technologies under the same Product Category (PC): 'PC1: Devices for hydrogen production'. Within this category, technologies with high TRL identified during the screening phase are included (e.g. steam methane reforming, coal gasification, PEMEC, and AEC). The potential functional unit would involve the amount of hydrogen produced, with additional specification in terms of purity, pressure, temperature and the time aspect.

The following findings are the outcome of additional research into the environmental performance of key hydrogen production technologies: (i) thermochemical processes typically present different environmental hotspots from electrochemical processes, e.g., feedstock production and direct emissions as hotspots in thermochemical hydrogen production systems (Susmozas et al., 2013) in contrast to electricity supply as the environmental hotspot in electrochemical ones (Bhandari et al., 2014; Bareiß et al., 2019; Zhao et al., 2020); and (ii) the potential representative product for thermochemical plants would be the natural gas steam reforming plant, while, for electrochemical devices, the potential representative product would be AEC and/or PEMEC. Considering these differences in vertical rules, the definition of subcategories is necessary. Therefore, within 'PC1: Devices for hydrogen production', two Product SubCategories (PSC) are defined: 'PSC1.1: Thermochemical plants for hydrogen production', and 'PSC1.2: Electrochemical devices for hydrogen production'. It is worth noting that the presented subcategories are not limited to the already available technologies with high TRL, but they could be extended to other hydrogen production

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(thermochemical/electrochemical) technologies that will find their way to the market in the coming years, with some exceptions such as biochemical and photochemical processes.

4.1.1.1. PSC1.1: Thermochemical plants for hydrogen production

This category includes the process units/devices for hydrogen production from thermochemical processes, including, but not limited to, steam reforming and coal gasification. Considering the definition of hydrogen provided in Section 2.1, the inclusion of a purification step is always required to reach a minimum of 98% purity. It should be noted that the level of purity needs to be specified for a further description of the product system functional unit. Further specification regarding the inclusion of Carbon Capture and Storage (CCS) within the system boundaries should be clearly stated when drafting the PEFCR set for this subcategory. The suggested CPA code is '28.29.6 Machinery n.e.c. for the treatment of materials by a process involving a change of temperature' (Eurostat, 2024).

4.1.1.2. PSC1.2: Electrochemical devices for hydrogen production

The second subcategory is based on hydrogen production through water splitting using electrochemical technologies. Different devices developed for water electrolysis are available, such as AEC, PEMEC, AEMEC, and SOEC. In particular, based on the hydrogen production technology screening (Section 3.2), the technologies associated with TRL ≥ 8 are PEMEC, AEC, and SOEC. The focus is expected to be placed on these technologies in this subcategory. The suggested CPA code is '28.29.1 Gas generators, distilling and filtering apparatus'.

4.2. Family ii: Devices for hydrogen conditioning

Hydrogen conditioning is an intermediate step that could be placed in different positions within the hydrogen life cycle stages. This family is specific to all processes and equipment used for hydrogen conditioning. The equipment within each category is hydrogen-specific, and hence other conditioning technologies such as those related to hydrogen carriers are not considered within the framework of this family. This family includes three product categories classified based on the difference in the system function (the first horizontal rule), as explained in Sections 4.2.1-4.2.3.

4.2.1. PC2: Compressors specific to hydrogen conditioning

This category includes compressors used for hydrogen preparation for storage as well as for any operation requiring hydrogen compression. Hence, this family is interconnected with different steps in the hydrogen value chain with the main function 'hydrogen compression'. The description of the state of hydrogen in the functional unit is required. In this sense, the potential functional unit would involve the amount of compressed gaseous hydrogen, with

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additional specification in terms of purity, pressure levels, temperature and the time aspect. The suggested CPA code is '28.13.26 Reciprocating displacement compressors' or '28.13.28 Other compressors'.

4.2.2. PC3: Liquefaction units specific to liquid hydrogen production

The second category involves liquefaction units for liquid hydrogen production, under which all equipment for hydrogen liquefaction is considered. The function of the devices under this category is 'hydrogen liquefaction'. A description of the liquefaction process of hydrogen can be found in Zhang et al. (2023). A description of the state of hydrogen in the functional unit is required. In this sense, the potential functional unit would involve the amount of liquid hydrogen produced, with additional specification in terms of purity, pressure, temperature and the time aspect. The suggested CPA code is '28.29.6 Machinery n.e.c. for the treatment of materials by a process involving a change of temperature'.

4.2.3. PC4: Regasification units of liquid hydrogen

After transportation, liquid hydrogen typically needs to be reconverted to gaseous state before usage, which leads to the third category: 'regasification units of liquid hydrogen'. A description of the regasification process of hydrogen can be found in Zhang et al. (2023). The function of the devices under this category is 'hydrogen regasification'. A description of the state of hydrogen in the functional unit is required. In this sense, the potential functional unit would involve the amount of gaseous hydrogen produced, with additional specification in terms of purity, pressure, temperature and the time aspect. The suggested CPA code is '28.29.6 Machinery n.e.c. for the treatment of materials by a process involving a change of temperature'.

4.3. Family iii: Devices for hydrogen storage

This family includes the principal hydrogen storage options. Depending on the context (e.g. use case), hydrogen needs to be stored in different states, requiring different storage techniques to maintain the desired physical properties of hydrogen (e.g. pressure, temperature and density) throughout the storage period. Such tailoring of properties ensures appropriate storage boundaries for safe and convenient hydrogen storage. In that sense, before storage, hydrogen should undergo conditioning to meet the storage requirements (Section 4.2). Different technologies and options are available for hydrogen storage. The storage techniques identified during the screening phase based on the available TRL are: different tanks for compressed hydrogen storage, liquid hydrogen storage, and salt caverns for large-capacity underground storage of gaseous hydrogen.

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According to the considered horizontal rule for the definition of product categories, the present family requires two product categories based on the difference in the system functions since underground storage is only available for large amount of gaseous hydrogen while tanks are for small to medium scale storing capacities for both gaseous and liquid hydrogen. Hence, two different categories are defined: 'PC5: Tanks for hydrogen storage' and 'PC6: Sites for large-scale geological storage of gaseous hydrogen'.

4.3.1. PC5: Tanks for hydrogen storage

Hydrogen can be stored in different states: LH2 (Liquid Hydrogen), CGH2 (Compressed Gaseous Hydrogen), and CcH2 (Cryo-compressed Hydrogen). Each state requires different tank characteristics to maintain the desired physical properties of hydrogen throughout the storage period. Under normal temperature and pressure (20 °C and 1 atm), hydrogen density is equal to 0.08375 kg/m^3. In order to facilitate hydrogen storage, increasing its density is essential. Additionally, pressure levels are significantly influenced by tank design, including the length-to-thickness ratio. Various standards such as EC79, ISO 11439, EN 12245, and ISO 11119-3 specify requirements for tank approval and storage purposes.

LH2 tanks require special insulation and construction materials compared to CGH2 tanks, leading to a difference in the potential representative products. Moreover, CGH2 storage tanks differ in terms of storage pressure. The specific pressure levels for CGH2 storage depend on the intended hydrogen use. In this regard, the differences in potential representative products and the need for further specification of the function of the device (tank) in close relation with the intended use of hydrogen lead to the definition of different subcategories for hydrogen storage in tanks.

The state of the stored hydrogen is highlighted when further describing the main function of the tanks, i.e., the storage of LH2/CGH2/CcH2. The potential functional unit would involve the amount of (liquid/gaseous/cryo-compressed) hydrogen stored, with additional specification in terms of purity, pressure, temperature and the time aspect (including leakage). For each product subcategory, the pressure level and temperature (if applicable) should be defined when describing the specific functional unit. In this product category, five subcategories are defined: 'PSC5.1: Tanks for liquid hydrogen storage', 'PSC5.2: Tanks for compressed hydrogen at moderate storage pressures', 'PSC5.3: Tanks for compressed hydrogen storage for passenger cars and tube trailers', 'PSC5.4: Tanks for compressed hydrogen storage for heavy-duty mobility', and 'PSC5.5: Tanks for cryo-compressed hydrogen storage' (Amirthan and Perera, 2022; Usman, 2022; AlZohbi et al., 2023).

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4.3.1.1. PSC5.1: Tanks for liquid hydrogen storage

One of the most effective ways to store large amounts of hydrogen in tanks is in its liquid state, where the density increases to approximately 70 kg/m^3. This occurs under cryogenic conditions at a temperature as low as -253°C. Therefore, temperature is the key factor influencing tank and storage system characteristics (Cheng et al., 2024). The tanks used to store liquid hydrogen should be resistant to hydrogen embrittlement, resistant to hydrogen permeation, mechanically strong, thermally robust, and fire and heat resistant. Hence, in order to maintain safe and effective storage conditions, a complex system is required. For this purpose, stainless steel tanks are one of the suggested solutions. The suggested CPA code for this product subcategory is 'H 52.10.11 Refrigerated storage services'.

4.3.1.2. PSC5.2: Tanks for compressed hydrogen at moderate storage pressures

This product subcategory groups vessels that are convenient for industrial storage and distribution tank trailers (250 bar) of CGH2, including Type I and Type II tanks. These tanks (Type I and Type II) are metal-based with working pressures normally around 200 and 300 bar, respectively (Cheng et al., 2024). These tanks operate at a different pressure depending on the hydrogen usage requirement after storage. For instance, a Type I vessel could be used for hydrogen transportation at a maximum pressure of 250 bar. Pressure limits are fixed by the manufacturer according to tank design and should be respected during the usage of the tank for safety reasons. In order to ensure comparability between products under the same subcategory, when further specifying the functional unit, the operating pressure of the vessel is expected to be defined and fixed with the aim of harmonising the PEF results. In this regard, a representative pressure, falling in the range of pressure requirement for all tanks under this subcategory, is expected to be fixed. The suggested CPA code for this subcategory is 'C 25.29.1 Other tanks, reservoirs and containers of metal'.

4.3.1.3. PSC5.3: Tanks for compressed hydrogen storage for passenger cars and tube trailers

This product subcategory includes tanks for hydrogen automotive applications with pressure up to 700 bar for onboard hydrogen storage. Type IV hydrogen tanks are the solutions for light automobile applications due to significant weight savings. Type IV tanks are also used for distribution trailer tanks at a pressure ranging from 500 to 635 bar. Furthermore, the tank specification (material) depends on the usage requirements. In mobile applications for cars, compressed gas storage at 700 bar is the most advanced solution to date (TÜV Rheinland, 2024). In this context, this product subcategory includes tanks for hydrogen mobile applications (light duty) that can operate at pressures as high as 700 bar as well as distribution tube trailer tanks. Further specification is expected to be required when drafting the set of PEFCRs for this product subcategory, fixing the pressure requirement to safeguard comparability between devices under the same product subcategory. The suggested CPA code for this product subcategory is 'C 26.20.21 Storage units'.

4.3.1.4. Tanks for compressed hydrogen storage for heavy-duty mobility

This product subcategory includes tanks used for storing hydrogen under a pressure typically employed for heavy-duty vehicles such as trucks, buses, or trains. Usually, 350 bar tanks are used in buses where multiple large tanks can be carried to store enough hydrogen for a fixed routine (Cheng et al., 2024). A harmonised pressure value is expected to be fixed to ensure the comparability of products under the same product subcategory for tanks when further specifying the functional unit. The suggested CPA code for this product subcategory is 'C 26.20.21 Storage units'.

4.3.1.5. Tanks for cryo-compressed hydrogen storage

Combining the advantages of LH2 and CGH2, CcH2 is proposed to attain higher density storage (Wang et al., 2022). CcH2 tanks present lower requirements for expensive carbon fibres due to designing for a maximum tank pressure of 350 bar compared with 700 bar for state-of-the-art CGH2 storage tanks. The storage vessel is designed to hold the internal pressure from the cryogenic fluid. By the end of 2023, Verne and Lawrence Livermore National Laboratory achieved the first demonstration of a CcH2 system large enough to meet the energy storage needs of semi-trucks. The temperature and the pressure of the stored hydrogen should be indicated when specifying the functional unit for this product subcategory. The suggested CPA code for this product subcategory is 'C 26.20.21. Storage units'.

4.3.2. PC6: Sites for large-scale geological storage of gaseous hydrogen

Theoretically, the options for Underground Hydrogen Storage (UHS) are similar to the ones used to store natural gas, including depleted gas fields, saline aquifers and salt caverns. However, due to its small molecular size, hydrogen diffuses easily and therefore requires storage reservoirs with excellent seals. Salt caverns are a good option for storing hydrogen because salt is inert with respect to hydrogen and is extremely gas tight (Matos et al., 2019). Very large amounts of hydrogen can be stored for instance in man-made underground salt caverns of up to 500000 m^3 at 200 bar. UHS has its own challenges, namely in areas of suitability of geographic location, risk assessment, leakage, cost, undesirable amount of water production upon hydrogen extraction, subsurface reactions, and geomechanics. Within this category, salt caverns are considered as a potential representative product. In addition, a purification step should be considered within the system boundaries (after hydrogen

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extraction, if purity is expected to be affected by side reaction during storage) whenever needed to meet the requirements for hydrogen purity as defined in Section 2.1. The potential functional unit would involve the amount of gaseous hydrogen stored, with additional specification in terms of scale, purity, pressure, temperature and the time aspect. The suggested CPA code for this product subcategory is 'H 52.10.122 Bulk liquid or gas storage services'.

4.4. Family iv: Devices for hydrogen transport

Hydrogen transportation technologies depend on the distance and geographical specifications that separate the production or storage site from the usage facility (Ishimoto et al., 2020; d'Amore-Domenech et al., 2021; Kanz et al., 2023). Moreover, when addressing hydrogen transportation, two aspects are included: (i) hydrogen transmission, referring to the transportation of hydrogen to a single location over a long distance; and (ii) hydrogen distribution for short-distance delivery (Yang and Ogden, 2007). Generally, after transmission, hydrogen is distributed to the usage facilities through local pipeline networks or via road transportation. It should be noted that only hydrogen-specific devices are considered within this family. This family includes, but is not limited to, pipelines, trailer vehicles (tanker trucks and compressed gas trucks) for on-road hydrogen transportation, and ships for hydrogen transmission. Based on differences and limitations in system function and hydrogen state during transportation, two product categories are defined within this family: 'PC7: Vehicles and ships for hydrogen transport', and 'PC8: Pipelines for hydrogen transport'.

4.4.1. PC7: Vehicles and ships for hydrogen transport

This product category involves devices for liquid and compressed hydrogen transportation (onshore and offshore) including the entire vehicle or ship (specifically designed/adapted for hydrogen transportation). This includes liquid hydrogen transportation by ships, liquid hydrogen transportation by trucks, and compressed hydrogen gas transportation by trucks (Cheng et al., 2024). This product category could be extended by including more devices related to all kinds of vehicles that could be developed in the future for liquid/gaseous hydrogen transportation. For the present document, the aforementioned technologies are selected for hydrogen transportation (U.S. Department of Energy, 2020). It should be noted that, when addressing tanks as a separate part of the vehicle for CGH2 and LH2 storage during transportation, PC5 is considered as the associated product category to address it.

The potential functional unit would involve the amount of liquid/gaseous hydrogen transported, with additional specification in terms of distance, purity, pressure, temperature and the time aspect. Differences in the potential representative products (vertical rule) lead to

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the definition of three product subcategories: 'PSC7.1: Trailer trucks for liquid hydrogen transportation', 'PSC7.2: Trailer trucks for gaseous hydrogen transportation', and 'PSC7.3: Large ships for hydrogen transmission'.

4.4.1.1. PSC7.1: Trailer trucks for liquid hydrogen transportation

This product subcategory involves the devices required for liquid hydrogen transportation. Generally, LH2 is transported in super-insulated, cryogenic tanker trucks specially designed to transport hydrogen in its liquid state. Nevertheless, this product subcategory is not limited to cryogenic tanker trucks, and it could include other truck technologies for LH2 transportation developed in the future provided that they do not present a significant difference in terms of vertical rules. The suggested CPA code is 'H 49.41.13 Road transport services of freight by tank trucks or semi-trailers, other bulk liquids or gases'.

4.4.1.2. PSC7.2: Trailer trucks for gaseous hydrogen transportation

PSC7.2 involves trailer trucks designed for CGH2 transportation. The most typical method for gaseous hydrogen transportation includes high-pressure tube trailers. These trailers typically have multiple cylinders or tubes mounted on a chassis, while CGH2 could be also transported in trailed vessel as discussed in Section 4.3.1.2. PSC7.2 is not limited to tube trailer trucks and it could include other trailer truck technologies for CGH2 transportation developed in the future provided that they do not present a significant difference in terms of vertical rules. The suggested CPA code is 'H 49.41.13 Road transport services of freight by tank trucks or semi-trailers, other bulk liquids or gases' along with 'C29.2 Bodies (coachwork) for motor vehicles; trailers and semi-trailers'.

4.4.1.3. PSC7.3: Large ships for hydrogen transmission

This product subcategory is dedicated to the transportation of large amounts of hydrogen overseas by large ships. It involves LH2 transmission devices, considering that LH2 shipment has already been tested with the first intercontinental shipment of LH2 (Kawasaki's Suiso Frontier ship) and that more efforts are being made for the development of new long-distance LH2 transportation ships. The suggested CPA code is 'C30.11 Ships and floating structures'.

4.4.2. PC8: Pipelines for hydrogen transport

Pipelines are one of the key transportation methods for gaseous hydrogen. Depending on the transportation distance, pipelines can be classified into two categories: pipelines for hydrogen transmission, and pipeline networks for hydrogen distribution. This category only includes pipelines specific to transportation of gaseous hydrogen (i.e. not of other gases). Hydrogen pipeline design requirements include adequate material selection, pipe sizing (diameter and

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wall thickness), and protection against hydrogen embrittlement and galvanic corrosion (Tsiklios et al., 2022).

The potential functional unit would involve the amount of gaseous hydrogen transported, with additional specification in terms of distance, purity, pressure, temperature and the time aspect (including leakage). Usually, transmission pipelines require several compression stations to keep the gas moving during transportation, which involves additional equipment to maintain the proper functioning of the pipeline. The pipes transport pressurised hydrogen gas from the feed-in station to substations, where it is expanded and delivered to the distribution network. The transmission and distribution pipelines differ in terms of diameters and operating pressure, leading to the use of different construction materials (Tsiklios et al., 2022). Therefore, based on differences in the potential representative products and further functional unit specifications (operating pressure of the pipeline), two product subcategories are defined: PSC8.1 and PSC8.2, for pipelines for gaseous hydrogen transmission and distribution, respectively.

4.4.2.1. PSC8.1: Pipelines for hydrogen transmission

PSC8.1 is a product subcategory specific to pipelines for hydrogen transportation over long distances. For large-scale hydrogen transmission, pipeline materials must have particular properties such as sufficient strength, toughness, ductility, and weldability. Therefore, the most suitable transmission pipeline materials are high-strength low-alloy steels, composed of iron (98–99 wt%), carbon (≤0.30 wt%), manganese (0.30–1.5 wt%), and small amounts of other alloying elements, such as molybdenum, vanadium, and titanium (Tsiklios et al., 2022). The operating pressure of the pipeline is expected to be fixed when further defining the functional unit to facilitate comparability between pipelines under this product subcategory. The suggested CPA code for this product subcategory is 'H 49.50.19 Transport services via pipeline of other goods'.

4.4.2.2. PSC8.2: Pipelines for hydrogen distribution

This product subcategory includes pipelines specific to hydrogen distribution. Compared to transmission pipelines, distribution ones are generally smaller (smaller diameter) and operate at lower pressure for regional last-mile gas delivery. These pipelines are dependent on daily hydrogen demand (Wulf et al., 2018). The operating pressure of the pipeline is expected to be fixed when further defining the functional unit to safeguard comparability between pipelines under this product subcategory. The suggested CPA for this product subcategory is 'H 49.50.19 Transport services via pipelines of other goods'.

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4.5. Family v: Devices for hydrogen use

Hydrogen is a versatile energy carrier that can be used in various devices and applications across different critical sectors. Under the hydrogen use family, three different functions are identified: (i) electricity production from hydrogen through fuel cells, (ii) combined heat and power generation through hydrogen fuel cells, and (iii) heat production from hydrogen. These differences lead to the definition of three different categories within this family: 'PC9: Hydrogen fuel cells intended for electricity production', 'PC10: Hydrogen fuel cells for combined heat and power generation', and 'PC11: Devices intended for heat production from hydrogen'. Typically, a conventional diesel genset generates electricity at efficiencies of 33% to 35%, while fuel cells can generate electricity at efficiencies up to 60% and even higher with cogeneration. Fuel cells are expected to be a major driver of distributed power in a variety of sectors such as marine, automotive, and stationary & back-up power generation for industrial and domestic applications. The search for other potential usages of hydrogen has led to other technologies such as hydrogen fuel cells for the cogeneration of heat and power and heat production from hydrogen through specific devices (e.g. ICEs for hydrogen-powered vehicles and large industrial devices for thermal energy production from hydrogen). Other technologies not fully focused on hydrogen, such as those for hydrogen use for chemical synthesis or treatments using hydrogen, are not considered within the framework of this family. In this sense, the technologies considered under this family are specifically developed for hydrogen and are dedicated mainly to electricity and/or heat production from hydrogen, allowing a classification based on differences in their system function (horizontal rule).

4.5.1. PC9: Hydrogen fuel cells intended for electricity production

Hydrogen fuel cells for electricity production can be widely used in various sectors in stationary and mobility applications. Different fuel cell types can be classified by the type of electrolyte used and their operating temperature range (e.g. low-temperature PEMFCs, and SOFCs and MCFCs as high-temperature fuel cells). In regard to applications, the global fuel cell market is segmented into stationary, portable, and transport. The fuel cells considered within this product category are intended for electricity production. Hence, the system function of the devices under this product category is electricity production from hydrogen. The potential functional unit would involve the amount of produced electricity, with additional specification in terms of, e.g., efficiencies and the time aspect. The suggested CPA code is 'C 27.90.42 Fuel cells'.

4.5.2. PC10: Hydrogen fuel cells for combined heat and power generation

Variations of fuel cell equipment for CHP (Combined Heat and Power) systems are deployed for quiet and reliable power applications ranging from urban commercial and industrial

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deployments to remote, off-grid power supply solutions. In this product category, heat together with electricity is considered as the main product. The system function of the devices under this product category is combined heat and electricity production from hydrogen. The potential functional unit would involve the quantity of produced exergy, with additional specification in terms of, e.g., efficiencies and the time aspect.

Stationary fuel cell systems present an interesting option for the conversion of hydrogen into electricity and heat as they allow achieving total efficiencies of above 90% when operated in cogeneration mode. With the increasing electrification of the heat sector, the heat and power peak demand are moving in the same direction. Although the main fuel cell technologies (PEMFC and SOFC) have the potential to open the path to commercialisation, further progress should be made to reduce costs, improve performance and durability, and improve the manufacturing processes. The suggested CPA code is 'C 27.90.42 Fuel cells'.

4.5.3. PC11: Devices intended for heat production from hydrogen

Devices intended for heat production from hydrogen include a wide range of technologies. Hydrogen combustion heaters and boilers are primary examples, functioning similarly to natural gas systems but burning hydrogen instead. The potential functional unit would involve the amount of produced heat, with additional specification in terms of, e.g., efficiencies and the time aspect.

The devices under this product category are hydrogen-specific, including new equipment and also redesigned equipment to meet the operating conditions needed for operating with pure hydrogen. Generally, burner technologies offer a unique opportunity to utilise existing infrastructure, thereby reducing investment costs in new infrastructure and facilitating a cost-effective transition to renewable gases and low-carbon energy generation. They can tolerate trace amounts of other substances in the fuel gas, making them suitable for large-scale adoption of cost-effective hydrogen conversion technologies. One significant challenge in harnessing hydrogen as an energy source lies in adapting existing industrial facilities to accommodate this new fuel. Technical hurdles associated with hydrogen combustion include managing its higher flow rate, flame temperature, and increased NO_x emissions compared to natural gas. Hydrogen combustion also poses challenges such as flame invisibility and heightened potential for leakage compared to other fuels. This product category includes different devices for heat production from hydrogen combustion, including hydrogen ICEs for mobility and large industrial devices. Based on differences in the potential representative products, two subcategories are defined: 'PSC11.1: Internal combustion engines for hydrogen-powered vehicles' and 'PSC11.2: Large industrial devices for thermal energy production from hydrogen'.

4.5.3.1. PSC11.1: Internal combustion engines for hydrogen-powered vehicles

Hydrogen ICEs can leverage existing technologies and, when run on green hydrogen, provide a viable zero-carbon option for various use cases in the mobility sector. Hydrogen ICE vehicles could complement fuel cell electric vehicles and battery electric vehicles across multiple applications, supporting the growth of hydrogen infrastructure (Candelaresi et al., 2021) and potentially providing advantages in terms of payload penalties, space requirements, refuelling time, costs, and tolerance for heat and vibrations. These benefits make hydrogen ICEs particularly advantageous for ships and various vehicle segments, such as light-duty vehicles (e.g. tow trucks), medium-duty vehicles (e.g. medium-haul and fire trucks), heavy-duty vehicles (e.g. concrete trucks), mining and construction vehicles (e.g. crawler dozers, excavators, and dump trucks), and agricultural vehicles (e.g. harvesting machinery and tractors). While hydrogen combustion releases no carbon emissions, it does produce NO_x, as a result of heating air to high temperatures, which should be taken into consideration. The suggested CPA code is 'C.29.10.1 Internal combustion engines of a kind used for motor vehicles'.

4.5.3.2. PSC11.2: Large industrial devices for thermal energy production from hydrogen

Large industrial devices for thermal energy production from hydrogen encompass advanced technologies tailored to efficiently harness hydrogen's energy potential on a large scale, particularly in hard-to-abate sectors. These include hydrogen-fired gas turbines and engines, which utilise hydrogen combustion to drive mechanical systems and generate substantial thermal energy. Hydrogen-fuelled boilers are also pivotal, producing high-temperature steam for industrial processes such as chemical synthesis and power generation. A further promising application is hydrogen use in blast furnaces. This subcategory is not limited to the aforementioned technologies and could include future developed devices for thermal energy production specifically designed for hydrogen. The suggested CPA code is 'C 28.21.1 Ovens and furnace burners and parts thereof'.

5. Conclusion

Given the diversity and complexity of technologies within the hydrogen value chain, there is a clear need for PEFCRs specific to FCH systems. These PEFCRs will help in accurately assessing and comparing the environmental impacts of various hydrogen production, conditioning, storage, transport and use systems belonging to the same product (sub)category. The present

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document successfully establishes a robust FCH product categorisation framework based on a comprehensive review, screening and reporting of the available FCH systems, while considering the latest European Commission recommendation for PEF studies. This framework addresses the hydrogen value chain from production to use.

The current document provides, for the first time, a list of FCH-specific product categories and subcategories for PEF studies in the hydrogen value chain. By defining the 11 product categories and 14 subcategories below, the document lays the groundwork for systematic and comparative environmental assessment of FCH systems. In this regard, HyPEF Task 2.3 relies on the product categorisation presented in this deliverable to subsequently select three product categories for which PEFCRs shall be developed and applied in HyPEF.

Family (i): Devices for hydrogen production	
PC1: Devices for hydrogen production	PSC1.1: Thermochemical plants for hydrogen production
	PSC1.2: Electrochemical devices for hydrogen production
Family (ii): Devices for hydrogen conditioning	
PC2: Compressors specific to hydrogen conditioning	
PC3: Liquefaction units specific to liquid hydrogen production	
PC4: Regasification units of liquid hydrogen	
Family (iii): Devices for hydrogen storage	
PC5: Tanks for hydrogen storage	PSC5.1: Tanks for liquid hydrogen storage
	PSC5.2: Tanks for compressed hydrogen at moderate storage pressures
	PSC5.3. Tanks for compressed hydrogen storage for passenger cars and tube trailers
	PSC5.4. Tanks for compressed hydrogen storage for heavy-duty mobility
	PSC5.5. Tanks for cryo-compressed hydrogen storage
PC6: Sites for large-scale geological storage of gaseous hydrogen	
Family (iv): Devices for hydrogen transport	
PC7: Vehicles and ships for hydrogen transport	PSC7.1: Trailer trucks for liquid hydrogen transportation
	PSC7.2: Trailer trucks for gaseous hydrogen transportation
	PSC7.3: Large ships for hydrogen transmission
PC8: Pipelines for hydrogen transport	PSC8.1: Pipelines for hydrogen transmission
	PSC8.2: Pipelines for hydrogen distribution
Family (v): Devices for hydrogen use	
PC9: Hydrogen fuel cells intended for electricity production	
PC10: Hydrogen fuel cells for combined heat and power generation	
PC11: Devices intended for heat production from hydrogen	PSC11.1: Internal combustion engines for hydrogen-powered vehicles
	PSC11.2: Large industrial devices for thermal energy production from hydrogen

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